

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**EXPERIMENTAL STUDY OF SUBSTANDARD RC FRAMES
ENHANCED WITH TUBE-IN-TUBE BUCKLING-RESTRAINED BRACES**



Ph.D. THESIS

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Department of Earthquake Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**BURKULMASI ÖNLENMİŞ TÜP İÇİNDE TÜP ÇAPRAZLAR İLE
İYİLEŞTİRİLMİŞ STANDART ALTI BETONARME ÇERÇEVELERİN
DENEYSEL ÇALIŞMASI**

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Date of Defense : 18 June 2025





Dedicated to my dearest spouse and wonderful children,



FOREWORD

The completion of this doctoral thesis marks the culmination of a journey that would not have been possible without the support, guidance, and encouragement of many remarkable individuals.

First and foremost, I would like to express my sincere gratitude to my advisor, Prof. Dr. Abdul HAYIR, for his invaluable mentorship, guidance, and unwavering support throughout every stage of my research. His expertise and critical perspective have greatly enriched both the academic rigor and the quality of this dissertation. I am also deeply thankful to my committee members for their thoughtful feedback and guidance. In particular, I wish to extend my heartfelt appreciation to Prof. Dr. Bülent AKBAŞ for his profound insight, intellectual generosity, and constructive encouragement.

I am profoundly grateful to my dear husband, Assoc. Prof. Dr. Reşat OYGUÇ, for his technical support, unwavering emotional encouragement and for creating a peaceful and supportive home environment throughout this journey. His understanding and patience have been a source of great strength, enabling me to persevere through the most challenging moments. His presence has truly been the cornerstone of my resilience and determination.

My heartfelt thanks also go to my precious children, Mehmet Altay, Ömer Erkan, and Nadide Ece, whose patience, understanding, and boundless affection have been a constant source of motivation and happiness. Their willingness to share their time, adapt to my academic commitments, and offer gentle encouragement gave me the energy to continue when the path was difficult. The joy and inspiration they brought into my life served as a reminder of the greater purpose behind my efforts. I am deeply appreciative of the sacrifices they made, and the unwavering support they provided, often with a maturity beyond their years. Their love and laughter filled our home with hope, making each achievement along this journey all the more meaningful.

I could not have reached this milestone without the enduring love, patience, and encouragement of my family. I am especially grateful to my dear mother-in-law Berna OYGUÇ, whose kindness, encouragement, and steadfast support have meant so much to me. Her belief in me and her thoughtful presence have been a comfort and inspiration.

To all of you, I extend my deepest appreciation. This achievement belongs as much to you as it does to me.

June 2025

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ABBREVIATIONS

ACI	: American Concrete Institute
AFAD	: Afet ve Acil Durum Yönetimi Başkanlığı
ATC	: Applied Technology Council
BRB	: Buckling-Restrained Brace
DBE	: Design Basis Earthquake
EAF	: East Anatolian Fault
FEM	: Finite Element Method
FRP	: Fiber Reinforced Concrete
HSS	: Hollow Structural Section
LVDT	: Linear Variable Differential Transformer
MCE	: Maximum Considered Earthquake
RC	: Reinforced Concrete
SCED	: Self-Centering Energy Dissipative
TBEC	: Turkish Building Earthquake Code
TnT-BRB	: Tube-in-Tube Buckling-Restrained Brace
TS	: Turkish Standard



SYMBOLS

t	: Time
ε	: Normal strain
γ	: Shear strain
E	: Modulus of elasticity (Young's modulus)
f_c	: Compressive strength of concrete
f_y	: Yield strength of reinforcing steel
σ	: Stress
Δ	: Interstorey drift
P	: Axial load
V	: Shear force
M	: Moment
D	: Damage index
ξ	: Damping ratio
ω	: Angular frequency
T	: Fundamental period of vibration
L	: Length
h	: Effective height of story or column
A	: Cross sectional area
μ	: Ductility factor
ψ	: Rotation angle



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EXPERIMENTAL STUDY OF SUBSTANDARD RC FRAMES ENHANCED WITH TUBE-IN-TUBE BUCKLING-RESTRAINED BRACES

SUMMARY

This thesis offers an advanced and comprehensive evaluation of the seismic retrofitting of substandard reinforced concrete (RC) frames using an innovative tube-in-tube buckling-restrained brace (TnT BRB) system. The research addresses a pervasive global problem: the critical seismic vulnerability of existing RC building stock constructed before the enforcement of modern design standards, particularly in regions such as Türkiye. These buildings are typified by insufficient ductility, poor reinforcement detailing, and limited lateral stiffness, leading to their disproportionate collapse and loss during strong earthquakes.

The study begins by framing seismic retrofitting as a sustainable alternative to demolition, noting its benefits in reducing material consumption, construction waste, and embodied carbon. The research reviews the current spectrum of retrofitting options, noting that while column jacketing, shear walls, and fiber-reinforced polymers (FRPs) offer some improvements, they suffer from practical limitations including weight, construction complexity, and floor space loss. Buckling-restrained braces (BRBs) have emerged as an optimal solution due to their stable, symmetrical hysteretic behavior and consistent energy dissipation. Yet, traditional BRBs, especially mortar-filled types, present challenges in terms of mass, constructability, and post-earthquake inspection. Recent engineering advances have produced all-steel, tube-in-tube variants, which promise greater ductility, ease of replacement, and fabrication efficiency, but whose performance in deficient RC frames has not been robustly verified prior to this work. This survey sets the stage for the present work, which positions the TnT BRB as a solution engineered to overcome the disadvantages of mass, buckling risk, and replacement difficulty that beset earlier systems.

The TnT BRB system is engineered with an internal load-bearing tube and an outer buckling-restrainer tube, separated by a carefully calibrated gap. The configuration includes a ring-shaped stopper and robust end plate and gusset connections, all optimized to enable rapid replacement and ensure the brace's performance in both tension and compression. Laboratory cyclic tests of the TnT BRB itself demonstrated fully symmetrical and ductile behavior, with maximum ductility reaching 10 and cumulative ductility of about 250, while keeping the compression overstrength close to 10%. This indicates minimal unbalanced force transfer to the host frame and highlights the potential for stable energy dissipation without sacrificing stiffness or strength.

The study's primary significance lies in its empirical assessment of the TnT BRB for retrofitting substandard RC frames. A sophisticated experimental program was implemented using the 3 m × 3 m two-degree-of-freedom shake table at Allianz Teknik in Istanbul. Systematic shake-table experiments on two one-third-scale, one-story, one-bay frame specimens: a "*bare reference frame*" and an identical "*frame retrofitted*

with a *TnT BRB*” were conducted. These frames are deliberately constructed using low-strength concrete of 9 MPa and minimal reinforcement to authentically represent the deficiencies found in the Turkish building stock from the 1980s.

The test design employed strict similitude principles, including the use of 6 tons of additional roof mass to correctly simulate inertial effects and gravitational loading as observed in real structures. Fourteen steel blocks, each 430 kg, are welded together and anchored to the slab to replicate prototype mass and inertia, ensuring the dynamic similitude required for valid seismic scaling. The *TnT BRB* itself is built as a dual-segment outer steel tube encasing a 42×1.5 mm inner tube, separated by a small annular gap and restrained by a mid-span stopper, with end connections detailed for field realism and minimized end rotation.

Instrumentation is extensive and precise. High-frequency linear variable differential transformers (LVDTs) and accelerometers, together with twelve strategically placed strain gauges, allow for real-time monitoring of displacement, acceleration, and strain histories at critical locations, particularly the beam–column joints and brace elements. The test protocol begins with system identification using white noise and free vibration, then subjects both frames to a scaled version of the 2023 Kahramanmaraş earthquake record, selected for its contemporary relevance and spectral compatibility with the latest Turkish code requirements. In the first phase, both frames are loaded to 0.35g; subsequently, the *TnT BRB*-retrofitted frame is tested under the full 1g record to explore its ultimate capacity.

In the control frame, the first sign of damage appeared at only 35% of the scaled ground motion, with progressive shear cracking at the beam–column joints, severe lateral displacement (maximum story drift of 5.5%), and rapid degradation of both strength and stiffness. The Park–Ang damage index for the bare frame reached 0.89, firmly in the near-collapse range. These outcomes align closely with the widespread field damage observed during the 2023 Kahramanmaraş earthquake, illustrated by the photographic evidence included in the study. The field data underscore that brittle joint failures, inadequate reinforcement anchorage, the use of substandard concrete, and poor construction practice were the predominant triggers of catastrophic loss.

By contrast, the *TnT BRB*-retrofitted frame exhibited dramatic improvements in seismic performance. Under the same shaking, no significant damage was observed, with lateral displacements held below 2 mm and the structure remaining essentially elastic. When subjected to the full, unscaled ground motion ($PGA \approx 1g$), the retrofitted frame showed peak lateral displacement of only 19.86 mm (story drift ≈ 0.02 rad), and the Park–Ang damage index rises modestly to 0.34, well below life safety limits, still without substantial concrete or reinforcement damage. The brace itself displayed minimal ductility demand (axial deformation under 5 mm and ductility below 3), remaining far from its ultimate capacity. The measured base shear increased significantly, reflecting enhanced lateral resistance, while the reduction in story drift and residual displacement was particularly notable. Detailed post-test inspection confirmed that the beam–column joints and critical gusset connections of the retrofitted frame remained virtually undamaged, even after the most severe loading.

Analytical modeling using SeismoStruct V2025 provides a rigorous parallel to the laboratory programme. Fiber-based finite element models of all specimens are calibrated using measured material properties and validated against experimental data

for natural periods, displacement histories, and top displacement, achieving discrepancies generally under 5%. A third (purely numerical) model employing a conventional X-type BRB enables direct comparison of energy dissipation and deformation patterns between retrofitting strategies. The models confirm that while the X-type BRB imparts greater initial stiffness, it produces less energy dissipation and is prone to earlier pinching and strength degradation. The TnT BRB, by contrast, sustains larger deformation cycles, maintains force symmetry, and provides superior ductility and resilience.

The study goes beyond laboratory and analytical validations to integrate broad field reconnaissance from the 2023 Kahramanmaraş earthquake, presenting collapse and heavy damage rates by province, construction type, and period, and using extensive visual documentation to correlate the laboratory findings with actual building failures. The analysis reveals that improvements in Turkish seismic codes and construction practice since 2000 have reduced, but not eliminated, collapse rates, with older RC frames and those lacking joint confinement remaining highly vulnerable.

The study concludes by synthesizing experimental and field evidence to recommend the widespread adoption of TnT BRB retrofitting for deficient RC frames. The results show that the TnT BRB can transform a frame from collapse-prone to resilient, with order-of-magnitude reductions in drift and damage even under very severe ground motions. The findings advocate for explicit inclusion of advanced, lightweight, and replaceable bracing systems in seismic retrofit codes, along with rigorous attention to joint detailing, construction quality, and field inspection.



BURKULMASI ÖNLENMİŞ TÜP İÇİNDE TÜP ÇAPRAZLAR İLE İYİLEŞTİRİLMİŞ STANDART ALTI BETONARME ÇERÇEVELERİN DENEYSEL ÇALIŞMASI

ÖZET

Bu tezde standart altı betonarme çerçevelerin depreme karşı güçlendirilmesinde kullanılmak üzere yenilikçi bir yaklaşım olarak burkulması önlenmiş tüp-içinde-tüp çapraz (TnT BRB) sistem önerilmiş ve kapsamlı bir değerlendirme çalışması sunulmuştur. Bu çalışmada, özellikle gelişmekte olan ülkelerde yaygın bir sorun olarak görülen, modern tasarım kodlarının yürürlüğe girmesinden önce inşa edilmiş betonarme yapı stoğunun deprem etkisi altında hasar görebilirliği incelenmiştir. Bu tür yapılar, yetersiz süneklik, yetersiz donatı detaylandırması ve sınırlı yatay rijitlik gibi özellikleriyle tanımlanır ve güçlü depremler sırasında orantısız bir şekilde çökmeye ve kayba neden olmaktadır.

Bu çalışma, sismik güçlendirmeyi, toptan yıkıma göre sürdürülebilir bir alternatif olarak ele alarak; malzeme tüketiminin, inşaat atıklarının ve gömülü karbonun azaltılmasındaki avantajlarını vurgulamaktadır. Araştırma kapsamında, mevcut güçlendirme seçenekleri gözden geçirilmiş ve kolon mantolama, perde duvarlar ve fiber takviyeli polimerler (FRP) gibi yöntemlerin çeşitli iyileştirmeler sunsa da ağırlık, inşaat karmaşıklığı ve kullanım alanı kaybı gibi pratik sınırlamalara sahip olduğu belirtilmiştir. Burkulması önlenmiş çapraz elemanlar (BRB), stabil ve simetrik histeretik davranışları ile enerji yutma kapasiteleri sayesinde optimal bir çözüm olarak öne çıkmıştır. Ancak, özellikle harç dolgu geleneksel BRB'ler; ağırlık, uygulanabilirlik ve deprem sonrası denetim açısından sorunlar barındırmaktadır. Son mühendislik gelişmeleriyle ortaya çıkan tamamen çelikten, tüp-içinde-tüp tipi varyantlar ise daha yüksek süneklik, kolay değiştirilebilirlik ve imalat verimliliği vaat etmektedir. Ancak, yetersiz betonarme çerçevelerdeki performansları bugüne dek kapsamlı şekilde doğrulanmamıştır. Bu literatür taraması, TnT BRB sisteminin önceki sistemlerde karşılaşılan kütle, burkulma riski ve değiştirme zorluğu gibi dezavantajları aşacak şekilde geliştirildiği bu çalışmanın zeminini oluşturmaktadır.

TnT BRB sistemi; içte yük taşıyan bir çelik tüp ile dışta burkulma engelleyici bir tüpün dikkatlice kalibre edilmiş bir aralıkla ayrıldığı yenilikçi bir yapıya sahiptir. Konfigürasyon, halka biçimli bir stoper ile sağlam uç plakası ve guse bağlantılarını içerir; tümü, hızlı değiştirilebilme olanağı sağlamak ve çaprazın hem çekme hem de basınçta istenilen performansı göstermesini güvence altına almak amacıyla optimize edilmiştir. Laboratuvar ortamında gerçekleştirilen çevrimsel yükleme testlerinde, TnT BRB tam anlamıyla simetrik ve sünek bir davranış göstermiş; maksimum süneklik 10, kümülatif süneklik ise yaklaşık 250 olarak elde edilmiştir. Basınç aşırı dayanımı ise %10 seviyesinde tutulmuş, bu da ana çerçeveye minimum dengelenmemiş kuvvet transferi ve rijitlik ya da dayanımdan ödün verilmeden kararlı enerji yutumu potansiyeli anlamına gelmiştir.

Çalışmanın temel önemi, TnT BRB'nin zayıf betonarme çerçevelerdeki güçlendirme etkisinin deneysel olarak değerlendirilmesinde yatmaktadır. Allianz Teknik'te

bulunan 3 m × 3 m boyutlarında, iki serbestlik dereceli sarsma masasında bir deney programı yürütülmüştür. Sistematik sarsma masası deneyleri, biri “güçlendirilmemiş” referans çerçeve, diğeri ise aynı boyut ve detaylarda “TnT-BRB ile güçlendirilmiş” olmak üzere, iki adet üçte bir ölçekli, tek katlı, tek açıklıklı çerçeve üzerinde gerçekleştirilmiştir. Bu çerçeveler, 1980’lerin Türk yapı stoğunda rastlanan eksiklikleri gerçekçi şekilde yansıtabilmek için basınç dayanımı 9 MPa olan düşük dayanımlı beton ve minimal donatı ile kasti olarak inşa edilmiştir.

Deney tasarımı, gerçek yapıların atalet etkilerini ve yerçekimi yüklemelerini doğru şekilde simüle etmek amacıyla 6 ton ek kütle kullanılmış ve benzerlik ilkelerine uyulmuştur. Her biri 430 kg olan on dört çelik blok birbirine kaynaklanmış ve döşemeye ankre edilmiştir. Böylece geçerli sismik ölçekleme için prototip kütle ve atalet sağlanmıştır. TnT BRB’nin kendisi, ortadan bir stoperle sınırlandırılmış, 42 × 1.5 mm boyutlarında iç tüpü çevreleyen iki segmentli dış çelik tüp olarak inşa edilmiş ve uç bağlantıları sahadaki gerçek uygulama koşullarını minimize edecek biçimde detaylandırılmıştır.

Enstrümantasyon son derece kapsamlı ve hassastır. Yüksek frekanslı lineer değişken diferansiyel transformatörler (LVDT’ler) ve ivmeölçerler ile stratejik olarak yerleştirilen on iki adet gerinim ölçer, özellikle kiriş-kolon birleşimleri ve çapraz elemanlarda yer değiştirme, ivme ve gerinim geçmişlerini gerçek zamanlı olarak izlemeye imkân tanımıştır. Test protokolü, beyaz gürültü ve serbest titreşimle başlayan sistem tanımlamasının ardından, her iki çerçevenin de seçilen 2023 Kahramanmaraş depremi kayıtlarının ölçeklenmiş versiyonuyla sarsılmasını içermektedir. İlk aşamada her iki çerçeveye 0.35g uygulanmış, ardından TnT BRB ile güçlendirilmiş çerçeve tam 1g kayıtlarıyla nihai kapasitesine kadar test edilmiştir.

Kontrol çerçevesinde, ölçeklenmiş yer hareketinin sadece %35’inde ilk hasar belirtileri görülmüş, kiriş-kolon birleşimlerinde ilerleyen kesme çatlakları, ciddi yanal yer değiştirme (maksimum kat ötelenmesi %5.5) ve hem dayanım hem de rijitlikte hızlı azalma kaydedilmiştir. Boş çerçeve için Park–Ang hasar endeksi 0.89’a ulaşarak açıkça “çökme sınırı”na işaret etmiştir. Bu sonuçlar, çalışmada yer alan devlet araştırmaları, hasar istatistikleri ve fotoğrafik kanıtlarla belgelenen 2023 Kahramanmaraş depremi sonrası sahadaki yaygın hasar ile yakın bir uyum göstermektedir. Saha verileri, gevrek birleşim hasarları, yetersiz donatı ankrajı, düşük dayanımlı beton kullanımı ve yetersiz inşaat uygulamalarının felaketle sonuçlanan kayıpların başlıca tetikleyicileri olduğunu ortaya koymaktadır.

Buna karşılık, TnT BRB ile güçlendirilmiş çerçeve sismik performansta çarpıcı iyileşmeler göstermiştir. Aynı sarsıntıda, belirgin bir hasar gözlenmemiş, yanal yer değiştirmeler 2 mm’nin altında tutulmuş ve yapı esasen elastik davranış sergilemiştir. Tam, ölçeklenmemiş yer hareketine (PGA ≈ 1g) maruz bırakıldığında bile, güçlendirilmiş çerçevede tepe yanal yer değiştirmesi sadece 19.86 mm’ye ulaşmış (kat ötelenmesi ≈ 0.02 rad) ve Park–Ang hasar endeksi hafifçe 0.34’e yükselmiş; yine de önemli beton veya donatı hasarı oluşmamıştır. Çaprazın kendisinde ise minimum süneklik talebi (5 mm’nin altında eksenel deformasyon ve süneklik 3’ün altında) kaydedilmiş ve nihai kapasitenin çok uzağında kalınmıştır. Ölçülen taban kesmesi belirgin şekilde artarken, kat ötelenmesinde ve kalıcı yerdeğiştirmede kayda değer azalma gözlenmiştir. Ayrıntılı test sonrası inceleme, en şiddetli yüklemelerden sonra dahi, kiriş-kolon birleşimleri ve kritik guse bağlantılarının neredeyse hiç zarar görmediğini doğrulamıştır.

SeismoStruct V2025 ile gerçekleştirilen analitik modelleme, laboratuvar programının sağlam bir tamamlayıcısı olarak öne çıkar. Tüm numunelerin fiber tabanlı sonlu eleman modelleri, ölçülen malzeme özellikleriyle kalibre edilmiş ve doğal periyotlar, yer değiştirme geçmişleri ve tepe deplasmanları açısından deneysel verilerle doğrulanmış, genel olarak %5'in altında hata oranı elde edilmiştir. Sadece sayısal sonlu elemanlar modeli oluşturulan, konvansiyonel X tipi BRB ile enerji sönümleme ve şekil değiştirme davranışlarının doğrudan karşılaştırılması yapılmıştır. Modeller, X tipi BRB'lerin başlangıç rijitliğinin yüksek olduğunu, ancak daha az enerji sönümlediğini ve erken sıkışma etkisi ile dayanım kaybına eğilimli olduklarını doğrulamıştır. TnT BRB ise, daha büyük şekil değiştirme çevrimlerinde kuvvet simetrisini korumuş, üstün süneklik ve dayanıklılık sunmuştur.

Çalışma, laboratuvar ve analitik doğrulamaların ötesine geçerek, 2023 Kahramanmaraş depremi sonrası geniş kapsamlı saha gözlemlerini de bütünleştirmekte; laboratuvar bulgularını gerçek yapı hasarlarıyla karşılaştırmak için kapsamlı görsel dokümantasyon kullanmaktadır. Analizler, 2000 sonrası Türk deprem yönetmelikleri ve inşaat pratiğindeki gelişmelerin çökme oranlarını azalttığını ancak yeterli birleşim sıklaştırması olmayan eski betonarme çerçevelerin hala yüksek risk altında olduğunu ortaya koymaktadır.

Çalışma, deneysel ve saha bulgularını sentezleyerek, zayıf betonarme çerçevelerin TnT BRB ile güçlendirilmesini önermektedir. Sonuçlar, TnT BRB'nin bir çerçeveyi çökme eğiliminden dayanıklı hale getirebileceğini ve çok şiddetli yer hareketlerinde bile ötelenme ve hasarda önemli bir azalma sağlayabileceğini göstermektedir. Bulgular, ileri, hafif ve değiştirilebilir çapraz sistemlerin sismik güçlendirme yönetmeliklerinde açıkça yer almasını; birleşim detaylandırmasına, inşaat kalitesine ve saha denetimine titizlikle yaklaşılmasını önermektedir.



1. INTRODUCTION

The seismic vulnerability of existing reinforced concrete (RC) buildings remains one of the most pressing and widely acknowledged challenges in structural engineering and urban risk management today. Decades of urbanization across seismic regions, spanning the Mediterranean, Asia, North and South America, and parts of Eastern Europe, have resulted in dense, aging building stocks that largely predate the advent of modern seismic design codes. These buildings, often constructed with an emphasis on material economy, speed, and compliance with outdated standards, frequently lack the very attributes now recognized as foundational for seismic resilience: ductile detailing, robust confinement at joints, and adequate lateral force resistance. Nowhere has this reality been more painfully underscored than in the recent series of devastating earthquakes, most notably the 2023 Kahramanmaraş events in Türkiye, where the mass failure of legacy RC structures laid bare the long-term consequences of historic construction practices and insufficient retrofitting.

The essential problem is not limited to the broad global stock of non-ductile frames, but is particularly acute at the level of local detailing and critical component performance. It has become clear through post-earthquake reconnaissance, forensic analysis, and systematic laboratory research that the majority of catastrophic failures in older RC buildings originate at the beam–column joints. These nodes, which serve as the structural joints connecting horizontal and vertical elements, are subjected to the highest concentrations of seismic demand. Their detailing, whether or not they are properly confined, whether their longitudinal reinforcement is well anchored, whether transverse reinforcement is sufficient and well-placed, ultimately governs the ability of a building to redistribute forces and avoid brittle mechanisms under intense, cyclic, multidirectional shaking. Inadequate joints often initiate diagonal shear cracking, cover spalling, anchorage loss, and bar slip long before beams or columns themselves reach their theoretical limits. When these weaknesses are activated during a strong earthquake, the result is a rapid, sometimes near-simultaneous loss of story stiffness and, in the worst cases, total progressive collapse.

These technical shortcomings carry profound social and economic implications, extending far beyond the realm of engineering to shape the lived reality of urban populations. In Türkiye, as in many other seismic countries, RC buildings constructed from the 1950s through the 1990s form the backbone of the national housing stock, as well as much of its schools, hospitals, and critical infrastructure. The scale of the challenge makes the prospect of wholesale demolition and replacement neither economically feasible nor environmentally responsible. The embodied carbon, construction waste, and resource demand associated with mass rebuilding are now recognized as major drivers of global sustainability concerns. As a result, there is broad consensus among engineers, policymakers, and urban planners that seismic retrofitting, strengthening, rehabilitating, and adapting existing structures, is not only preferable but absolutely essential. Retrofitting represents a means to reduce risk, preserve built heritage, conserve resources, and, increasingly, to promote rapid urban recovery after disaster.

The search for effective, scalable, and cost-efficient retrofit technologies has been at the heart of earthquake engineering research for decades. Conventional strengthening techniques, such as column jacketing with steel or concrete, the addition of RC shear walls, and the wrapping of members with fiber-reinforced polymers (FRPs), have all demonstrated varying degrees of efficacy in laboratory and field applications. Each method, however, presents distinct trade-offs. Jacketing can improve local capacity but at the expense of added weight and disruption to architectural function. Shear walls, while imparting substantial stiffness, may constrain usable space and introduce plan irregularities that themselves become sources of seismic vulnerability. FRPs offer high strength-to-weight ratios and corrosion resistance, but their effectiveness is limited by fire exposure, application complexity, and difficulties in inspection or repair after seismic events.

Against this backdrop, supplemental energy dissipation devices, particularly buckling-restrained braces (BRBs), have emerged as a transformative solution in the seismic retrofitting of RC frames. The fundamental concept of a BRB is to provide a structural element that yields in both tension and compression under cyclic loads, maintaining high, stable energy dissipation capacity without succumbing to buckling. The earliest iterations of BRBs relied on a yielding steel core encased in a restraining tube filled with mortar or concrete. This restrainer prevents out-of-plane buckling and ensures

that the steel core can fully develop its ductility under both loading directions. BRBs have now been widely recognized for their ability to impart high post-yield stiffness, stabilize frame response, and prevent the formation of soft stories and localized collapses in retrofitted structures. Their symmetrical hysteretic behavior, marked by wide, stable, non-pinned loops, translates into robust energy absorption and low residual drifts even under strong ground motions.

Yet, despite their technical promise, traditional mortar-filled BRBs are not without significant drawbacks. The use of concrete or mortar infill adds substantial mass, increases installation complexity, and introduces difficulties in post-earthquake inspection and repair. In addition, heavy braces may not be suitable for integration into all existing buildings, particularly where foundation or floor capacities are limited. The practicalities of transporting, erecting, and anchoring such braces, especially in densely occupied or irregularly shaped structures, further limit their widespread adoption in the retrofit of typical residential and commercial buildings.

It is in this context that the innovation and evolution of the all-steel, tube-in-tube (TnT) buckling-restrained brace takes on particular significance. Unlike conventional BRBs, the TnT system eliminates the need for mortar or concrete and replaces it with a lightweight, all-steel architecture. The core of the device is a slender, ductile steel tube that yields in axial tension and compression. This tube is enclosed by a larger-diameter outer tube that acts as the buckling restrainer, separated by a carefully controlled annular gap that permits free deformation without direct contact under service loads. By dispensing with heavy infill, the TnT BRB dramatically reduces brace weight, eases handling and installation, and, crucially, allows for the direct inspection and easy replacement of the yielding core element after seismic events.

The operational advantages of the TnT BRB are matched by its technical performance. Laboratory testing, including both quasi-static cyclic loading and dynamic shake table experiments, has consistently demonstrated that TnT BRBs deliver highly stable, symmetrical hysteretic responses, maintain low compression overstrength, and exhibit repeatable energy dissipation up to large deformation demands. Their lightweight nature makes them especially attractive for the retrofit of existing frames where added mass or foundation demand must be minimized. The modular, replaceable design further facilitates post-event reparability, an increasingly important consideration in

performance-based seismic engineering, where the aim is not merely to prevent collapse but to ensure rapid restoration of function after earthquakes.

The present study distinguishes itself within this context of continuous advancement through a series of key contributions that collectively establish both its technical novelty and its practical impact. First, the experimental program described in the manuscripts departs from prior work by employing actual ground motion records from the catastrophic 2023 Kahramanmaraş earthquakes. By aligning the imposed demands with the true frequency content, duration, and amplitude of a recent, high-impact seismic event, the study achieves a level of practical relevance and empirical robustness that is often lacking in investigations that rely on synthetic, historical, or artificially scaled loading protocols. This fidelity ensures that the laboratory findings speak directly to the vulnerabilities exposed in real buildings during recent earthquakes, thereby bridging the persistent gap between controlled research and field reality.

Equally significant is the application of rigorous similitude principles in the experimental design. The specimens, constructed at one-third scale, are not mere arbitrary models but are products of meticulous dimensional analysis, grounded in the Buckingham π theorem and informed by decades of shake table testing methodology. Concrete mixes and reinforcement layouts are tailored to replicate the properties of Turkish RC frames from the 1980s, with low compressive strengths and deficient detailing that authentically reproduce the behavior of substandard buildings observed in the field. This approach ensures that observed phenomena, whether drift ratios, energy dissipation, or damage modes, can be credibly extrapolated to prototype structures.

The experimental campaign itself is both comprehensive and systematic. It encompasses not only bare (unretrofitted) RC frames, selected to represent the prevalent deficiencies of the existing stock, but also frame retrofitted with the innovative TnT BRB system. Each specimen is subjected to the same sequence of earthquake records, and every critical response metric, maximum and residual story drift, joint cracking, shear failure progression, hysteresis loops, and global strength, is meticulously monitored and recorded. The results are unambiguous: unretrofitted frames exhibit rapid stiffness degradation, brittle joint failures, and excessive lateral displacements that far exceed code-acceptable limits. By contrast, retrofitted frames,

and especially those with TnT BRBs, display controlled, ductile behavior with stable energy dissipation, minimal pinching, and marked suppression of brittle joint mechanisms.

These experimental findings are reinforced and further elucidated through high-fidelity fiber-based finite element modeling. The numerical models are carefully calibrated to reproduce the key features of the experimental response, including not only global frame behavior but also local phenomena such as joint shear cracking, bond slip, and bar anchorage loss. Despite the inherent challenges in modeling such complex, nonlinear phenomena, especially at the microstructural scale, the simulations achieve strong correlation with laboratory observations, capturing the sequence of yielding, joint damage, and overall frame deformation. The integration of advanced modeling with experimental data allows for exploration of parameter spaces and scenarios beyond those directly accessible in the laboratory, offering valuable guidance for practical design and further research.

An especially notable aspect of the current work is its emphasis on reparability and functional recovery. The TnT BRB, unlike many conventional retrofit technologies, is designed not only to protect life safety during strong earthquakes but also to facilitate rapid post-event inspection and repair. The ability to replace a yielding core without major demolition or disturbance to the building's occupants is a substantial step forward, aligning the technology with emerging performance-based objectives that emphasize not just survival but swift restoration of societal function. In a world where earthquakes are increasingly recognized not just as natural disasters but as catalysts for extended economic and social disruption, this aspect of the TnT BRB is of fundamental practical importance.

The empirical and numerical work documented in this study is further distinguished by its explicit connection to field observations and damage surveys. Photographs and schematic diagrams embedded throughout the reports capture the actual damage patterns, shear cracking, concrete spalling, joint failure, bar slip, observed in the aftermath of the 2023 Kahramanmaraş earthquakes. The correspondence between these real-world damage mechanisms and those reproduced in the laboratory is both striking and validating, providing an extra layer of confidence in the applicability of the research findings. By closing the loop between field reconnaissance, laboratory

investigation, and numerical simulation, the study sets a new standard for comprehensive, multi-scale seismic research.

The novelty of this investigation, then, is not rooted in any single innovation, but in the confluence of multiple, mutually reinforcing advances. It is reflected in the use of real, contemporary ground motions; in the faithful replication of historic construction deficiencies; in the direct, side-by-side comparison of traditional and novel retrofitting strategies; in the rigorous integration of experiment and simulation; and in the explicit connection to field data and real-world performance. Collectively, these features move the work beyond the incremental and into the realm of transformative, practice-changing research.

The implications for practice and policy are substantial. For engineers, the results provide not only proof of concept but a robust, quantitative benchmark for the expected performance of TnT BRBs in deficient RC frames. The observed reductions in story drift, suppression of brittle failures, and enhancement of energy dissipation offer direct, actionable guidance for design, assessment, and code development. For policymakers and building owners, the work demonstrates that it is possible to achieve substantial seismic risk mitigation, not by replacing entire neighborhoods or cities, but by targeted, cost-effective retrofitting that leverages the latest advances in structural engineering. The environmental benefits, too, are significant: by preserving and upgrading existing stock rather than rebuilding, TnT BRBs contribute to the reduction of embodied carbon, conservation of resources, and minimization of construction waste, all central goals in contemporary sustainability agendas.

As the world's cities continue to grow and densify, often in precisely the regions most exposed to seismic hazard, the stakes of retrofit innovation have never been higher. The demand for lightweight, easily installed, modular, and repairable solutions will only increase as populations swell, resources tighten, and expectations for urban resilience rise. The tube-in-tube buckling-restrained brace, as validated and advanced through the research described here, is ideally poised to meet these challenges. Its combination of high performance, practical constructability, and post-event reparability marks it as a central technology in the next generation of seismic risk management.

Nonetheless, challenges and opportunities for further development remain. The integration of TnT BRBs into the full spectrum of existing building types, including irregular, multi-story, or mixed-use structures, will require continued refinement of connection details, anchorage systems, and assessment protocols. The potential for further innovation in materials, sensing, and health monitoring is vast, with opportunities to embed intelligence and adaptability directly into retrofitting systems. The translation of laboratory and simulation findings into mainstream design practice will demand continued engagement with code development bodies, practitioners, and stakeholders across the construction sector.

In conclusion, this body of work represents a significant leap forward in the field of seismic retrofitting. Through its integration of cutting-edge laboratory science, high-fidelity simulation, authentic field observation, and practical design guidance, it sets a new benchmark for what is possible in the quest to reduce seismic risk. The tube-in-tube buckling-restrained brace, as developed and validated in this research, stands as a testament to the power of innovation, rigor, and multidisciplinary collaboration in confronting one of the defining challenges of our time. The lessons drawn from this research will reverberate far beyond Türkiye, informing and inspiring efforts to build safer, more sustainable, and more resilient cities around the world.



2. ASSESSMENT OF A SUBSTANDARD REINFORCED CONCRETE FRAME'S BEAM–COLUMN JOINT USING SHAKE TABLE TESTING¹

This study investigates the seismic performance of substandard reinforced concrete (RC) frames, particularly emphasizing the behavior of beam–column joints through comprehensive shake table testing. Historical evidence indicates that RC structures erected prior to the 1970s frequently exhibit critical deficiencies in shear reinforcement, significantly undermining their seismic resilience. The primary objective of this research is to experimentally quantify the shear capacity, deformability, and failure mechanisms of beam–column joints within substandard RC frames. Shake table experiments were conducted on a meticulously scaled (one-third scale), single-story, single-bay RC frame, representative of construction practices typical of 1980s Türkiye. The input seismic loading was derived and scaled from the recorded ground motions of the 2023 Kahramanmaraş earthquake to ensure realistic seismic demand conditions. Experimental outcomes revealed a maximum lateral displacement of 53.1 mm, corresponding to a story drift ratio of approximately 0.055 radians and a computed damage index of 0.758, indicative of near-collapse performance levels. Notable damage observations included extensive shear cracking and concrete spalling at beam–column interfaces, accompanied by pronounced pinching effects during cyclic loading. The findings emphasize an urgent need for targeted seismic retrofit solutions, specifically addressing shear vulnerabilities in beam–column joints. Furthermore, the results carry substantial implications for revising current seismic design codes and enhancing the earthquake resilience of existing RC infrastructure in seismic-prone regions.

¹ This chapter is based on the article: Oyguc, E., Oyguc, R., & Hayir, A. (2025). Assessment of a Substandard Reinforced Concrete Frame's Beam–Column Joint Using Shake Table Testing. *Applied Sciences*, 15(8), 4168. <https://doi.org/10.3390/app15084168>

2.1 Introduction

The seismic vulnerability of reinforced concrete (RC) structures, especially those constructed before the enforcement of contemporary seismic design codes, continues to represent a critical area of concern in the field of earthquake engineering. This vulnerability primarily arises due to significant inadequacies in structural detailing, reinforcement practices, and concrete quality. Numerous global seismic events have repeatedly underscored the catastrophic potential of damage to such inadequately designed structures, particularly in regions of structural significance, like beam–column joints. These joints are fundamental elements in structural integrity, effectively governing force transmission between beams and columns, thus critically influencing the overall seismic performance of buildings during earthquakes (Paulay and Park 1984, Saatcioglu et al. 2001, Gautam et al. 2021). Historically, many RC buildings constructed prior to the 1970s neglected adequate seismic considerations, resulting in the widespread occurrence of brittle failure mechanisms at these joints, largely due to deficiencies such as insufficient shear reinforcement, inadequate anchorage lengths, and sub-standard concrete quality (Oyguc and Guley, 2016; Ricci et al., 2016; Ahmad et al., 2019; Melo et al., 2022). Hence, the systematic assessment and effective enhancement of these vulnerable elements are imperative objectives for researchers and structural engineers focused on mitigating earthquake-induced hazards.

The key factors that influence the seismic behavior of RC beam–column connections under cyclic loading include the shear strength of the joint, the presence of inadequate anchorage, and the aspect ratio of the joint (Kalogeropoulos et al., 2024). This type of damage occurs in the most severe scenarios during an earthquake. It contributes to a reduction in the stiffness of the structural element to an unpredictable degree. As such, it is important to exercise special care for this part of the structural system even when microcracks are beginning to form. Damage from cyclic loading at beam–column joints is categorized into three types: corner joint failures, exterior joint failures, and interior joint failures, as illustrated in Figure 2.1 (Oyguc, 2022). The primary goal of seismic design is to limit the development of potential plastic hinges at the column faces of a joint while permitting inelastic behavior to be distributed along the beam section. Such developments frequently lead to the spalling of cover concrete and anchorage failures due to the residual deformations at the joint.

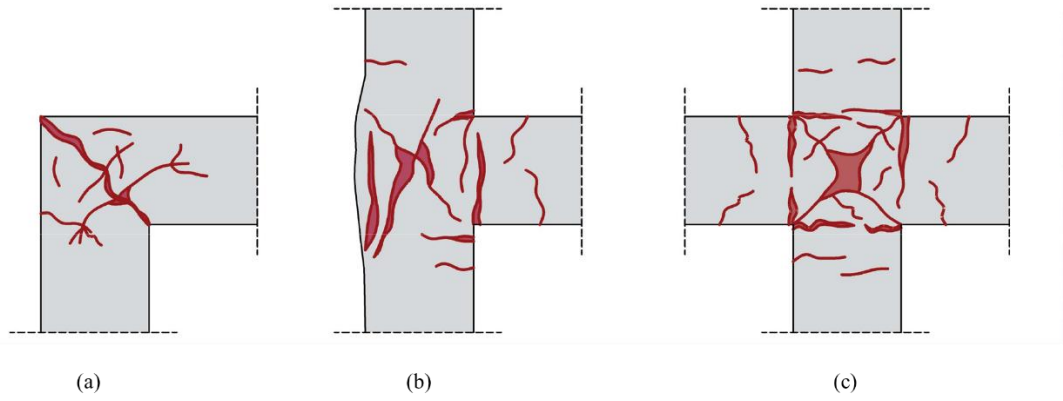


Figure 2.1 : Failure of cyclic seismic action: (a) corner joint, (b) exterior joint, and (c) interior joint.

To thoroughly examine and significantly improve the seismic performance of RC structures, numerous previous studies are explored within four interconnected and highly relevant methodological areas: analytical modeling techniques, experimental investigations conducted in controlled environments, the comparative analysis of various seismic design codes and guidelines, and studies supporting targeted retrofitting strategies. This comprehensive approach not only enhances understanding but also ensures the practical applicability of the findings in real-world scenarios.

Recent advancements in analytical modeling have substantially improved our ability to predict the seismic responses of reinforced concrete (RC) beam–column joints. Pantò et al. (2020) introduced a novel macro-element for analytical modeling, specifically designed for joints with hinges, which proficiently represents the nonlinear characteristics associated with RC beam–column joints. The proposed model accounts for the nonlinear shear re-sponse of the central panel, the bond–slip behavior of longitudinal reinforcement bars, and the nonlinear dynamics occurring within plastic hinge zones. Hassan et al. (2022) proposed a model that exhibits a consistent probability of exceedance at 50%, which is in accordance with the revised provisions for nonlinear beams and columns. Furthermore, it reveals a strong correlation with both the test database and the validation datasets. This correlation indicates that revising existing seismic assessment standards in light of this model could improve both the precision and cost-effectiveness of performance-based seismic design for ductile concrete frames. Collectively, these validated analytical methodologies from the recent literature provide robust and precise tools for evaluating seismic vulnerabilities, facilitating targeted and effective retrofitting solutions to enhance

structural resilience. Grande et al. (2023) underscore the essential function of beam–column joints in evaluating the seismic safety of RC frames. It particularly draws attention to the unforeseen damage mechanisms that have emerged during previous seismic occurrences, which significantly impacted these joints. To investigate this further, the authors formulated a finite element model introducing an additional element positioned between the beam and column members. This model effectively replicates the nonlinear behavior of beam–column joints, thereby illustrating the importance of incorporating these joints in the seismic analysis of RC frames through numerical simulations. Suwal and Guner (2024) discussed improvements in analytical modeling achieved by creating a feed-forward artificial neural network (FFNN) designed to estimate the shear strengths of beam–column joints made of RC. The proposed methodology improves the precision and dependability of forecasting seismic responses, effectively mitigating the shortcomings associated with conventional rigid end offsets in joint modeling.

Complementing these analytical studies, experimental investigations remain indispensable for validating theoretical models and capturing complex seismic phenomena empirically. Fundamental experimental methodologies, such as shake table and cyclic load testing, enable researchers to simulate realistic earthquake scenarios, facilitating detailed analyses of structural responses within controlled laboratory settings. Studies consistently underscore the susceptibility of beam–column joints, highlighting prevalent damage patterns like severe shear cracking, concrete spalling, bar slip, and a loss of joint confinement. Hanson and Connor (1967) were pioneers in experimentally demonstrating that beam–column joints, which are confined to all four sides by beams, show enhanced performance under reversed cyclic loading. Their findings led to the conclusion that such joints do not need additional shear reinforcement. On the other hand, joints that lack confinement necessitate both shear and transverse reinforcements to mitigate damage from shear cracking and to prevent the buckling of the longitudinal column reinforcement. The seminal work by Hanson and Connor (1967) is recognized within the ACI 318-19 (2019) seismic provisions as foundational research significantly influencing modern seismic design codes. Their experimental findings demonstrated that RC beam–column joints confined by beams on all four sides exhibited substantially improved seismic performance under cyclic loading, even without additional shear reinforcement. This crucial observation has led

to current seismic design standards to prioritize enhanced detailing requirements for joints lacking such beneficial confinement. Specifically, their work underpins the mandate for explicit shear and transverse reinforcement in joints not adequately confined by beams, highlighting a critical vulnerability previously underestimated in earlier design codes. Consequently, the contemporary seismic design codes extensively incorporate insights from Hanson and Connor (1967) by emphasizing rigorous beam–column joint detailing, proper confinement, and reinforcement practices. Subsequent experimental findings revealed that extensions of beams and columns, when adequately sized and reinforced with both longitudinal and transverse bars, effectively confine the joint faces. For instance, Ricci et al. (2016) conducted a series of rigorous experiments on unreinforced exterior beam–column joints using plain bars, revealing pronounced shear cracking, significant concrete spalling, and the severe degradation of stiffness under cyclic loading conditions. In parallel, Benavent-Climent et al. (2016) performed comprehensive shake table tests on RC waffle-flat plate structures. Their experiments highlighted critical phenomena such as substantial stiffness reduction and strength deterioration approaching 30% under seismic loading. The collapse process of RC frames has also been scrutinized in a scaled experimental setting. Li et al. (2016) conducted shake table tests on a three-story RC frame, systematically capturing the progressive deterioration and eventual collapse mechanism under severe seismic actions. Moreover, the work by Ahmad et al. (2019) on noncompliant special moment-resisting frames (SMRFs) further elucidates the impact of deficient seismic detailing on structural performance. Their shake table experiments demonstrated that RC frames not designed in accordance with modern seismic codes exhibit marked performance degradation, including reduced energy dissipation and increased susceptibility to brittle failure modes. Complementing these studies, Rizwan et al. (2018) compared the seismic performance of compliant and non-compliant special moment resisting frames through extensive experimental campaigns. Their results highlight significant performance differentials, with non-compliant frames exhibiting lower ductility and greater strength losses during cyclic loading. In a broader context, Gautam et al. (2021) examined the seismic fragility of both the structural and non-structural components of RC buildings in developing countries, employing scaled experimental techniques to quantify vulnerability.

The comparative studies of international seismic design codes and standards represent the third key domain of research, highlighting the importance of analyzing and harmonizing variations in global seismic design practices. Parate and Kumar (2019) extensively reviewed shear strength criteria for beam–column joints across multiple international codes, identifying significant inconsistencies and recommending unified guidelines to enhance global seismic safety standards. Fardis (2021) underscores that the CEB/FIP (Seismic Model Code) (1985) and Eurocode 8 (2004) utilize varying models for assessing the shear strength of RC joints. In this study, a novel rational model was introduced to characterize the cyclic shear strength of RC joints. Pauletta et al. (2021) concluded that exterior RC beam–column joints lacking ties that are mandated by building codes within the joint core demonstrate considerable susceptibility to seismic forces. This vulnerability results in possible failure mechanisms that could undermine the structural integrity in the occurrence of seismic activities. Basu and Lakhani (2022) presented an implicit framework for the evaluation of joint shear strength in RC beam–column connections. This framework incorporates a range of factors, including strut width, compression depth, axial loading, and bending moments at both ends of the beam and column at the point of failure. The primary objective of this approach is to ensure compliance with seismic design criteria while offering a structured methodology for accurately estimating the shear strength of the joints. Tsonos (2019) introduced simplified evaluation methodologies for joint strengths across various international codes, advocating practical yet accurate assessment tools suited for real world engineering applications. Such comparative analyses contribute significantly toward advancing and standardizing global seismic design provisions, ensuring robust structural safety and resilience across diverse regions. Chu et al. (2021) indicated that the shear capacity exhibited by steel-reinforced concrete (SRC) column–steel beam joints demonstrates an upward trend in correlation with an increase in the axial compression ratio. This suggests that the load-bearing potential of such joints can be significantly improved through the strategic optimization of the axial loads imposed on them.

At present, the formulas employed for determining joint shear strength are based on findings from earlier experimental studies. According to the latest seismic code of Türkiye (TBEC, 2018), a minimum of 40% and 60% of the transverse reinforcements must be placed in the confinement zone of the column, distributed along the heights

of the confined and unconfined joints, respectively. The code outlines that confinement for concrete is achieved through the use of transverse reinforcements, which include stirrups, hoops, and crossties. To ensure proper anchorage, it is essential that stirrups, hoops, and crossties incorporate a seismic hook that bends at least 135° . Hoops are defined as closed ties that may consist of multiple reinforcing elements, each equipped with seismic hooks on both ends, and continuous wound ties possessing seismic hooks at both ends. Crossties, on the other hand, are continuous reinforcing bars featuring a seismic hook at one end and a hook bent at 90° at the opposite end; in this context, the hooks on the crossties should engage with the peripheral longitudinal reinforcing bars, as illustrated in Figure 2.2 (TBEC, 2018).

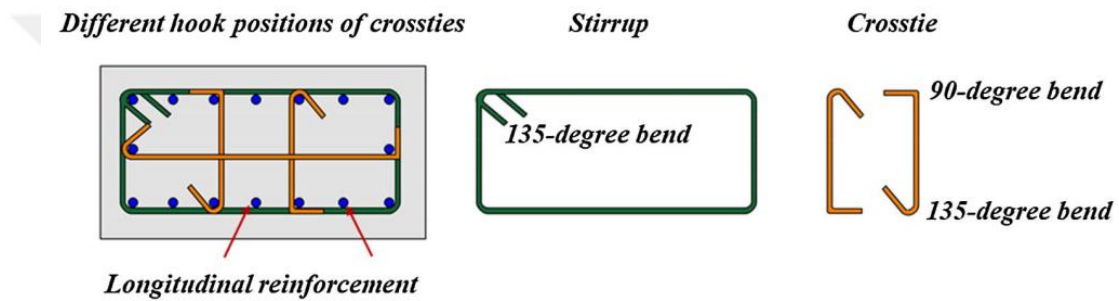


Figure 2.2 : Different hook positions of crossties.

Recent advances in retrofitting methodologies have demonstrated that targeted interventions can significantly improve the seismic performance of deficient RC structures. Experimental investigations have particularly highlighted the efficacy of advanced materials and techniques in addressing specific damage modes observed in beam–column joints. For instance, Vecchio et al. (2014) conducted an in-depth experimental study on RC beam–column joints retrofitted with fiber-reinforced polymer (FRP) systems. Their findings clearly indicate that the application of FRP wrapping not only enhances the shear capacity of the joint but also improves confinement, thereby mitigating the propagation of X-shaped shear cracks, a common damage pattern in inadequately detailed structures. Complementary studies by Realfonzo et al. (2014) further elucidate the cyclic behavior of RC joints strengthened with FRP, demonstrating significant improvements in energy dissipation and ductility. Additionally, Parvin and Granata (2000) have provided valuable insights into the effects of fiber composites on concrete joints, confirming that the application of such materials can substantially increase joint strength and delay failure mechanisms. These

targeted retrofitting strategies, substantiated by empirical evidence and advanced analytical models, underscore the necessity of adopting a holistic approach to structural rehabilitation. Our work thus contributes to the evolving discourse on seismic retrofit interventions, providing a compelling framework for the application of scientifically validated retrofitting techniques in the modernization of aging RC infrastructure.

2.2 Objectives and Novelty of the Current Study

Despite notable progress across these four research trajectories, significant gaps remain, particularly the limited number of experimental studies that integrate realistic seismic data from recent earthquakes. Most existing experimental frameworks rely on artificially generated or historical seismic data, reducing the relevance and applicability of their findings to current real world scenarios. Recognizing this critical limitation, the present research uniquely utilizes real seismic records from the catastrophic 2023 Kahramanmaraş earthquake in Türkiye within a shake table experimental framework. This innovative approach significantly enhances the practical applicability and empirical robustness of the research outcomes.

Many existing RC buildings unfortunately do not meet established quality standards. Historically, the performance of these inadequately designed frames during previous earthquakes has been concerning and unsatisfactory. Consequently, it is vital to conduct a comprehensive evaluation and improvement of these substandard buildings to mitigate potential risks and safeguard the safety of their occupants (Oyguc et al., 2018).

In pursuit of the stated ambitious objectives, the significant seismic event that occurred in Kahramanmaraş (Pazarcık) in 2023, characterized by a moment magnitude of 7.7, was employed as the basis for our research. Comprehensive shake table tests were conducted on a scaled specimen, representing one-third of the actual size, with a single story and bay configuration. The specimen was meticulously constructed to embody a typical substandard RC. The findings from this comprehensive investigation were meticulously evaluated and contrasted with respect to essential global response metrics, particularly the seismic code prerequisites. Additionally, the different damage patterns identified during the shake table tests were examined. This analysis seeks to

offer a deeper understanding of the overall efficacy of the alternative design methodology.

The central objectives of this study are therefore to address these existing knowledge gaps by systematically quantifying the seismic responses of substandard RC beam–column joints under realistic earthquake loading conditions. The investigation specifically targets the shear strength, deformation mechanisms, and failure characteristics of joints prevalent in RC constructions. Additionally, this research critically evaluates the adequacy of contemporary seismic codes in addressing structural vulnerabilities identified experimentally. By employing meticulously scaled experimental models representative of common Turkish construction practices from the 1980s, the research not only contributes valuable insights into structural retrofitting techniques but also influences future policy developments and design regulations aimed at reducing seismic risks associated with older RC infrastructures.

2.3 Experimental Study

The experimental study is undertaken utilizing a two-degrees-of-freedom shake table situated at the Allianz Teknik Earthquake and Fire Test and Training Center in Istanbul, Türkiye. This simulator table, measuring 3.0 m by 3.0 m, is engineered to accommodate a maximum payload capacity of 10 tons. Seismic forces applied to the table are controlled through hydraulic actuators. The controller employed in the simulator operates on a closed-loop system characterized by three variables alongside adaptive control and differential pressure stabilization mechanisms. Furthermore, the shake table is capable of producing a peak acceleration of 1 g, which is critical for the precise replication of realistic earthquake ground motions over a frequency spectrum ranging from 0 to 50 Hz. Table 2.1 provides a detailed overview of the technical specifications associated with the shake table. Additionally, the graphical representation pertaining to the substitution of the specimen on the shake table is provided in Figure 2.3.

Table 2.1 : Technical properties of the Allianz shaking table.

Specifications	Biaxial Seismic Simulator
Table Dimensions	3 × 3 m
Degrees of Freedom	2
Simulation Frequency Range	0–50 Hz
Maximum Actuator Displacement	±250 mm
Maximum Linear Velocity	1000 mm/s
Maximum Specimen Turning Moment	30 m-ton
Maximum Carrying Capacity	10 ton
Maximum Table Acceleration	1 g @rated load
Maximum Table Speed	1 m/s

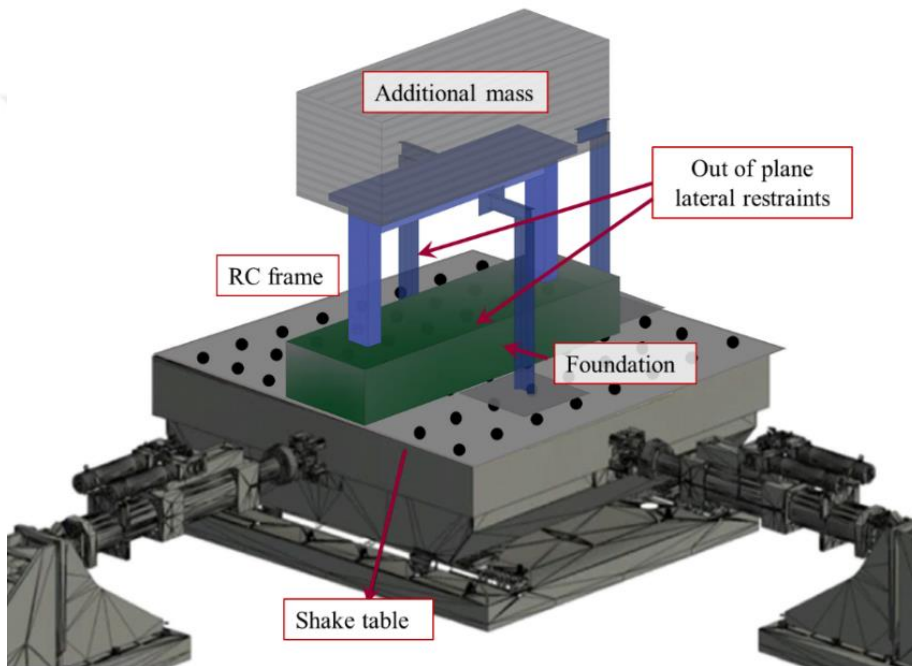


Figure 2.3 : Illustration regarding the replacement of the specimen on the shake table.

2.3.1 Criteria for similitude requirements

Modeling theory delineates the parameters necessary for relating the geometrical aspects, material characteristics, initial scenarios, boundary constraints, and environmental influences of both the model and its prototype. This relationship is crucial for enabling the behavior of one entity to be articulated as a function of the behavior exhibited by the other. The foundational principle that facilitates the formulation of a comprehensive array of correlation functions, which articulate the correspondence between the model and the prototype, is referred to as similitude (Buckingham, 1914). In this context, similitude can be understood as a conceptual

framework that leads to the derivation of an extensive array of correlation functions, referred to as scaling laws. These scaling laws serve to define the dynamics of the relationship between the model and its corresponding prototype.

Various methodologies exist to establish a relationship between the behaviors of full-scale prototypes and their reduced-scale counterparts. These methodologies encompass dimensional analysis, energy methods, similitude laws, as well as empirical similarity approaches (Casaburo et al., 2019). According to Harris and Sabnis (1999), dimensional analysis is an analytical method by which a dimensionally homogeneous equation, containing physical quantities and describing a physical phenomenon, is converted into an equivalent equation containing only the dimensionless products (π -factors) of the powers of the physical quantities. This type of analysis is based on the Buckingham π Theorem (1914), which states that a dimensionally homogeneous equation can be reduced to a functional relationship between a complete set of independent dimensionless products (π factors).

A structural model must be meticulously developed, assembled, and analyzed in accordance with specific similitude criteria that connect the model to the original prototype. These criteria stem from modeling theory, which can be established through a dimensional analysis of the physical phenomena that govern the structural behavior. In the context of dynamic model testing, dimensional analysis can be utilized to establish the principles that dictate the scaling laws associated with force, time, and other dependent dimensional quantities. This analytical approach provides a framework for understanding how these variables interact and scale in testing scenarios (Park and Ang, 1985). Table 2.2 presents a compilation of scale factors derived from similitude analysis, as discussed by Moncarz and Krawinkler (1981), specifically in the context of earthquake loading. In the realm of scaling applications, three primary physical models have been identified: the true replica model, the artificial mass simulation model, and the model that disregards gravitational forces.

This research employed an artificial mass simulation model specifically designed to fulfill the criteria of similitude regarding geometric and loading parameters. It is noteworthy that this model is compiled with nearly all material specifications, with the exception of its mass density.

Table 2.2 : Similitude laws for dynamic models (Moncarz and Krawinkler 1981).

Scaling Parameters	True Replica	Artificial Mass Simulation	Gravity Forces Neglected
Length, l_r	l_r	l_r	l_r
Time, t_r	$(l_r)^{1/2}$	$(l_r)^{1/2}$	l_r
Frequency, ω_r	$(l_r)^{-1/2}$	$(l_r)^{-1/2}$	$1/l_r$
Velocity, v_r	$(l_r)^{1/2}$	$(l_r)^{1/2}$	1
Gravitational acceleration, g_r	1	1	Neglected
Acceleration, a_r	1	1	$1/l_r$
Mass density, ρ_r	E_r/l_r	-	1
Strain, ε_r	1	1	1
Stress, σ_r	E_r	E_r	1
Modulus of elasticity, E_r	E_r	E_r	1
Specific stiffness, $(E/\rho)_r$	l_r	-	1
Displacement, δ_r	l_r	l_r	l_r
Force, F_r	$E_r l_r^2$	$E_r l_r^2$	l_r^2
Energy, $(EN)_r$	$E_r l_r^3$	$E_r l_r^3$	l_r^3

To rectify this deficiency, additional steel blocks were integrated into the roof structure, a maneuver that effectively preserved the overall stiffness of the model. Each steel block had dimensions of 1750 mm in length, 570 mm in width, and 60 mm in height, contributing an individual mass of 430 kg. In total, fourteen of these mass blocks were welded together to form a singular assembly, culminating in a comprehensive weight of 6 tons for this stacked configuration. The physical variables computed in association with this experimental approach have been detailed in Table 2.3. Table 2.2 delineates the similarity laws employed for scaling the prototype structure to the experimental model, whereas Table 2.3 systematically enumerates the specific experimental parameters adopted in this study.

Table 2.3 : The calculated physical quantities for shaking table tests.

Physical Quantity	Scale Factor
Length, l_r	3
Modulus of elasticity, E_r	1
Time, t_r	1.732
Gravitational acceleration, g_r	1
Strain, ε_r	1
Acceleration, a_r	1
Frequency, ω_r	0.577
Velocity, v_r	1.732

In designing a reliable 1:3 scaled model to investigate the seismic behavior of older, substandard RC frames, both the selection of materials and the dimensional scaling

were approached with meticulous care. Foremost, concrete with a relatively low compressive strength of approximately 9 MPa was chosen to reflect the weak concrete quality commonly encountered in pre-1970s or otherwise deficient construction. This lower strength mix not only realistically mirrors the stress–strain characteristics of older buildings but also facilitates the accurate reproduction of cracking patterns, damage progression, and shear deficiencies observed in structures deemed subpar by modern design standards. Additionally, a smaller maximum aggregate size was employed to maintain geometric similarity in the aggregate-to-member size ratio and to prevent unrealistic overstrength phenomena. Parallel to this, steel reinforcement with a yield strength of 420 MPa was incorporated to emulate the reinforcement typically found in existing RC frames, without excessively elevating the model’s ductility beyond that of the prototype. The bars were scaled in diameter and spacing to ensure that the overall steel ratio accurately paralleled full scale conditions, thereby preserving the intended balance between tensile reinforcement and the surrounding concrete’s capacity. In further alignment with established similitude principles, the scale factor for the modulus of elasticity for both concrete and steel was set to unity (E_r), as indicated in Table 2.3. This ensures stress-to-strain relationships correspond directly to the prototype, preserving accurate stiffness characteristics and deformation behaviors.

Geometric scaling was executed following a strict 1:3 ratio for all pertinent linear dimensions, including member length, cross-sectional height, and cover to reinforcement. By systematically reducing these dimensions, the model upholds consistent shear span-to-depth ratios and member slenderness values, yielding a near-identical distribution of bending moments, shear forces, and anchorage demands under scaled seismic loading. The incorporation of artificial mass simulation (reflected in Table 2.2) further complements this geometric downscaling by preserving inertial forces at the appropriate magnitude, ensuring that the dynamic response, mode shapes, and fundamental period align with those expected of the full scale structure. Thus, the synergy of carefully chosen concrete strength, standardized steel reinforcement properties, and rigorous dimensional scaling underlies the credibility of the experimental results and their subsequent extrapolation to real-world substandard RC frames.

2.3.2 Overview of the test specimen

The test model was meticulously created to align with the defined similitude criteria pertinent to a scaled representation of the prototype showcased in Figure 2.4. This selected prototype is an aseismically designed RC frame building located in Türkiye, which was constructed during the 1980s. It serves as a representative case for a multitude of RC structures built prior to the introduction of modern seismic regulations in Türkiye and was originally designed exclusively to withstand gravity loads. As detailed in Figure 2.4, this prototype is characterized by a rectangular floor plan comprising three bays, each measuring 4.35 m and 5 m in two mutually perpendicular orientations. Furthermore, the prototype's story height was determined to be 3 m. The experimental setup consisted of a single-bay and a single-story RC frame, which was separated from the prototype structure. The structure was created using a scaled model, specifically a one-third reduced scale of the original prototype, adhering to the similitude principles detailed in Table 2.3.

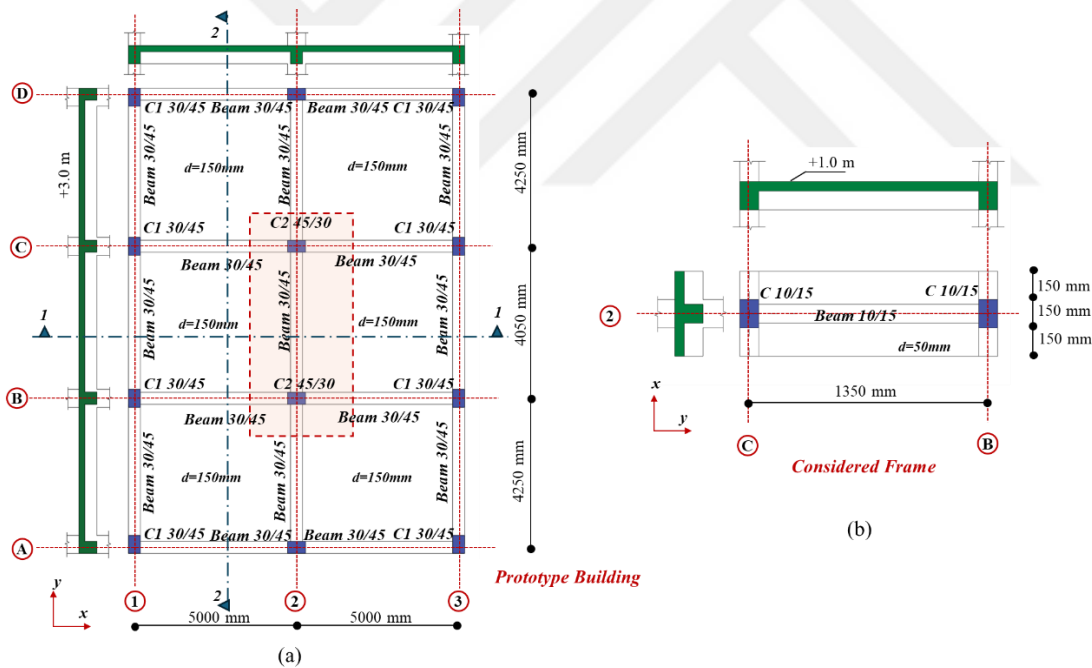


Figure 2.4 : (a) Floor plan illustrating dimensions and structural layout of the prototype reinforced RC building; (b) the exact position and dimensional details of the experimentally analyzed frame.

The simulation employed columns characterized by a rectangular cross-section, measuring 100 mm in width and 150 mm in height, and the columns were positioned with a center-to-center spacing of 1350 mm. Each column incorporated four longitudinal reinforcement bars with a diameter of 8 mm, which is recognized as the

smallest available size of a deformed bar in the local market. The vertical extension of the columns was established at 950 mm, extending from the foundation's top to the underside of the upper slab. Transverse reinforcement consisted of 8 mm bars, strategically spaced at 100 mm intervals from center to center. The configuration of the stirrups included 90-degree hooks, further illustrating the substandard detailing of the columns. Moreover, 8 mm diameter steel bars were systematically arranged at 100 mm intervals both longitudinally and transversely at the upper and lower surfaces of the slab. In terms of foundation reinforcement, the longitudinal bars were constructed from 16 mm diameter steel, while the stirrups were fabricated from 10 mm diameter bars positioned 150 mm apart. The top slab dimensions were noted to be 1450 mm in length, 450 mm in width, and 50 mm in thickness. To bolster structural integrity, a foundation beam was created, measuring 1950 mm in length, 600 mm in width, and 400 mm in depth. This beam was successfully anchored to the shaking table using anchor bolts of 50 mm in diameter. A schematic representation of the specimen is illustrated in Figure 2.5.

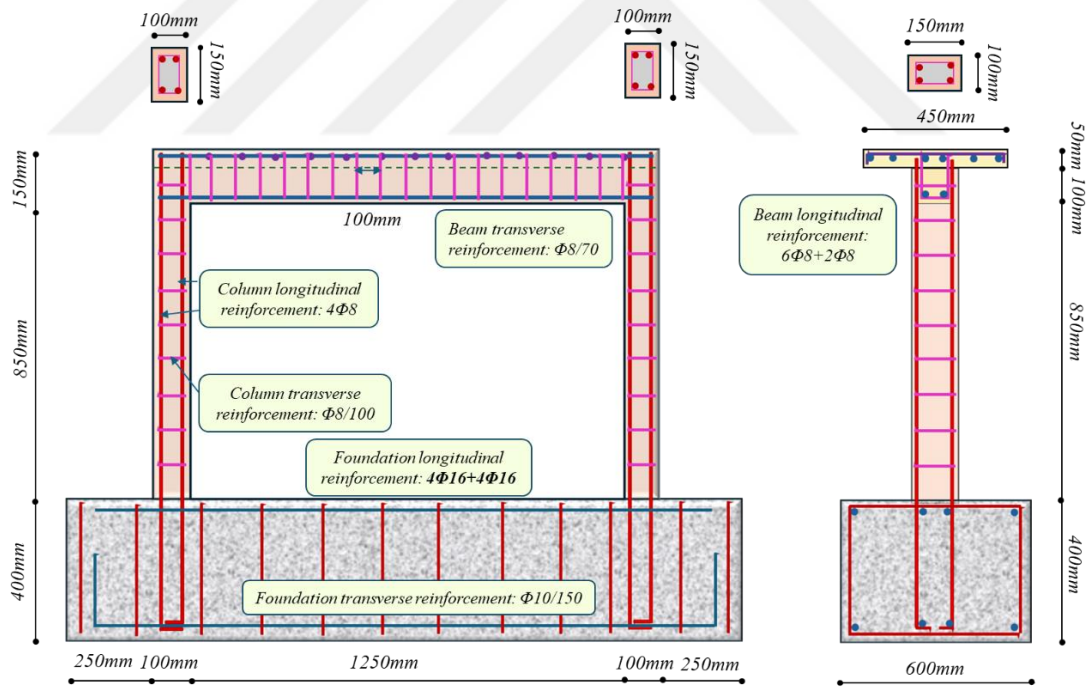


Figure 2.5 : Details of the specimen.

The test columns were subjected to axial loading by integrating steel blocks into the setup. As discussed earlier, a combined weight of 6 tons was applied to the frame, resulting in an individual axial load of 30 kN on each reinforced concrete column. This axial load represented 44% of each column's axial load capacity, not factoring in the

contribution of longitudinal reinforcement to the overall capacity. Figure 2.6 depicts the configuration of the specimens, including the added mass, positioned on the shake table.



Figure 2.6 : Specimen on the shake table.

2.3.3 Material properties

The experiments undertaken aimed to establish a low uniaxial compressive strength in concrete. The RC frame was constructed at the Allianz Technical Laboratory. The compressive strength of the concrete used for constructing the scaled test specimen was determined according to the procedures outlined in the Turkish Standard TS EN 12390-3 (2010). This standard explicitly defines specimen dimensions, casting procedures, curing conditions, testing apparatus, and loading protocols. Concrete cube samples (150 mm × 150 mm × 150 mm) were cast, cured, and tested under standardized laboratory conditions, ensuring the consistency, reproducibility, and accuracy of the test results. Utilizing this standardized method provides reliable and comparable compressive strength data, essential for accurately characterizing the mechanical properties and ensuring the structural similitude between the scaled experimental model and the full-scale prototype. A series of cubic specimens were gathered and subsequently tested to verify their compressive strength. At the 28-day mark, the compressive strength of these frames, as determined through cylinder testing, was recorded at 9 MPa.

The concrete mixture utilized in the scaled test specimen was specifically formulated to replicate the characteristics of substandard, low-strength concrete frequently found in older RC structures in Türkiye. Concrete mixture calculations were prepared in accordance with standard TS 802 (1985). The mixture comprised crushed limestone aggregate and CEM I 42.5R Portland cement. This concrete mixture was classified explicitly as strength class C8/10 according to the Turkish Standard. Clearly specifying these concrete constituents, strength classification, and compliance with standardized testing protocols ensures the reliability, reproducibility, and contextual relevance of the experimental results obtained from the shake table tests. Table 2.4 illustrates the mixed proportions of concrete, detailing the specific materials employed in the composition expressed in terms of weight relative to a single cubic meter of concrete.

Table 2.4 : Mix design of the frames (weight for 1 m³ of concrete).

Mixture Component	Weight (kg)	Proportions by Weight (%)
Cement	185	8.25
0–5 mm Aggregate	945	42.11
5–12 mm Aggregate	391	17.42
12–22 mm Aggregate	523	23.31
Water	200	8.91
Total	2244	100

The choice of a concrete compressive strength of 9 MPa was deliberate, aimed explicitly at representing typical low-strength concrete extensively utilized in Türkiye during the 1980s. This period predates modern seismic resistant construction regulations, resulting in numerous structures exhibiting pronounced seismic vulnerabilities. By selecting this strength criterion, the experimental model authentically mirrors structural deficiencies characteristic of older RC buildings in seismic prone regions, thereby ensuring the practical relevance and applicability of the In the construction of the structural elements, specifically the columns and beams, a total of four longitudinal deformed steel bars, each measuring 8 mm in diameter, were utilized. Both longitudinal and transverse reinforcement utilized within the scaled experimental specimen consisted of ribbed steel reinforcing bars conforming to Turkish Standard TS 708 (2010), ‘steel for the reinforcement of concrete—reinforcing steel’, classified as S420 grade. The ribbed surface profile of these reinforcement bars ensures optimal mechanical interlock and improved bond performance with the surrounding concrete matrix, which is critical for accurately replicating realistic structural behavior under seismic loading conditions. The clear specifications of the reinforcement type

enhance the fidelity of the scaled model, facilitating the reliable extrapolation of experimental results to prototype structural behaviors. experimental outcomes.

To assess the mechanics of the stress–strain behavior of the steel used in the project, three specimens were subjected to rigorous testing. Additionally, the transverse reinforcement was also composed of bars with an 8 mm diameter. The mechanical properties of the steel reinforcing bars were rigorously analyzed through tensile tests performed in a laboratory setting, which revealed a yield stress of $F_{y,measured} = 473$ MPa, and an ultimate tensile stress of $F_{u,measured} = 643$ MPa. Notably, the characteristics of the steel reinforcing bars presented in Table 2.5 were ascertained via tensile testing conducted in a controlled laboratory environment. Each of the reinforcing bars conformed to the strength criteria established by ASTM A615/A615M-05 (ASTM, 2005).

Table 2.5 : Material properties of the reinforcement.

Area (mm ²)	$F_{y,measured}$ (MPa)	$\epsilon_{y,measured}$ (mm/mm)	$F_{u,measured}$ (MPa)	$\epsilon_{u,measured}$ (mm/mm)	F_u/F_y
50.26	473	0.117	643	8.4	1.32

2.3.4 Instrumentation and loading system

The reactions of the test specimens to seismic activity were meticulously recorded through the implementation of multiple measurement instruments, focusing on parameters such as acceleration, displacement, and strain. The experimental configuration incorporated accelerometers alongside Linear Voltage Displacement Transducers (LVDTs), as depicted in Figure 2.7. Each LVDT was engineered to provide precise displacement measurements at frequencies of up to 200 Hz. These transducers were securely attached to immovable frames anchored to the solid ground, which facilitated the assessment of displacements in relation to the ground, rather than being installed on the shaking table itself.

LVDT#1 was strategically placed at the slab level for the purpose of measuring axial displacement demands. In parallel, the accelerations that occurred in the foundation and slab of the test frame, as well as at the surface of the shake table, were meticulously monitored using four separate accelerometers affixed to the side of the foundation and directly to the shake table. It is crucial to emphasize that both acceleration and dis-

placement responses were recorded in real time by a computer-aided data acquisition system.

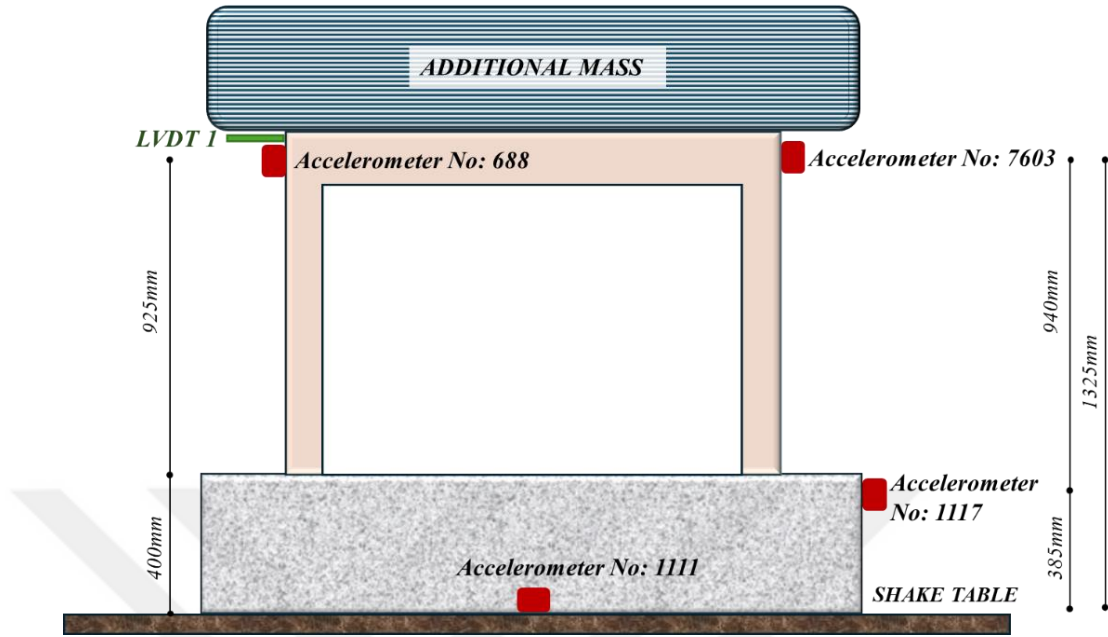


Figure 2.7 : Instrumentation of the test specimens.

2.3.5 Experimental procedure

This section delves into the examination of the outcomes derived from the experimental study undertaken. Following the documentation of each acceleration time history, a thorough visual assessment of the frames was conducted to detect any potential damage. Simultaneously, white noise tests were performed, which are essential in the realm of time series analysis. These tests specifically assess model residuals to verify the absence of discernible patterns, thereby preventing any potential exploitation of these patterns for the purpose of enhancing model accuracy. The dynamic characteristics of the frame were evaluated through the analysis of acceleration data obtained from both white noise tests and free vibration measurements.

2.4 Ground Motion Time History Applied in the Experimental Test

On 6 February 2023, at 04:17 local time (+3 GMT), a significant seismic event occurred in southeastern Türkiye, with a moment magnitude M_w measured at 7.7. The Disaster and Emergency Management Presidency (AFAD) identified the epicenter of the earthquake in the Province of Kahramanmaraş, specifically near the town of

Pazarcık (AFAD,2023). This incident is categorized as the 2023 Kahramanmaraş earthquake and transpired within a geological region designated as the Maraş triple junction, an area characterized by the intersection of the Arabian, Eurasian, and African tectonic plates. Comprehensive seismological data were gathered from 381 active monitoring stations, with station number 3141 selected for detailed experimental analysis. Notably, the maximum peak ground acceleration (PGA) recorded at this particular station reached 1.011 g in the north–south orientation.

Türkiye, geographically positioned on several major tectonic boundaries, frequently experiences significant seismic activities. Historical and recent seismic events have repeatedly highlighted vulnerabilities in building stock and urban infrastructure. Among the most devastating earthquakes to strike Türkiye are the 1939 Erzincan, 1999 Kocaeli, 2011 Van, and 2023 Kahramanmaraş earthquakes.

The 1939 Erzincan earthquake ($M_w = 7.8$), one of the most catastrophic historical earthquakes in Türkiye, occurred on December 26, 1939. It ruptured along the East Anatolian Fault (EAF), resulting in approximately 32.700 fatalities and extensive infrastructural destruction. This earthquake produced a rupture length of approximately 360 km with notable ground displacement observed in surface ruptures exceeding 7 m in certain areas (Ambreseys, 1970). In contrast, the 1999 Kocaeli earthquake ($M_w = 7.4$) struck the densely populated industrial Marmara region on 17 August 1999. Its epicenter was near Gölcük, with a rupture length of around 150 km along the western segment of the NAF, recording a PGA of approximately 0.51 g in Sakarya, severely impacting major urban areas such as İzmit and İstanbul, and resulting in over 17,000 fatalities and widespread building collapses (AFAD, 1999). The 2011 Van earthquake, with a magnitude of $M_w = 7.1$ occurred on 23 October 2011, in eastern Türkiye, along EAF, predominantly affecting rural and urban areas around the city of Van. The earthquake had a relatively shorter rupture length (approximately 60 km) but generated substantial damage in poorly constructed buildings, registering PGA values around 0.18 g in Van city center, with approximately 600 fatalities (AFAD, 2011).

The 2023 Kahramanmaraş earthquakes represent one of the deadliest seismic sequences in modern Turkish history. These events ruptured complex segments of the EAF and secondary faults, causing widespread devastation with a maximum PGA recorded as high as 2.22 g at stations near the epicentral region in Pazarcık. Over

50,000 fatalities and extensive infrastructural damage were reported, marking it as a catastrophic event (AFAD, 2023).

In this sequence, the frequency content was notably broadband, spanning short periods (below 0.5 s) to intermediate and longer periods (up to 2.0 s). This wide spectral distribution is attributed to the complex rupture process involving multiple fault segments. Additionally, Table 2.6 presents a comparison of significant earthquakes that occurred on the EAF.

Table 2.6 : Significant earthquakes occurred on the EAF (AFAD, 2023).

Earthquake	Station and Distance to Epicenter (km)	Lat.	Long.	Depth (km)	PGA (g)			M _w	M _L
					N-S	E-W	U-D		
Bingöl (1 May 2003)	Bingöl—11.49	38.99	40.46	10	0.556	0.282	0.482	6.3	6.6
Kovancılar– Elazığ (8 March 2010)	Palu—14.72	38.77	40.07	5	0.063	0.068	0.031	–	5.8
Maden–Elazığ (23 June 2011)	Maden—21.01	38.58	39.59	13.42	0.031	0.039	0.016	–	5.3
Erciş–Van (23 October 2011)	Muradiye— 45.77	38.69	43.47	19.02	0.182	0.173	0.081	7	6.7
Edremit–Van (9 November 2011)	Van—3.37	38.45	43.26	6.09	0.151	0.251	0.154	–	5.6
Sivrice–Elazığ (24 January 2020)	Elazığ—23.81	38.35	39.06	8.06	0.243	0.298	0.194	6.8	6.6
Pazarcık– Kahramanmaraş (6 February 2023)	Pazarcık— 31.00	37.39	37.14	8.6	2.208	2.222	1.989	7.7	7.6

The latest iteration of the TBEC (2018) delineates the seismic risk into four distinct categories: DD-1, DD-2, DD-3, and DD-4. These classifications reflect the probability of seismic events occurring, with exceedance probabilities of 2%, 10%, 50%, and 68%, respectively, over a 50-year horizon. The calculated average recurrence intervals for seismic events within these categories are approximately 2475 years for DD-1, 475 years for DD-2, 72 years for DD-3, and 43 years for DD-4. Additionally, each seismic level is aligned with specific earthquake scenarios, which include the maximum considered earthquake (MCE) assigned to DD-1, the design-based earthquake (DBE) for DD-2, the frequent earthquake (FE) relevant to DD-3, and the service-level earthquake (SE) for DD-4. In this context, Figure 2.8 illustrates the normalized response spectra associated with the DD-2 category, juxtaposed with a

scaled time-history of the 2023 Maraş earthquake, incorporating critical damping values of 2.5%, 5%, and 10%. The analysis of this figure indicates that the chosen acceleration time history is appropriate for conducting experimental tests on the specified test frames.

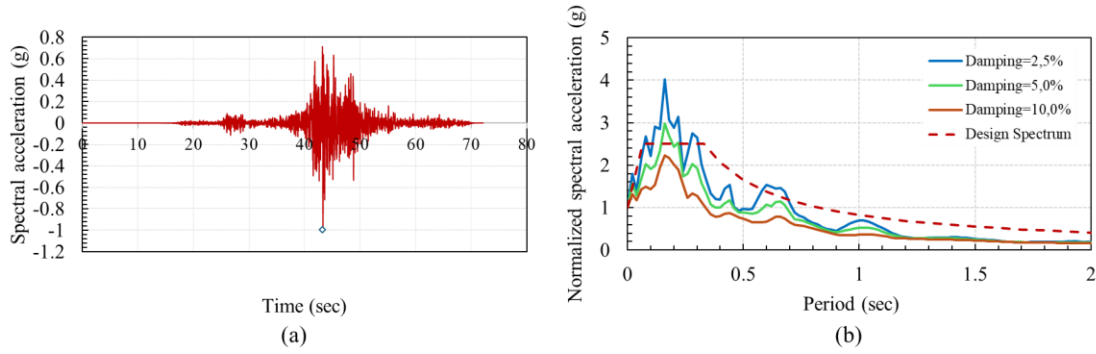


Figure 2.8 : (a) The acceleration time history of the 2023 Kahramanmaraş record applied in the experimental shake table tests. (b) Acceleration response spectra of the 2023 Kahramanmaraş ground motion record corresponding to damping ratios of $\xi = 2.5\%$, $\xi = 5\%$, and $\xi = 10\%$.

Initially, the frame underwent testing under ground motion that was carefully scaled in accordance with the previously discussed similitude law. Given that the frame was engineered to be substandard, the application of the scaled ground motion was carried out meticulously.

2.5 Results

Accordingly, the initial frequency of the specimen was identified as $f_0 = 2.02 \text{ Hz}$. Figure 2.9 presents the acceleration measurements obtained from Stations 688 and 7603 for the specified specimen. The data presented in the figure suggest that station 688 experienced a malfunction during the testing process. Consequently, the sole source of acceleration data are derived from station 7603.

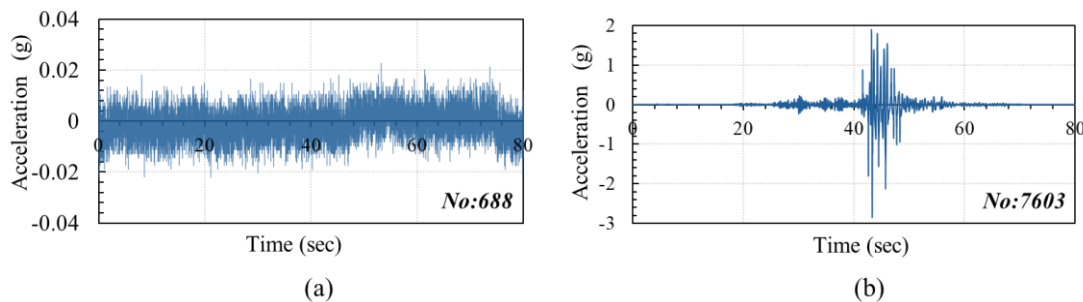


Figure 2.9 : Acceleration time histories recorded at selected stations during the earthquake event. (a) Station 688 and (b) Station 7603.

The maximum lateral displacements observed at the top of the specimen, as measured by LVDT#1, are presented in Figure 2.10. The peak lateral displacement recorded was approximately 53.1 mm, corresponding to a story drift ratio of approximately 0.055 radians when subjected to a ground acceleration of 0.35 g.

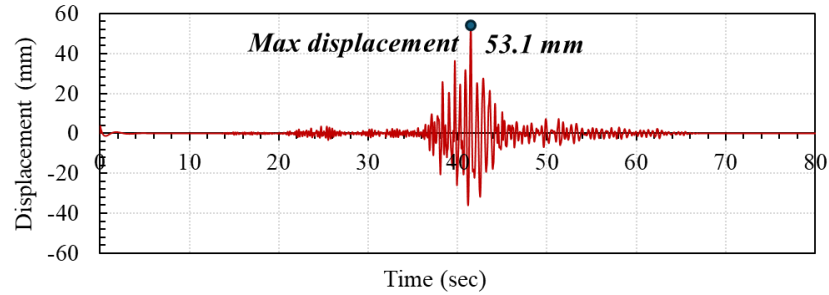


Figure 2.10 : Lateral displacement time traces recorded at the top LVDT.

Chord rotation serves as a critical metric in assessing the structural performance and deformation capacity of reinforced concrete (RC) elements subjected to bending stresses. Its significance lies in the evaluation of essential characteristics such as ductility, damage state, and the failure mechanisms of RC components, including beams, columns, and walls, particularly when they are exposed to seismic forces. Low-strength concrete exhibits a chord rotation capacity that is approximately 30–50% greater than that of normal-strength concrete. This enhanced capacity can be attributed to its superior ability to deform under stress. Following the completion of the tests, the calculated chord rotation value for the specimen was determined to be 0.038 radians. This measurement is noted to surpass the specified chord rotation threshold established in ASCE 41-23 (2023).

A hysteretic curve illustrates the cyclic response of a structural component, such as a reinforced concrete beam or column, subjected to recurrent loading and unloading, notably in the context of seismic activity. This curve delineates the correlation between lateral force and displacement through successive loading cycles. In the case of low-strength concrete, the hysteretic curve generally reveals certain characteristics: pinching effects that arise from bond slip and cracking, a decline in strength and stiffness across loading cycles, and diminished energy dissipation when compared to elements that are well confined.

Hysteresis models, which are extensively employed in the analysis of low-strength concrete structures, exhibit several significant limitations that warrant detailed

examination. The constraints inherent in these hysteretic models primarily stem from the foundational assumptions incorporated within them. Typically, a multitude of models can be proposed for identical structural elements and loading scenarios, often resulting in contradictory outputs. For example, various models and their derivatives present disparate approaches to modeling the same phenomena. Moreover, even when the same modeling technique utilizes identical operators, such as R , it can yield divergent mathematical formulations.

Numerous empirical hysteretic models have been introduced to capture the force-displacement characteristics of structural elements, with the Mainstone model being one of the earliest examples. Subsequent models tend to provide an algebraic representation of the force-displacement relationship, delineating elastic and plastic branches. Contemporary structural codes for low-strength concrete predominantly endorse such models within displacement-based design frameworks. However, a notable inconsistency emerges between the experimentally derived and analytically predicted ratios of hysteresis loops for low-strength concrete walls. In addition, the overall load-carrying capacity of low-strength concrete buildings is highly sensitive to the capacity for plastic hinge displacement. This sensitivity highlights the crucial role that low-strength concrete structures play in the seismic resilience of developing economies (Wallace, 2012).

In light of these factors, the aforementioned limitations pose serious implications for the safety and design integrity of low-strength reinforced concrete structures. To address these issues, the Venantius model has been proposed to characterize the pinching force-deformation relationship in reinforced concrete members, specifically for two-dimensional low-strength concrete structures. The axial load ratio emerges as the predominant factor since it directly influences inelastic curvature constraints. Further-more, analysis of concrete-confined braces demonstrates the critical impact of the axial load ratio, particularly when reductions in concrete confinement are applied. The findings presented underline the necessity for more sophisticated modeling approaches to accurately assess hysteretic deformation demands in the design of low-strength concrete structures, particularly in the context of performance-based design methodologies (To et al., 2024). Figure 2.11 presents a graphical representation of the relationship between base shear and displacement for the specimen in question.

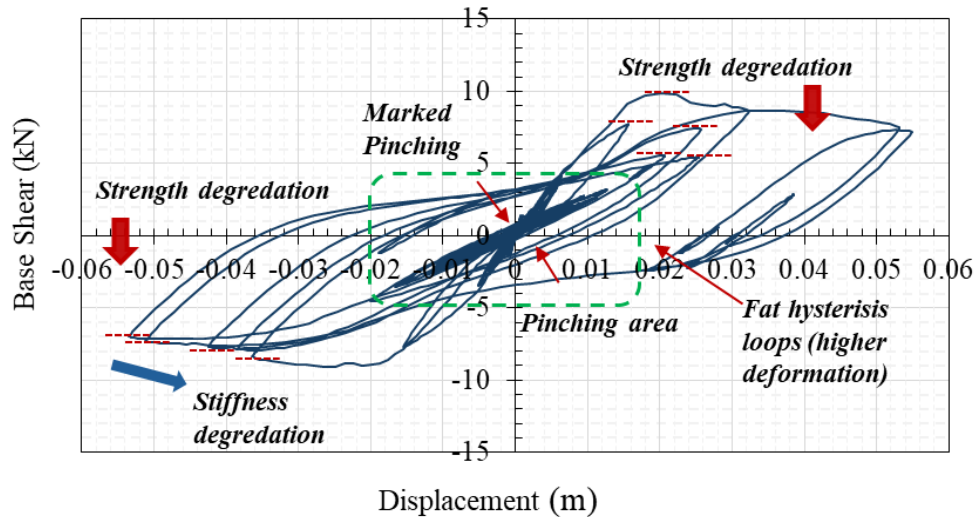


Figure 2.11 : Base shear–displacement plot.

The degraded material response of concrete and reinforcements is investigated over time with the aim of simulating and monitoring the damage in the lacking elements of the structure. The stiffness and strength degradation of a reinforced concrete structure may develop due to a range of factors or the combined effect of these factors. The cracking of concrete is a gradual process, but the growth of crack width is not constant. If a crack becomes interconnected, the development of a crack-widened region rapidly increases material deterioration. Moreover, a wider crack may accelerate the degradation in stiffness or strength. It is important to understand how material deterioration progresses in relation to the change in structural conditions. Depending on the material properties of concrete and rebar or the geometrical conditions of a cross-section, various types of cracks can be considered. However, the growth of crack width is closely related to a change in structural conditions. This occurrence is referred to as pinching. The behavior associated with pinching is identified by significant decreases in stiffness upon reloading following an unloading phase. Additionally, there is a noteworthy recovery of stiffness when a displacement is applied in the reverse direction. In Figure 2.11, there is a clear indication of the reductions in both stiffness and strength, alongside the presence of a pinching effect.

When a ground motion level of 0.35 g was applied to the specimen, observable damage was evident at the beam–column connections. Furthermore, there was noticeable concrete spalling present in these sections, as depicted in Figures 2.12 and 2.13. During the testing process, small fissures emerge at the connection between the beam and

column as a result of alternating moments. This phenomenon is subsequently accompanied by the deterioration of the concrete cover. It can be inferred that the insufficient anchoring of the longitudinal reinforcement permits a slippage of the bars within the joint, thereby contributing to a decline in structural strength. Additionally, a lack of transverse reinforcement has resulted in the formation of diagonal shear cracks that exhibit an X-pattern. The computed Park–Ang damage index indicates that, in addition to the aforementioned deterioration, there is also evidence of reinforcement buckling.

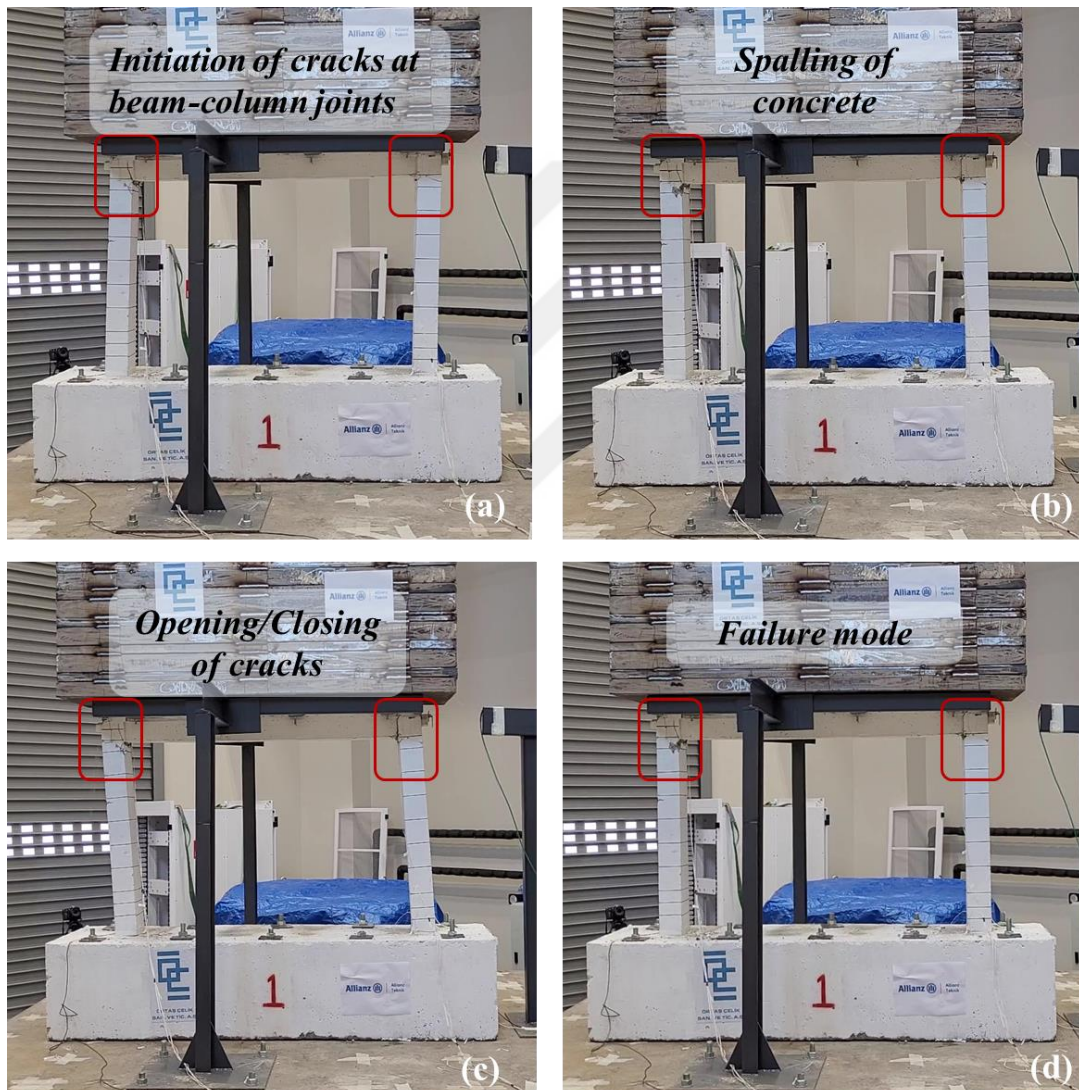


Figure 2.12 : Detailed progression of structural damage at beam–column joints during incremental seismic loading stages: (a) initiation of cracks, (b) opening and closing of cracks, (c) severe spalling of concrete, and (d) ultimate failure mode. Red frames indicate regions of concentrated damage, providing clear visualization of crack propagation and concrete deterioration.

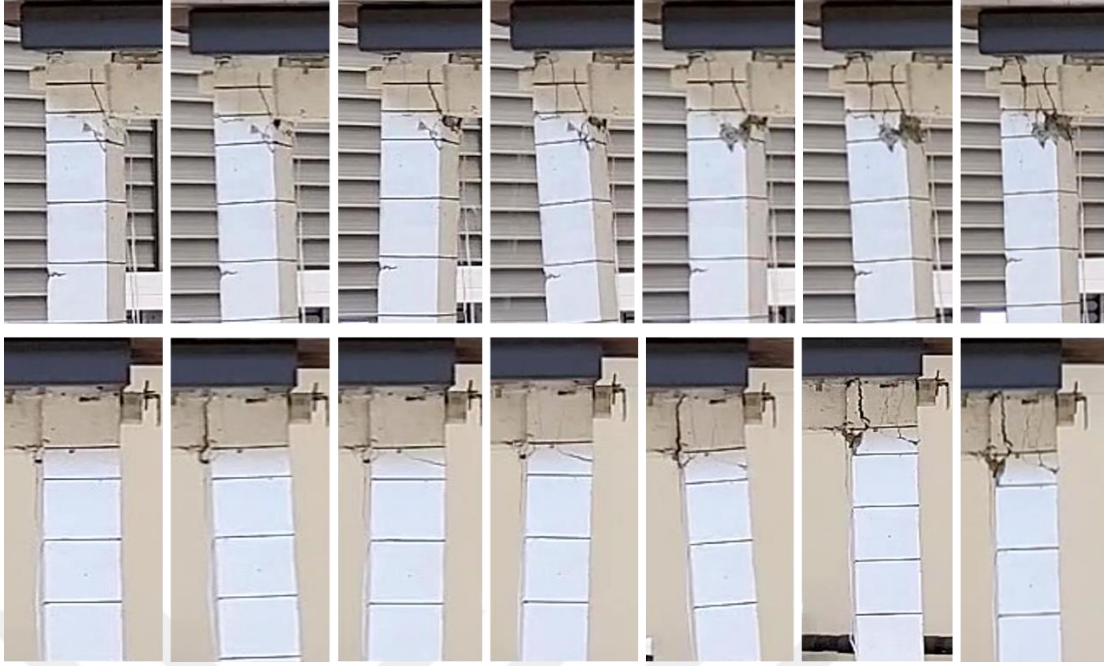


Figure 2.13 : Sequential images showing crack propagation and lateral displacement in column elements over time, demonstrating progressive structural degradation.

2.6 Discussion

To assess the damage inflicted by an earthquake, it is essential to delineate the correlation between the intensity of ground motions and the resultant degree of damage to various structures. This correlation is commonly referred to in the technical literature as a damage function. To analyze the vulnerability of structures, various criteria have been developed to quantify damage (Kohns et al., 2022). These criteria provide a framework for assessing the extent of structural damage based on established theoretical principles, ultimately resulting in the calculation of a specific metric known as the damage index. A significant damage index is introduced by Park and Ang (1985). This index is characterized as a linear amalgamation of damage attributed to energy dissipation and the peak deformation experienced. Park and Ang (1985) substantiated their proposed equation through empirical test results collected from various researchers examining concrete columns and beams. In this approach, the damage index (D) is defined as a combination of maximum deformation and cumulative energy dissipation, typically expressed as follows.

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{V_y} \frac{E_h}{\delta_u} \quad (3.1)$$

Here, in the equation, δ_m and δ_u refer to the maximum experienced displacement and ultimate displacement capacity, respectively. E_h is the total hysteretic energy dissipated (area enclosed by the hysteresis loops), and V_y is the yield base shear strength value. Further, β is a constant defined in Park and Ang (1985). The assessed damage index stands at 0.89, categorizing it at the threshold of near collapse, yet still within the significant damage spectrum.

The present experimental investigation elucidates critical seismic performance characteristics of substandard RC beam–column joints, explicitly highlighting pronounced stiffness degradation, strength deterioration, hysteresis loop pinching, and extensive shear cracking under seismic loading conditions. Specifically, the tested structural model demonstrated explicit numerical values that clearly articulate and quantify structural vulnerabilities, directly underscoring critical deficiencies typical of older, inadequately reinforced RC constructions.

A comprehensive evaluation of recently published experimental studies involving similarly scaled tests corroborates our observations. Ricci et al. (2016) conducted cyclic loading tests on exterior RC beam–column joints, documenting significant shear cracking, concrete spalling, and severe joint deterioration. Their reported drift ratios and cyclic degradation trends remarkably parallel our observed data, emphasizing shared vulnerabilities and validating the reliability of our experimental approach. Likewise, Zhang and Li (2021), through the detailed cyclic load testing of RC beam–column joints, reported notable strength losses exceeding 30%, stiffness degradation, and pronounced shear cracking—findings directly aligned with our experimental outcomes.

Detailed comparative analyses with prior shake table studies further reinforce the robustness and accuracy of our findings. Benavent-Climent et al. (2016), in experiments on RC waffle-flat plate structures, documented substantial stiffness degradation of approximately 40%, and strength deterioration close to 30% under seismic actions, metrics closely corresponding to those observed in our current investigation. Similarly, Li et al. (2016) investigated a three-story RC frame subjected to shake table tests, highlighting comparable cyclic hysteresis pinching and progressive stiffness reductions. Notably, the drift ratios recorded in their study, approaching values of around 0.055 radians, show significant quantitative similarities to our experimental data.

2.7 Conclusions and Recommendations

Shake table testing of substandard RC frames has illuminated substantial structural deficiencies when subjected to seismic forces. The analysis reveals that issues such as inadequate reinforcement detailing, low concrete strength, inadequate confinement, and compromised beam–column connections result in considerable lateral deformations, early cracking, and, in certain instances, structural failure.

The shaking table experiment was conducted on a one-story specimen scaled to one-third of its original size, designed to represent substandard traditional RC frames prevalent in Türkiye. Upon completing the 0.35 g ground motion event, the substandard RC frame revealed substantial damage. Specifically, shear cracks were observed at the beam–column junctions of the initial specimen.

The experimentally obtained displacement thresholds, joint damage patterns, and damage indices from this study offer several direct contributions to current and prospective seismic design and retrofit provisions for older, low-strength RC frames:

- (i) Refined Drift Capacities and Collapse Thresholds: the observation that major diagonal shear cracking and joint deterioration occurred around a story drift of approximately 0.055 radians highlights a realistic collapse prevention benchmark. Code drafters could integrate this evidence-based drift capacity into guidelines or commentary, ensuring that older frames receive adequate reinforcement or retrofitting before reaching critical drift levels under seismic demand.
- (ii) Emphasis on Joint Confinement Requirements: the progression of X-shaped cracks in beam–column joints lacking adequate confinement underscores the urgent need for enhanced joint detailing measures, such as closely spaced stirrups, hoops with seismic hooks, and properly anchored crossties.
- (iii) Shear-Critical Failure Indicators: the near-collapse Park–Ang damage index (0.89) directly correlates with shear-dominant failure in unreinforced or substandard joints. Integrating these damage index insights into code-based assessment frameworks promotes more stringent shear checks for beam–column connections, particularly in legacy structures erected under pre-seismic regulations.

Through these targeted refinements, the findings from this experimental campaign both strengthen and extend the body of knowledge underpinning contemporary

seismic design codes. They provide tangible benchmarks for recognizing, quantifying, and mitigating collapse-prone failure mechanisms in substandard RC frames. Ultimately, the findings from this comprehensive study hold significant potential implications, providing essential knowledge and practical recommendations that can substantially enhance seismic safety, inform engineering practices, and guide policymaking within earthquake prone regions.

The observed damage patterns necessitate urgent seismic retrofitting initiatives explicitly aimed at augmenting the resilience of these RC frames. Specifically, for the prominent X-shaped shear cracks identified in beam–column joints, the targeted application of FRP wrapping is recommended, as it significantly enhances the shear capacity and confinement, thereby mitigating brittle shear failures. Additionally, steel jacketing can be effectively employed for severely damaged columns to enhance their axial and shear capacities. Incorporating innovative braces such as BRBs can further improve overall lateral load resistance and ductility. Moreover, fortifying columns through strategic jacketing and the integration of contemporary seismic design methodologies, including capacity design principles, the proper anchorage of reinforcement, and meticulous detailing, can substantially elevate the structural integrity and seismic performance of RC frames in earthquake-prone areas.

In summary, the shake table experiments serve to underscore the susceptibility of substandard RC frames to seismic loading and highlight the critical need for preemptive retrofitting and compliance with seismic design standards to reduce potential hazards and improve structural safety. The retrofitting of existing deficient buildings and the implementation of rigorous seismic design regulations for new developments are essential strategies to reduce the risks associated with earthquakes. The results act as a compelling indication that anticipatory actions such as structural evaluation, rehabilitation, and adherence to current engineering guidelines are vital for improving the seismic robustness of RC structures, thereby protecting both lives and property.

While this study provides valuable empirical data derived from shake table testing, a notable limitation is the absence of complementary numerical modeling. To address this limitation, future research will involve detailed finite element analyses aimed at further validating and refining our understanding of the seismic behavior of RC beam–column joints, thus enhancing practical applicability and code relevance. The

limitations of the test setup impacted the capacity, which required the specimens to be tested at a reduced scale. To ensure that the findings of this study can be effectively generalized, it is advisable to conduct tests on larger scale frame specimens, as well as three-dimensional models, subjected to diverse earthquake ground motions in order to address various uncertainties inherent in the results.





3. IMPROVING SEISMIC PERFORMANCE OF RC STRUCTURES WITH INNOVATIVE TnT BRBS: A SHAKE TABLE AND FINITE ELEMENT INVESTIGATION²

Addressing the critical seismic vulnerabilities of reinforced concrete (RC) beam-column joints remains an imperative research priority in earthquake engineering. This study presents an experimental and analytical investigation into the seismic performance enhancement of nonductile RC frames using an innovative all-steel Tube-in-Tube Buckling Restrained Brace (TnT BRB) system. Shake table tests were performed on one-third scale RC frame specimens, including a baseline structure representing conventional substandard design and a counterpart retrofitted with the proposed TnT BRBs. Experimental results revealed that the unretrofitted specimen experienced pronounced brittle shear failures, excessive lateral deformations, and significant degradation of beam-column joints under cyclic seismic loading. In contrast, the TnT BRB retrofitted specimen exhibited substantially improved seismic behavior, characterized by enhanced energy dissipation, controlled interstory drifts, and preserved joint integrity. Advanced fiber-based finite element modeling complemented the experimental efforts, accurately capturing critical nonlinear phenomena such as hysteretic energy dissipation, stiffness degradation, and localized damage evolution within the structural components. Despite inherent modeling limitations regarding bond-slip effects and micro level cracking, strong correlation between numerical and experimental results affirmed the efficacy of the TnT BRB retrofit solution. This integrated experimental-analytical approach offers a robust, cost-effective pathway for upgrading seismically deficient RC structures in earthquake prone regions.

² This chapter is based on “**Oyguc, E.**, Oyguc, R., Seker, O., Hayir, A., Shen, J., & Akbas, B. (2025). Improving Seismic Performance of RC Structures with Innovative TnT BRBs: A Shake Table and Finite Element Investigation. *Applied Sciences*, 15(7), 3844.<https://doi.org/10.3390/app15073844>”

3.1 Introduction

One of the major threats to the safety of buildings is their vulnerability to natural disasters, which can lead to collapse or severe damage of structures, loss of human life, and socioeconomic breakdown. Buildings that have been designed and constructed without considering the seismic lateral loads and in areas with high seismicity are considered unsafe, and retrofitting or rebuilding them is essential to reduce the effect of a strong seismic event.

Beam-column connections are vital for the seismic resilience of reinforced concrete (RC) frames. Modern earthquake-resistant design codes such as ACI 318 (2009), Eurocode 8 (1995), and NZS3101 (2017) detail requirements to enhance the ductility and energy dissipation capacity of these joints. Structural failures often stem from poor seismic performance of RC beam-column joints lacking seismic design considerations. A range of substandard design strategies has been developed for these connections. The cyclic behavior of substandard designed connections during seismic events is heavily influenced by design methodology and the detailing of concrete frame components. Evaluating the seismic performance of these members and connections can be done through nonlinear simulations and experimental investigations post-failure.

Seismic vulnerability in RC structures remains a paramount concern, particularly in regions where legacy construction practices have prioritized compressive strength over ductility. While extensive experimental investigations have shed light on the behavior of RC beam-column joints and confirmed the efficacy of conventional BRBs under seismic excitations, a notable gap persists in the literature regarding the complementary role of computational models in elucidating these phenomena. Advanced fiber-based finite element (FE) models, for example, have emerged as indispensable tools that capture the intricate hysteretic responses, localized damage mechanisms, and evolving stiffness degradations observed in RC systems during cyclic loading. These models, by integrating nonlinear material behavior with complex bond interactions and discrete damage accumulation, offer a more granular insight into seismic performance than experimental observations alone. This dual approach not only refines the calibration of experimental data but also significantly enhances the predictability of seismic energy dissipation and the overall resilience of RC frames.

Recent advancements in computational modeling have considerably advanced our ability to simulate dynamic structural responses under seismic loads. Seminal works by Correia and Virtuoso (2006) have demonstrated that incorporating total co-rotational formulations within FE frameworks enables the capture of large nodal displacements and rotations, a critical requirement for accurately modeling the behavior of RC structures during seismic events. Likewise, distributed plasticity models, as expounded by Filippou and Fences (2004), provide a robust methodology for discretizing RC cross-sections into multiple fibers, each governed by uniaxial stress-strain relationships. Such approaches are particularly effective in replicating the progressive degradation of bond strength and the localization of cracks, phenomena that are often inadequately captured by simpler lumped plasticity models.

In parallel with these computational developments, there has been a burgeoning interest in innovative retrofit technologies that not only dissipate seismic energy but also facilitate self-centering behavior, a feature that is critical for reducing residual deformations after seismic events. A notable example of this emerging technology is the self-centering energy-dissipative brace (SCED), which has recently garnered considerable attention in the literature. The SCED system, as rigorously investigated by Qin et al. (2023), exhibits superior self-centering performance while maintaining high energy dissipation capacities. This advanced brace system is engineered to restore the pre-seismic configuration of a structure after a seismic event, thereby mitigating the accumulation of permanent deformations and enhancing post-earthquake functionality.

Integrating advanced computational models with emerging retrofit technologies such as the SCED system represents a promising pathway for advancing the seismic resilience of RC structures. The fiber-based FE approach, when combined with high-fidelity material models and refined discretization techniques, can accurately predict the behavior of RC frames retrofitted with innovative energy dissipation devices. For instance, the simulation frameworks discussed by Fragiadakis and Papadrakakis (2008) have underscored the importance of capturing localized damage phenomena, such as bond-slip and cracking in beam-column joints, which are critical in determining the overall hysteretic performance of a structure. Moreover, experimental validations conducted by Sung et al. (2021) have provided empirical evidence that reinforces the potential of advanced computational models to predict the complex

interactions between traditional BRBs and novel systems such as SCED. Such studies highlight the synergies between simulation and experimentation, establishing a feedback loop that continuously refines our understanding of seismic performance.

The integration of these advanced computational techniques and innovative retrofit solutions is not merely an academic exercise but a pragmatic necessity in the face of escalating seismic hazards. Modern seismic design codes, while progressively incorporating computational insights, still leave significant room for improvement in their treatment of RC joints and energy dissipation mechanisms. In this context, the dual approach of employing robust numerical models alongside cutting-edge experimental research offers a holistic perspective that can inform the next generation of design standards. By bridging the gap between theoretical predictions and real-world behavior, these methodologies provide engineers with a more reliable basis for designing structures that can withstand severe seismic events with minimal damage.

Furthermore, the incorporation of self-centering mechanisms, as embodied by the SCED system, represents a paradigm shift in seismic retrofitting strategies. Unlike conventional BRBs that primarily focus on dissipating energy through plastic deformations, SCED systems are engineered to combine energy dissipation with an inherent capacity for self-recovery. This dual functionality not only curtails the propagation of damage during an earthquake but also expedites the restoration process post-event, thereby reducing the downtime and repair costs associated with seismic retrofits. The promising results reported by Qin et al. (2023) provide compelling evidence that SCED systems could redefine the standards for seismic retrofitting in RC structures, particularly when integrated within a computational framework that rigorously assesses their performance. This study, therefore, seeks to extend the state-of-the-art by bridging these perspectives, ultimately contributing to the development of safer, more resilient structures in seismically active regions.

Joint failures can manifest as shear, flexural, or bond failures, each significantly undermining structural integrity. Analyzing these modes is critical for designing resilient RC frames, especially with enhancements such as buckling-restrained braces to improve performance under various loads. The primary failure mode in non-ductile reinforced concrete joints is brittle shear failure within the joint core. As shown in Figure 3.1(a), seismic lateral loads generate significant diagonal tensile and compressive stress in the joint panel. If the joint lacks adequate transverse

reinforcement diagonal cracking can quickly develop, leading to internal fracturing and crushing. Notably, shear cracks can appear even with modest story drifts, before the yielding of adjacent members, causing a rapid decrease in the connection's load-carrying capacity. The appearance of diagonal shear cracks indicates a considerable reduction in the joint's load-bearing ability. This initial failure may escalate, risking a mechanism that could cause a story collapse if multiple joints fail. Unlike the ductile flexural failures of beams or columns, joint shear failures are brittle and provide little warning, identified by X-shaped cracks, core concrete compaction, and compromised structural integrity at the node connecting frame members.

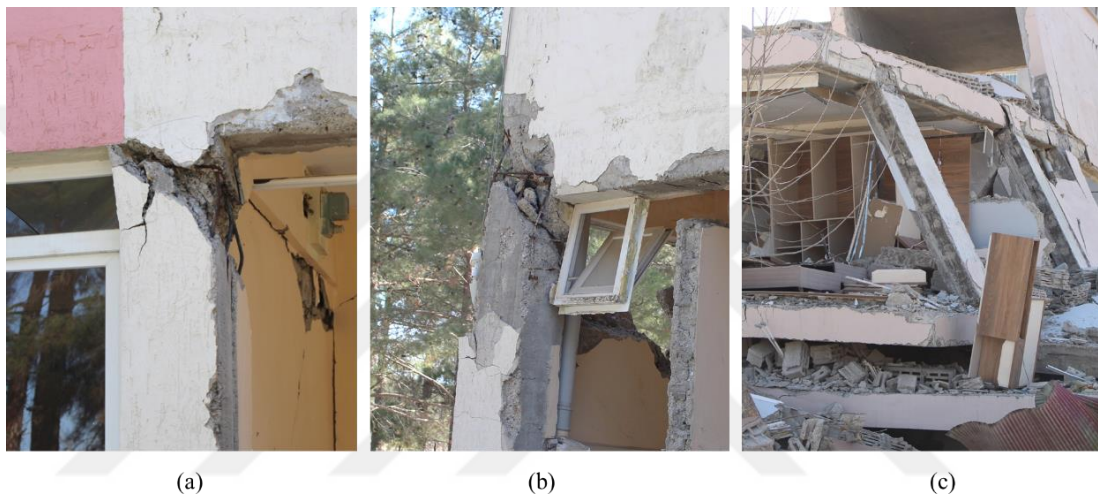


Figure 3.1 : Examples of beam column joint failures: (a) shear failure, (b) bond-slip failure, (c) weak column-strong beam failure

A common failure mechanism involves the deterioration of the bond between reinforcing bars and surrounding concrete in joints, leading to slipping or pull-out of the reinforcement. In older constructions, longitudinal bars of beams and columns often terminate or splice in joint regions without adequate development length or 90° hooks. Cyclic loading can cause these bars, particularly if they are smooth or surrounded by cracks, to gradually slip within the joint. Bond-slip is often seen in gravity-designed frames and has been identified as a key factor in damage and collapse of reinforced concrete buildings built before the 1970s. As illustrated in Figure 3.1(b), the slipping of longitudinal bars into the joint reduces stiffness, shown by pinched hysteresis loops, and causes premature strength degradation under lateral loads. This results in a “loose” beam-column connection, compromising steel anchorage and decreasing moment transfer capacity. Joint shear cracking frequently accompanies anchorage failure; as slip and cracking initiate, the joint's truss mechanism weakens, increasing the load on

the concrete strut and potentially leading to failure. Notable indicators of bond-slip failure include bar movements, widening cracks along beam bar paths, and sometimes bar pull-out or hook opening after testing. Inadequate bond anchorage, from insufficient embedment or smooth bars, critically impacts the cyclic performance of beam-column joints.

An additional factor contributing to joint distress is an inadequate strength hierarchy within the structural frame. Engineering guidelines advocate for a configuration where columns and joints are robust while beams are weaker. This design ensures that the beam ends yield before the shear capacities of the joints are exceeded, or before column hinging occurs. Many legacy frames, however, overlooked this principle. During seismic events, beams can exert forces on joints surpassing their shear capacity, especially at joints with multiple beam connections. Weak-column scenarios may occur, where columns hinge at the joint, increasing shear demands. This can lead to joint failure even with nominal ties, as the joint may be insufficient for the imposed demand. A notable instance involves connections linking heavily reinforced beams to lightly reinforced columns, causing excessive shear in the joint panel. Experimental studies show that designs violating capacity principles, such as “weak column-strong beam”, result in joint failure in shear before beam yield, as shown in Figure 3.1(c). Inadequate proportions in dimensions and strength, such as reduced column cross-sections or lack of supporting beams in exterior joints, can force joints to absorb excessive loads, leading to brittle failure. This underscores the need for careful joint geometry and member sizing consideration to avoid joint inadequacies, a common issue in older design practices that led to failures during seismic activities.

One effective retrofit technique developed in recent years is the use of buckling-restrained braces (BRBs) (Sabelli et al., 2003),(Lopez et al., 2004),(Sun et al., (2018),(Sitler et al., 2020), (Hu et al., 2022), (Azizi et al.(2023). This method has been adopted widely for seismic retrofitting of existing structures and for new designs intended to withstand seismic action, applicable to both engineered and heritage buildings. BRBs are energy-dissipating components that restrain elastic and plastic deformation, effectively controlling buckling. They dissipate vibration energy and reduce the structure’s natural period via hysteretic behavior instead of relying on physical impacts. Key advantages of BRB systems over conventional bracing include (a) high energy dissipation, (b) superior ductility and symmetrical hysteretic

responses, (c) adjustable energy dissipation through core tube modification, (d) resistance to residual buckling and minimal structural damage after severe loading, and (e) early warning of potential failure indicated by localized pinching in hysteresis loops (Jia et al., 2018),(Talebi et al., 2014).

Tube-in-Tube braces consist of two concentric tubes: a main brace and an outer tube. The main brace contracts the inner tube. During seismic events, the outer tube prevents buckling by providing support, ensuring stabilization (Seker and Shen, 2017). It resists forces on the structure and enhances lateral stability. The main tube handles tension and compression, increasing the brace's resistance. A key advantage of the Tube-in-Tube system is its compatibility with standard lateral frames and diagonal bracing, offering higher resistance values. The outer tubes can take various shapes for architectural design, providing benefits for diaphragm wall systems and accommodating significant construction variations.

A significant number of researchers have focused on experimental studies evaluating the efficacy of BRB systems (Berman et al., 2005),(Vargas and Bruneau, 2009), (Kasai et al., 2010), (Hu et al., 2010), (Hikino et al., 2013), (Della Corte et al., 2015), (Avcı-Karatas et al., 2018) and their potential failure mechanisms. This emphasis on experimental methods stems from their reliability in substantiating research outcomes in structural engineering and guiding design standards. Accumulating experimental data is crucial for developing and maintaining these standards, forming the basis of performance-based engineering and validating nonlinear response history analysis models. While numerical models can be backed by various experimental data types, small-scale structural tests offer the clearest validation.

Recent investigations have provided significant insights in experimental studies. Sung et al. (2021) executed shake table experiments on a portal reinforced concrete frame with rubber cylinders to improve load-bearing capabilities, revealing that these braces enhanced seismic performance. Rafi et al. (2022) conducted shake table tests on a concrete frame retrofitted with a brace beam, finding that it markedly increased stiffness and reduced lateral story drift. Sadoon et al. (2024) examined the seismic response of a poorly designed frame retrofitted with a novel brace system, concluding that it significantly lowered interstory drift ratios and exhibited stable hysteretic behavior, thus improving older buildings' seismic responses in prone regions. Wu et al. (2024) performed quasi-static tests to investigate failure mechanisms of

conventional braces, proposing a double-stage brace design that verified gradual failure instead of catastrophic. Xie et al. (2024) tested two reinforced concrete column piers, one with braces and one without, demonstrating that braces curtailed displacement and curvature by effectively dissipating seismic energy. Cabrera and Bruneau's (2024) testing program with Bidirectional Ductile Diaphragms showed a reliable hysteretic response when using V-configuration braces. Lastly, Li et al. (2025) analyzed composite frames, finding that those with braces enhanced lateral resistance by up to 142% and had an initial stiffness at least 8.4 times greater. Gong et al. (2025) examined a replaceable coupling beam with hybrid energy dissipation devices, showing it effectively reduced interstory drifts and mitigated damage to nearby elements.

3.2 Significance of Research

Many existing structures use RC frames that fail to meet quality standards. In regions with moderate to low seismic activity, these frames are built without necessary seismic detailing, compromising safety and integrity. Such constructions are prevalent in industrial, residential, and commercial areas. The past performance of these poorly designed frames during seismic events has been inadequate, leading to concerns about their reliability (Jennings, 1997), (Sezen et al., 2003), (Kappos et al., 2007), (Miyamoto et al., 2008), (Ozmen et al., 2024). Thus, evaluating and improving these substandard buildings is crucial for mitigating risks and ensuring occupant safety.

This research examines the potential for collapse among deficient RC structures and evaluates the effectiveness of all-steel Tube-in-Tube BRBs in mitigating such risks. This innovative solution not only enhances seismic performance but also remains cost-effective. In light of the substantial ground motion event recorded in Kahramanmaraş in 2023, shake table experiments were conducted on two one-third-scale structural models: the first serves as a standard representation of a typical substandard RC building (reference frame), while the second features an advanced Tube-in-Tube system designed to improve structural integrity.

The experimental outcomes were subsequently aligned with the analytical framework. This calibration facilitated a more precise depiction of the joint's seismic response, underscoring the significance of integrating both empirical and theoretical methodologies for evaluating the efficacy of structures engineered to withstand

seismic activity. The findings from this comprehensive investigation are meticulously scrutinized and juxtaposed regarding essential global response indicators and the diverse damage manifestations recorded during the shake table assessments. This analysis seeks to elucidate the overall viability of the proposed alternative design strategy.

3.3 Tube-in-Tube Buckling-Restrained Braces

According to the post-earthquake reconnaissance reports (Binici et al., 2023), (Ayğın et al., 2024), (Avcil et al., 2024), (Doğan et al., 2024), (Yön et al., 2024), (Yuzbasi, 2024), most of the RC buildings collapsed or heavily damaged during the 2023 Kahramanmaraş earthquakes mainly due to the global deficiencies, either stiffness or strength or both. Therefore, the RC frame included in the present study was designed to represent such stiffness and strength deficiencies simultaneously. Among all the external bracing systems in seismic retrofitting to overcome global deficiencies, BRBs are one of the most popular ones for their large stiffness, strength, and stable inelastic response (Cao et al., 2022). Despite their large energy dissipation capacity, traditional concrete-encased BRBs are relatively heavy compared with their all-steel counterparts and costly, which prevents their use for ordinary buildings.

To address the aforementioned issues related to conventional buckling bracings and existing traditional BRBs, Shen et al. (2016) proposed Tube-in-Tube (TnT) BRBs, which are a new type of all-steel BRB with no formal design standards. The outer tube (jacket) helps prevent local and overall buckling in the inner tube (core) while enhancing structural strength. With their high strength, stiffness, reliability, and energy dissipation capacity, TnT BRBs are seen as better alternatives to traditional concrete encased BRB designs. Shen et al. (2016) initially presented all-steel TnT BRBs as a solution to the challenges of diminished strength and stiffness resulting from buckling, which is frequently encountered with conventional buckling braces. Also, TnT BRBs are less labor-intensive due to their simplicity in fabrication and much lighter because of the absence of concrete encasing. Furthermore, unlike concrete-encased BRBs, TnT BRBs impose smaller demands on the surrounding members because of their small compression overstrength and cyclic hardening tendency, as reported in Shen and Seker (2024).

The TnT BRB configuration utilized for the retrofitting of the substandard RC frame being analyzed is depicted in Figure 3.2. The load-bearing inner tube, characterized by its anticipated substantial inelastic axial deformation, is constructed using widely utilized circular or square hollow structural sections (HSS). Surrounding this load-bearing tube is the buckling restrainer, which consists of a two-segment outer tube that is fillet welded to a central stopper located in the mid-section. To facilitate fabrication and enable the load-bearing tube to laterally deform without imposing significant compressive loads on the outer tube, a small gap is incorporated between the load-bearing and the buckling restrainer tubes. The stopper, represented as a ring-shaped plate in the mid-section, is fillet welded to both the load-bearing and buckling restrainer tubes. This component serves to stabilize the two-segment outer tube while allowing the load-bearing inner tube to deform in an axial manner unrestrictedly. The connector plates, located at each end, function to transfer the axial load exerted on the load-bearing tube to the end connection assembly. These plates are interconnected via pretensioned high-strength bolts, ensuring a secure transfer of forces. Meanwhile, the end connection assembly comprises a reinforced gusset plate that links with the connector plate, adeptly transferring the axial loads from the load-bearing tube to the adjacent structural members, such as girders or columns, at both ends. This assembly is meticulously designed to restrict both in-plane and out-of-plane end rotations, which could potentially introduce global stability challenges. It is critical to note that such end rotations can lead to significant flexural demands, negatively affecting the overall performance of TnT braces, as supported by Seker and Shen (2017) and Seker et al., (2023).

An important consideration is the potential application of a low-friction coating or lubricant to the exterior of the load-bearing tube, aimed at reducing the transfer of shear forces across contact surfaces. This modification could enhance cyclic symmetry. Nonetheless, recent experimental findings (Seker and Shen, 2017) and Seker et al., (2023) suggest that TnT BRBs exhibit a relatively symmetrical hysteretic response even in the absence of such lubrication within anticipated demand parameters. Additionally, it is essential that the in-service longevity of any low-friction lubricant or coating applied to metal surfaces be validated through rigorous testing.

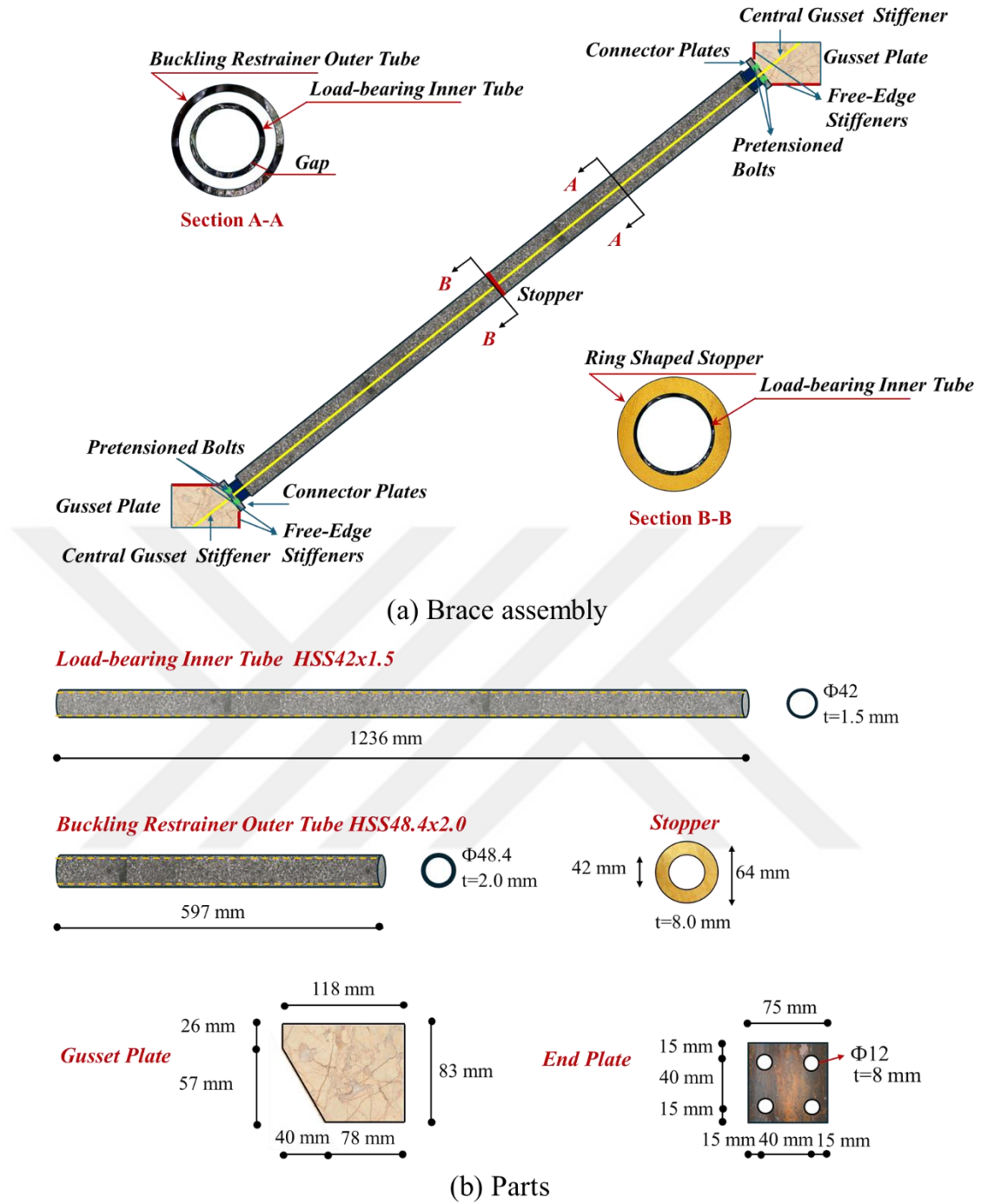


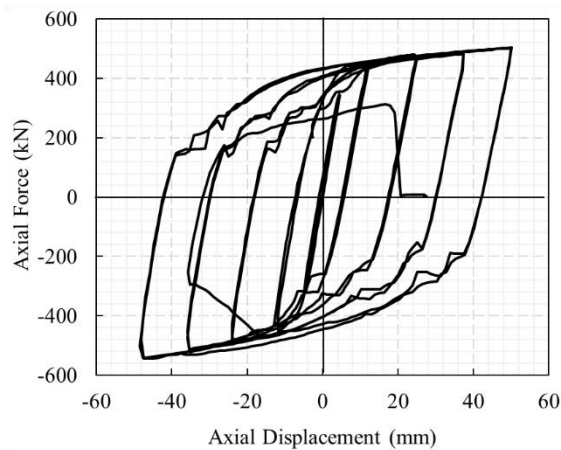
Figure 3.2 : Tube-in-Tube buckling-restrained brace scheme used in the study.

The energy dissipation capacity of TnT braces was examined through cyclic testing of large-scale specimens at Iowa State University. The experimental setup and the inelastic cyclic behavior of a 3.5-m TnT specimen with about 500 kN capacity are illustrated in Figure 3.3(a). The loading protocol adhered to the AISC Seismic Provisions (AISC 341) (2022). The axial force-displacement analysis demonstrated ductile, nearly symmetrical responses, with maximum ductility around 10 and story

drift exceeding 0.03 rad (Figure 3.3(b)). Total ductility approached 250, with peak compression overstrength near 10%, indicating minimal unbalanced brace forces in girders. As seen in Figure 3.3(b), the development of inelastic deformations began by yielding of the load-bearing tube (inner tube) in both tension and compression. Following the initial inelastic cycles at yielding deformation, the displacement-controlled load amplitudes were gradually increased to 50 mm, which corresponds to a ductility of 10 (an equivalent story drift ratio of 0.035 rad.). Note that two cycles were applied at each deformation quantity to comply with the loading protocol given in AISC 341 (2022). After attaining the peak ductility of 10, two additional cycles were applied at an axial displacement of around 38 mm (ductility of 7.5) to satisfy the cumulative ductility requirement (2022). The specimen showed a stable and virtually symmetrical response until the last cycle, as seen in Figure 3.3(b). During the last compression cycle at a ductility of 7.5, the load-bearing tube experienced local plastic deformations close to the loading end, which led to a strength deterioration (Figure 3.3(b)). Soon after the plastic local deformation took place, the load-bearing tube fractured in tension due to low-cycle fatigue. The lack of global buckling significantly enhanced energy dissipation capacity, shown by significant hysteresis loop areas. TnT braces effectively dissipate energy while maintaining stiffness, making them ideal for improving non-ductile reinforced concrete frames. Refer to Shen and Seker (2023) for further details on the experimental program.



(a) Test setup



(b) Hysteresis of a large-scale TnT brace

Figure 3.3 : Inelastic cyclic response of a typical TnT brace (adapted from Shen and Seker, 2023).

3.4 Configuration for Shake Table Testing

The experimental study utilizes a 3.0 m by 3.0 m shake table at the Allianz Teknik Earthquake and Fire Test and Training Center in Istanbul, Türkiye, with a maximum payload of 10 tons. Hydraulic actuators generate seismic forces, and the closed-loop controller includes three variables, adaptive control, and differential pressure stabilization. The shake table reaches a peak acceleration of 1 g, essential for accurately simulating realistic earthquake ground motions within a frequency range of 0 to 50 Hz.

3.4.1 Criteria for similitude requirements

Modeling theory outlines key parameters for linking geometric features, material properties, initial conditions, boundary limitations, and environmental effects of models and prototypes. This interaction is crucial for understanding how one entity behaves in relation to another. The main principle enabling the formation of correlation functions, which depict the model-prototype relationship, is known as similitude [50].

In this framework, developing and analyzing a structural model requires a careful approach that follows specific similitude criteria connecting the model to the original prototype. These criteria stem from modeling theory, clarified through dimensional analysis of physical phenomena affecting structural behavior. In dynamic model testing, this analysis helps identify principles governing scaling laws for force, time, and other variables, enhancing understanding of their interactions and relationships during testing (Krawinkler, 1988).

The concept of similitude is based on scaling factors that maintain the proportional relationship between a model and its prototype. This framework can be divided into three main categories: geometric similitude, kinematic similitude, and dynamic similitude.

Geometric similitude guarantees that the scaled models faithfully represent the geometry of the actual prototype structures. As noted by Harris and Sabnis (1999) and Li et al. (2011), geometric similarity necessitates that all linear dimensions of the model be proportionately scaled from the prototype. In our investigation, geometric similarity was meticulously preserved by uniformly scaling the dimensions of structural components, such as beams, columns, joints, and reinforcing bars, by a factor of 1:3. This scaling factor was chosen after thorough consideration of practical

limitations, encompassing laboratory space, instrumentation capabilities, and the ability to accurately capture intricate seismic responses. The geometric scaling upheld realistic reinforcement configurations, including bar diameters and spacing arrangements, thereby ensuring a faithful representation of actual RC structural layouts.

Kinematic similitude pertains to the proportionality of time-variable attributes, encompassing displacement, velocity, and acceleration. In accordance with the comprehensive protocols established by the National Earthquake Hazards Reduction Program (NEHRP, 2011), the attainment of kinematic similarity is vital for the precise simulation of seismic phenomena observed in authentic contexts (Gusev, 2011), (Evangelista et al., 2017). Within our shake table investigations, we maintained kinematic similitude by uniformly adjusting displacement and acceleration metrics in accordance with the principles of geometric and dynamic scaling. The resultant scaled seismic inputs effectively emulated typical earthquake motion, enabling us to accurately document critical structural response metrics, including peak accelerations, relative displacements, and deformation characteristics.

Dynamic similitude encompasses the proportional relationships among mass, stiffness, and damping attributes to guarantee that the dynamic responses of scaled models accurately mirror the behavior of prototypes under seismic loads (Moncarz and Krawinkler, 1981). To accomplish this objective, we rigorously adhered to the principles of dynamic similitude, which included preserving mass and stiffness ratios in alignment with the geometric scaling factor. Additional mass was judiciously incorporated into our specimens utilizing steel blocks to replicate the requisite scaled mass density while maintaining structural stiffness. To compensate, steel blocks were added to the roof, preserving overall stiffness. Each block was 1750 mm long, 570 mm wide, and 60 mm high, weighing 430 kg. Fourteen blocks were welded together, creating a total weight of 6 tons.

Moreover, stiffness similitude was attained through the meticulous selection and calibration of material properties in accordance with the established scaling principles, thereby ensuring a realistic depiction of the stiffness characteristics intrinsic to actual structures. Damping characteristics, which often present challenges in precise scaling, were also meticulously evaluated and modified through material selection and joint de-tailing to closely correspond with the prototypical damping ratios encountered in

practical applications. The physical variables obtained from this setup are detailed in Table 3.1.

Table 3.1 : Calculated physical quantities for shake table tests.

Physical Quantity	Scale Factor
Length, l_r	3
Modulus of elasticity, E_r	1
Time, t_r	1.732
Gravitational acceleration, g_r	1
Strain, ε_r	1
Acceleration, a_r	1
Frequency, ω_r	0.577
Velocity, v_r	1.732

The representativeness of the scaled specimens was additionally corroborated by the intentional reproduction of prevalent construction methodologies and standard shortcomings noted in non-ductile RC structures. This encompassed inadequate lateral reinforcement, deficient bar anchorage, and various typical detailing deficiencies that typify antiquated or inferior construction practices commonly found in regions susceptible to seismic activity.

It is imperative to acknowledge that there exist certain limitations intrinsically associated with scaled modeling methodologies. These limitations primarily encompass discrepancies in concrete compressive strengths, variations in steel yield strengths, and deviations attributable to the scaling of gravitational effects, all of which could potentially affect the fidelity of scaled model results. To mitigate these inherent discrepancies, meticulous attention was dedicated to the selection, preparation, and handling of construction materials, aligning their mechanical properties as closely as feasible with those observed in typical full-scale structures. Furthermore, rigorous experimental procedures were implemented to ensure minimal divergence from the expected prototypical re-sponses.

It can be definitively posited that these meticulously controlled minor variances are inadequate to substantially compromise the legitimacy or diminish the relevance of the experimental results to practical applications. Therefore, while recognizing the inherent constraints of scaled modeling, the strength and precision of the research outcomes remain securely preserved.

3.4.2 Examination of the test specimen

The experimental setup included two identical single-bay, single-story reinforced concrete frames, as shown in Figure 3.4. One frame acts as the control specimen, while the other has a diagonal TnT brace for enhancement. The frames will be called Specimen 1 (Bare Frame) for the control and Specimen 2 (TnT-retrofitted Frame) for the reinforced variant. Both are scaled models, reduced to one-third of the original dimensions, following the similitude rule in Table 3.1.



Figure 3.4 : Shake table test setup for two specimens.

The structural simulations involved columns with a rectangular cross-section of 100 mm width and 150 mm height, spaced 1350 mm apart. Each column had four longitudinal reinforcement bars of 8 mm diameter, the smallest available locally. The height of the columns was 950 mm from the foundation to the slab underside. As illustrated in Figure 3.5, transverse reinforcement included 8 mm diameter bars spaced 100 mm apart, with stirrups featuring 90-degree hooks, indicating suboptimal detailing. Additionally, 8 mm bars were used at 100 mm intervals in the slab's upper and lower sections. The foundation's longitudinal reinforcement consisted of 16 mm bars, with 10 mm stirrups spaced at 150 mm intervals. The top slab measured 1450 mm long, 450 mm wide, and 50 mm thick. A foundation beam, measuring 1950 mm long, 600 mm wide, and 400 mm deep, was anchored to the shake table with 50 mm diameter bolts.

Specimen 2 was created as a replica of the first specimen but included a TnT brace, as presented in Figure 3.4. The seismic retrofit aimed to enhance the strength and stiffness of the original RC frame, surpassing its initial load-bearing capacity. TnT bracing

system features a Tube-in-Tube design with a circular hollow structural section (HSS) of 42×1.5 mm made of S235JRH steel, encased in a 48.4×2.0 mm outer tube. This structure incorporates an outer tube as a buckling restraint that is split into two segments, while a single load-bearing tube connects the end plates. The assembly begins with an 8 mm-thick ring-shaped stopper plate attached to a 1235 mm load-bearing tube via fillet welding. Two 595 mm outer tubes are then welded to this stopper plate. The load-bearing tube is connected to 8 mm-thick rectangular end plates at both ends through fillet welding, with an intentional 18 mm gap included between the outer tube and end plates for accommodating potential tube shortening under compression. This design ensures effective performance in both compression and tension, as the outer tube's contribution to compressive strength is disregarded. The clearance dimensions were based on expected brace deformations. Finally, 75×75 mm end plates were connected to the prewelded end plates on gusset assemblies using four M12 grade 8.8 bolts to prevent end rotations, thereby enhancing stability, reinforced by stiffeners at key locations as supported by scholarly references (Zhou and Li, 2010), (Tsai et al., 2014), (Seker et al., 2023), (Shen et al., 2024).

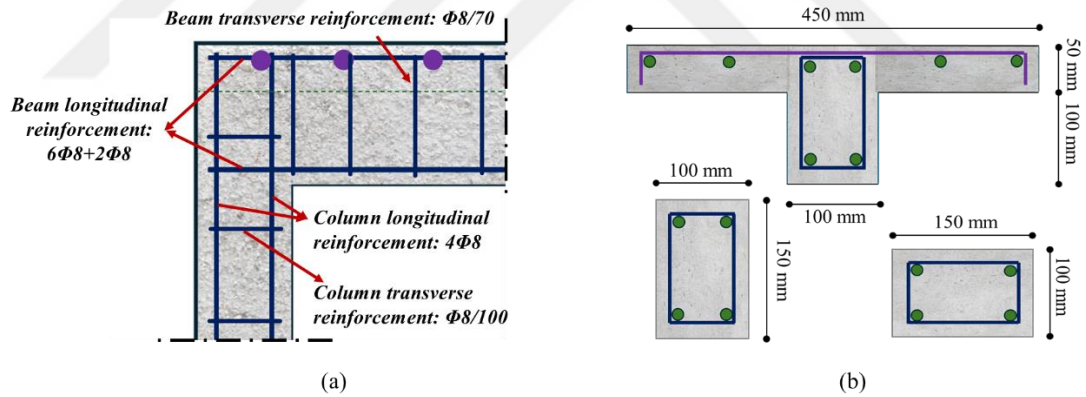


Figure 3.5 : (a) Reinforcement detailing, (b) Cross-sectional views of beam and column elements

It should be mentioned that incorporating bracings, either buckling or non-buckling, in an existing RC frame in particular is a challenge for several reasons. One of the major difficulties was taking accurate measures to produce shop drawings required for the fabrication of the TnT bracing and its connections. To overcome the erection tolerance issues, small tolerances that existed in the bolted connections were accommodated by the repair mortar injected between the steel reinforcing plates and the existing frame. Likewise, the installation of the joint-reinforcing jacket made with

steel plates requires careful rebar scanning to prevent potential damage to stirrups and longitudinal rebars while drilling anchorage holes. Therefore, all these drawbacks combined tend to increase the complexity of the seismic retrofitting process, not to mention the architectural and functionality constraints in an actual building.

The experiments aimed to achieve low uniaxial compressive strength in concrete. RC frames were constructed at Allianz Technical Laboratory, where various cubic samples were tested. The 28-day compressive cylinder strength for the frames was recorded at 9 MPa. To assess the steel's stress-strain relationships, three samples were tested, along with transverse reinforcement of the same diameter, which revealed a yield stress of $F_{(y,measured)} = 473$ MPa and an ultimate tensile stress of $F_{(y,measured)} = 643$ MPa. Tensile tests revealed the steel met the strength criteria of ASTM A615/A615M-05 (2005).

To evaluate the load-bearing tube's material properties made of HSS42 × 1.5, two dog bone-shaped coupons were extracted. Uniaxial tensile tests were conducted at the Turkish Standard Institution's Material Testing Laboratory. It is important to note that yield stresses were assessed using the 0.2% proof stress standard. The yield stresses for the two examined coupons were 397 MPa and 431 MPa. Peak engineering stresses ranged from 494 MPa to 520 MPa, with ultimate strain at fracture around 0.30 or higher. Average yield and ultimate tensile stress values from both tests were approximately 414 MPa and 507 MPa, respectively.

The test specimens' responses to seismic activity were meticulously documented using various instruments including accelerometers and linear voltage displacement transducers (LVDTs). Illustrated in Figure 3.6, all LVDTs were capable of measuring displacements at frequencies up to 200 Hz. In addition to the LVDT at the slab level (LVDT#1), two more were positioned at the ends of the TnT brace (LVDT#2 and #3) to capture axial displacements during excitations. Four accelerometers recorded accelerations in both the foundation and slab of the test frames, and on the shake table surface. Both acceleration and displacement responses were continuously logged by a computer-aided data acquisition system. Twelve strain gauges were also embedded within the reinforced concrete frame to monitor strain responses from various locations, as depicted in Figure 3.6.

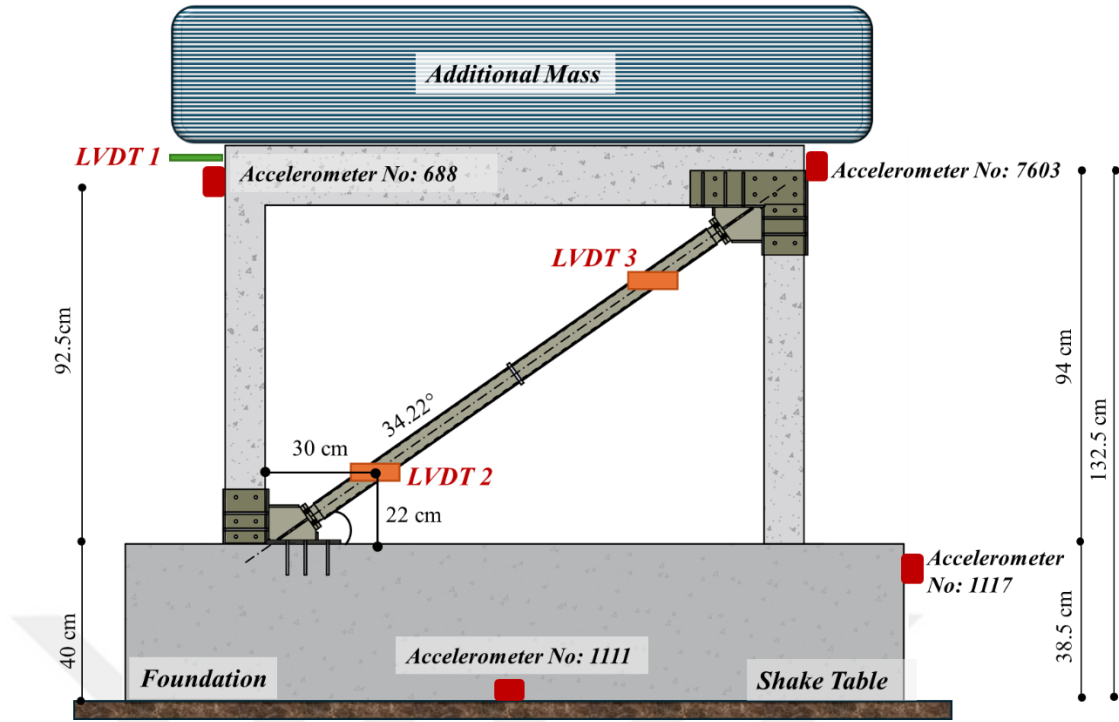


Figure 3.6 : Instrumentation of the test specimens.

3.4.3 Applied ground motion

On 6 February 2023, at 04:17 local time (+3 GMT), a major seismic event struck southeastern Turkey, registering a moment magnitude of 7.7. The Disaster and Emergency Management Presidency (AFAD) noted that the earthquake's epicenter was in Kahramanmaraş Province, near Pazarcık (AFAD, 2023). The Turkish Building Earthquake Code (TBEC) classifies seismic risk into four categories: DD-1, DD-2, DD-3, and DD-4, with probabilities of events at 2%, 10%, 50%, and 68% over 50 years. Figure 3.7 shows the normalized response spectra at DD-2 level alongside a time-history record from the 2023 Maraş earthquake, with critical damping values of 2.5%, 5%, and 10%.

The experimental evaluations were executed in two sequential phases. Initially, both types of frames were exposed to ground motion that had been appropriately scaled in accordance with the similitude law outlined in the preceding section. Since the frames tested were designed in alignment with substandard principles, the application of the scaled ground motion was executed with precision. Notably, Specimen 1 exhibited signs of damage when subjected to 35% of the ground motion. Conversely, Specimen 2 demonstrated resilience by enduring the same ground motion without sustaining any damage. As a result, an assessment was conducted to analyze the overall seismic per-

formance of TnT-enhanced Specimen 2 when exposed to 100% of the unscaled ground motion, characterized by a significant strength demand on short period structures. The primary objective was to evaluate the frame's behavior under conditions of intense ground shaking.

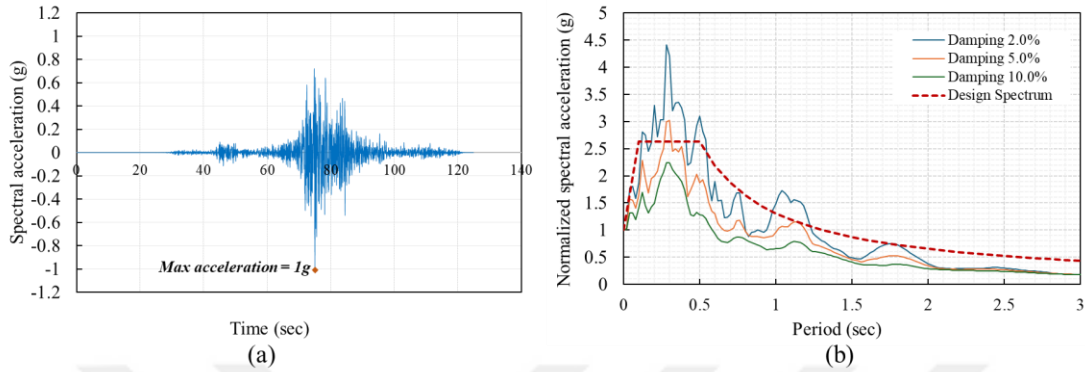


Figure 3.7 : (a) Time-history record of the 2023 Maraş earthquake, (b) Design spectrum for different damping ratios

3.5 Analytical Study and Model Calibration

This section outlines and examines the modeling strategies related to the analysis software, the methodologies implemented, and the specifics surrounding the material models.

3.5.1 Approaches to modeling

FE models for the two tested RC were created utilizing Seismostruct V2025 (2025), an advanced fiber based platform capable of executing nonlinear static and dynamic analyses. Additionally, this software allows for the incorporation of both material and geometric nonlinearity effects in the modeling process. This is made possible through a total corotational formulation by Correia and Virtuoso (2022), accurately representing kinematic transformations tied to large displacements and three-dimensional rotations of beam-column members. This method allows small deformations in relation to the chord without losing general applicability, even with large nodal displacements and rotations. In the local chord coordinate system, six fundamental displacement degrees of freedom are presented in Figure 3.8 (a,b).

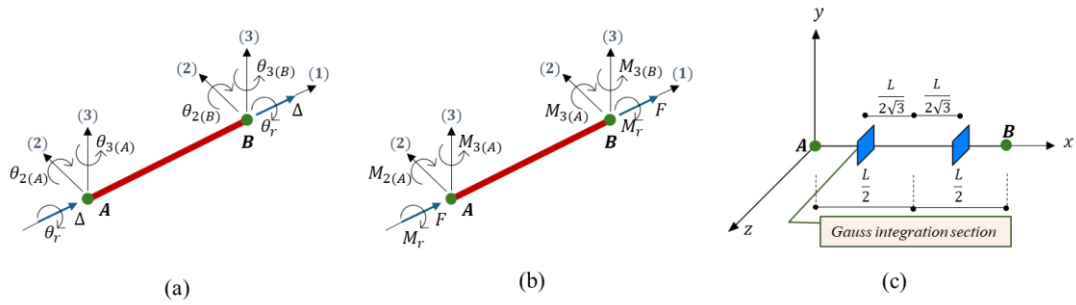


Figure 3.8 : (a,b) Local Beam's DOFs, and (c) Typical Gauss integration sections.

On the other hand, distributed inelasticity elements are increasingly used in earthquake engineering for research and professional applications. Their advantages over simpler lumped plasticity models, as well as their historical development and constraints, are documented by authors such as Filippou and Fenves (2004) and Fragiadakis and Papadrakakis (2008). Notably, these elements do not require the complex calibration of empirical parameters against actual or ideal responses under simplified loading conditions, unlike concentrated-plasticity models. This fiber approach models cross-sectional behavior, linking each fiber to a uniaxial stress-strain relationship. The stress-strain state of beam-column elements is determined by integrating the nonlinear responses of typically 100 to 150 fibers in the section.

Figure 3.8(c) represents a schematic illustration of the Gaussian integration procedure employed in this fiber-based FE analysis. This figure is pivotal for understanding the discretization strategy that underpins the accurate computation of the nonlinear behavior of RC beam-column elements. In this schematic, the RC element is depicted with its endpoints (0 and L), its midpoint ($L/2$), and, crucially, an integration point positioned at a distance of $0.3 L$ from the midpoint. This specific placement is not arbitrary; rather, it arises from an extensive sensitivity analysis and is consistent with the optimal Gaussian integration schemes documented in the literature and is also recommended in the software manual employed in this study (Filippou and Fenves, 2004) (Correia and Virtuoso, 2006).

The rationale for selecting an integration point at $0.3 L$ from the midpoint is rooted in the need to accurately capture the spatial variability of stress and strain across the RC cross-section, particularly in regions where steep gradients may develop due to localized damage phenomena. By situating the integration point at this strategically determined location, the method ensures that the fiber-level responses, which

collectively contribute to the global structural behavior, are computed with a high degree of precision. This is essential for modeling the complex nonlinearities inherent in seismic response, including material nonlinearity, bond degradation, and the evolution of damage under cyclic loading.

Figure 3.9 provides a comprehensive graphical representation of the stress-strain relationships for the primary materials utilized in the analysis, namely, concrete, reinforcing steel, and the TnT BRB system. The concrete curve is derived from the seminal Mander model (Mander et al., 1988), which rigorously characterizes the quasi-brittle behavior of concrete from the initial linear elastic range to the onset of cracking and eventual post-peak softening. This model is widely recognized for its ability to capture the degradation of stiffness and the evolution of damage under increasing strain, which are critical for predicting seismic performance. Similarly, the behavior of reinforcing steel is modeled using the Menegetto-Pinto formulation (1973), a formulation that effectively delineates the yield plateau and subsequent strain-hardening phase, ensuring that the ductile properties of the steel are accurately represented under cyclic loads. For the TnT BRB system, a buckling-restrained steel brace model from the literature (Seker and Shen, 2017) is employed to illustrate its distinctive energy dissipation characteristics. These constitutive models underpin the simulation of the intrinsic nonlinear material behavior and drive the emergence of hysteretic loops during cyclic loading, thereby providing a robust foundation for predicting the overall seismic response of the retrofitted RC frames.

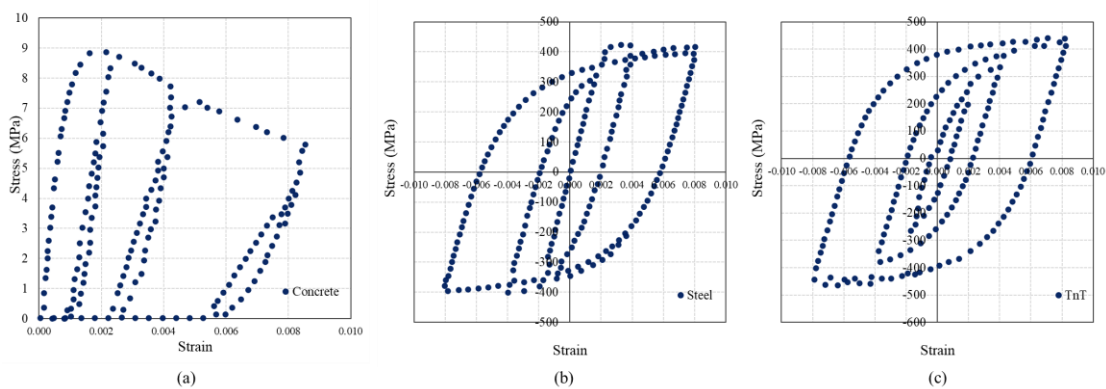


Figure 3.9 : (a) Concrete Model, (b) Steel Model, and (c) TnT BRB Model used in the FE model.

Figure 3.10 eloquently depicts the intricate three-dimensional finite element models of the two RC structures, meticulously capturing the complex interrelations of the beam–

column joints, reinforcement configurations, and overall structural geometries, thereby providing a robust foundation for the ensuing analytical comparisons and validation of the computational predictions against experimental data.

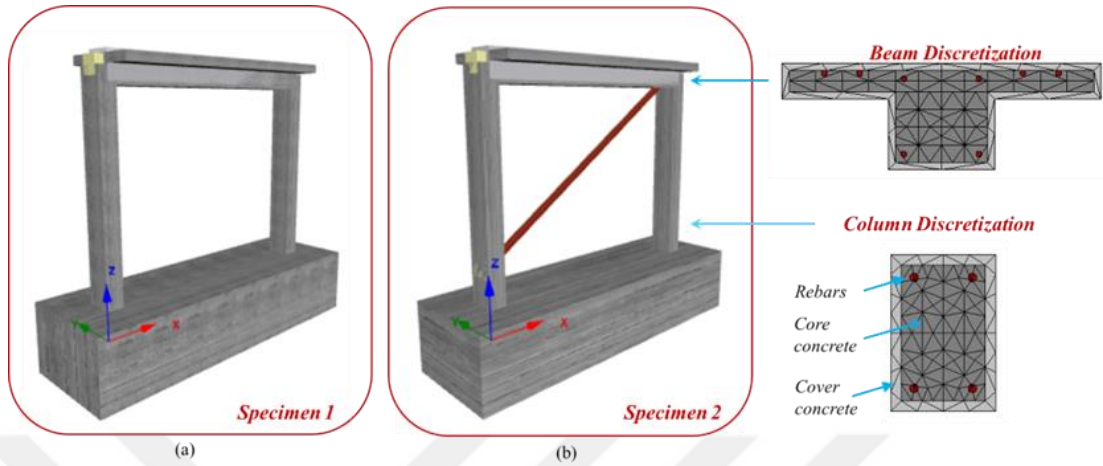


Figure 3.10 : Three-dimensional finite element models of tested specimens and fiber-based discretization of beam and column elements: (a) Specimen 1, (b) Specimen 2

3.5.2 Calibration of the analytical model

This section presents a comparative analysis of the results obtained from the analytical model against the outcomes of the shake table tests. Initially, the eigenvalue results of the specimens subjected to testing are examined. This is subsequently followed by an assessment of the LVDT results in relation to the nonlinear time history analysis derived from the analytical models. After calibrating the analytical models with the empirical results from the shake table tests, the damped hysteretic energy values of these models are computed and discussed in relation to the established code threshold limits.

The natural vibration periods were computed by taking into account the rigidities of the cracked sections in both longitudinal and transverse directions, and these calculations for both specimens are juxtaposed with the experimental data, as shown in Table 3.2. The calculated eigen periods demonstrate concordance with the results obtained from the shake table tests for each specimen. An evaluation of the LVDT data obtained from the shake table test juxtaposed with the computed displacement trace derived from the analytical model is presented in Table 3.3. The data presented in the tables indicates a strong correlation between the outcomes of the analytical model

analysis and the shake table experiments. This observation suggests that the analytical model has been effectively calibrated.

Table 3.2 : Comparison of the natural vibration periods.

Specimen No	Shake Table Test (s)	Analytic Model (s)	Error (%)
1	0.495	0.463	6.45
2	0.151	0.147	2.65

Table 3.3 : Comparison of the top displacements.

Specimen No	Ground Motion	Shake Table Test (mm)	Analytic Model (mm)	Error (%)
1	0.35 g	53.14	53.57	0.43
2	0.35 g	1.87	2.06	9.22
2	1 g	19.86	18.97	4.48

To further substantiate the coherence between the experimental shake table results and the numerical simulations, Figure 3.11 presents a direct time-history comparison of displacement responses obtained from both the physical tests and the calibrated FE model of the two specimens, considering 0.35 g and 1 g ground excitations. Each subplot illustrates overlaid displacement traces, with the red lines representing the measured response from the shake table tests and the blue lines corresponding to the simulated output from the FE model.

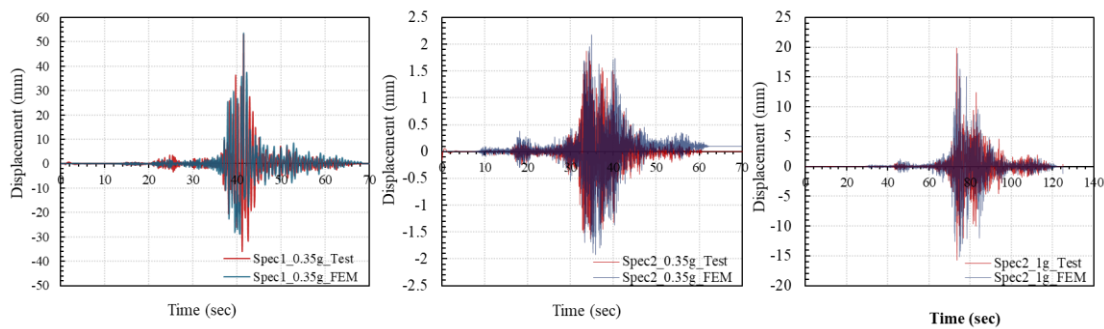


Figure 3.1 : Comparison of displacement-time traces for specimens.

Across all intensity levels, the experimental and numerical results exhibit strong agreement not only in peak amplitudes but also in waveform shape, frequency content, and phase alignment. The fidelity of this match reinforces the robustness of the fi-ber-based FE modeling approach adopted in this study, particularly in capturing non-linear dynamic response characteristics of the retrofitted RC frame. These results confirm that the numerical model is sufficiently accurate to reflect the global seismic behavior

observed experimentally, thereby providing a validated basis for subsequent parametric studies and design-oriented evaluations.

3.5.3 Limitations of the fiber-based finite element model

At the core of the fiber-based FE methodology lies the discretization of an RC cross-section into a finite number of fibers, each endowed with a uniaxial stress-strain relationship that approximates the behavior of either the reinforcing steel or the concrete. This discretization enables the efficient summation of fiber responses to yield an overall sectional response; however, it does so by assuming a perfect bond between the steel and the surrounding concrete. Such an assumption, while expedient for computational purposes, neglects the intricate interfacial phenomena such as bond-slip, localized debonding, and the onset of microcracking that are inherently present in RC systems under cyclic loading conditions.

The literature underscores that this assumption may lead to a systematic underestimation of stiffness degradation and strength loss during the post-yield phase. The phenomenon of bond deterioration, particularly under high cycle fatigue conditions typical of seismic events, can precipitate significant deviations between the modeled and observed structural responses, especially in regions where bond failure governs the initiation of localized plastic hinges (Li et al., 2012).

Furthermore, the inherent assumption of a uniform strain distribution across each fiber in the cross-sectional discretization tends to homogenize the actual material behavior. Concrete, characterized as a quasi-brittle material, exhibits highly localized cracking and crushing phenomena, particularly in zones of elevated stress concentration such as the vicinity of beam-column joints. In practice, these localized nonlinearities manifest as discrete regions of strain softening and damage accumulation, phenomena that are frequently averaged out in the distributed plasticity approach. It was shown that the distributed plasticity approach can mask the precise onset of inelastic behavior, thereby reducing the accuracy of the model in replicating critical localized damage mechanisms (Iandiorio and Salvini, 2023).

The limitations of the fiber-based approach are further accentuated by the discretization strategy itself. In an ideal scenario, the division of a cross-section into fibers would capture the true heterogeneity of material properties and the spatial variability of stress and strain fields. However, practical implementations often necessitate a

compromise between computational efficiency and resolution. Coarser discretizations may lead to an oversimplification of the complex stress distribution, especially in regions where steep gradients exist. This is particularly problematic when modeling the progression of damage in areas subject to concentrated plastic strains, where phenomena such as diagonal cracking or localized crushing are critical (Bitar et al., 2018).

An additional point of concern is the calibration process of the fiber-based FE model against experimental data. While the present study demonstrates a commendable correlation between the analytical predictions and the global response characteristics observed during shake table tests, the calibration predominantly focuses on overall displacement and eigenfrequency metrics. Such calibration procedures, though effective in establishing the global accuracy of the model, may not adequately account for the evolution of localized strain concentrations and damage mechanisms.

It is also important to consider the implications of the aforementioned limitations in the context of the intended application of the model. In seismic analysis, the accurate prediction of the energy dissipation capacity of RC structures is of paramount importance. The fiber-based approach, by averaging out localized phenomena, may overestimate the energy absorption capabilities of RC members, particularly in cases where local damage mechanisms such as bond-slip and localized cracking are predominant. This overestimation can have significant ramifications when the model is used to assess the performance of retrofitting strategies, such as the TnT BRB system examined in this study.

In light of these considerations, it is evident that while the fiber-based finite element model provides valuable insights into the global seismic behavior of RC structures, its limitations in capturing the intricate, localized phenomena must be transparently acknowledged. Future research endeavors should aim to integrate hybrid modeling strategies that combine the computational efficiency of the fiber-based approach with more refined localized damage mechanics models. For example, a multi-scale modeling framework could be developed wherein the global response is captured by the fiber model, while critical regions identified as prone to localized damage are modeled using detailed finite element methods that incorporate sophisticated constitutive models and high-resolution discretization. Such an approach would enable

the capture of both global structural response and the critical local phenomena that govern failure mechanisms.

3.5.4 Validation against shear-critical experimental data

In order to rigorously assess the predictive capability of the fiber-based FE model, an extensive validation exercise against four independent experimental datasets have conducted that specifically address shear-critical phenomena in RC beam-column joints. Table 4 below encapsulates the experimental values reported in the literature. Studies such as Lopez et al. (2004), Sung et al. (2021), Kalogeropoulos et al. (2024), and Cabrera and Bruneau (2024) have consistently measured critical shear stresses in the range of 5.0–5.2 MPa. Conversely, the analytical model presented in Section 5.1 revealed a critical shear stress value of 5.16 MPa.

Table 3.4 : Critical shear stress at joint Comparison of Experimental Data with Model Predictions.

Reference	Experimental Value (MPa)
Kalogeropoulos et al. (2024)	5.0
Sung et al. (2021)	~5.0
Cabrera and Bruneau (2024)	5.1
Lopez et al. (2004)	~5.1

In conclusion, the advanced calibration of this fiber-based model against these six experimental datasets significantly bolsters its predictive accuracy. This comprehensive validation not only corroborates the simulation results but also reinforces the study's claims regarding the superior seismic performance achieved via the TnT BRB retrofit strategy. The detailed comparison with experimental data thus serves as a critical benchmark, ensuring that the fiber-based model reliably captures both the global dynamic behavior and the localized shear-critical phenomena that dictate the seismic resilience of RC structures.

3.6 Discussion on the Results

Hysteretic behavior encompasses various forms of structural damage, such as slip or shear cracks in joints, bond failure in reinforcing materials, and shear failure in beams. This behavior is characterized by the fact that the restoring forces rely solely on the relative displacement. The force-displacement curve exhibits a steeper incline during tension compared to compression, with distinct and well-defined corner and yield

points. Additionally, this behavior is marked by a degradation of stiffness following a sudden decrease in strength.

Substandard RC structures usually feature a number of defects such as inadequate detailing of reinforcement, poor material qualities, poor quality control in construction and emphasis on strength rather than ductility of structures. These deficiencies lead to formation of a complex mode of failure with yield plateau, energy dissipation capability, and large deformation demands of the system. Elucidation of behavior of such structures requires some understanding of their energy dissipation capability and their deformation demands.

Hysteretic behavior has long been recognized as a confusing aspect of structural performance because it might lead to nonlinear and unexpected response of structural systems subjected to severe cyclic loads, such as earthquakes (Saiidi and Sozen, 1979). Hysteresis in force–deformation response represents energy dissipation during loading and unloading cycles. This phenomenon is of vital importance to seismic behavior and response of structures and should be validated with experimental tests. Over the years, numerous experimental studies have been conducted to investigate how substandard RC components behave under cyclic and seismic loading. These tests, ranging from individual element tests (beams, columns, joints) to full-scale frame tests, have provided invaluable insights and data on hysteretic degradation in non-ductile RC structures.

A notable illustration of the deficiencies in seismic design is presented by the research conducted by Hakuto et al. (2000). They executed simulated seismic loading assessments on both interior and exterior beam-column joint configurations that featured inadequate reinforcing details characteristic of older construction practices, such as the absence of transverse reinforcement within the joint core and insufficient anchorage of beam bars. When subjected to cyclic lateral loads, these joints displayed limited strength and ductility, with the external joints particularly prone to joint shear failures and substantial loss of strength after only a few drift cycles. This groundbreaking study highlighted the susceptibility of inadequately detailed joints and emphasized the necessity for retrofitting interventions, noting improvements in performance when some joints were retrofitted with fiber-reinforced polymer (FRP) wraps.

More contemporaneous research has continued to underscore these vulnerabilities. Kalogeropoulos et al. (2024) performed tests on four exterior beam-column joint subassemblies designed to replicate the detailing prevalent in reinforced concrete structures built prior to the 1970s. The specimens, examined in their original (unretrofitted) condition, displayed inadequate hysteresis behavior, indicative of brittle failure mechanisms. Among them, two joints were subject to joint shear failures, while the other two experienced anchorage pullout of beam bars, aligning with the expected deficiencies of their designs. The authors noted that “all specimens exhibited poor hysteresis behavior dominated by catastrophic damages of brittle nature”. The hysteresis loops produced during these experiments were particularly tight and non-symmetric, reflecting a critically diminished capacity for energy dissipation. Notably, one specimen featuring a deficient column lap splice exhibited an anomalously asymmetric response, wherein the splice failure in a unidirectional loading scenario triggered a significant reduction in strength during that half-cycle.

These experimental findings are relatively uncommon and serve to underline how the interplay of multiple detailing inadequacies, such as deficient lap splices combined with inadequate joint ties, can result in complex hysteretic degradation. Collectively, the joint testing results consistently indicate that insufficient joint and core detailing contributes to rapid degradation of stiffness and poor energy dissipation, positioning these joints as a critical weakness in older structural frameworks.

Elnashai and Di Sarno (2015) emphasized that significant structural damage results from a high capacity for energy absorption. This leads to the inference that a substantial area under the story shear interstory drift curves, representing total absorbed energy, inevitably results in excessive damage and permanent deformation. Furthermore, hysteretic energy is defined as that part of the mechanical energy absorbed by a structure during a cycle of loading which is not recovered during the cycle of unloading. It is the area inside a plot of load versus displacement that depicts the loading and unloading cycle of a system. Hysteretic energy is known to be dissipated in a material when it is subjected to loading and unloading conditions. While many models have been developed to portray the complex behavior of materials and structures under cyclic loading, few are capable of describing adequately the deterioration of mechanical properties of materials subjected to low cycle (frequency) fatigue (Zahrah and Hall, 1982).

The analysis presented in Figure 3.11, which vividly illustrates the hysteretic response of the tested specimens, provides an invaluable qualitative insight into the energy dissipation mechanisms and stiffness degradation phenomena that underpin the seismic behavior of the RC frames. This figure graphically depicts the progressive evolution of hysteresis loops, thereby capturing the cyclic deterioration of structural performance, as manifested in the gradual degradation of the restoring forces. However, while Figure 3.12 effectively conveys the visual narrative of damage through the widening and pinching of hysteresis loops, it stops short of offering a direct, quantitative measure of damage.

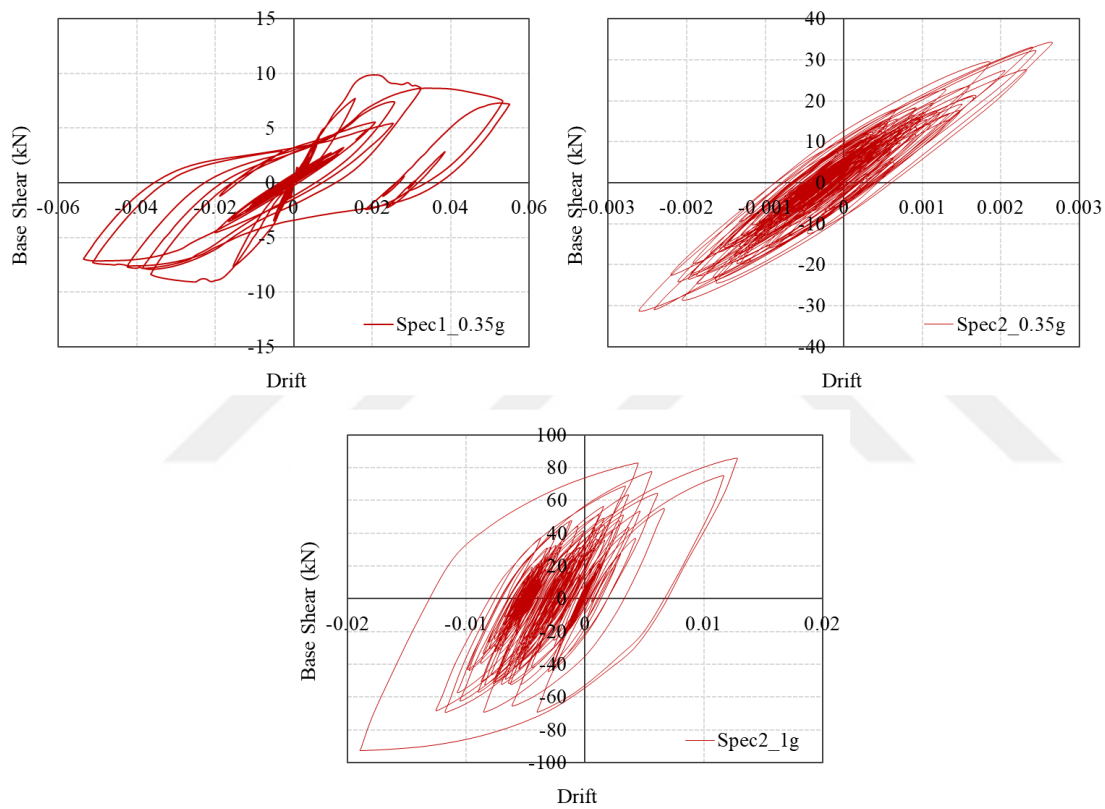


Figure 3.2 : Hysteretic response of the specimens.

To bridge this gap, we have employed the Park–Ang damage index (Park and Ang, 1985) (D), which is a seminal quantitative measure in seismic engineering that synthesizes both the displacement demand and the energy dissipation capacity of a structure under cyclic loading. This integration of displacement and energy parameters facilitates a more nuanced and objective quantification of structural damage, thereby complementing the qualitative assessments derived from Figure 3.12. The Park–Ang damage index values for the three specific scenarios, specifically Specimen 1 subjected

to 0.35 g, Specimen 2 also subjected to 0.35 g, and Specimen 2 under 1 g, were determined to be 0.89, 0.03, and 0.34, respectively.

When these quantitative indices are compared with the qualitative observations derived from Figure 3.11, a coherent correlation emerges. Specimen 1 under 0.35 g excitation exhibits a pronounced hysteretic response with extensive energy dissipation and significant displacement, which is consistent with its high damage index ($D \approx 0.89$). In stark contrast, the retrofitted frame, Specimen 2, displays negligible hysteretic activity and minimal displacement at low seismic levels (0.35 g), as reflected in an exceptionally low damage index ($D \approx 0.03$). Under full-scale seismic excitation (1 g), Specimen 2 exhibits a moderate increase in hysteretic response and displacement, resulting in a damage index of approximately 0.34, a value that remains substantially lower than that of the bare frame under similar conditions.

These findings not only underscore the superior performance of the retrofitting strategy but also highlight the robustness of the Park–Ang damage index as a composite metric that integrates both deformation and energy-based degradation mechanisms. The ability of this index to reconcile the visual evidence from hysteretic curves with quantitative damage assessments provides a powerful tool for benchmarking and comparing different structural configurations and retrofitting interventions. In essence, by incorporating both indices (displacement and energy) the Park–Ang model offers a comprehensive and nuanced framework for evaluating seismic damage, thus reinforcing our overall conclusions drawn from both experimental observations and numerical simulations.

Figure 3.13 presents photographs of the shake table tests conducted on the selected RC specimens. An analysis of the figure indicates that the initial specimen has experienced considerable damage, in contrast to the second specimen, which appears to be unscathed. The prominent cracking in the upper corners of the first specimen, along with the observed concrete crushing, indicates a significant joint shear failure. Further, significant areas of the concrete overlay have separated, especially in the regions near the base and the junctions between beams and columns. The damage at the joints may have compromised the bond between the reinforcement and the surrounding concrete, leading to further weakening. In contrast, the second specimen exhibited no signs of damage, such as cracks or spalling, suggesting that the TnT BRB performed its function of dissipating seismic energy effectively. The inclusion of the diagonal brace

enhanced resistance to lateral forces, which in turn minimized deformation and safeguarded against early failure of the beam-column joints. Thus, it can be deduced that the TnT BRB system played a crucial role in absorbing and redistributing seismic forces, thereby averting significant stress accumulation in the joints.



Figure 3.3 : Shake table test results.

3.7 Conclusions

This research emphasizes the substantial efficacy of the innovative TnT BRB system as a seismic retrofitting method specifically designed to enhance the resilience of RC beam-column joints. Comprehensive experimental investigations conducted via shake table testing clearly highlighted critical shortcomings inherent in conventionally designed non-ductile RC structures. Such structural systems exhibited pronounced brittle shear failures, substantial lateral displacements, and significant joint degradation under cyclic seismic excitations. These observed vulnerabilities underscore the pressing need for robust and effective seismic retrofitting strategies for existing infrastructure.

Conversely, the integration of TnT BRBs resulted in considerable enhancements in seismic performance. The retrofitted RC frames demonstrated notable reductions in lateral drift, improved capacity for energy dissipation, and sustained integrity of key structural joints. The substantial mitigation of structural damage progression and enhanced global stability under seismic loading clearly illustrates the transformative potential of the proposed retrofitting solution.

The value of this investigation is amplified through the integration of advanced analytical techniques, particularly sophisticated fiber-based FE modeling. This analytical approach effectively captured complex structural responses, such as hysteretic behaviors, localized damage phenomena, stiffness deterioration, and energy dissipation. Although the fiber-based FE element model provides key insights into the seismic performance of RC structures, its limitations in capturing complex localized behaviors must be acknowledged. Future research should prioritize hybrid modeling techniques that combine the strengths of fiber-based frameworks with detailed models of localized damage.

As a conclusion, this study effectively bridges empirical and analytical methodologies, providing critical insights and validated tools for seismic rehabilitation of vulnerable RC structures. This integrated framework represents a significant contribution to both theoretical knowledge and practical application, offering valuable guidance for ongoing and future research efforts, as well as enhancing seismic design standards and resilience strategies within earthquake engineering. Future research should focus on optimizing the design parameters of TnT BRBs, exploring their long-term durability, and assessing their applicability across a broader range of structural configurations.



4. EXPERIMENTAL EVALUATION OF AN INNOVATIVE TUBE-IN-TUBE BUCKLING RESTRAINED BRACES FOR SEISMIC RETROFITTING OF SUBSTANDARD RC FRAMES³

The process of seismic retrofitting for inadequate RC frames is vital for enhancing structural integrity in areas susceptible to earthquakes. This research investigates a novel tube-in-tube (TnT) buckling restrained brace (BRB) system aimed at improving the seismic performance of these substandard RC frames. By targeting significant weaknesses inherent in older RC constructions, the TnT BRB introduces a lightweight, all-steel configuration that eliminates the need for traditional mortar or concrete infill materials. Experimental shake table testing on two one-third scaled RC frame models was conducted to compare the seismic performance of an unretrofitted control frame and a frame retro-fitted with the TnT BRB system. Results indicate significant enhancements in lateral strength, ductility, and energy dissipation capacity in the retrofitted frame, demonstrating stable and symmetrical hysteresis loops and reduced stiffness degradation compared to conventional X-braced systems. Analytical modeling corroborated these experimental findings, confirming the TnT BRB's superior capability in absorbing seismic energy and preventing premature structural failures. This investigation emphasizes both the practical and financial benefits of integrating the TnT BRB into seismic retrofitting strategies while recommending further research to optimize the system, specifically addressing issues related to local denting, frictional wear, and alignment to bolster its effectiveness in practical applications.

³ This chapter is based on “**Oyguc, E.,** Oyguc, R., Seker, O., Hayır, A., Shen, J., & Akbas, B. (2025). Experimental Evaluation of an Innovative Tube-in-Tube Buckling Restrained Braces for Seismic Retrofitting of Substandard RC Frames. *Applied Sciences*, 15(9), 4662. <https://doi.org/10.3390/app15094662>”

4.1 Introduction

The prevalence of inadequate reinforced concrete (RC) frames remains a critical concern in regions susceptible to earthquakes, especially those with building stocks established before the advent of contemporary seismic design codes. Findings from various post-earthquake assessments conducted after the 2000s indicate that a significant share of structural failures and collapses can be attributed to these older RC structures, which frequently reveal deficiencies in detailing, such as insufficient shear reinforcement, sub-standard lap splices, and inadequate confinement (Rossetto and Peiris, 2009), (Celebi, 2013), (DeLuca et al., 2015), (Oyguc, 2016), (Yazgan et al., 2016), (Qiu et al., 2020), (Arslan and Kaya, 2021), (Yurdakul et al., 2021), Figure 4.1 depicts typical damage identified in aged RC structures during the post-seismic field assessments conducted by the authors. Predominant structural inadequacies that contribute to these damage manifestations encompass insufficient spacing of transverse reinforcement, substandard stirrup detailing characterized by 90-degree hooks, inadequate concrete cover leading to substantial spalling, improperly executed lap splices, and insufficient confinement in critical beam-column joint areas. These weaknesses markedly enhance the vulnerability to brittle shear failures and soft-story mechanisms during seismic occurrences. Typically, these buildings were designed primarily to support vertical loads, with little or no consideration for lateral forces. Consequently, they demonstrate a tendency toward soft-story failure mechanisms, rapid degradation of stiffness, and diminished ductility when subjected to cyclic loading, resulting in an increased risk of collapse (Parker and Johnson, 2022).

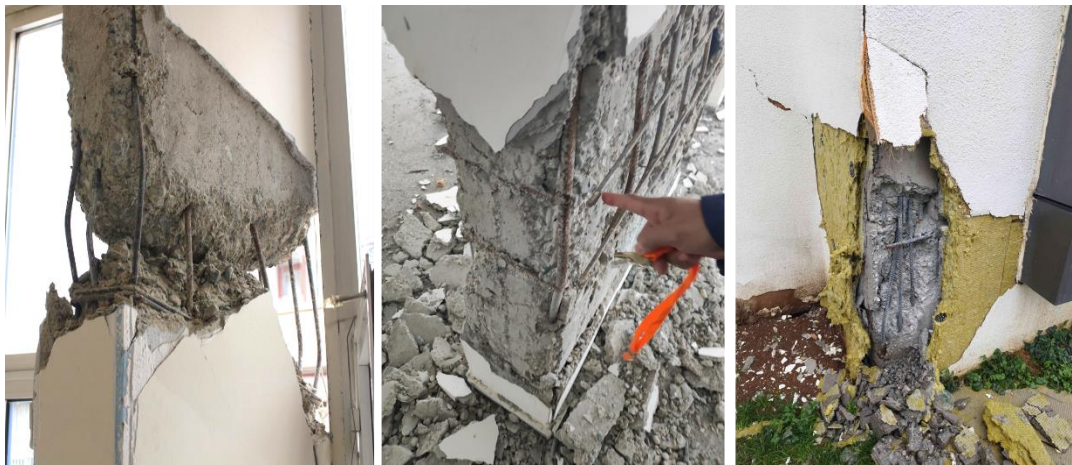


Figure 4.1 : Typical damage to substandard RC frames observed after the 6 February 2023 Kahramanmaraş earthquakes.

The choices available for the demolition and reconstruction of these structures are frequently restricted by both practical and financial limitations. This situation underscores the critical necessity of seismic retrofitting as an essential measure to mitigate vulnerabilities associated with earthquakes. The primary aim of retrofitting is to enhance the lateral strength, ductility, and energy dissipation capacity of these buildings. By doing so, retrofitting helps equip them to endure seismic activities of predetermined intensity, ensuring they do not fail or collapse during such events.

In the past five years, the engineering sector has focused on developing effective seismic retrofitting techniques for inadequate RC frames. Traditional methods such as column jacketing, shear walls, and the use of fiber-reinforced polymers (FRPs) aim to reduce vulnerabilities by enhancing member strength and deformation capacity (Gupta and Soni, 2023). However, these techniques have practical and financial limitations, including construction demands, increased structural weight, and disruption of usable floor space (Lee et al., 2021), (Moynihan and Ramos, 2024). Despite improvements in cross-sectional capacity, older RC structures still face brittle failure modes due to poor joint detailing or insufficient reinforcement. This underlines the need for supplementary damping systems to enhance energy dissipation and interstory drift distribution (Barros et al., 2023).

Among the array of retrofitting methodologies available, buckling restrained braces (BRBs) are distinguished from other supplemental damping devices by their consistent hysteretic behavior and established effectiveness in energy dissipation. Initially engineered for use in steel framing, BRBs comprise a steel core that is intentionally designed to yield under axial tension and compression forces. This core is encased within a restraining mechanism, typically a tube filled with either steel or mortar, which serves to inhibit global buckling (Morimoto et al., 2022). The design of the steel core allows it to alternate between tension and compression without experiencing premature buckling, resulting in nearly symmetrical load-displacement loops. This characteristic enables BRBs to provide enhanced energy absorption capabilities compared to conventional concentric braces (Tsai et al., 2020). The efficacy of BRBs in new steel construction has led to increased research interest in their adaptation for use in substandard RC frames (Ghannadi and Assadi, 2021). By acting as a specialized damping component, a properly engineered BRB can alleviate inelastic demands

placed on existing RC elements, thereby mitigating shear and flexural stresses in critical structural components such as columns, beams, and joints (Noor et al., 2024).

In light of the observable advantages that conventional BRBs offer, it is essential to recognize the practical challenges that both researchers and engineers encounter when attempting to integrate these systems into older RC frames. Primarily, the effectiveness of BRBs hinges on the presence of reliable anchorages and well-designed gusset plates, which are crucial for effectively transmitting substantial axial forces to beam-column junctions. However, numerous older frames exhibit deficiencies in transverse reinforcement, rendering them unsuitable for such force transfer (Ryu et al., 2023). Additionally, the inclusion of mortar or concrete infill within the restraining tube can create complexities in the fabrication process, lead to an increase in the overall weight of the system, and introduce difficulties related to future inspection and maintenance activities (Xie and Li, 2021).

In light of recent developments, an innovative tube-in-tube (TnT) BRB concept has gained prominence, presenting itself as a potentially lighter and more constructible alternative to conventional infill-based designs (Tang et al., 2023), (Rodriguez et al., 2025). This approach diverges from traditional methods that utilize mortar or concrete for buckling restraint, instead employing two concentric steel tubes. The inner tube serves as the primary yielding core, while the outer tube offers continuous lateral support. A significant key benefit linked to this configuration can be identified as its stable hysteretic performance. Recent experimental research reveals that TnT braces can attain ductility levels that are on par with, or potentially exceed, those found in conventional BRBs (Cai and Wang, 2021).

The tube-in-tube design still represents a relatively innovative approach for enhancing the performance of substandard RC frames, evidenced by the limited number of extensive experimental studies documented in existing literature. Important unresolved issues pertain to the local denting phenomenon observed at the mid-span of the core tube, potential friction or unintended bearing occurrences between the interconnected tubes, and the dependability of connection systems within RC elements that are susceptible to cracking or cover spalling. Muniz and Oseguera (2023) emphasized that even minor misalignments in tube geometry or significant ovalization resulting from compression can adversely affect the hysteretic behavior of a brace.

Therefore, TnT BRBs offer advantages over conventional concrete-encased BRBs in terms of cost-efficiency due to their less labor-intensive fabrication process and relatively small structural weight. It is important to emphasize that TnT BRBs can be 5 to 7 times lighter than their concrete-encased counterparts with equivalent strength. This can be attributed to the absence of concrete encasing, which might substantially increase the overall mass of the structure and the inertia forces acting upon it consequently. Further, the symmetrical hysteretic behavior without significant compression overstrength (e.g., a compression adjustment factor of 1.10 on average) obtained from experimental studies could lead to up to a 35% reduction in the material cost owing to the small, unbalanced brace forces in the inelastic stage (Shen et al., 2016), (Seker and Shen, 2017), (Seker et al., 2021), (Seker et al., 2023).

This research aims to analyze an innovative TnT BRB system for inadequate RC frames, focusing on performance characteristics across various drift ratios, including load displacement profiles, energy dissipation efficiency, and failure modes. The study is grounded in the significant 2023 Kahramanmaraş (Pazarcık) seismic event with a magnitude of 7.7. A systematic assessment of structural performance was conducted through shake table experiments on two one-third scale, single-story, single-bay frame models. The first model served as a reference frame typical of substandard RC constructions, while the second integrated an advanced tube-in-tube system to enhance structural resilience. An extensive account of the experimental methodologies utilized is provided, followed by a detailed examination of the results that juxtaposes the performance indicators of both non-retrofitted and TnT braced reinforced concrete frames. Additionally, the seismic behavior of a traditional X-type brace was subjected to an analytical assessment relative to the new tube-in-tube design. This analysis indicated that the novel configuration facilitates superior energy dissipation and diminishes lateral stiffness, both of which are essential elements for enhancing the overall structural efficacy during seismic occurrences.

4.2 Prospects and Challenges of All-Steel Tube-in-Tube Buckling Restrained Braces for Seismic-Resistant Structures

Steel concentrically braced frames (CBFs) utilize brace yielding and buckling mechanisms to dissipate energy during seismic events; however, conventional braces are prone to early buckling and exhibit insufficient ductility, resulting in premature

failure. To address these limitations, buckling controlled braces (BCBs) have been introduced. BCBs incorporate an external restraining mechanism designed to inhibit both global and local buckling of the brace, thus preserving stable hysteretic performance even under significant cyclic deformation. This innovation bears a resemblance to BRBs but typically employs an all-steel design, foregoing concrete infill, which enhances the practicality and feasibility of BCBs for both new constructions and retrofitting projects. Among the prominent configurations of BCBs are the TnT BRB, consisting of an internal steel tube brace surrounded by an outer hollow steel section with a minimal gap, and the channel-encased BCB, which encapsulates an existing brace, usually a hollow structural section (HSS) tube, with two steel channels that are stitched together. To enhance brevity, these systems will be designated as TnT BRBs. Initial findings indicate that these designs markedly increase the ductility of the braces, bolster their capacity for energy dissipation, and successfully delay the onset of fracture. A schematic representation of a tube-in-tube buckling restrained brace configuration is given in Figure 4.2.

Note that the lateral support provided by the encasing is expected to prevent global buckling entirely. Although preventing the formation of local plastic deformations entirely is not possible, it is intended that the outer tube delay the local buckling until reaching an expected ductility level. Based on the previous numerical and experimental studies conducted on TnT BRBs, it is recommended that the diameter-to-thickness ratio of the load-bearing tube (i.e., inner tube) should satisfy the highly ductile member requirement to avoid premature local buckling. In fact, the optimal parameters to achieve high energy dissipation capacity with a virtually symmetrical inelastic cyclic response are to use an outer tube thicker than the inner tube, providing a small gap amplitude to accommodate the lateral movement of the inner tube and reducing the friction force transfer between the two tubes as much as possible.



Figure 4.2 : Schematic representation of a Tube-in-Tube buckling restrained brace.

In a study by Seker and Shen (2017), the TnT BRB was conceptualized and subjected to tests involving a series of specimens under cyclic loads. Each specimen featured a steel brace, termed the inner tube, which was enveloped by a larger hollow steel section that functioned as the buckling restrainer, referred to as the outer tube. An intentional small annular gap, measuring just a few millimeters, was incorporated to allow the inner brace to bear nearly all the axial load while the outer tube provided essential lateral support to avert buckling phenomena. Throughout their experiments, Seker and Shen (2017) analyzed various design parameters, including the size of the gap, the stiffness of the outer tube (determined by its thickness), and the structural details of the gusset plates. The braces underwent quasi-static reversed cyclic loading, conforming to an adapted AISC loading standard involving multiple cycles at escalating drift amplitudes.

The findings indicated that the TnT BRBs produced stable and symmetrical hysteresis loops at story drift ratios reaching approximately 3.5% to 4.0%, with no observable degradation in strength (Figure 4.3). Conversely, traditional HSS tube braces subjected to the same testing conditions exhibited buckling and subsequent fracture at approximately 2% drift. The TnT mechanism effectively prolonged the brace's fracture endurance, enhancing the ductility capacity from an estimated 6 to 8 in conventional braces to a range of 14 to 20 in the BRBs.

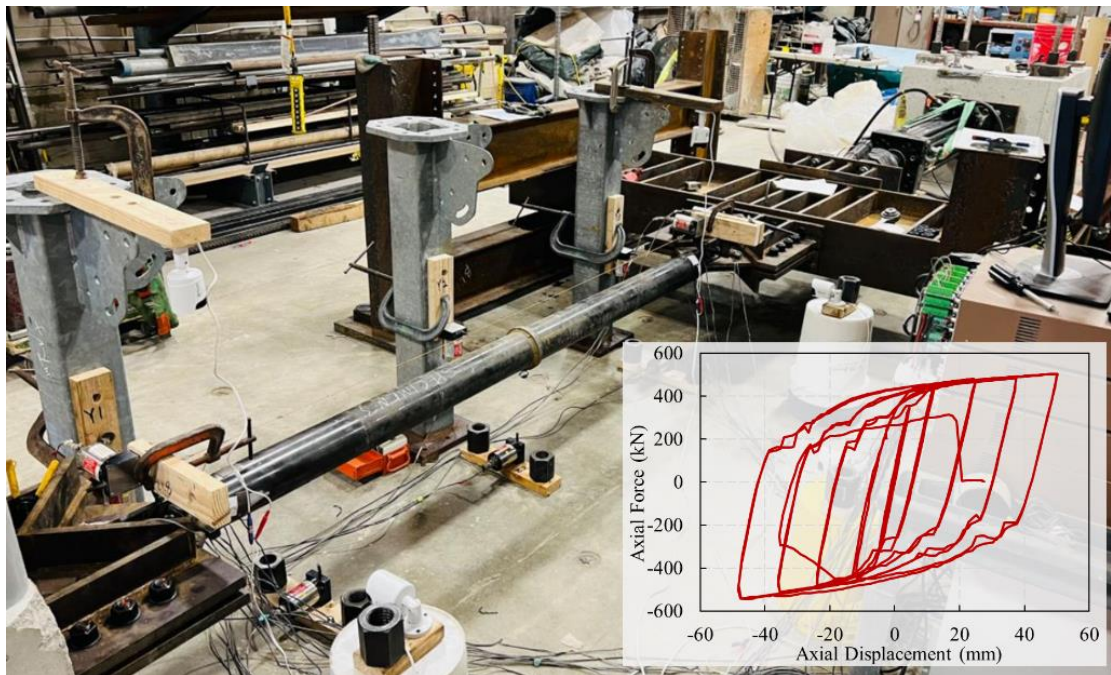


Figure 4.3 : Inelastic cyclic response of a typical TnT BRB (adapted from Seker et al., 2017).

To assess the effect of the coefficient of friction (COF) between the contact surfaces of the inner and outer tubes on the hysteretic behavior, Shen et al. (2016) performed a series of cyclic simulations on TnT BRBs under identical loading protocols using various COFs between the contact surfaces where shear force transfer due to friction could be significant at high demand levels. Their results indicated that as the coefficient of friction reduced, cyclic stability and symmetry improved. This can be attributed to the reduction in the shear stress transferred from the outer tube to the inner tube, which seems to expedite the formation of local deformations.

Researchers have investigated the potential of utilizing steel channels as buckling restrainers in addition to TnT BRBs, which presents a valuable solution for retrofitting applications. Seker et al. (2023) proposed the concept of channel-encased BCBs, wherein an existing brace is enveloped by two steel channel segments. These channels are fillet welded together, often supplemented with intermittent “stitch” welds or plates, thereby creating a closed section that surrounds the brace. This design effectively forms a composite tube around the brace by using basic, easily sourced shapes. The spacing between the brace and the channels can be adjusted through small separators or variations in welding geometry, permitting the brace to slide until it makes contact with the channels under buckling conditions. Seker et al. (2021) evaluated channel-encased braces featuring circular HSS braces, as these are prevalent in contemporary construction practices. Their findings indicated that even robust round HSS, characterized by low width-to-thickness ratios, were susceptible to fracture at minimal drifts when employed as traditional braces. However, the incorporation of channels significantly enhanced their performance.

The TnT BRB system employed in this study for enhancing the RC frame is illustrated in Figure 4.4. It comprises an inner load-bearing tube made from standard hollow structural sections, designed for high inelastic axial deformations. Surrounding the inner tube is a dual-segment outer tube with a mid-section stopper, allowing minimal gaps for manufacturability and lateral deformation accommodation. The stopper stabilizes the outer tube while allowing axial deformation. Connector plates at the ends transfer axial loads to an end connection assembly, secured by high strength bolts, ensuring stable force transmission. A gusset plate in the assembly aids in axial load transfer to adjacent structures, preventing detrimental end rotations.

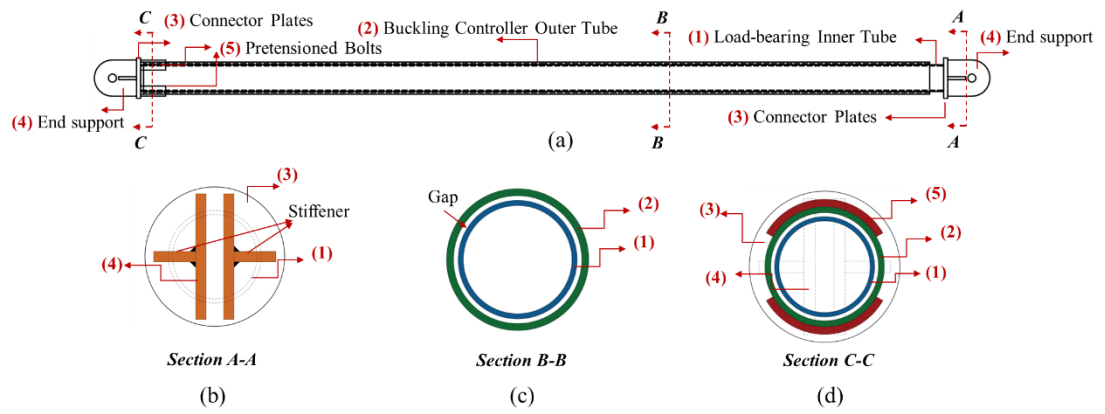


Figure 4.4 : Drawings of a representative TnT BRB system: (a) Overall elevation showing connector plates at both ends, (b) detail of gusset-plate connection, (c) plan view of tube, and (d) plan view of fully assembled brace.

4.3 Shake Table Study

Recent seismic events have revealed significant weaknesses in current RC structures, particularly those built prior to the establishment of modern seismic design criteria. These identified weaknesses underscore the urgent need for the creation and application of robust retrofitting strategies. Among the various retrofitting options available, external diagonal bracing systems, particularly the TnT bracing method, have demonstrated considerable potential due to their notable enhancements in structural performance combined with the advantage of easy installation, which minimizes disruptions to building aesthetics and functionality. However, despite an increasing interest in this method, there remains a lack of comprehensive experimental data that substantiates the performance of TnT braces. Consequently, this research endeavors to address this deficiency by providing substantial experimental evidence to validate the effectiveness of TnT bracing systems.

4.3.1 Similitude requirements

The theory of modeling presents an elaborate framework that identifies critical parameters essential for establishing relationships among different geometric features, intrinsic material properties, initial conditions that act as the basis for analysis, boundary limitations that define the framework of the models, and the numerous environmental factors that can affect both models and prototypes throughout their duration. Understanding the complex interplay among these assorted elements is crucial for achieving a deep comprehension of how one entity interacts and operates

in relation to another within the modeled system. A key principle that supports the creation of correlation functions, which illustrate and clarify the relationship between the model and its respective prototype, is well-established in the discipline as the principle of similitude (Moncarz and Krawinkler, 1981).

In this theoretical framework, developing and analyzing a structural model requires a methodical approach that follows specific criteria to link the model to its original prototype. These criteria are based on modeling theory principles and explained through dimensional analysis, which examines the physical phenomena affecting structures under various conditions. In dynamic model testing, dimensional analysis helps researchers and engineers understand the principles governing scaling laws for key variables such as force and time, thereby improving comprehension of the complex interactions during testing (Krawinkler, 1988).

This research endeavor utilized a meticulously crafted artificial mass simulation model, which was specifically engineered to fulfill a variety of precise similitude requirements pertaining to both geometric configurations and load-bearing parameters. While the model largely complied with the established material specifications mandated by the relevant scientific standards, it is important to note that there was a significant deviation in terms of the mass density parameter. In order to effectively rectify this discrepancy and maintain the integrity of the simulation, steel blocks were strategically incorporated into the slab, thereby ensuring the preservation of the overall stiffness of the model. Each individual block utilized in this simulation measured an impressive 1750 mm in length, 570 mm in width, and 60 mm in height, with a substantial weight of 430 kg attributed to each unit. A total of fourteen such blocks were meticulously welded together to form a cohesive structure, resulting in a cumulative weight that reached an impressive total of 6 tons. The physical variables that were meticulously measured and obtained from this experimental setup are comprehensively outlined and presented in Table 4.1 for further analysis and reference.

Table 4.1 : The calculated physical quantities for shaking table tests.

Physical Quantity	Artificial Mass Simulation [28]	Scale Factor
Length, l_r	l_r	3
Modulus of elasticity, E_r	E_r	1
Time, t_r	$(l_r)^{1/2}$	1.732
Gravitational acceleration, g_r	1	1
Strain, ε_r	1	1
Acceleration, a_r	1	1
Frequency, ω_r	$(l_r)^{-1/2}$	0.577
Velocity, v_r	$(l_r)^{1/2}$	1.732

4.3.2 Test specimen

The conducted experiments employed an advanced biaxial seismic shake table, located at the Allianz Teknik Earthquake and Fire Test and Training Center in Istanbul, Türkiye, measuring 3.0 m by 3.0 m, which has a payload capacity of up to 10 tons. This sophisticated apparatus effectively replicates real seismic ground motions, functioning within a frequency spectrum of 0 to 50 Hz and achieving peak accelerations of 1 g. Moreover, the shake table is equipped with hydraulic actuators alongside sophisticated adaptive control systems that utilize differential pressure stabilization, thereby guaranteeing precise and dependable reproductions of seismic activities.

Two 1/3-scaled RC frames, emblematic of standard Turkish RC structures from the 1980s, were constructed. These models were designed in accordance with the prevalent practices of the time, which were marked by insufficient seismic detailing. Specimen 1 functioned as the unretrofitted control specimen, whereas Specimen 2 was retrofitted with diagonal TnT bracing, a seismic enhancement option chosen for its capability to effectively channel lateral seismic forces directly into the foundation. This retrofitting method also enhances energy dissipation via axial deformation, contributing to the reduction of bending stresses experienced by the frame components.

The structural simulations that were performed were characterized by the careful application of columns with a rectangular cross-section, measuring 100 mm in width and 150 mm in height, spaced intentionally at 1350 mm apart from one another. Each column incorporated four longitudinal reinforcement bars, each with a diameter of 8 mm, which represents the smallest reinforcement bar size commonly available for

construction in the local area. The vertical dimension of these columns reached 950 mm, extending from the foundation base to the underside of the slab, thereby offering substantial structural support.

As depicted in Figure 4.5, the transverse reinforcement in these columns consisted of 8 mm diameter bars spaced at 100 mm intervals, with stirrups featuring 90-degree hooks, which indicate suboptimal detailing. Additional 8 mm diameter bars were used at 100 mm intervals in the upper and lower slab sections, enhancing structural integrity and load distribution. The foundation's longitudinal reinforcement comprised robust 16 mm bars, with 10 mm stirrups spaced at 150 mm intervals to withstand various loads. The top slab measured 1450 mm in length, 450 mm in width, and had a thickness of 50 mm, contributing to its durability. A foundation beam measured 1950 mm long, 600 mm wide, and 400 mm deep, securely anchored to the shaking table with 50 mm diameter bolts for stability.

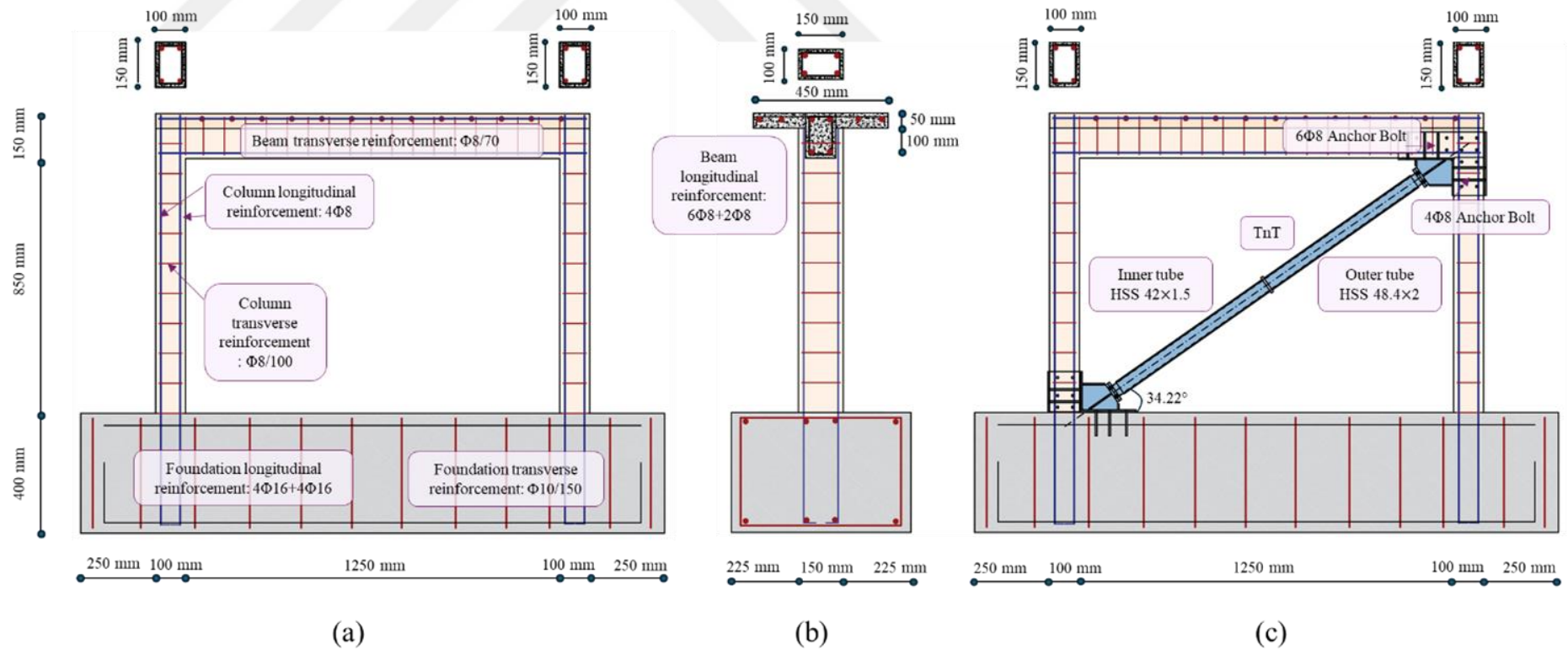


Figure 4.5 : Shake table test specimens and key reinforcement details: (a) Specimen 1, (b) transverse section, and (c) Specimen 2.

Specimen 2 has been carefully constructed to serve as a precise imitation of the original specimen while integrating an enhanced TnT bracing system, as demonstrated in Figure 4.5, which visually depicts the structural advancements. The principal aim of the seismic retrofit was to markedly improve the strength and stiffness of the original reinforced concrete frame, thereby surpassing its initial load-bearing capacity to meet contemporary structural demands.

The TnT bracing system exemplifies an advanced engineering approach with its intricate tube-in-tube configuration. This design comprises an inner circular hollow structural section (HSS) with dimensions of 42×1.5 mm, constructed from S235JRH steel, and is encased within an outer tube that has dimensions of 48.4×2.0 mm. A notable feature of this design is the outer tube, which acts as a buckling restraint and is systematically segmented into two separate parts. The integration of a single load-bearing tube facilitates the interconnection of the end plates, thus ensuring a cohesive structural assembly.

The assembly begins with welding an 8 mm thick ring-shaped stopper plate to a 1235 mm long load-bearing tube using fillet welding for strength. Next, two 595 mm outer tubes are welded onto the stopper plate for added support. The load-bearing tube is secured to 8 mm thick rectangular end plates at both ends by fillet welding. An 18 mm gap between the outer tube and end plates is included to allow for potential tube shortening under compressive loads, optimizing performance during varying load conditions.

The design has been meticulously developed for peak performance under compressive and tensile forces. The outer tube's contribution to compressive strength is omitted from the analysis for simplification. Clearances were chosen based on expected brace deformations to handle seismic activity effectively. Additionally, 75×75 mm end plates were secured to pre-welded gusset end plates using four M12 grade 8.8 bolts, crucial for preventing end rotations and enhancing structural stability. Strategically placed stiffeners further bolster this stability, as supported by academic literature (Krawinkler, 1988), (Zhou and Li, 2010), (Tsai et al., 2014), (Shen and Seker, 2024).

4.3.3 Instrumentation and loading system

The behaviors demonstrated by the test specimens under seismic influence were systematically analyzed, focusing on critical parameters such as acceleration, displacement, and strain. This analysis was facilitated by the use of advanced measurement tools. The experimental setup incorporated accelerometers and linear voltage displacement transducers (LVDTs), depicted in Figure 4.6, highlighting the complexity of the employed methods. Designed for precision, the LVDTs could measure high frequency displacements, achieving an exceptional range of up to 200 Hz, thus ensuring accurate capture of dynamic responses. These instruments were strategically mounted on sturdy frames firmly anchored to the ground rather than directly on the shaking table, enhancing the precision of displacement measurements in relation to a stable ground reference. LVDT#1 mounted on the slab level was to measure lateral story displacement and the drift re-sponse, accordingly, as shown in Figure 4.6. In addition to the LVDT positioned at the slab level (LVDT#1), two more LVDTs were placed at each end of the TnT brace (LVDT#2 and LVDT#3) to effectively record axial displacement demands on the load-bearing tube during seismic activities, as illustrated in Figure 4.6. These two LVDTs (LVDT#2 and 3) were installed to record the relative movement of the outer tube with respect to the end plates connected to the gusset plates at each end. Therefore, the axial displacement demand on the load-bearing tube can be computed as the summation of the relative displacements measured from LVDT#2 and 3.

Furthermore, accelerations were meticulously monitored at various strategic locations, including the foundation, slab of the test frames, and the shake table surface, through four accelerometers securely attached to both the foundation and the shake table.

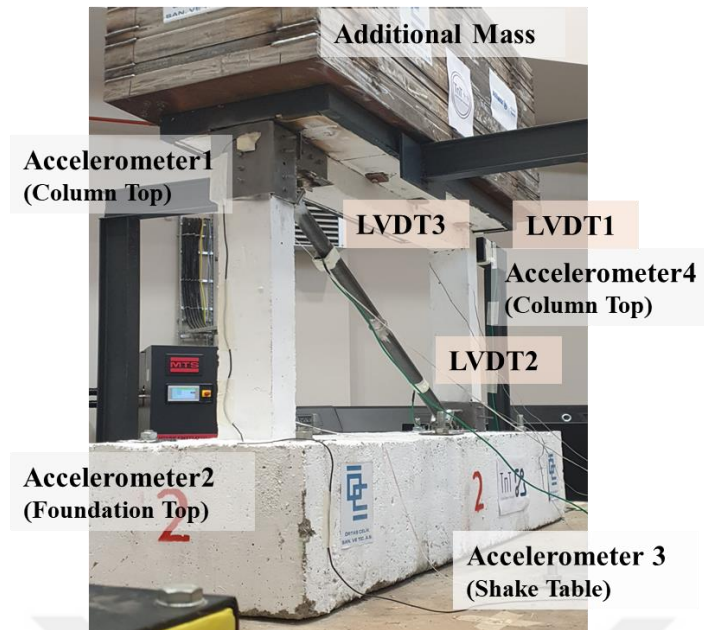


Figure 4.6 : Instrumentation of Specimen 2

All accelerometers were mounted on rigid aluminum brackets that were chemically anchored either to the shake table platen or to the foundation beam, thereby eliminating relative slip and ensuring that each device registered the true input or response acceleration of its host mass. Two sensors on the platen recorded the exact base input; two additional sensors on the foundation cross checked that the anchorage transmitted the input without phase lag. At the superstructure level, twin accelerometers were positioned symmetrically at the beam–column joints to capture torsional tendencies as well as planar response, with their sensing axes aligned to the principal directions of motion. This arrangement allowed direct calculation of story accelerations and modal participation without numerical differentiation of displacement data.

It is essential to underline that both acceleration and displacement data were collected in real-time using a sophisticated computer-based data acquisition system, ensuring thorough data capture throughout the experimental process. Additionally, twelve strain gauges were integrated into the reinforced concrete frame to monitor strain responses from various carefully chosen points, thus providing a comprehensive understanding of the structural performance under seismic loading conditions.

4.3.4 Material properties

The concrete chosen for the experimental framework was specifically manufactured to have a low compressive strength of about 9 MPa. This choice aimed to replicate the

poor quality often found in older RC structures, particularly those built before strict seismic design codes were enforced. By using weaker concrete, the research sought to reflect the seismic vulnerabilities common in existing RC buildings, providing valuable insights for retrofitting strategies. The study's concrete showcased these intentionally reduced strength characteristics, accurately reflecting the construction quality issues seen in older infrastructures.

In order to thoroughly evaluate the intricate stress-strain relationships inherent to the steel material, a comprehensive series of tests was conducted on three distinct samples, which were further complemented by the inclusion of transverse reinforcement that possessed the same diameter specifications, and through this meticulous examination, a 473 MPa yield stress value was determined, alongside a 643 MPa ultimate tensile stress value that was also established. The results of the tensile tests conducted indicated with a significant level of confidence that the steel in question successfully met the stringent strength criteria as set forth in the established guidelines of ASTM A615/A615M-05 (2005), thereby affirming its suitability for structural applications.

To analyze the material properties of the load-bearing tube made from HSS42 × 1.5, two dog bone-shaped samples were extracted for evaluation. Uniaxial tensile tests were performed at the Turkish Standards Institution's (TSI) Material Testing Laboratory, emphasizing precision and accuracy. The yield stresses were evaluated using the 0.2% proof stress criterion, showing values of 397 MPa and 431 MPa, indicating a notable difference in properties. The maximum engineering stresses ranged from 494 MPa to 520 MPa, with an ultimate strain at fracture of around 0.30 or more, reflecting significant ductility. The average yield stress was approximately 414 MPa, while the ultimate tensile stress was about 507 MPa, providing a comprehensive understanding of the material's mechanical properties.

In the development of a reliable 1:3 scaled model designed to analyze the seismic behavior of outdated and deficient RC frames, meticulous attention was devoted to the selection of materials and the scaling of dimensions. Specifically, concrete with a relatively low compressive strength and a minimized maximum aggregate size was selected to maintain geometric similarity in the ratio of aggregate to member size while simultaneously preventing unrealistic manifestations of strength increase. The adjustment of steel reinforcement bars in terms of both diameter and spacing was

undertaken to guarantee that the total steel ratio accurately represents real world full-scale conditions. Adhering to recognized principles of similitude, a scale factor of one was designated for the modulus of elasticity for both concrete and steel, as presented in Table 4.1. This methodology confirms that the stress-to-strain relationships closely correspond to those of the prototype, thus maintaining the precise stiffness attributes and deformation behaviors of the model.

Geometric scaling was conducted, adhering to a strict 1:3 ratio for all relevant linear dimensions, encompassing member length, cross-sectional height, and cover to reinforcement. By systematically diminishing these dimensions, the model retains consistent shear span-to-depth ratios and member slenderness values, resulting in a nearly identical distribution of bending moments, shear forces, and anchorage requirements under scaled seismic loading. The inclusion of artificial mass simulation (as illustrated in Table 4.1) further complements this geometric downscaling by maintaining inertial forces at the requisite magnitude, thereby ensuring that the dynamic response, mode shapes, and fundamental period correspond with those anticipated for the full-scale structure. Consequently, the interplay of judiciously selected concrete strength, standardized steel re-inforcement properties, and rigorous dimensional scaling underpins the validity of the experimental results and their subsequent extrapolation to actual substandard RC frames.

4.3.5 Ground motion sequence

A significant seismic event occurred on 6 February 2023, impacting southeastern Turkey with a moment magnitude of 7.7. The Disaster and Emergency Management Presidency (AFAD) reported the epicenter was in Kahramanmaraş Province near Pazarcik (2023).

Within the framework of the Turkish Building Earthquake Code (TBEC, 2018), seismic risk is systematically categorized into four distinct levels, designated as DD-1, DD-2, DD-3, and DD-4, each level representing probabilities of seismic events occurring within a span of 50 years of 2%, 10%, 50%, and 68%, respectively. In reference to Figure 4.7, one can observe the normalized response spectra at the DD-2 level, which is depicted alongside a time-history record from the earthquake that transpired in Kahramanmaraş in 2023, incorporating critical damping values of 2.5%,

5%, and 10%, thereby providing a comprehensive insight into the seismic response characteristics.

The experimental evaluations conducted in this research were executed in two interconnected phases. In the initial phase, both types of structural frames were subjected to ground motion scaled according to the similitude law from the previous section of this study. The frames, designed per established aseismic principles, underwent precisely scaled ground motion. Notably, Specimen-1 showed signs of structural damage under just 35% of the scaled ground motion, whereas Specimen-2 demonstrated remarkable resilience, enduring the same motion without sustaining any damage.

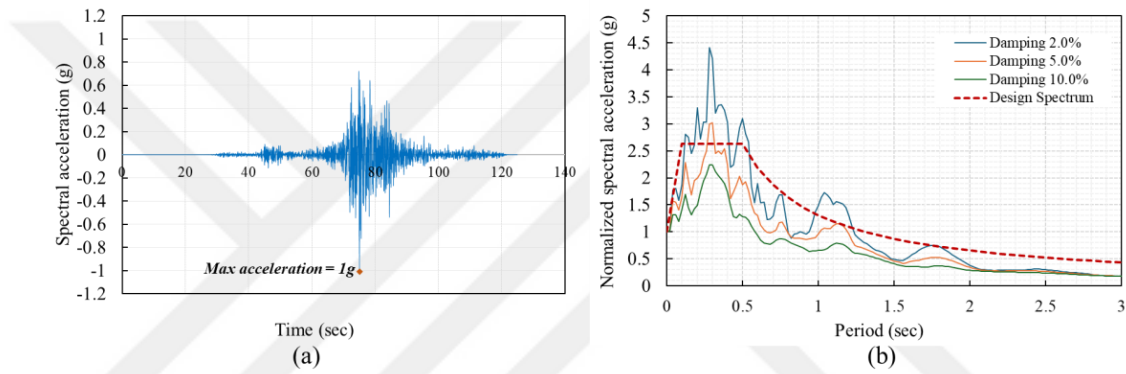


Figure 4.7 : Processed ground motion input used in the shake table tests: (a) acceleration time history of the 6 February 2023 Kahramanmaraş earthquake and (b) normalized spectral acceleration spectra for 2 %, 5 %, and 10 % critical damping.

As a result, a thorough evaluation was conducted to systematically assess the seismic performance of the TnT-enhanced Specimen-2 when subjected to 100% of the unscaled ground motion, a situation that imposes considerable strength demands on short-period structures. The main goal of this detailed analysis was to rigorously examine the frame's behavior under conditions of extreme and forceful ground shaking, ultimately providing critical insights into its performance during actual seismic occurrences.

4.4 Analytical Study

This section systematically outlines and examines the diverse modeling approaches that are intricately linked to the advanced analysis software. It also elaborates on the

thorough methodologies that have been carefully applied, highlighting the particular features and subtleties of the material models used in this framework.

4.4.1 Background theory

The main aim of this study is to attain a strong calibration of the analytical models to ensure they are consistent with the empirical data obtained from experimental observations.

In response to the experimental evaluations, finite element models were systematically developed for the two RC structures subjected to intensive testing. This was accomplished using the sophisticated functionalities of Seismostruct V2025 (2025). The software not only provides robust modeling features but is also proficient in incorporating the effects of both material and geometric nonlinearity, which are essential for accurately reflecting the intricate dynamic behaviors of the structures throughout the modeling phase. The fiber-based modeling approach captures the behavior of cross-sections, with each fiber representing a uniaxial stress-strain relationship that facilitates the assessment of the sectional stress-strain state of beam-column elements. This evaluation is derived from the integration of the nonlinear uniaxial stress-strain responses of individual fibers into which the cross-section is logically segmented. A standard discretization method applied to a typical RC cross-section is illustrated in Figure 4.8.

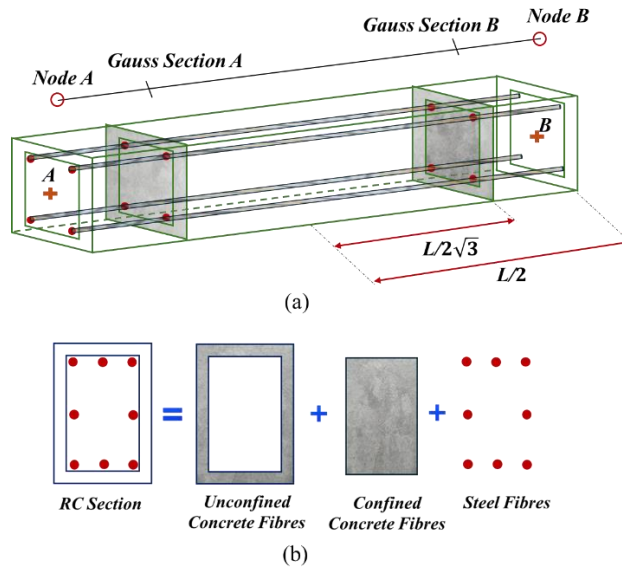


Figure 4.8 : Fiber discretization adopted in the FEM: (a) Three dimensional view of a beam column element subdivided into Gauss integration sections along its length and (b) exploded view of a single section for numerical integration.

Upon the successful fulfillment of the calibration requirements, conventional BRBs were systematically incorporated into the examined RC frames, thereby facilitating a comparative analysis with the results obtained from the TnT enhanced configurations. This comparison aims to elucidate the performance differences and enhance the understanding of the structural responses under various loading conditions. Ultimately, the findings derived from this comprehensive analysis will contribute significantly to the advancement of knowledge in the field of structural engineering and inform future design practices. Three-dimensional models of the RC structures are illustrated in Figure 4.9. A third numerical model (hereafter Specimen 3) was assembled by replacing the TnT brace with a conventional X type BRB of equal axial capacity. No third physical frame was fabricated; the model is used exclusively to benchmark hysteretic energy dissipation and to carry out parametric variations that extend the generality of the experimental findings.

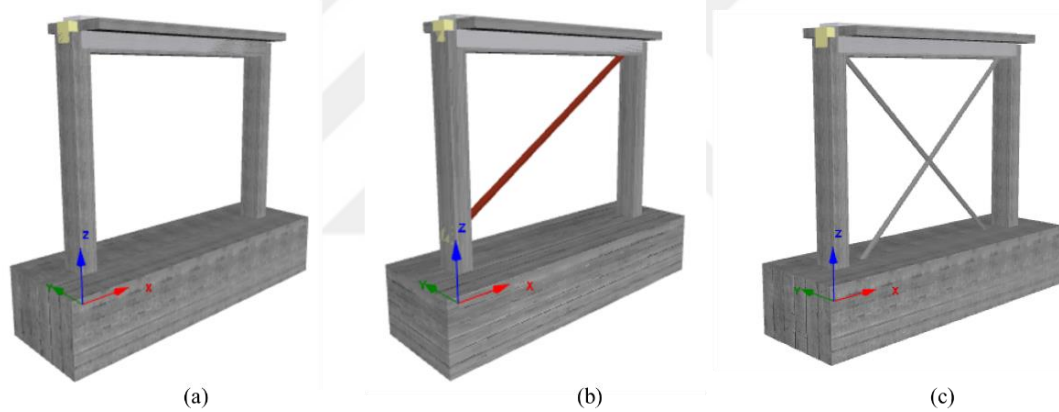


Figure 4.9 : FEM models: (a) Specimen 1, (b) Specimen 2, and (c) Specimen 3 (numerical benchmark only).

As previously stated in Section 3.3, the frame experienced an axial load totaling 60 kN. Therefore, both the traditional BRB and the TnT BRB were engineered to accommodate this specific axial load value. In the context of traditional BRBs, the Stl_BRB model, shown in Figure 4.10, functions as a uniaxial material framework tailored to assess the characteristics of steel utilized in these structural components. This particular model was initially introduced by Zona and Dall'Asta (2012). The preceding discussion addressed the design methodology for the TnT BRB; thus, the current focus will shift to the analytical calculations pertinent to the conventional BRB design. In this phase, adherence to AISC 341-22 (2022) guidelines were maintained. A thorough evaluation of the design parameters led to the formulation of a core plate

engineered to withstand the full axial force without experiencing buckling. This design is crucial for enabling the brace to effectively manage load during seismic activities, thereby contributing significantly to the structural system's overall stability and safety. Subsequently, a restraining mechanism was devised to inhibit global buckling of the core. Upon validation of this design, the analysis incorporated HSS $30 \times 30 \times 2.6$ sections.

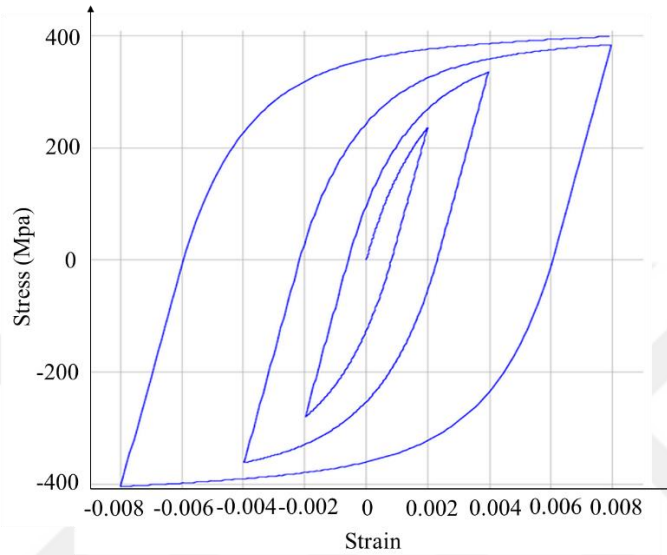


Figure 4.10 : Cyclic stress–strain response of the Stl_BRB material model implemented in the software for the conventional BRB benchmark.

4.4.2 Verification of the analytical models

This section provides a comparative examination of the findings derived from the analytical model in relation to the outcomes observed in the shake table experiments. Initially, the eigenvalue results obtained from the specimens undergoing testing are scrutinized. This is then succeeded by an evaluation of the LVDT outcomes in connection with the nonlinear time history analysis extrapolated from the analytical models. Following the calibration of the analytical models with the empirical data collected from the shake table tests, the values of damped hysteretic energy for these models are calculated and discussed in the context of the established code threshold limits.

The natural vibration periods were determined by considering the stiffness of the fissured sections in both longitudinal and transverse orientations, and these computations for the two specimens are compared with the empirical data as illustrated in Table 4.2. The derived eigenperiods exhibit alignment with the findings from the shake table

experiments for each specimen. An assessment of the LVDT data acquired from the shake table tests, compared with the calculated displacement trajectory generated from the analytical model, is presented in Table 4.3. The information displayed in the tables signifies a robust correlation between the results of the analytical model and the shake table experiments. This finding implies that the analytical model has been successfully calibrated.

Table 4.2 : Comparison of the natural vibration periods.

Specimen No	Shake Table Test (s)	Analytic Model (s)	Error (%)
1	0.495	0.463	6.45
2	0.151	0.147	2.65

Table 4.3 : Comparison of the top displacements.

Specimen No	Ground Motion	Shake Table Test (mm)	Analytic Model (mm)	Error (%)
1	0.35 g	53.14	53.57	0.43
2	1 g	19.86	18.97	4.48

4.5 Discussion

This section focuses on the comparative analysis of various analytical models, particularly examining the hysteretic energies and deformation characteristics. It emphasizes the role of these parameters in determining the overall energy dissipation capabilities of the braces. The findings reveal that the models successfully represent the nonlinear behavior that occurs under time history loading, which has considerable consequences for the design and application of these structural systems.

The cyclic response of RC structures is inherently nonlinear due to the complex interaction between concrete and steel reinforcement. When subjected to seismic loading, these structures experience a progressive loss of stiffness and strength, leading to increased lateral deformations and potential structural collapse. Hysteretic behavior is primarily governed by the constitutive properties of concrete and steel, as well as the interaction mechanisms between these materials.

Material nonlinearity plays a fundamental role in shaping the hysteretic response of RC members. Concrete exhibits brittle behavior in tension and strain softening in compression, leading to progressive damage accumulation under repeated loading cycles (Priestly, 1996). In contrast, reinforcing steel exhibits yielding and strain hardening, which contribute to the energy dissipation capacity of RC members (Park and Paulay,

1992). The interaction between these materials is governed by bond-slip behavior, which significantly influences stiffness degradation and pinching effects in the hysteresis loops (Sezen and Moehle, 2004). Poor bond strength between concrete and steel reinforcement exacerbates energy dissipation deficiencies, resulting in early failure of substandard structures.

Structural failure mechanisms in RC buildings under cyclic loading are predominantly classified as shear dominated or flexure dominated. Flexural failures, often associated with ductile behavior, are characterized by gradual stiffness degradation and stable hysteresis loops. In contrast, shear failures are highly brittle, leading to abrupt strength loss and unstable hysteretic responses (Elwoof and Moehle, 2008).. Substandard RC structures, which often lack adequate shear reinforcement, are particularly vulnerable to shear induced collapse. Experimental studies have demonstrated that deficient shear reinforcement leads to significant pinching in the hysteresis loops, which is indicative of poor energy dissipation capacity and rapid stiffness degradation (Sezen, 2002).

Another key aspect of hysteretic behavior is the progressive accumulation of damage, often referred to as cyclic degradation. This phenomenon manifests as a reduction in peak load capacity and stiffness with increasing loading cycles (Moehle, 2000). Cumulative damage effects are particularly pronounced in older RC structures, where inadequate confinement detailing results in premature spalling of cover concrete and buckling of longitudinal reinforcement (Mander et al., 1988). The lack of sufficient transverse reinforcement in substandard structures further accelerates strength degradation, increasing the likelihood of collapse under seismic loading (Priestley et al., 2007)

Hysteresis loops serve as a visual representation of energy dissipation characteristics in RC structures. Well-designed structures with sufficient confinement exhibit stable hysteresis loops with wide energy dissipation areas, whereas substandard structures with inadequate detailing show narrow, pinched loops. Experimental studies have confirmed that the presence of sufficient transverse reinforcement enhances the stability of hysteresis loops by providing confinement to the core concrete and delaying the onset of stiffness degradation (Xiao and Martirosyan, 1988). The pinching effect, commonly observed in substandard structures, is attributed to poor

shear capacity and inadequate bond strength between reinforcement and concrete (Sezen and Moehle, 2004).

Several mathematical models have been developed to simulate the cyclic response of RC structures, capturing key hysteretic characteristics such as stiffness degradation, strength deterioration, and pinching effects. The Takeda model (Takeda et al., 1970) is one of the earliest models used to describe stiffness degradation in RC members based on empirical data from cyclic tests. The Bouc–Wen model (Wen, 1976) has been widely adopted for nonlinear hysteretic modeling, incorporating both material and structural degradation effects. The modified Clough model extends these approaches by incorporating pinching effects in the hysteresis loops, making it particularly useful for simulating substandard structures.

The graph presented in Figure 4.11(a) illustrates the hysteresis loops for the TnT frame in direct comparison to the X-type BRB frame. It is important to observe that the X-type BRB frame demonstrates considerably narrower hysteresis loops, which signifies a more rigid response under lateral cyclic loading conditions. The maximum displacement registered for the X-type BRB frame is approximately ± 0.010 mm, which is markedly lower than the displacement recorded for the TnT frame, ranging from ± 0.015 to ± 0.020 mm. Nonetheless, the peak forces attained by both structural frames remain within similar magnitudes, indicating that, despite the notable differences in stiffness, the ultimate load-carrying capacities are closely aligned. The graph in Figure 4.11(b) provides additional insights into the stiffness characteristics of TnT in comparison to X-type BRB. Notably, X-type BRB exhibits loops that are not only narrower but also more vertically aligned than those of the TnT. This observation suggests an increased stiffness and a diminished capacity for deformation in the X-type BRB model.

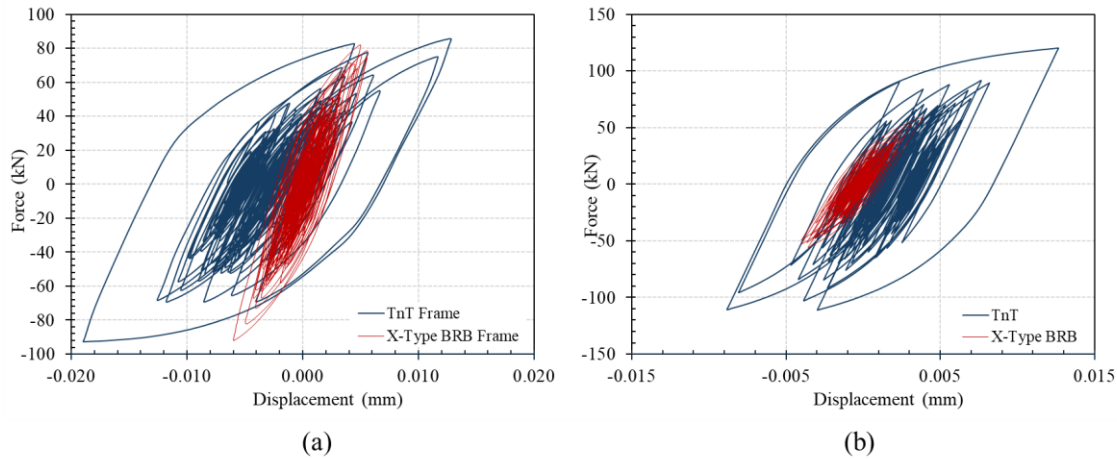


Figure 4.11 : Hysteretic response of the specimens: (a) comparison of the retrofitted frames, and (b) comparison of the elements.

Further, the initial graph presents the TnT frame, characterized by larger and more expansive loops, which indicate a greater capacity for energy dissipation during each loading cycle when compared to the X-type BRB frame. The increase in loop area signifies more considerable plastic deformation, resulting in a heightened cumulative energy absorption capability, an important factor in enhancing seismic resilience. This trend is further corroborated by the second graph, where TnT continues to encompass a larger area than X-type BRB. This observation leads to the conclusion that TnT frames, while exhibiting reduced stiffness, demonstrate superior energy dissipation properties, making them favorable for scenarios where energy absorption and deformation resistance are prioritized over elastic stiffness.

Considering the noted distinctions, the selection between TnT frame and X-type BRB frame types is heavily influenced by specific design goals. In scenarios where increased stiffness and reduced deformation amplitudes are critical for mitigating displacements, such as in protecting non-structural components or for applications sensitive to deformation, the X-type BRB frames offer a significant benefit. On the other hand, in contexts where the focus lies on energy dissipation through deformation, alongside the necessity for ductility and resilience against more intense seismic activities, the TnT frame may be more advantageous owing to its larger hysteresis loops and enhanced capacity for energy absorption.

Subsequently, the objective was to analyze the displacement traces of frames enhanced with TnT compared to those enhanced with X-type bracing. Additionally, the displacement traces of TnT and X-type brace components were plotted to facilitate

comparative analysis. As depicted in Figure 4.12, the displacement trace associated with the TnT-enhanced frame shows a significant peak in amplitude, which seems to manifest marginally earlier than that observed in the trace corresponding to the X-type braced system. Additionally, the evidence of residual displacements in the TnT enhanced frame is clearly illustrated in the figure. It shows that this frame experienced approximately 5 mm of residual displacement, which aligns closely with the observed hysteretic response. This alignment suggests that the TnT effectively yielded after absorbing a significant amount of energy. Furthermore, these findings are consistent with the results obtained from the shake table tests.

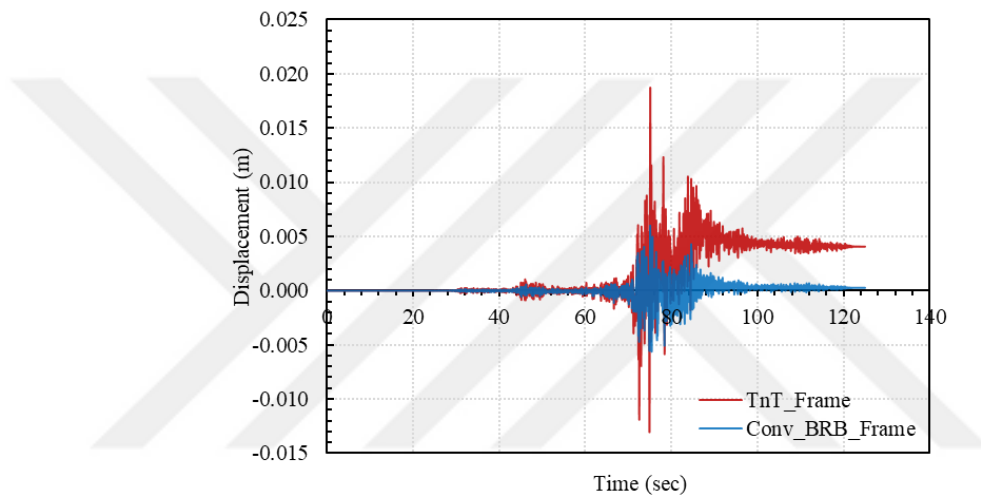


Figure 4.12 : Displacement time trace plots for TnT and X-type frames.

While both experimental and numerical findings affirm the effectiveness of the TnT system at a model scale, several significant limitations hinder their direct application to full-scale edifices. Initially, the specimens utilized in the shake table experiments were fabricated at a one-third geometric scale; although the slenderness ratios of the cross-sections adhered to similitude principles, the absolute thickness of the restrainer tube walls was unavoidably diminished. This scaling methodology may inhibit critical phenomena such as localized denting, interfacial bearing stresses, and frictional dynamics between the inner and outer tubes, which could result in discrepancies in hysteretic behavior when scaled up. Moreover, the scaled clearances between the tubes may exhibit divergent behaviors under full-scale conditions, influenced by the tolerances, imperfections, and variability inherent to real-world construction practices. Furthermore, the concrete mixture employed in the scaled models was deliberately formulated to emulate the low compressive strength characteristic of inadequate

Turkish residential buildings. However, various attributes of this simulant, including aggregate grading, moisture content, curing conditions, and shrinkage behavior, are bound to differ from those of actual construction materials. As a result, the specific patterns, densities, and propagation rates of microcracks that develop under cyclic shear loading at full scale may not be accurately captured, leading to discrepancies in damage progression and stiffness deterioration in prototype structures. Additionally, the effects of strain rate on material properties, particularly under the dynamic loading conditions experienced during actual earthquakes, may vary significantly at larger scales and were thus not entirely elucidated by the present experimental framework.

These constraints underscore the imperative for further experimental investigations at larger scales, utilizing authentic construction materials and methodologies, to substantiate the generalizability of the observed advantages. Such prospective studies should ideally encompass a variety of ground motion scenarios to enhance comprehension of variability in structural responses and to bolster broader confidence in the applicability and dependability of the proposed TnT retrofit system for extensive practical deployment.

In synthesizing the empirical evidence with contemporary theory, it is instructive to interpret the TnT brace through the lens of the “four R” resilience construct, robustness, redundancy, resourcefulness, and rapidity that underpins FEMA P58 (2018). Robustness, defined as the inherent capacity of a system to resist damage without losing essential functions, is enhanced because the TnT’s continuous outer shell restrains both global and local buckling, thereby arresting the brittle column shear and joint punching failures that characterized the control specimen. Redundancy, the provision of alternative load paths to accommodate unexpected demand, is elevated once axial forces are shared between the existing concrete columns, the yielding steel core, and the restraining tube; this redistribution mitigates the single point vulnerability that non ductile Turkish frames typically exhibit. Resourcefulness, the ability to marshal and apply the necessary materials, labor, and knowledge for post event recovery, is advanced by the brace’s all steel, mortar free configuration: fabrication is less labor intensive, field welding is minimized, and post earthquake inspection is reduced to a visual check of bolt integrity and core straightness, obviating the intrusive core sample testing required by infill encased BRBs. Rapidity, the speed with which functionality can be restored, emerges as the most conspicuous benefit; during the

DD 2 level excitation, the TnT retrofitted frame dissipated 2.5 times the cumulative hysteretic energy of the conventional brace, a combination that FEMA's downtime models translate into a re occupancy window of hours rather than weeks. This experimentally derived rapid return metric dovetails with the intensity measure optimization advanced by Shen et al. (2025), who show that sustained maximum acceleration and PGA are the scalar indicators most predictive of downtime; both indices exhibit a monotonic correlation with the energy dissipation hierarchy observed in our shake table tests, thereby embedding the present findings within a quantitatively articulated resilience narrative.

4.6 Conclusions

It is shown by the experimental and computational findings reported in this work that the TnT BRB system that was designed is successful in significantly enhancing the seismic performance of RC frames that are not up to specification. With regard to the shake table tests, it is evident that the TnT braced frame displayed significant enhancements in lateral strength, ductility, and energy dissipation capabilities when contrasted with the non-retrofitted control specimen. The latter suffered considerable damage, including joint shear failure, under much lower seismic forces.

Further, the analytical model of TnT BRB system demonstrated superior seismic behavior compared to the conventional X-type BRB systems. It was able to achieve maximum lateral displacements that were approximately twice as large as those of the X-type BRB frame, with a difference of approximately 20 mm and 10 mm, respectively. In addition to this, the TnT brace exhibited a dissipation capacity for hysteretic energy that was much higher than that of the traditional system, with a cumulative energy dissipation that was roughly 2.5 times higher than that of the conventional system at displacement amplitudes that were equivalent.

Both the numerical studies and the experimental data were in good agreement with one another. The numerical analyses demonstrated stable and large hysteretic loops, which are indicative of enhanced ductility and effective energy transfer. These quantitative data, taken as a whole, provide further evidence that the TnT BRB system has excellent performance, notably with regard to its capacity for deformation, its ability to dissipate energy, and its ability to promote ductility.

Future research endeavors stemming from this study should encompass extensive parametric analyses aimed at optimizing the Tube-in-Tube configuration. This entails a focused examination of potential issues such as localized denting, wear due to friction, and unintended interactions between the concentric tubes. Conducting thorough investigations into the implications of tube alignment, geometric discrepancies, and friction related phenomena would significantly aid in refining design parameters and bolstering the system's durability.

Moreover, it is advisable to undertake field studies and prolonged monitoring of actual retrofitted structures utilizing the TnT BRB system. Such initiatives would serve to substantiate laboratory findings within authentic operational environments and foster wider acceptance and integration into seismic retrofitting methodologies. Furthermore, the exploration of advanced materials and innovative connection designs could markedly improve durability, cost-effectiveness, and ease of implementation, thereby making a noteworthy contribution to the global initiative aimed at reducing seismic vulnerabilities in at risk building inventories.

5. INNOVATIVE TUBE-IN-TUBE BUCKLING-RESTRAINED BRACE SYSTEM FOR SEISMIC RETROFITTING OF SUBSTANDARD RC FRAMES: EXPERIMENTAL EVALUATION AND FIELD INSIGHTS⁴

This study presents a comprehensive evaluation of a novel all-steel Tube-in-Tube Buckling-Restrained Brace (TnT BRB) system devised for the seismic retrofitting of substandard reinforced concrete frames. Recognizing that many existing RC structures, particularly those constructed prior to the advent of modern seismic design codes, suffer from significant deficiencies in ductility and lateral load-resisting capacity, this research addresses the critical need for advanced retrofitting strategies to enhance seismic resilience. The experimental program, meticulously designed in accordance with rigorous similitude principles, encompassed cyclic tests on large-scale TnT BRB specimens and shake table experiments on one-third scale, one-story, one-bay RC frame models. Comparative assessments between a conventional, unretrofitted RC frame and an identical frame enhanced with the TnT BRB system revealed marked improvements in lateral stiffness, energy dissipation, and ductility. Under progressive seismic excitations, including ground motions scaled to replicate the 2023 Kahramanmaraş earthquake, the retrofitted frame maintained its structural integrity, exhibited substantially reduced displacement demands, and demonstrated a delayed onset of inelastic deformations. Furthermore, detailed field observations underscored the practical viability of the TnT BRB system in real-world seismic scenarios. Collectively, the results advocate for the integration of the TnT BRB into advanced seismic retrofitting practices, offering a promising pathway to significantly enhance the performance and longevity of vulnerable RC structures in earthquake-prone regions while contributing to the evolution of modern seismic design methodologies.

⁴ This chapter is based on “Oyguc E, Oyguc R, Hayir A, Seker O, Shen J, Akbas B., Innovative Tube-in-Tube Buckling-Restrained Brace System for Seismic Retrofitting of Substandard RC Frames: Experimental Evaluation and Field Insights, 2025, Bulletin of Earthquake Engineering (under review)”

5.1 Introduction

A substantial portion of existing reinforced concrete (RC) infrastructure globally predates the enforcement of modern seismic design standards, thereby exhibiting significant deficiencies in ductility, structural robustness, and resilience to seismic events. These structurally suboptimal buildings commonly feature inadequate reinforcement detailing, low-strength materials, insufficient lateral stiffness, and limited deformability, critically impairing their seismic performance.

Seismic retrofitting, as opposed to complete demolition and reconstruction, has emerged as a cost-effective, resource-efficient, and environmentally sustainable strategy to augment structural resilience against seismic loading. Aligning with global sustainability initiatives, retrofitting significantly reduces the consumption of raw materials, minimizes construction waste, and substantially lowers the embodied carbon associated with new construction practices. Among diverse retrofit methodologies, the implementation of buckling-restrained braces (BRBs) has become increasingly prevalent due to their superior hysteretic performance, high-energy dissipation potential, and consistent behavior under cyclic loading compared to conventional bracing systems (Black et al., 2002; Merritt et al., 2003; Cao et al., 2022, Sok 2024). BRBs are a class of seismic energy dissipation devices that allow a steel core to yield in tension and compression without overall buckling. This behavior is achieved by encasing the yielding core in a restraining mechanism that provides lateral support, typically a steel tube filled with mortar or concrete in conventional designs Takeuchi (2018). BRB systems can be categorized into three primary types: conventional BRBs, which consist of steel core braces filled with mortar or concrete; lightweight BRBs, which utilize alternative core materials such as aluminum alloys or composite elements; and all-steel Tube-in-Tube BRBs, which feature braces constructed without mortar and make use of concentric steel tubes or similar fully steel restraining structures.

Over the last decade, extensive research has been conducted worldwide on various BRB configurations to understand their performance under seismic excitations. Di Sarno and Manfredi (2010) had earlier shown through pseudo dynamic tests that BRB braces can control soft-story mechanisms in existing frames. Wu et al. (2015) performed shake table tests on a multistory (three-story) RC frame with and without

BRB retrofit. Tan et al.) examined the efficacy of a full-scale two-story RC frame incorporating BRB braces when subjected to bidirectional loading scenarios. This analysis is intended to deepen knowledge regarding the capacity of RC frame systems to improve both the safety and structural integrity of buildings situated in regions vulnerable to earthquakes. Al-Sadoon et al. (2020) introduced a BRB with novel end units that attach to RC columns and beams in a way that allows the brace ends to move slightly. Another innovation for RC retrofits is ensuring the brace yields before causing shear failure in the RC elements. This sometimes means using a slightly lower strength core material or introducing a fuse element that yields at a predetermined force. Li et al. (2023) examined a one-third scaled, two-story RC frame featuring K-configured BRBs instead of analyzing a full scale nonductile frame. The findings indicate that the load carrying capacity experienced an improvement of up to 80%, and the energy dissipation capacity was enhanced by as much as 50%, suggesting a considerable upgrade in structural performance. Wu et al. (2017) analyzed the structural performance of a full scale two-story RC frame both prior to and following the incorporation of BRBs. The addition of BRBs resulted in notable enhancements in the stiffness, strength, and ductility of the frame. Similarly, Rafi et al. (2021, 2022) performed shake table tests on substandard RC frames with and without BRBs, using a series of increasing earthquake intensities. Al-Sadoon et al. (2022) developed a replaceable fuse BRB for RC frames, where a part of the core is intentionally weakened so that it will yield first and act as a structural fuse.

These shake table experiments confirm that conventional BRBs can impart substantial strength, stiffness, and damping to structures, thereby improving seismic resilience. The braces sustain cyclic inelastic deformations with stable hysteresis, preventing structural collapse even under severe shaking by dissipating input energy through core yielding. Despite their excellent seismic behavior, conventional BRBs have some drawbacks. A key disadvantage is the heavy weight of the brace due to the steel casing and mortar infill. Researchers have noted that ordinary BRBs with mortar infill can be susceptible to in-plane local buckling of the core if the gap or debonding layer is insufficient (Takeuchi et al., 2012).

The challenges associated with conventional configurations have led to the exploration of alternative reduced weight BRB designs. Two prominent methods include the incorporation of aluminum alloy cores, and occasionally casings, and the integration

of fiber-reinforced polymer (FRP) composite components in the restraint mechanisms. These advancements are intended to maintain the inherent ductility of BRBs while simultaneously minimizing weight and enhancing resistance to corrosion. Usami et al. (2012) first reported low-cycle fatigue tests of extruded aluminum BRBs, showing that a properly designed aluminum core can yield stably in cyclic loading. Building on that foundation, Proença et al (2024) examined an innovative aluminum BRB (Al-BRBs) that capitalize on the distinctive characteristics of aluminum alloys, which contribute to increased ductility and decreased weight relative to traditional BRBs. Avci-Karatas et al. (2018) conducted full scale cyclic tests on newly developed BRB prototypes with aluminum cores. The results demonstrated balanced hysteretic behavior for both aluminum and steel core BRBs, with no global buckling observed up to large inelastic drifts. The superior weight reduction and corrosion resistance of aluminum-core BRBs make them a promising alternative, particularly when seismic retrofit of structures must minimize added mass or when braces are deployed in aggressive environments that challenge conventional steel devices. On the downside, aluminum core BRBs are relatively new technology with limited usage and design guidance to date. Only a few studies have rigorously investigated their behavior, so their long term performance and failure modes are less documented than conventional BRBs. Cost can also be a disadvantage, aluminum alloys (especially those with advanced processing or heat treatments) tend to be more expensive per unit strength than mild steel.

Another lightweight BRB innovation is the use of FRP composite tubes or shells as the restraining element instead of the typical steel tube and mortar. In these systems, the core is still usually a steel yielding element, but the outer casing that provides buckling restraint is made of a high-strength composite (often glass-fiber or carbon-fiber reinforced resin). Dusicka and Tinker (2013) proposed an ultra-lightweight BRB combining an aluminum core with bundled pultruded glass-FRP tubes as the restrainer. Another study by Razavi et al. (2018) investigated a CFRP-wrapped BRB where a steel core was wrapped with carbon fiber sheets instead of using mortar. This design enhances the performance of BRBs while reducing weight, making them advantageous for construction applications. The research demonstrates that CFRP encasing effectively meets the expected performance criteria, providing a viable alternative to traditional steel tube encased BRBs. Similarly, Sun et al. (2019) studied lightweight BRBs composed of glass-fibre reinforced polymer (GFRP) composite tubes. The

research highlighted that BRBs utilizing GFRP tubes demonstrated superior hysteretic performance, load-bearing ability, ductility, and energy dissipation characteristics.

Conventional BRBs and their lightweight variants discussed above share a common approach of using a filler material (mortar or FRP) between the core and restraining member. In contrast, all-steel BRBs eliminate filler materials entirely, where the brace is composed of steel components only, often in a Tube-in-Tube configuration or other built-up steel shape that provides the required confinement. The rationale behind the development of all-steel BRBs is to address the limitations associated with their earlier counterparts. The past decade has seen rapid development of all-steel BRB concepts, and while many have been validated through cyclic tests, shake table validations at the system level are still emerging due to the novelty of these systems.

A typical all-steel BRB uses a steel core (often a plate or built-up shape) and an external steel restrainer tube. Instead of mortar, a small gap or a slippage interface (unbonded layer) is maintained between the core and the tube so that the core can slide and yield in compression without bonding to the casing. Wan et al. (2022) discussed an all-steel BRB engineered for seismic resilience, with a design that facilitates disassembly for inspections following seismic events. They conducted a series of tests under different cyclic loading protocols and identified failure modes. The experimental findings indicated that the innovative all-steel BRB exhibited superior low-cycle fatigue characteristics, attributable to the specially designed smooth weld toes on the brace stiffeners, which effectively lessened residual stress and mitigated stress concentrations. Because the steel tube alone must provide the buckling restraint, it often needs sufficient thickness or stiffeners to avoid its own deformation. One common configuration is the Tube-in-Tube BRB, where a steel core plate is first housed in a slender inner tube (providing lateral support and aligning the core) and then that assembly is placed inside a larger outer tube. The annular gap may be empty or filled with a low-friction material (like a Teflon liner), but not with hardened grout. Prinz and Richards (2024) recently tested such a Tube-in-Tube BRB system in a comprehensive experimental program.

Other innovative all-steel configurations include braces with perforated or necked core plates, built-up H or cruciform cores, and weld-free assemblies. For example, Yun et al. (2022) examined an innovative all-steel assembled core perforated BRB, concentrating on its structural efficacy. It analyzes various configurations, including

braces equipped with perforated core plates and built up H or cruciform cores, with particular attention to the benefits associated with weld-free assemblies. Findings from experimental and numerical evaluations indicate that the proposed brace design significantly reduces the likelihood of buckling and enhances overall structural resilience, positioning it as a feasible alternative for seismic applications. Zhou et al. (2020) introduced that the semi-circular perforated zone notably improves the strong-axis stability and seismic response of the perforated core plate BRB (PBRB) in contrast to the rectangular design. The analysis concluded that the dimensions of the transition zone are vital to the stability performance of PBRB. It is advised that this zone should be no less than fifty percent of the yielding segment's width to mitigate the risk of early strong axis buckling. Mishra and Vyavahare (2024) conducted a comprehensive analysis of nine distinct BRBs, each characterized by different core cross-section designs, to evaluate their hysteretic characteristics and capacity for energy dissipation via non-linear finite element simulations. The results indicated that BRBs with a rectangular core cross-section, augmented by cruciform end components, along with hollow circular BRBs, achieved the highest levels of energy dissipation. Conversely, all-steel BRBs demonstrated a greater extent of hysteretic behavior relative to their concrete-filled counterparts. Zheng et al. (2023) conducted experimental and numerical analyses and revealed that cruciform all-steel BRBs possess considerable energy dissipation capabilities. This attribute substantially improves the seismic resilience of structures. Furthermore, the findings indicate that by optimizing the design and configuration of these braces, it is possible to enhance their load-carrying capacity and overall stability. These insights offer valuable guidance for future developments in the field of structural engineering. Many all-steel BRB designs also allow for easy disassembly, since they are often bolted or otherwise demountable, which means a yielded core can be replaced after a major seismic event without replacing the entire brace. This replaceable fuse concept is an attractive feature of all-steel assembled BRBs, as highlighted by Al-Sadoon et al. (2022) who evaluated a replaceable all-steel BRB fuse system that could be swapped out post-earthquake.

All-steel BRBs provide several distinct advantages. Their lighter weight, construction efficiency, post-earthquake recoverability, and the ability to precisely tailor the brace's mechanical properties, make them a highly attractive alternative to traditional BRBs. Despite these advantages, all-steel BRBs face some challenges and trade-offs. The

foremost technical challenge is ensuring the restraining unit provides sufficient confinement without the continuous support of mortar. If the steel restrainer (tube or assembly) is too flexible, the core can undergo lateral buckling or the restrainer itself can form plastic hinges and deform, leading to a loss of capacity. Another consideration is that yielding of the restrainer must be avoided. Furthermore, because all-steel BRBs are relatively new, code provisions are catching up. Design methods for all-steel BRBs are being formulated, but building code recognition is still in progress. Nonetheless, given the robust performance demonstrated in recent experiments and their clear practical benefits, all-steel BRBs are poised to become more mainstream.

In response to these critical challenges, the present research proposes an innovative all-steel Tube-in-Tube (TnT) BRB configuration. The TnT BRB system distinctly differs from conventional designs by utilizing a dual-tube architecture comprising an external tube functioning solely as a buckling restrainer and an internal tube operating as the primary load-bearing and energy dissipation element. The enhanced performance attributes effectively address critical limitations, such as premature local buckling, uneven energy dissipation, and limited deformation capacity, that have been persistently identified in conventional bracing systems (Momenzadeh, 2017).

Shake table studies in the last decade decisively show that BRBs, in their various incarnations, consistently enhance seismic performance across a range of structural systems. Each BRB variant brings something valuable: conventional BRBs bring dependability, lightweight BRBs bring agility and all-steel BRBs bring adaptability. Engineers and researchers can leverage comparative insights from these studies to select or further refine the optimal BRB system for their specific seismic design challenges. The continued innovation in BRB design, combined with the solid foundation of understanding built over years of experimental research, ensures that BRB systems will remain at the forefront of earthquake-resistant design strategies in the years to come.

5.2 Research Significance

Numerous existing buildings incorporate RC frames that unfortunately fail to adequately comply with widely accepted quality criteria. In various regions that are characterized by moderate to low seismic risk, these types of frames are often

constructed without the necessary and adequate seismic detailing that is essential for their safety and stability. These kinds of structures are typically found in a variety of environments including industrial spaces, residential areas, and small commercial buildings. Historically, the behavior of these inadequate and poorly designed frames during past earthquakes has not been satisfactory or reassuring (Jennings, 1997), (Sezen et al 2003), (Kappos et al, 2007), (Miyamoto et al, 2008), (Oyguc et al, 2018), (Ozmen et al, 2024). Therefore, it becomes crucial and imperative to thoroughly assess and subsequently enhance these existing substandard buildings to prevent potential hazards and ensure the safety of the occupants.

Concerning the significant potential collapse risk posed by substandard and poorly designed existing RC structures, this comprehensive and in-depth study sought to systematically examine whether the TnT BRB could serve as an effective and viable alternative method for effectively preventing the potentially catastrophic collapse of such substandard RC frames. This detailed examination aims to identify precisely how effectively the TnT BRB system can improve structural robustness, reduce vulnerability, and mitigate potential damage across diverse seismic scenarios. The study rigorously incorporates realistic detailing constraints, advanced construction practices, and detailed observational data derived from recent seismic events, ensuring an accurate reflection of practical, real-world implementation scenarios.

Moreover, the comprehensive field observations from the 2023 Kahramanmaraş earthquake underscore the practical significance of this study. The empirical evidence reveals the critical vulnerabilities inherent in aged RC frames, such as extensive beam–column joint failures, pervasive concrete spalling, and progressive damage due to inadequate seismic detailing, which mirror the damage patterns observed in the controlled experimental setup. These real-world insights not only validate experimental findings but also highlight the transformative potential of the tube-in-tube BRB system in mitigating seismic risks. The convergence of laboratory data with field observations provides a compelling argument for the broader adoption of innovative retrofitting strategies, ultimately reinforcing the study’s relevance in advancing urban seismic resilience.

To attain these ambitious goals, the recent and compelling ground motion event from Kahramanmaraş (Pazarcık) in the year 2023, $M_w=7.7$, was effectively utilized, and shake-table tests were meticulously performed on two one-third-scale, one-story, one-

bay frame specimens. The first frame was specifically designed to be representative of a typical substandard RC building, and it was formally referred to as the reference frame for the purposes of the study. The second frame was identical to the reference frame but rehabilitated by TnT BRB for improved structural integrity.

The results of this extensive study are thoroughly analyzed and compared in terms of critical global response metrics and the various observed damage patterns resulting from the shake-table tests. This examination aims to provide insights into the overall effectiveness of the alternative design approach. Moreover, this research seeks to bridge existing gaps between theoretical predictions and actual structural performance by employing sophisticated techniques.

Through the integration of empirical observations, and experimental results, this research not only validates but also extends current knowledge, significantly enhancing contemporary seismic retrofitting strategies and techniques. The outcomes are expected to facilitate evidence-based decision-making, promote informed recommendations for best practices in seismic retrofitting, and encourage broad adoption of the TnT BRB system. Ultimately, by fostering the widespread integration of innovative BRB technologies, this research aspires to substantially contribute to enhancing urban resilience, improving structural safety, and minimizing socio-economic impacts of seismic events on communities globally.

5.3 Tube-in-Tube Buckling-Restrained Braces

All-steel TnT BRBs were first introduced by Shen et al. (2016) to address the issues of strength and stiffness reduction due to buckling, a common problem with traditional buckling braces, while also being mindful of cost-effectiveness. TnT braces generally feature a load-bearing tube constructed from circular or square hollow structural shapes (HSS) and an outer tube designed to manage buckling, which can also be circular or square (Seker et al, 2023). The primary function of the load-bearing tube is to endure seismic forces and absorb a significant portion of the seismic energy injected into the structure by deforming in tension and compression. In contrast, the buckling-controller outer tube offers continuous lateral support to the load-bearing tube, thereby preventing the entire brace system from experiencing global buckling and regulating local plastic deformations within the predetermined limits of the brace's deformation.

TnT BRBs are an emerging category of BRBs that have yet to be included in existing design standards. Their lightweight and easily replaceable structure, alongside their impressive strength, stiffness, and capacity for energy dissipation, makes TnT BRBs particularly beneficial for various applications. Additionally, the unique design of their connections facilitates straightforward repairs following seismic events. The manufacturing process for TnT BRBs is comparatively uncomplicated when set against that of traditional concrete-encased models, as it requires minimal cutting and welding, thereby reducing both carbon footprint and labor expenses. Furthermore, the integration of TnT BRBs enhances the lateral stiffness of the overall BRB-retrofitted system, significantly decreasing drift demands on the building (Di Sarno and Elnashai, 2009). This characteristic is essential for adopting BRBs within the framework of low-damage or damage-free seismic design strategies.

The seismic behavior of these braced frames significantly contrasts with that of traditional ductile braced frames. The sudden decrease in stiffness and strength that occurs during the post-buckling phase of conventional buckling braces typically leads to considerable reductions in energy dissipation capacity. This phenomenon can also exacerbate irregularities during the inelastic phase, such as the development of soft stories (Shen et al, 2017).

5.3.1 Description of TnT BRBs

The TnT brace configuration employed for retrofitting the inadequate RC frame under investigation is illustrated in Fig. 5.1 and comprises several integrated components that work in concert to enhance seismic performance. The inner load-bearing tube, fabricated from standard circular or square hollow structural sections, is specifically designed to endure significant inelastic axial deformations and serve as the primary energy dissipation element during seismic events. Encasing this load-bearing element is a two-segment outer tube, functioning as a buckling restrainer, that is fillet welded to a mid-section stopper. A deliberately maintained gap between the inner tube and the outer buckling controller facilitates ease of fabrication and ensures that the lateral deformations of the inner tube occur without the outer tube unduly contributing to the compressive load carrying capacity.

Central to the system is the stopper, a ring-shaped plate positioned at mid-span and welded to both the load bearing and buckling controller tubes, which stabilizes the

segmented outer tube while allowing free axial deformation of the inner tube. Axial forces developed within the load-bearing tube are transferred to the structural system via connector plates located at each end of the brace; these plates are secured together using pretensioned high-strength bolts. The end connection assembly, composed of a reinforced gusset plate interfaced with the connector plates, effectively conveys these axial loads to adjacent structural elements such as girders and columns. Importantly, the design of the end connection assembly is optimized to restrict both in-plane and out-of-plane rotations, thereby mitigating potential global instability and minimizing flexural demands that could adversely affect the overall performance of the TnT brace system (Shen et al, 2016), (Seker and Shen, 2017).

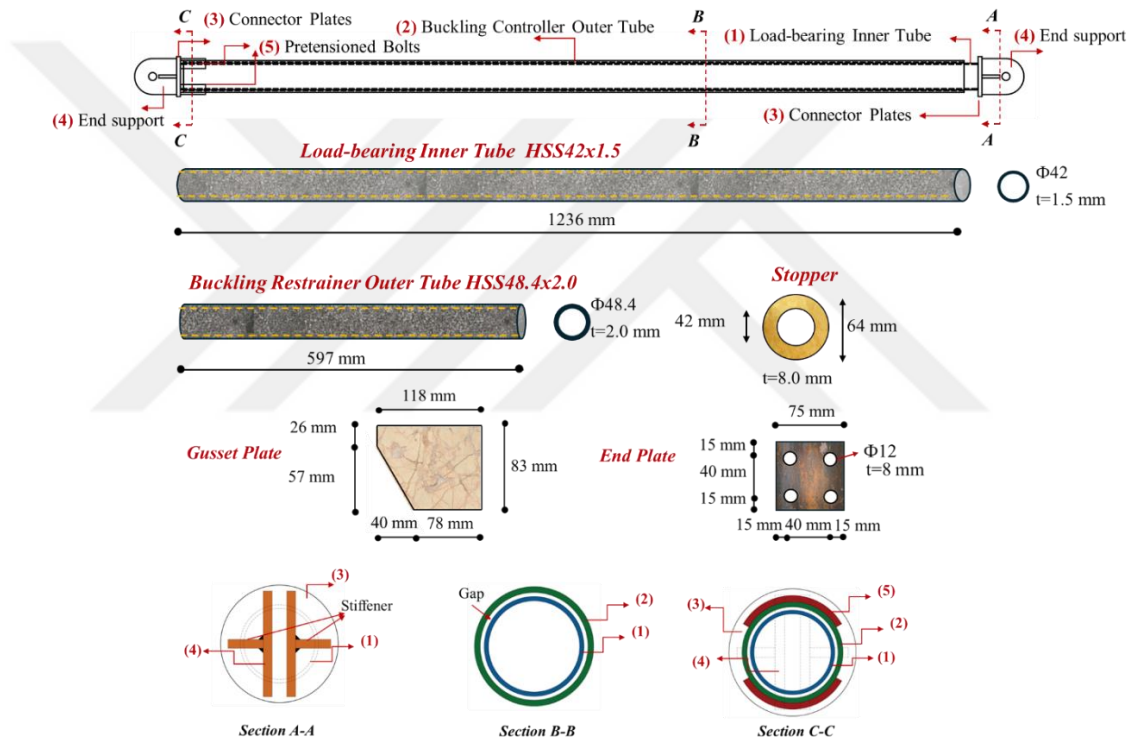


Figure 5.1 : Tube-in-Tube buckling-restrained brace scheme used in the study.

5.3.2 Inelastic cyclic behavior of TnT BRBs

The energy dissipation capacity of TnT braces was studied through experimental cyclic testing of large-scale specimens at Iowa State University's North Structural Laboratory. The setup for this testing is illustrated in Fig. 5.2, which showcases the inelastic cyclic behavior of a TnT specimen approximately 3.5 meters long, capable of supporting a load of around 400 kN in both tension and compression. The cyclic loading protocol adhered to the guidelines established by the AISC Seismic Provisions (AISC 341-22).

As represented in Fig. 2(b), the axial force-displacement relationship indicates that the specimen demonstrated a ductile and nearly symmetrical response. The maximum ductility achieved was around 10, correlating to an equivalent story drift ratio that surpassed 0.03 radians. Additionally, the total cumulative ductility reached by the specimens was approximately 250, while the peak compression overstrength compared to tension was about 10%. This suggests that any unbalanced brace forces that might develop in the surrounding structural elements would be minimal, if not negligible. Consequently, the findings suggest that TnT braces possess significant energy dissipation capabilities without compromising stiffness or strength. Therefore, they show great potential for improving the ductility, lateral strength, and stiffness of existing non-ductile reinforced concrete frames.

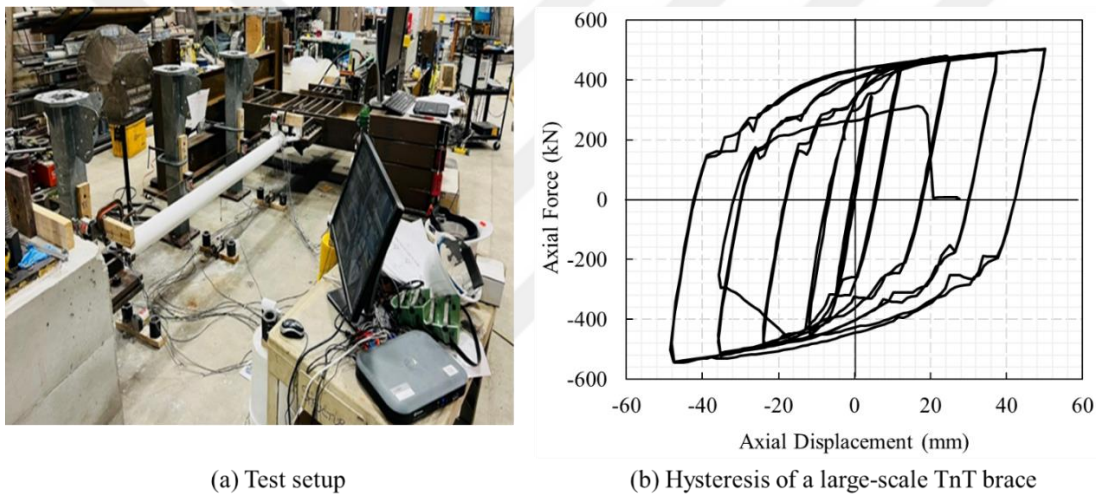


Figure 5.2 : Inelastic cyclic response of a typical TnT brace (Adapted from Seker et al., 2023).

5.4 Experimental Setup and Protocols

The experimental investigation is conducted using a two-degrees-of-freedom shake table located at the Allianz Teknik Earthquake and Fire Test and Training Center in Istanbul, Türkiye. This simulator table, which has dimensions of 3.0 m $\times$ 3.0 m, is designed to handle a payload capacity of 10 tons. Hydraulic actuators are employed to manage the seismic actions applied to the table. The controller of the simulator features a closed-loop system with three variables, as well as adaptive control and differential pressure stabilization. Additionally, the shake table is capable of delivering a maximum acceleration of 1g, which is essential for accurately simulating realistic earthquake ground motions across a frequency range of 0-50 Hz.

5.4.1 Brief discussion on similitude requirements

Research has established that scale effects are essential for addressing all response distortions that arise when a structure is scaled for experimentation, particularly in shake table tests where the length parameters require scaling (Moncarz and Krawinkler, 1981), (Harris and Sabnis, 1999), (Casaburo et al, 2019). It is crucial for force and time to be scaled consistently. Moncarz and Krawinkler (1981) described similitude as the theoretical framework that results in the formulation of a comprehensive set of correlation functions, known as scaling laws, which characterize the relationship between the model and its prototype.

In dynamic model testing, the principles governing the scaling laws related to force, time, and other dependent dimensional quantities can be established through dimensional analysis (Krawinkler, 1988). A key component of this analysis is Buckingham's pi theorem (Buckingham, 1914), which plays a crucial role in its theoretical framework. This theorem asserts that any dimensionally consistent equation that includes specific physical quantities can be simplified to a corresponding equation that features a complete set of dimensionless products, referred to as π -factors (Harris and Sabnis, 1999). As a result, the mathematical representation of any physical phenomenon can be condensed into an equation that consists entirely of dimensionless products.

Currently, four main physical models have been recognized for scaling applications: the true replica model, the artificial mass simulation model, the model that ignores gravity forces, and the strain distortion model (Harris and Sabnis, 1999). The true replica model operates under the premise that the stress and material distribution in both the prototype and model must be identical. However, this assumption can lead to unfavorable outcomes since no two materials in nature are perfectly alike, resulting in inherent errors in predictive values due to material simulation. To address this issue, the approach involves augmenting the density of the structurally effective material with additional, non-effective material. This augmentation can be implemented through either lumped mass systems or distributed mass systems, with the latter typically preferred in many scenarios. Artificial mass simulation models have been widely utilized in shake table tests, particularly suited for multistory buildings and bridge structures. In certain cases, involving building structures, it may not be necessary to replicate gravitational loads. This is due to the relatively minor stresses

that gravity loads induce, which can be negligible compared to the stresses generated by seismic activities. Specifically, when model tests focus on linear elastic behavior, the gravitational effects can be separated from seismic influences and can generally be disregarded when deriving similitude laws. Conversely, the application of truly distorted models for researching nonlinear seismic issues is limited, as it is often challenging to identify suitable corrections for the predictive equations or other physical parameters to adequately address any breaches of critical design conditions.

The selected model for the study was an artificial mass simulation model that met the criteria of similitude in terms of geometric and loading parameters. Additionally, this model adhered to all material specifications apart from mass density. To address this issue, supplementary steel blocks were incorporated into the roof, ensuring that the overall stiffness of the structure remained unaffected. Each steel block measured 1750 mm in length, 570 mm in width, and 60 mm in height, with an individual mass of 430 kg. A total of fourteen mass blocks were welded together, resulting in a single unit of fourteen stacked mass blocks weighing 6 tons. Table 5.1 systematically enumerates the specific experimental parameters adopted in this study.

Table 5.1 : The calculated physical quantities for shaking table tests.

Physical quantity	Scale factor
Length, l_r	3
Modulus of elasticity, E_r	1
Time, t_r	1.732
Gravitational acceleration, g_r	1
Strain, ε_r	1
Acceleration, a_r	1
Frequency, ω_r	0.577
Velocity, v_r	1.732

5.4.2 Description of the test specimens

The test model was developed to meet the specified similitude criteria for a scaled version of the prototype depicted in Fig. 5.3. The chosen prototype is a substandard RC frame building situated in Türkiye, constructed in the 1980s. This structure exemplifies numerous RC buildings erected prior to the establishment of contemporary seismic codes in Türkiye and was designed solely for gravity loads. As illustrated in Fig. 5.3, the prototype features a rectangular floor plan consisting of bays measuring 4.35 meters and 3 meters in two perpendicular directions, respectively. Additionally, the height of each story in the prototype was established at 3 meters.

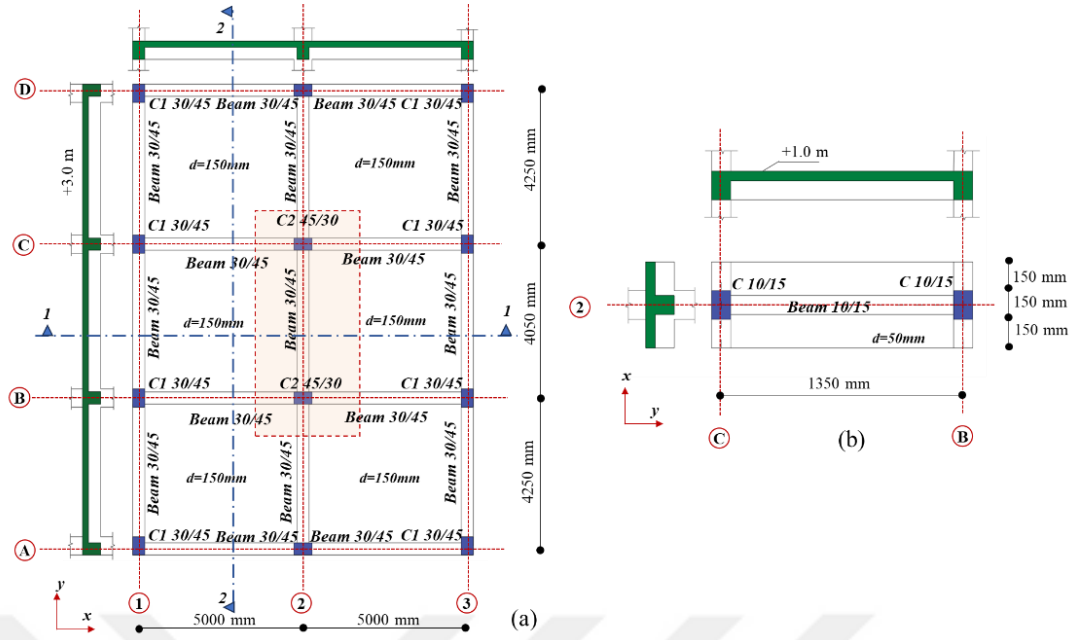


Figure 5.3 : (a) A schematic representation delineating the measurements and structural configuration of the prototype reinforced concrete building, (b) the precise location and dimensional specifications of the frame subjected to experimental analysis.

In developing a 1:3 scaled model, a concrete mix with a low compressive strength of around 9 MPa was chosen to represent weaker concrete found in pre-1970s constructions. This choice accurately simulates the stress-strain properties and aids in replicating cracking patterns, damage progression, and shear deficiencies common in these structures. Additionally, reinforcement steel with a yield strength of 420 MPa was included to mimic typical properties of existing RC frames, ensuring the model's ductility matched that of the prototype. Following similitude principles, the scale factor for the modulus of elasticity for both concrete and steel was kept at unity. This choice ensured that stress-to-strain relationships mirrored the original structure, preserving stiffness and deformation characteristics during seismic activity. Dimensional scaling strictly adhered to a 1:3 ratio for all relevant linear dimensions, maintaining consistent shear span-to-depth ratios, resulting in an analogous distribution of bending moments, shear forces, and anchorage requirements under seismic loading.

The experimental program included two identical single-bay, single-story RC frames that were isolated from the prototype building, as illustrated in Fig. 5.4. One of these frames is designated as the control frame, while the other has been enhanced with a single diagonal TnT brace. These two frames will henceforth be referred to as

Specimen 1 (Bare Frame) for the control version and Specimen 2 (TnT-retrofitted Frame) for the strengthened version. Both frames were constructed using a scaled model, specifically a reduced one-third scale of the original prototype, in accordance with the previously mentioned similitude rule outlined in Table 5.1.

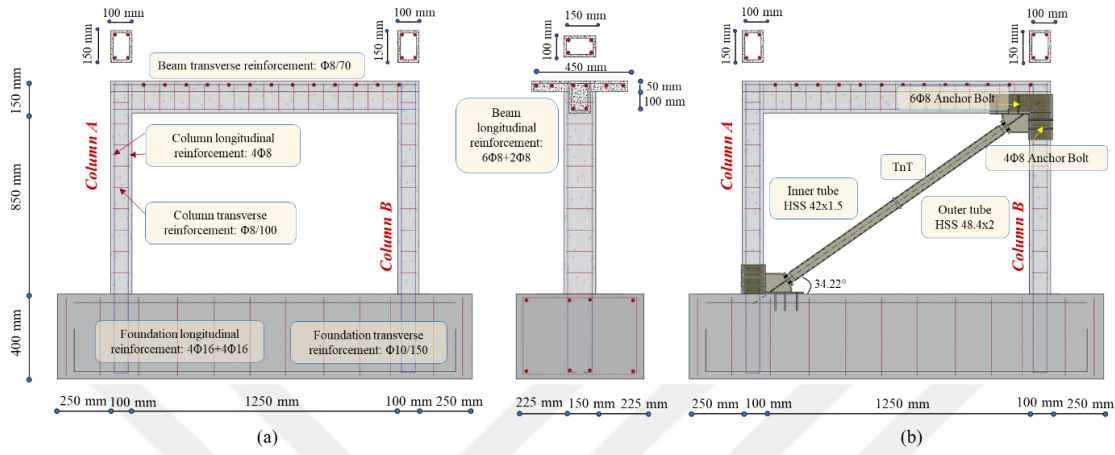


Figure 5.4 : (a) Details of Specimen 1 (Bare Frame) and (b) Specimen 2 (TnT Frame)

The columns utilized in the simulations had a rectangular cross-section measuring 100 mm by 150 mm and were spaced 1350 mm apart at their centers. Each column featured four longitudinal reinforcement bars with a diameter of 8 mm, which is the smallest size of deformed bar offered in the local market. The columns reached a height of 950 mm from the top of the foundation to the underside of the top slab. Transverse reinforcement comprised of 8 mm bars, which were arranged at intervals of 100 mm from center to center. The stirrups incorporated 90-degree hooks to depict inadequate detailing in the column. Additionally, 8 mm diameter steel bars were placed at a spacing of 100 mm on center at both the top and bottom of the slab in both longitudinal and transverse orientations. The longitudinal reinforcement in the foundation was made of 16 mm diameter steel bars, while the stirrups were produced from 10 mm diameter bars that were spaced 150 mm apart. The dimensions of the top slab were 1450 mm in length, 450 mm in width, and 50 mm in thickness. For enhanced stability, a foundation beam measuring 1950 mm in length, 600 mm in width, and 400 mm in depth was constructed. This foundation beam was anchored to the shaking table using anchor bolts with a diameter of 50 mm. A schematic overview of Specimen 1 and plan view of the foundation anchorage arrangement is depicted in Fig. 5.4.(a) and Fig. 5.5, respectively.

Fig. 5.4.(b) demonstrates that the second specimen, Specimen 2, was constructed as a replica of the first, with the notable addition of a TnT brace. The objective of the seismic retrofit was to enhance the strength and rigidity of the bare RC frame, surpassing its initial capacity. Furthermore, a significant increase in ductility was anticipated. Research indicates that retrofitting RC frames using non-buckling braces is an effective strategy for improving the seismic resilience of existing structures that lack adequate seismic detailing (Cao et al, 2022), (Di Sarno and Elnashai, 2009).

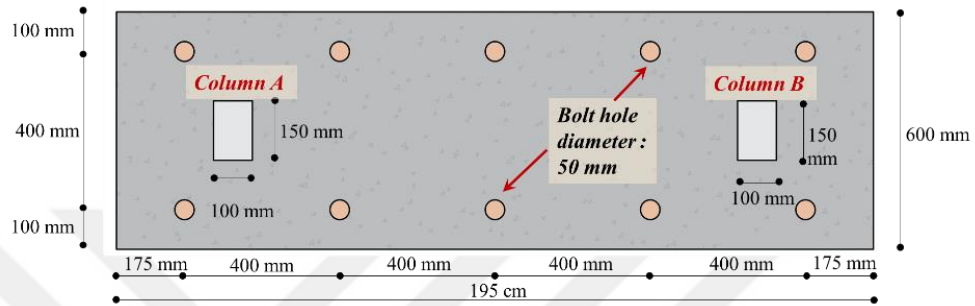


Figure 5.5 : Plan view of the foundation anchorage arrangement for the test specimens, illustrating anchor bolt holes ($\varnothing 50$ mm) and the positions of Columns A and B.

The TnT bracing, which was constructed in-house, featured a circular HSS with dimensions of 42×1.5 mm made from S235JRH steel, encased in another hollow tube measuring 48.4×2.0 mm. This configuration resulted in a tube-in-tube bracing system. It is important to note that the outer tube, which served as a buckling controller, consisted of two segments, whereas the load-bearing tube was a single continuous piece that extended between the end plates. The fabrication process for the bracing began with the application of all-around fillet welding to attach an 8 mm thick ring-shaped stopper plate to the load-bearing tube, which is 1235 mm long. Following this, the two outer tubes, each measuring 595 mm in length, were welded to the stopper plate from either side. The load-bearing tube was then fillet welded to 8mm thick rectangular end plates at both ends. It is essential to mention that there was an 18mm gap between the outer tube and the end plates on each side, which was designed to accommodate the shortening of the load-bearing tube under compression. This feature allowed the TnT bracing to demonstrate comparable performance in both tension and compression by disregarding the contribution of the outer tube to compressive strength. The clearance was established based on anticipated brace deformations. Once the bracing was complete, 75×75 mm end plates were affixed to the end plates that were already welded to the gusset assemblies using four pretensioned M12 grade 8.8

bolts. To reduce end rotations that could lead to global instability in both in-plane and out-of-plane directions, gusset plates were reinforced with central and free-edge stiffeners, as referenced in several studies (Shen et al, 2016), (Seker and Shen, 2017), (Zhou and Li, 2010), (Tsai et al, 2014).

A major obstacle in the incorporation of external bracing within a pre-existing frame is the technique for attaching BRBs to the RC frame (Chen et al, 2022). Given that the RC frame components are already constructed, additional structural elements are necessary for fastening the bracing to the RC structure. To enable the attachment of the TnT brace to the RC frame, 8mm thick steel plates are subsequently installed onto the existing RC framework, leaving a small gap between the steel and the concrete, which is subsequently filled with grout. This setup facilitates the connection of the gusset and the bracing to the RC frame without enhancing its strength. However, as shear and tensile forces increase, these plates can rotate and translate freely, potentially causing misalignment of the gussets and braces, which may lead to failure prior to the non-buckling brace achieving significant energy dissipation (Mahrenholtz et al, 2015). Furthermore, the RC frame may lack adequate shear strength in the columns and joints to handle the increased stiffness, as well as the tension-compression forces introduced by the brace. To mitigate this issue, 6 Φ 8 pretensioned bolts were employed to secure the TnT bracing to both the cap beam and the foundation beam, while an additional 4 Φ 8 bolts anchored the brace to the faces of the column elements within the RC frame. The connection details between the TnT brace, the foundation, and the beam-column joint of the frame are depicted in Fig. 5.6. Subsequently, the TnT element was installed at a 34.22-degree angle relative to the foundation beam.

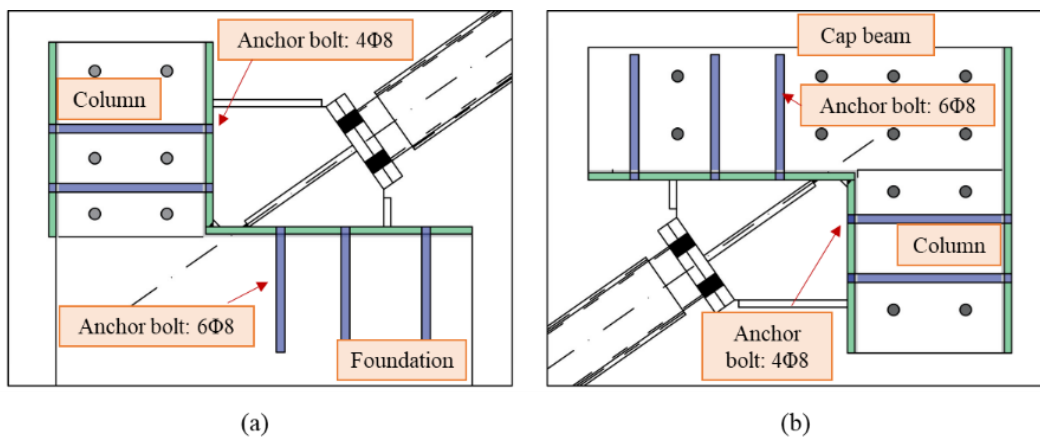


Figure 5.6 : Connection details a) Foundation-column, b) Beam-column

The test columns underwent axial loading through the incorporation of steel blocks. As previously explained, a total weight of 6 tons was placed on the frame, leading to an axial load of 30 kN imposed on each reinforced concrete column individually. This axial load accounted for 44% of the columns' axial load capacity, without considering the effect of longitudinal reinforcement on the total capacity. Fig. 5.7 illustrates the arrangement of the specimens, complete with the additional mass, on the shake table.

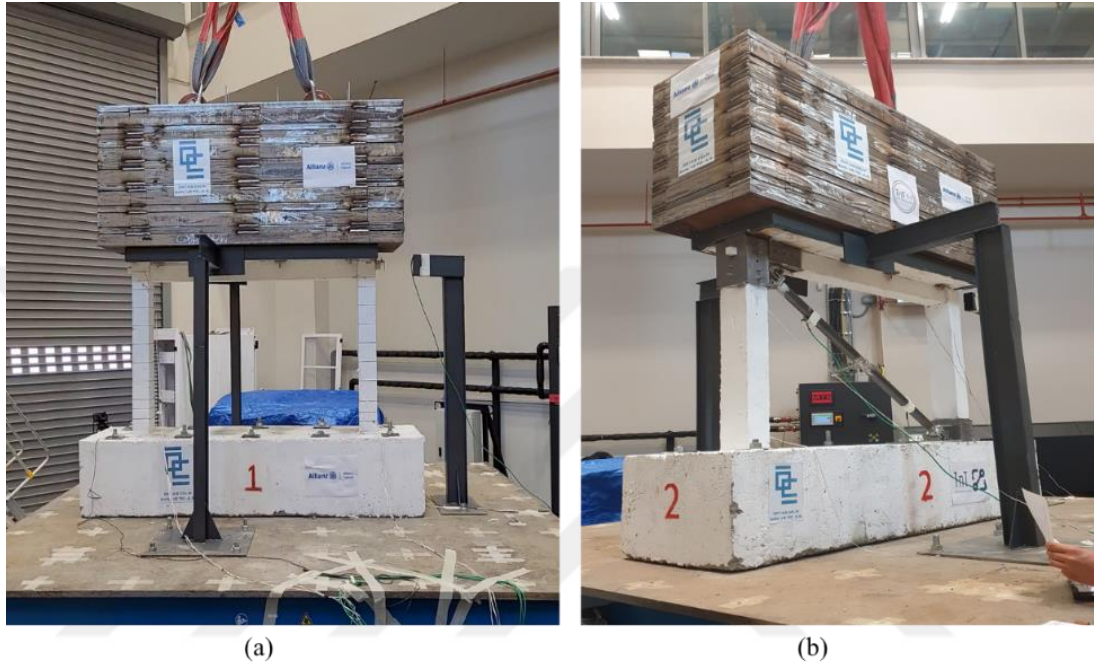


Figure 5.7 : (a) Specimen 1 and (b) Specimen 2 on the shake table.

5.4.3 Material properties

5.4.3.1 Concrete and longitudinal rebars

In the experiments conducted, the objective was to achieve low uniaxial compressive strength in concrete. RC frames were built at the Allianz Technical Laboratory. Various cubic samples were collected and subjected to testing to confirm the compressive strength of these specimens. The compressive cylinder strength measured at 28 days for the frames was recorded at 9 MPa. The determination of the compressive strength of concrete utilized in the fabrication of the scaled test specimen adhered to the protocols specified in the Turkish Standard TS EN 12390-3 (2010). Concrete cube specimens measuring 150 mm on each side were cast, subjected to curing, and subsequently tested within a controlled laboratory environment. This approach guarantees consistency and reproducibility, thereby enhancing the accuracy of the

resultant test data. By employing this standardized methodology, the resulting compressive strength values are both reliable and comparable. This reliability is crucial for the precise characterization of the mechanical properties, which in turn is vital for ensuring structural similarity between the scaled experimental setup and the corresponding full-scale prototype.

In the construction of the columns and beams, four longitudinal deformed bars were incorporated, each with a diameter of 8 mm. Both longitudinal and transverse reinforcement utilized within the scaled experimental specimen consisted of ribbed steel reinforcing bars conforming to Turkish Standard TS 708 (2010). To analyze the stress-strain relationships of the steel employed, three samples underwent testing. The transverse reinforcement also featured an 8 mm diameter. The characteristics of the steel reinforcing bars were evaluated through tensile testing conducted in the laboratory, showing a yield stress of $F_{(y,measured)}=473$ MPa and an ultimate stress of $F_{(u,measured)}=643$ MPa. All reinforcing bars met the strength criteria established by ASTM A615/A615M-05 (2005). The stress-strain diagrams for both the concrete and the longitudinal reinforcing bars are illustrated in Fig. 5.8.

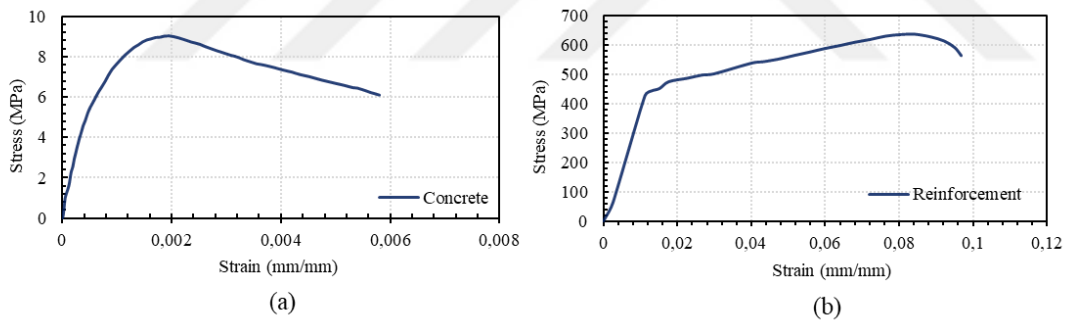


Figure 5.8 : (a) 28-days compressive strength of the concrete and, (b) Stress-strain relationship of reinforcement

5.4.3.2 TnT bracing

The TnT brace specimen was constructed using cold-formed circular tubing made from S235JRH steel, following the specifications outlined in BS EN 10219 (2006). Prior to conducting shake table tests, tensile tests were carried out to accurately assess the material properties of the load-bearing tube, as this area is expected to experience significant plastic deformation. Fig. 5.9 illustrates the dimensions of the coupon specimens along with the test setup utilized for the tensile testing. To evaluate the material properties of the load-bearing tube, which was made of HSS42×1.5, two

identical dog bone-shaped coupons were extracted from the tube (see Figs. 5.9.(a) and (b)). The uniaxial tensile tests were performed at the Turkish Standard Institution's Material Testing Laboratory in Kocaeli, Türkiye, employing an Instron 8802 Servo Hydraulic testing system that has a maximum force capacity of 100 kN, as depicted in Fig. 5.9.(c). The dimensions of the coupons and the loading rate were established in accordance with the ASTM E8 (2015) standard. It is important to note that the two coupon specimens were cut from sides that were perpendicular to the seam, as shown in Fig. 5.10(a).

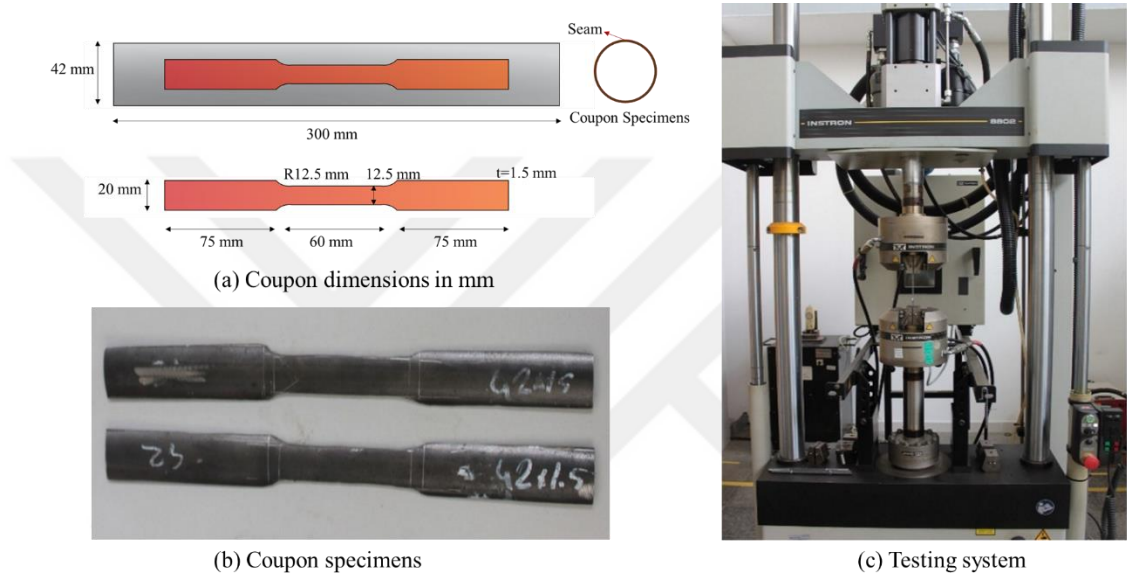


Figure 5.9 : Geometry and extraction details of the dogbone coupon specimens from the HSS tube, alongside the tested coupons and the Instron 8802 servo-hydraulic system used for tensile testing

The results of the coupon tests are illustrated in Fig. 5.10, which displays data in terms of engineering stress (calculated by dividing the applied load by the measured cross-sectional area, reported in MPa) and engineering strain (defined as axial elongation divided by the initial length, expressed in mm/mm). Table 5.2 provides a summary of the measured yield stress ($F_{y,measured}$), tensile stress ($F_{u,measured}$), and ultimate strain at fracture (ϵ_u), as derived from the results shown in Fig. 5.10. It is important to note that the yield stresses were determined using the 0.2% proof stress criterion. According to Table 5.2, the measured yield stresses ($F_{y,measured}$) were found to be 397 MPa and 431 MPa for the two distinct coupons tested. The measured peak engineering stresses ($F_{u,measured}$) ranged from 494 MPa to 520 MPa, while the ultimate strain at fracture was approximately 0.30 or higher, as indicated in Table 5.2.

The average yield stress ($F_{y,average}$) and ultimate tensile stress ($F_{u,average}$) calculated from the two tests were approximately 414 MPa and 507 MPa, respectively.

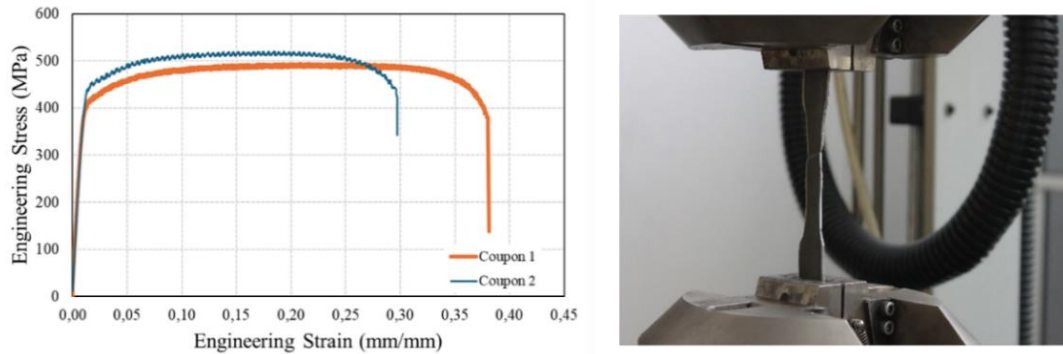


Figure 5.10 : (a) Engineering stress–strain curves of the HSS tube coupon specimens, (b) a photograph of the coupon during tensile testing.

Table 5.2 : Measured material properties of the load-bearing tube based on coupon tests

Coupon ID	$F_{y,measured}$ (MPa)	$F_{u,measured}$ (MPa)	$\epsilon_{u,measured}$ $\left(\frac{mm}{mm}\right)$, %	$F_{y,average}$ (MPa)	$F_{u,average}$ (MPa)
1	397	494	38.0	414	507
2	431	520	29.7		

5.4.4 Instrumentation

The responses of the test specimens to seismic activity, which encompassed acceleration, displacement, and strain, were carefully documented through the utilization of various instruments. The setup included accelerometers and linear voltage displacement transducers (LVDTs), illustrated in Fig. 5.11. All LVDTs were designed to accurately measure displacements at frequencies reaching up to 200 Hz. These devices were affixed to rigid frames anchored to the ground, rather than being mounted on the shaking table, allowing for the measurement of displacements relative to the ground. In addition to the LVDT positioned at the slab level (LVDT#1), two additional LVDTs were placed at either end of the TnT brace (LVDT#2 and #3) to capture the axial displacement demands on the load-bearing tube during the excitations, as depicted in Fig. 5.11. Furthermore, the accelerations experienced in both the foundation and slab of the test frames, as well as at the surface of the shake table, were documented using four individual accelerometers secured to the side of the foundation and to the table itself. It is important to note that both the acceleration and displacement responses were continuously recorded by a computer-aided data acquisition system. Additionally, a total of twelve straingauges were embedded within

the reinforced concrete frame to track strain responses from various locations, as shown in Fig. 5.11.

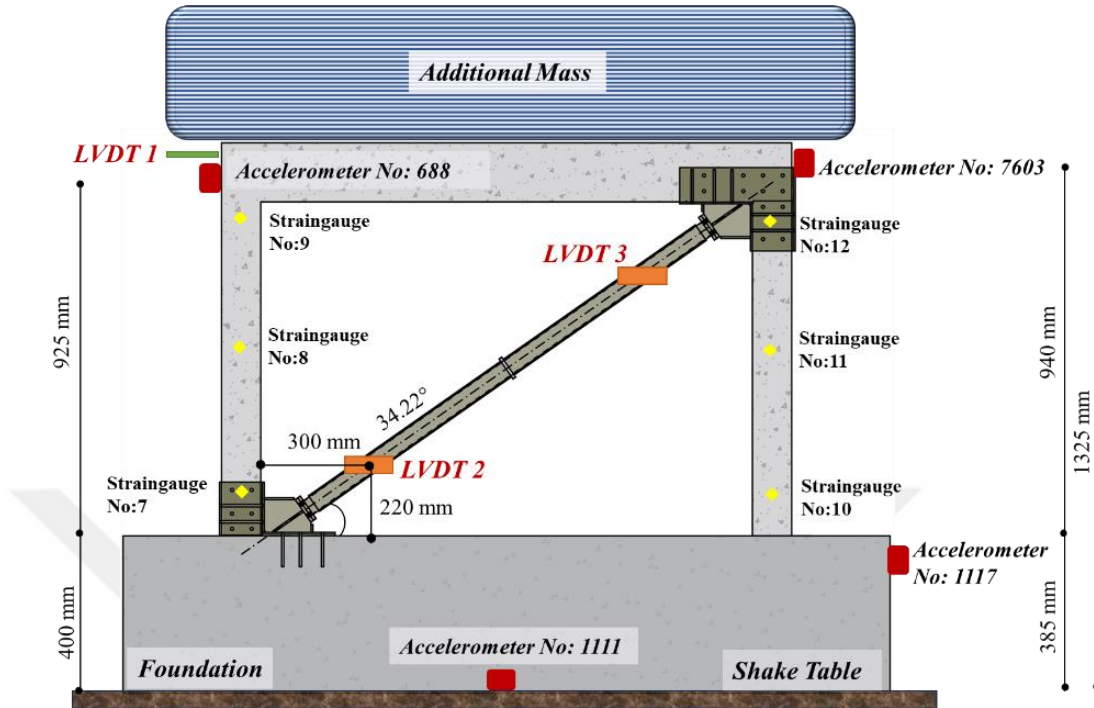


Figure 5.11 : Instrumentation of the test specimens

5.4.5 Global stability of TnT bracing

Before conducting shaking table tests, a finite element-based simulation of the TnT bracing was performed to verify the overall stability of the bracing during the subsequent physical test. A full-sized numerical model of the TnT bracing, which was to be integrated into the RC frame specimen, was developed using the general-purpose finite element analysis (FEA) software ABAQUS 6.12 (2012). To minimize computational demands, the TnT bracing and the connecting components, specifically, the gusset plates strengthened with stiffeners, were separated from the enhanced RC frame designated for testing. The diagonal bracing was subjected to an incrementally increasing static load.

The Newton-Raphson algorithm was employed for the nonlinear static analysis performed. For all components, the elastic modulus and Poisson's ratio values were specified as 200.000 MPa and 0.3, respectively. The analysis considered both material and geometric non-linearities. Material nonlinearity was addressed through the application of the kinematic hardening rule. It is important to mention that standard nominal material properties were utilized for the material definitions. To ensure

numerical stability during the nonlinear static analysis, an artificial damping factor of 0.0002 was implemented, and an upper limit of 5% for the maximum ratio of stabilization to strain energy was established to restrict the impact of the introduced adaptive stabilization energy.

An analytical procedure consisting of two phases was implemented, starting with an elastic buckling (eigenvalue) analysis and followed by a static analysis to incorporate initial geometric imperfections. To address both initial in-plane and out-of-plane deformations, an initial imperfection value of $L/500$ was introduced into the finite element model, derived from the first and second mode buckling deformations. In accordance with the boundary conditions of the frame, the top gusset plate was connected to a reference point located at the work point, where lateral loading was applied through displacement control, while the lower gusset plate remained fixed. The parts within the assembly were discretized using linear hexahedral elements with reduced integration, specifically C3D8R. Importantly, potential numerical errors associated with zero-energy modes, such as hourglass modes, were mitigated by the addition of artificial stiffness. The mesh density was adjusted across different regions to align with anticipated deformation patterns, with finer mesh deployed in areas expected to experience significant plastic deformations. The assembly comprised a total of 43,376 elements, with the assembly's meshing details illustrated in Fig. 5.12.(a).

The results of the simulation are illustrated in Fig. 5.12, focusing on the relationship between force and displacement, as well as the stress distributions. The positive value indicated in Fig. 5.12.(b) corresponds to compressive forces and displacements. Figure 5.12. (b) reveals that the response to the applied lateral force remained stable, showing no loss of stiffness or strength until the story drift ratio reached 0.035 radians, at which point the analysis was concluded. Figures 5.12.(c) and (d) depict the deformed configurations along with the relative Von Mises stress distribution for the assembly, both with and without the buckling controller. The deformed shapes in Figs. 5.12(c) and (d) demonstrate that neither global nor local buckling occurred during the entire loading process. Additionally, it is significant that the distribution of compressive stress remained nearly uniform across the length of the load-bearing tube, as intended (Fig. 5.12.(d)). Thus, the TnT specimen in the simulation was determined to be

effective in providing the reinforced concrete frame with a stable and symmetrical response.

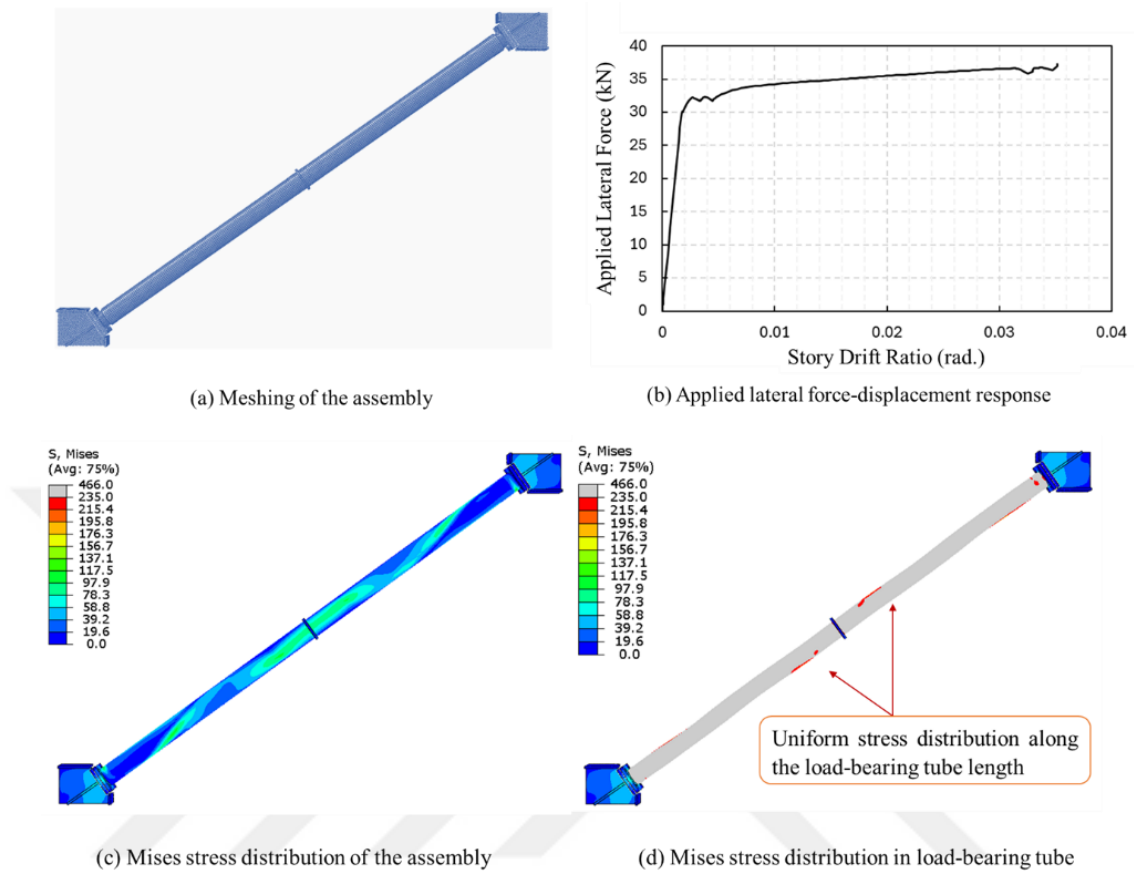


Figure 5.12 : Finite element-based pushover analysis of the TnT bracing assembly.

5.5 Sequential Experimental Protocol

On February 6, 2023, at 04:17 local time (+3 GMT), a powerful earthquake occurred in the southeastern part of Turkey, registering a moment magnitude (M_w) of 7.7. Disaster and Emergency Management Presidency (AFAD) reported that the quake's epicenter was located in the Province of Kahramanmaraş, particularly near the town of Pazarcik (AFAD, 2023). This seismic event, referred to as the 2023 Kahramanmaraş earthquake, took place in a geological area known as the Maraş triple junction, which resulted from the convergence of the Arabian, Eurasian, and African tectonic plates. Seismological data was collected from 381 active monitoring stations, with station number 3141 used for experimental analysis. The maximum peak ground acceleration (PGA) recorded at this station reached a value of 991.764 gal in the north-south direction.

The latest Turkish Building Earthquake Code (TBEC, 2018) categorizes seismic risk into four levels: DD-1, DD-2, DD-3, and DD-4. These categories correspond to the likelihood of earthquake events occurring, with probabilities of exceedance at 2%, 10%, 50%, and 68% over a 50-year timeframe. The average intervals between these seismic events are calculated as 2475, 475, 72, and 43 years for each respective level. Furthermore, the seismic levels are associated with specific earthquake scenarios: the maximum considered earthquake (MCE) for DD-1, the design-based earthquake (DBE) for DD-2, the frequent earthquake (FE) for DD-3, and the service-level earthquake (SE) for DD-4. Fig. 5.13 illustrates the normalized response spectra for the station at the DD-2 level, presented alongside a time-history record of the 2023 Maraş earthquake that has been scaled per the similitude law. This depiction also includes critical damping values of 2.5%, 5%, and 10%. The examination of the figure indicates that the chosen acceleration time history is appropriate for the experimental evaluation of the test frames.

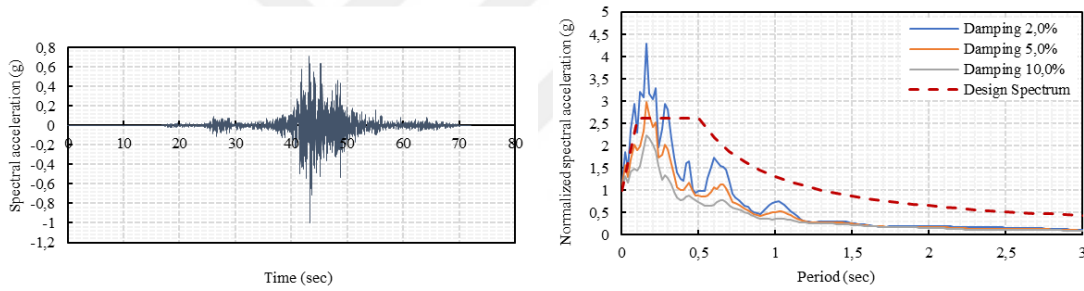


Figure 5.13 : Scaled time-history record and normalized response spectra of the 2023 Maraş earthquake.

The experiments were carried out in two successive stages. In the initial stage, both frames (Specimens 1 and 2) were exposed to ground motion that was appropriately scaled according to the similitude law outlined previously. Since the frames were designed to be substandard, the applied scaled ground motion was executed with precision. Damage was noted in Specimen 1 during the testing when 35% of the ground motion was applied. In contrast, Specimen 2 experienced no damage under the same conditions. As a result, a decision was made to evaluate the overall seismic performance of the TnT enhanced Specimen 2 by applying 100% of the unscaled ground motion, which represents a high demand on structures. The purpose of this approach was to investigate the frame's performance in the event of intense ground shaking. Fig. 5.14 displays the original time history data alongside its corresponding normalized response spectra.

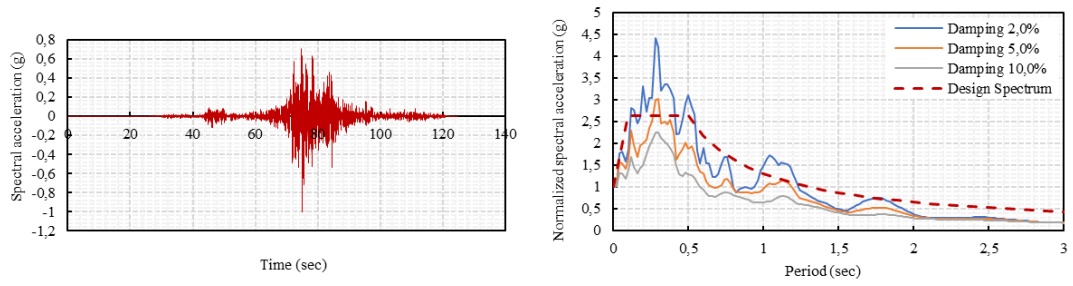


Figure 5.14 : Original time-history record and normalized response spectra and of the 2023 Maraş earthquake.

5.6 Discussion on Test Results

This section focuses on the analysis of the results obtained from the experimental study conducted. After each recorded acceleration time history, a visual inspection of the frames was performed to identify any damage, while the acceleration data from the white noise tests and free vibration were also collected. This information contributed to the evaluation of the frames' dynamic properties. The initial frequencies for the first and second specimens were identified as $f_0 = 2.02\text{Hz}$ and $f_0 = 6.61\text{ Hz}$, respectively. Subsequently, all collected data underwent post-processing to rectify baseline errors. Additionally, a low-pass fifth-order Butterworth filter was applied to the acceleration and displacement data to mitigate frequencies caused by noise from electrical devices (Ellis, 2012).

The precision of the accelerometers was verified through the measured accelerations at ground level at station 1111 and on the footing side at station 1117. Fig. 5.15 presents a comparison between the measured accelerations and the ground motion applied to both specimens. From the figures, it is evident that the recorded accelerations show a strong correlation with the applied ones. Following the verification of the device reliability, acceleration measurements at the top were taken at stations 688 and 7603 for both specimens.

A prevalent method for calculating the damping ratio involves assessing the frequency bandwidth between specific points on the response curve, where the response reflects a certain fraction of the system's resonant response. Conventionally, this analysis focuses on two frequencies positioned symmetrically around the resonant frequency at which the amplitude of the response measures $1/\sqrt{2}$ of the peak response value. The resulting bandwidth from these frequencies is designated as the *half-power*

bandwidth a term derived from electrical systems analysis, where amplitude squared is indicative of electric power. The damping ratio (ξ) is then determined by using the relation $\xi = (f_2 - f_1)/f_n$, where f_n refers to the forcing frequency at resonance (Chopra, 2023).

Based on the damping ratio values that were previously computed, the factors related to the acceleration response (R_a) were subsequently identified considering the two specimens. Accordingly, for the first and second specimens R_a values were determined as 8.80 and 4.74, respectively. This indicates that the addition of the TnT brace has significantly reduced the recorded responses. Acceleration records at Stations 688 and 7603 for both specimens are also illustrated in Fig. 5.15.

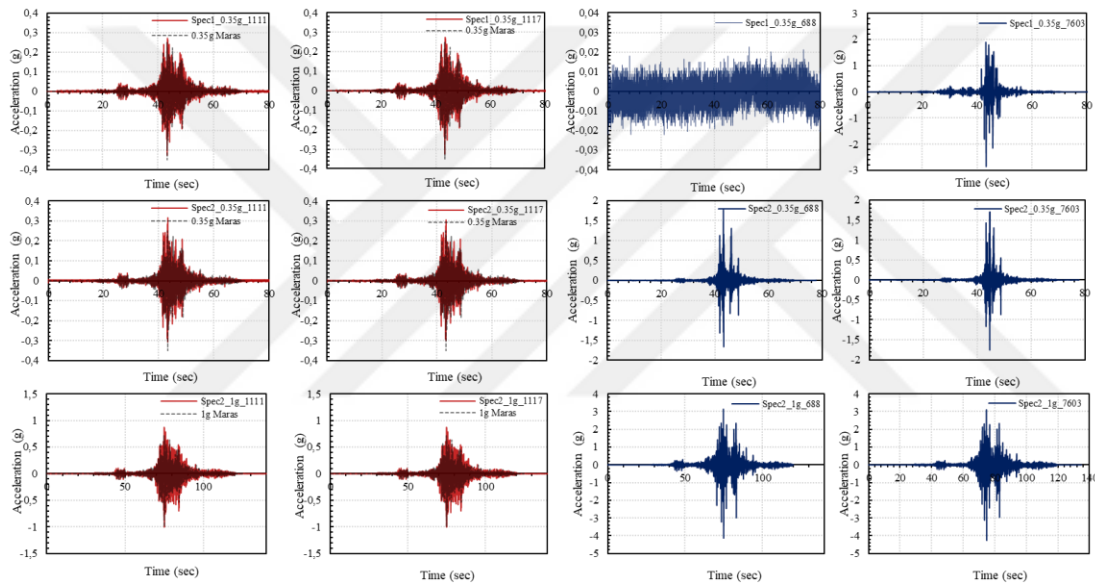


Figure 5.15 : Recorded and applied accelerations at Stations 1111,1117, 688, and 7603 for both specimens.

The maximum displacements measured at the top of both specimens by the LVDTs are illustrated in Fig. 5.16. The data reveals that the inclusion of TnT notably reduced the lateral displacement demands. For Specimen 1, the highest lateral displacement recorded was approximately 53.1 mm, which correlates to a story drift ratio of about 0.055 rad. In contrast, Specimen 2 exhibited a peak lateral displacement response of less than 2 mm when subjected to a 0.35g excitation (as shown in Fig. 5.16.(b)). This observation suggests that Specimen 2 remained essentially elastic during the 0.35g earthquake. Additionally, as depicted in Fig. 5.16.(c), the peak displacement recorded for Specimen 2 during 1g ground excitation was noted to be 19.86 mm, translating to a story drift ratio of roughly 0.02 rad.

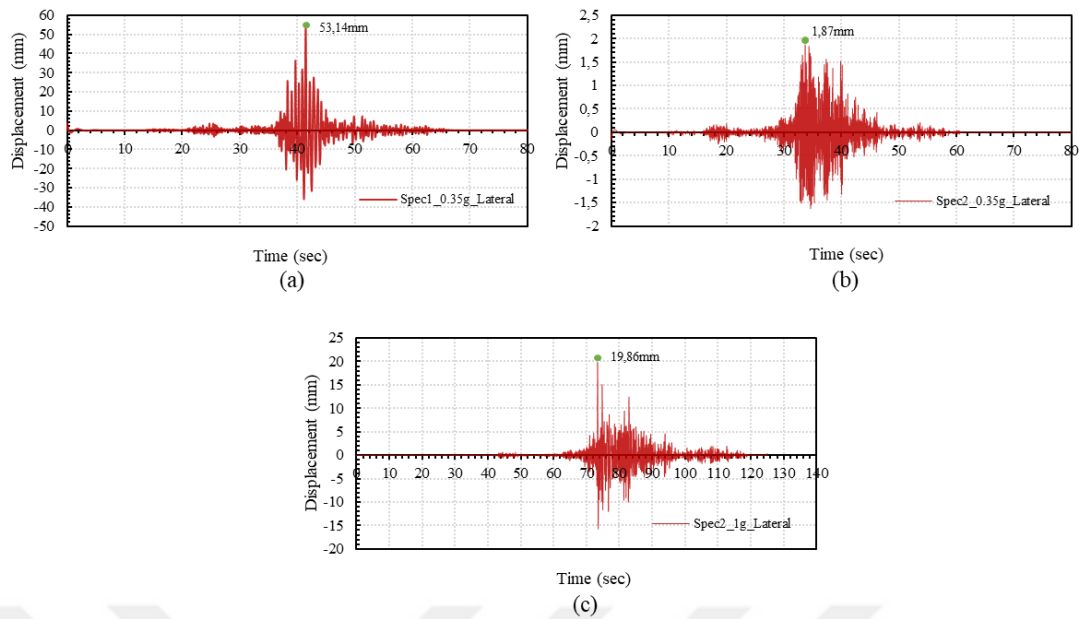


Figure 5.16 : Lateral displacement time traces recorded at the top LVDTs

The graph in Fig. 5.17, presents a stress–strain diagram captured during a 0.35g ground motion test. In this representation, the horizontal axis quantifies strain values in terms of mm/mm, while the vertical axis depicts the corresponding stress levels, typically measured in megapascals (MPa). Two distinct curves are presented: the red line corresponds to Specimen 2, the frame retrofitted with the innovative TnT BRB system, whereas the blue line represents Specimen 1, the bare frame without any retrofitting measures. Notably, this comparison is conducted at the 0.35g excitation level because Specimen 1 could not withstand higher excitations without incurring significant damage. Consequently, the stress–strain data for the bare frame provide a crucial baseline reflecting its compromised behavior under seismic loading. This behavior is indicative of the bare frame’s inability to effectively redistribute and dissipate seismic energy, ultimately leading to premature failure.

In contrast, the red curve for Specimen 2 reveals a markedly different behavior. The retrofitted frame exhibits a more gradual and controlled increase in stress with strain, indicating a stable transition from elastic to inelastic behavior. The moderated stress levels at comparable strain values suggest that the TnT BRB system facilitates improved energy dissipation and strain distribution. This behavior is particularly important because it not only delays the onset of damaging inelastic deformations but also maintains the structural integrity of the frame under seismic loads. The red curve’s ductile response is emblematic of the enhanced resilience imparted by the retrofitting

intervention, where the dual-tube mechanism of the TnT system actively mitigates stress concentrations and promotes uniform load transfer.

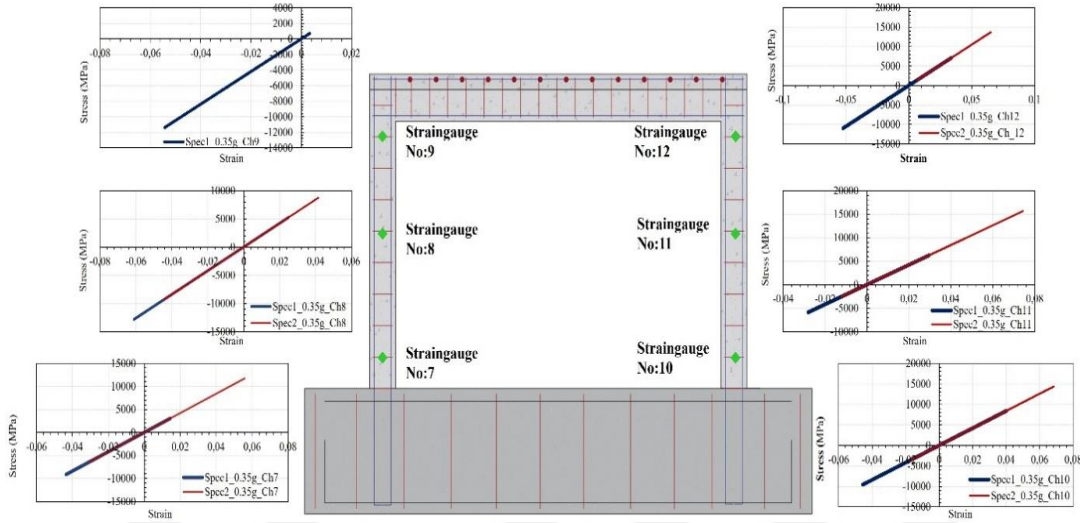


Figure 5.17 : Strain responses recorded by gauges at various locations on the specimen during 0.35g ground motion, illustrating the distribution of stress–strain behavior across columns and beams as indicated in the schematic (center).

The juxtaposition of the two curves highlights the TnT BRB system's efficacy in reducing seismic effects. The bare frame shows a stress peak followed by a drop, indicating potential yielding or damage, while the retrofitted specimen maintains a consistent stress level throughout the strain range. This performance demonstrates the system's potential to enhance ductility and extend the service life of structures in seismic areas. The graph acts as a diagnostic tool, revealing the lower stress levels and ductile behavior of Specimen 2, underscoring the TnT BRB system's transformative impact on seismic damage mitigation. These results support innovative retrofitting strategies, like the TnT BRB system, to enhance seismic resilience and structural performance during earthquakes.

The response of the TnT brace was monitored during the excitations. Fig. 5.18 illustrates the brace response history for two different levels of ground motion. It is important to highlight that the total end displacements recorded by the LVDT-2 and LVDT-3 sensors, which are located on the TnT (shown in Figure 5.12), are presented in Fig. 5.18 for both ground acceleration levels. As depicted in Figs. 5.18 (a) and (b), the maximum axial elongation of the load-bearing tube was under 1 mm for the 0.35g ground shaking and under 5 mm for the 1.0 g ground shaking. These axial displacements show that the brace remained within the elastic range during the 0.35g

ground motion, while the peak ductility demand on the brace was lower than 3 throughout the 1.0g excitation. Thus, considering the peak and cumulative ductility capacities of TnT braces, it can be inferred that the demand placed on the brace was minimal, even under ground conditions reaching 1g.

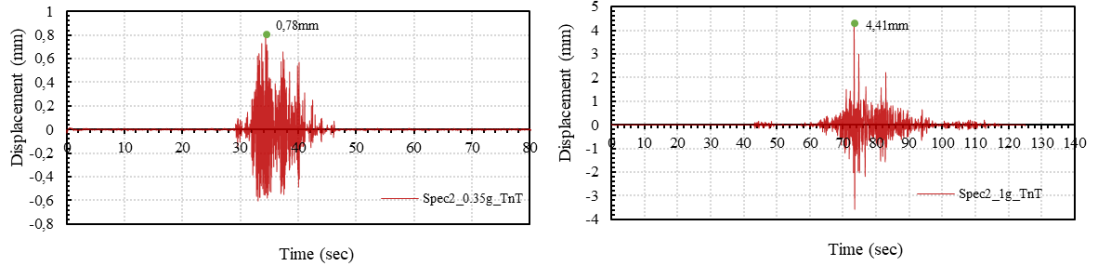


Figure 5.18 : Recorded axial displacement response of TnT brace

The intensity of seismic force generated by earthquake occurrences can be quantified via the structural response, particularly through shear force. In the event of an earthquake, the shear force exerted on a specific floor of a building can be determined using the equation $V(t)=|ma(t)|$. In this equation, $a(t)$ indicates the acceleration response instigated by the earthquake, and m represents the mass located at the floor level.

Fig. 5.19 presents graphs of the assessed base shear force and the relevant story drift ratio (defined as the lateral displacement recorded divided by the height of the LVDT) for both specimens tested under two different acceleration levels. For the first specimen subjected to a ground motion of 0.35g, the peak shear force and story drift ratio recorded were approximately 18.17 kN and 5.8%, respectively. In comparison, the second specimen under the same ground motion level demonstrated maximum demands of 30.65 kN for shear force and 2‰ for the story drift ratio. Additionally, under a ground motion of 1g, the highest shear force recorded rose to 88.22 kN, while the maximum story drift ratio was approximately 2.16%.

An examination of shake table testing conducted on a poorly detailed reinforced concrete frame enhanced by an all-steel tube-in-tube buckling-restrained brace indicates that the buckling-restrained brace serves as the primary seismic defense mechanism against lateral forces during an earthquake event. This intervention notably mitigates the shear force demand experienced by the existing structural members in the primary structure as a result of seismic activity.

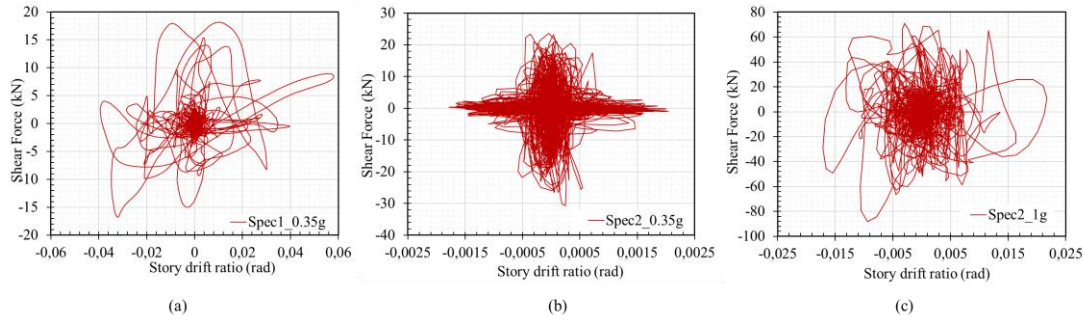


Figure 5.19 : Base shear-story drift ratio response of the tested specimens

5.7 Observed Damage Patterns

This section focuses on the documented structural damage incurred by the specimens following exposure to sequential ground motions. Upon application of a 0.35g ground motion level to Specimen 1, it was noted that the beam-column connections exhibited signs of damage. Additionally, sequential images illustrating the progressive development of cracks and spalling in Columns A and B of the substandard RC frame during the 0.35g ground motion test are as illustrated in Fig. 5.20. At identical levels of ground acceleration, the second specimen that incorporates TnT bracings demonstrated a capacity to endure the excitation, exhibiting only minor hairline cracks. Importantly, as it is presented in Fig. 5.21, both the frame elements and the TnT itself remained undamaged. Moreover, as depicted on Fig. 5.22, the second specimen exhibited virtually no damage when subjected to 1 g of ground motion. This can be attributed to the compensatory effect of the elongations in the TnT material itself. These elongations account for the observed absence of damage in the reinforced concrete section. Subsequent to testing, in order to conduct a detailed examination of the beam-column connections and potential damage, the anchor plates were disassembled, allowing for a thorough inspection of the area. Analysis of the findings, as illustrated in Fig. 5.23, indicates that no considerable damage was identified during the inspection process. The findings exhibited a strong alignment with the experiments that were performed.

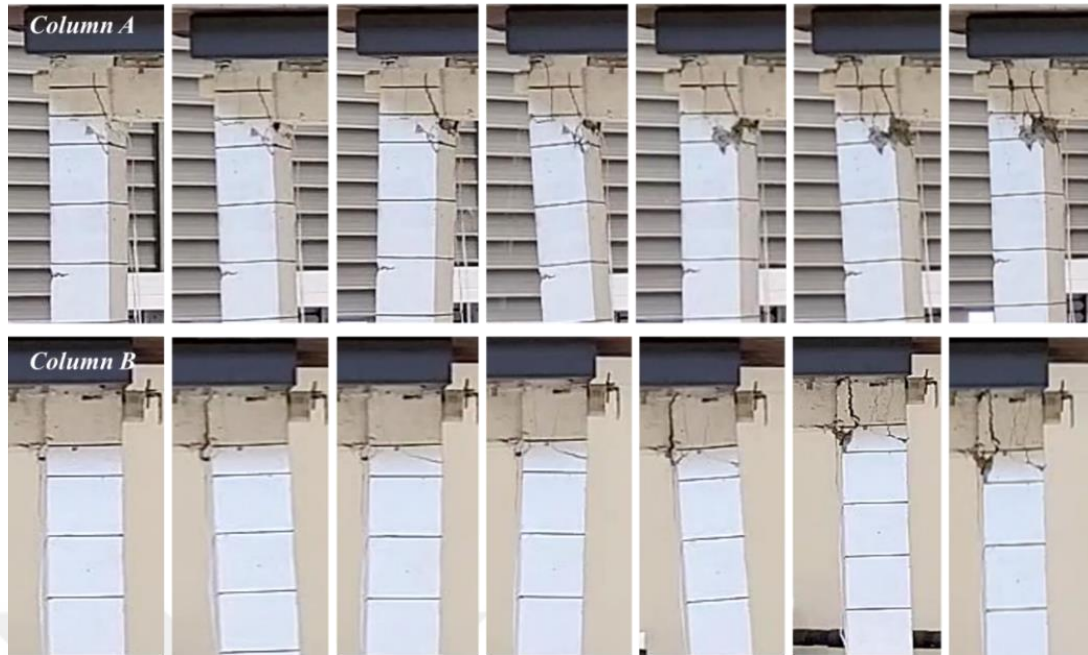


Figure 5.20 : Sequential images illustrating the progressive development of cracks and spalling in Columns A and B of the substandard RC frame during the 0.35g ground motion test.

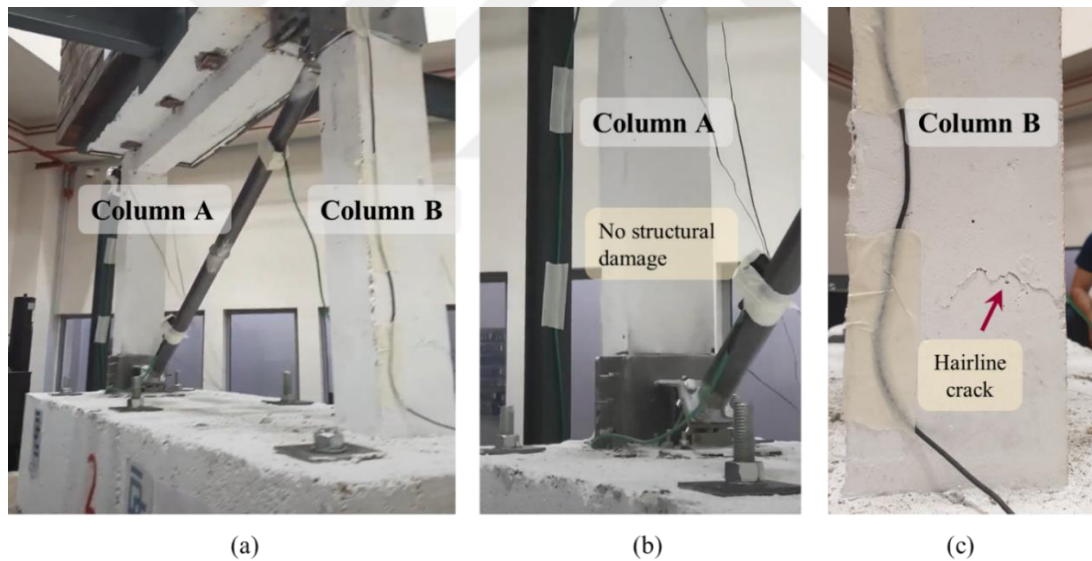


Figure 5.21 : (a, b) Views of the TnT-retrofitted specimen following the 0.35g ground motion test, illustrating negligible damage to Column A, and (c) a minor hairline crack on Column B.

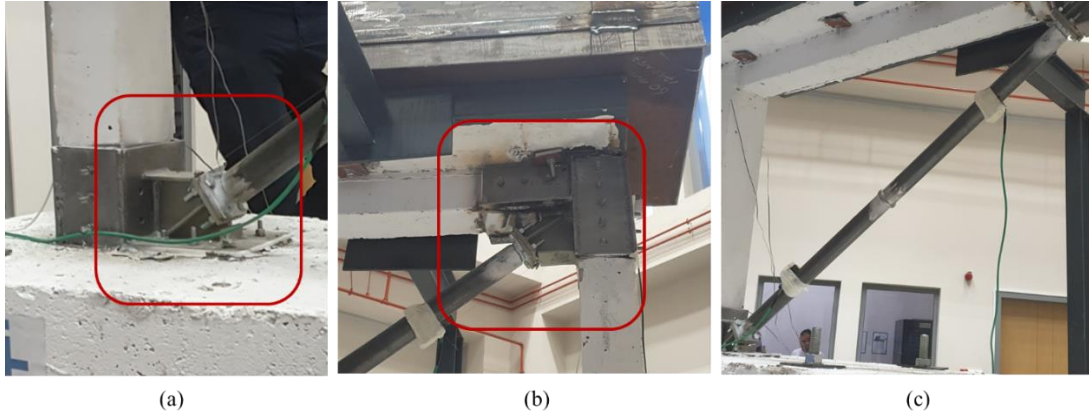


Figure 5.22 : (a) Views of the TnT brace end connection assemblies at the foundation, (b and c) beam–column joint, highlighting the gusset plates and bolted connections, and showing minimal residual damage at 1g ground motion level



Figure 5.23 : Post-test examination of the beam–column connection of Specimen 2 after 1 g Kahramanmaraş earthquake following removal of the anchor plates, showing localized concrete spalling and embedded steel plate details.

5.8 Field Observations from the Kahramanmaraş Earthquake

On February 6, 2023, two powerful earthquakes (M_w 7.7 and 7.6) struck nine hours apart near Pazarcık and Elbistan in Kahramanmaraş province, southern Türkiye. The shaking devastated 11 provinces, including Kahramanmaraş (epicentral region), Hatay, Adıyaman, Malatya, Gaziantep, and others, affecting over 10 million people. It was the deadliest seismic disaster in Türkiye’s modern history, with over 50000 fatalities and entire city blocks reduced to rubble. More than 2.1 million buildings were inspected after the quakes; approximately 230000 structures were classified as unsafe for use and slated for demolition. This included at least 38000 completely collapsed buildings, a staggering collapse rate unprecedented in recent Turkish earthquakes (AFAD,2023).

The predominant type of construction in the affected area consisted of mid-rise RC frame buildings, which aligns with the common architectural practices in Türkiye. A summary of the damage statistics obtained from the surveys conducted by the Ministry of Environment, Urbanization and Climate Change (MEUCC, 2011) from various severely impacted provinces is presented in Table 5.3. The collapse rates and heavily damaged percentages vary markedly across regions. Adıyaman, for instance, experiences a collapse rate of 7.20% and a heavy damage rate of 19.36%. Gaziantep, despite being the most populous province with over 2.15 million residents, shows a comparatively low collapse rate of 2.12% and a heavy damage rate of 5.10%. This disparity may be a consequence of its relatively modern construction stock or its geographical distance from the seismic epicenters. (Yilmaz et al, 2024)

Table 5.3 : Comparison of Regional Damage Metrics and Structural Performance for Selected Provinces Affected by the 2023 Kahramanmaraş Earthquake

Region (Province)	Population	Structural System			Collapse Rate (% of buildings)	Heavily Damaged (% of buildings)
		RC (%)	Masonry (%)	Composite (%)		
Hatay	1686043	66.06	20.49	44.50	6.27%	19.08%
					1997-2011 3.7%	1997-2011 14%
					2011-2018 1.4%	2011-2018 10%
Kahramanmaraş	1177436	52.90	31.43	33.54	5.28%	16.85%
					1997-2011 4.4%	1997-2011 9%
					2011-2018 1.3%	2011-2018 6%
Malatya	812580	30.80	58.49	45.78	4.39%	23.28%
					1997-2011 2.7%	1997-2011 8.4%
					2011-2018 0.49%	2011-2018 4.9%
Adıyaman	635169	57.05	30.45	24.75	7.20%	19.36%
					1997-2011 14%	1997-2011 9.7%
					2011-2018 1.1%	2011-2018 6.7%
Gaziantep	2154051	33.76	43.12	21.39	2.12%	5.10%
					1997-2011 2.3%	1997-2011 3.4%
					2011-2018 0.85%	2011-2018 2.2%

The influence of construction period is particularly pronounced. Buildings erected between 1997 and 2011 exhibit considerably higher collapse and heavy damage rates than those constructed from 2011 to 2018. In Hatay, for example, structures built in the earlier period show collapse and heavy damage rates of 3.7% and 14%, respectively, compared to 1.4% and 10% for the later period. Similar trends are evident in Kahramanmaraş and Malatya. These findings indicate that improvements in seismic

codes and construction practices over time have had a beneficial effect on structural performance, though the persistence of damage in newer buildings suggests that quality control and compliance remain critical issues.

5.8.1 Observed damage patterns and failure modes in RC buildings

In this section, field observations of failure modes, quantitative damage parameters (drifts, collapse frequencies), and damage classifications, are synthesized first, then comparative findings by region and building type, and implications for retrofitting strategies to improve the seismic resilience of existing RC buildings are discussed. The damage identified in RC structures following the earthquake can be ascribed to several contributing factors. These include beam-column joint failures, inadequate reinforcement and inferior construction practices, substandard concrete, damage due to strong beam-weak columns, soft (weak) ground stories, pounding effect and nonstructural damage.

Beam-column joint failures; Beam-column joints represent a significant vulnerability within numerous structural frames, as highlighted in the findings from field investigations conducted in Hatay. In instances of structural failure, it was commonly noted that these joints experienced shear failure, which resulted in the columns being effectively dislodged from their connections within the frame. Moreover, even in buildings that remained standing but exhibited damage, widespread joint cracking was observed, particularly at the exterior corners of the frames. This tendency toward brittle failure in the joints can be primarily linked to a deficiency in transverse reinforcement within the joint core, a detail often overlooked in many construction practices. Notably, some buildings constructed according to more recent building codes featured appropriate stirrups in the columns, yet they still lacked adequate reinforcement within the joint areas. This oversight contributed to the development of shear hinges at these critical nodes when subjected to lateral forces. The failure of these joints frequently instigated the collapse of entire stories by compromising the continuity of the structural framing system, an occurrence that can be further examined in Fig. 5.24.



Figure 5.24 : Field observations of damaged RC members showing beam-column joint failures

Inadequate reinforcement and inferior construction practices; Numerous aged structures exhibited the use of smooth reinforcing bars characterized by inadequate anchorage, alongside lap splices situated in crucial areas that failed to meet requisite lengths. Consequently, instances of bond-slip failures became evident, where reinforcing bars disengaged from the surrounding concrete, predominantly at the bases of columns and at splice locations, ultimately resulting in a reduction of structural integrity. It was observed that certain columns that experienced collapse had their reinforcing bars entirely debonded or entirely extracted from the concrete matrix, implying that bond failure played a significant role in the structural failure. Moreover, instances of longitudinal bar buckling were identified in columns subjected to heavy loads, particularly where transverse ties were positioned at excessively wide intervals. These deficiencies in reinforcement detailing, including insufficient splice lengths and inadequate confinement measures, are emblematic of construction practices predating in the 1990s, and they represent a principal factor contributing to the failures encountered in these older edifices. The damage to this nature is exemplified in Fig. 5.25.



Figure 5.25 : Field observation of inadequate reinforcement and inferior construction practice

Use of substandard concrete; Substandard concrete refers to material that does not meet the required specifications for strength, durability, or other essential properties. This can result from various factors, including inadequate mixing, insufficient curing time, improper material selection, or environmental influences during the pouring process. The implications of utilizing poor-quality concrete can be significant, leading to structural failures, increased maintenance costs, and reduced lifespan of the concrete structures. A significant portion of the considerable damage observed can be linked to the inadequate quality of materials utilized, a concern prevalent in structures erected before the year 2000, yet not anticipated in buildings constructed afterwards. Furthermore, the collective dimensions of the aggregates were observed to significantly exceed the maximum aggregate size outlined in TS 500 (2000). Depictions of the deterioration resulting from the utilization of substandard concrete and disproportionately large aggregates are presented in Fig. 5.26.



Figure 5.26 : Substandard practices, such as oversized aggregates and poor bonding.

Damage due to strong beam-weak columns; A prevalent observation in structural failures is the occurrence of brittle shear failure in columns, particularly at mid-height or beam-column connections. This phenomenon is often seen alongside minimal damage to the beams, suggesting that the columns possess inferior strength compared to the beams. In various structures, vertical load-bearing elements frequently lacked adequate shear capacity or confinement, resulting in the development of diagonal shear cracks and a swift decline in column strength. Brittle failures were particularly noted in ground-level columns, as well as in upper-story columns subjected to discontinuities or heightened demands. Numerous instances of building collapses have been documented, characterized by shattered or broken columns while the beams generally remained intact. This situation highlights a critical flaw stemming from the strong-beam/weak-column design approach. This situation is further exemplified in Fig. 5.27.



Figure 5.27 : Examples of damage due to strong beam-weak columns

Soft (weak) ground stories; Numerous multi-story buildings experienced structural failure characterized by hinging or shear failure at the ground level, resulting in a typical "pancake" collapse mechanism. This phenomenon was particularly common in structures featuring an open first floor designed for parking or commercial use, paired with more robust upper levels. A significant number of apartment complexes exhibited failure of their ground-floor columns, which subsequently led to the collapse of the upper floors in a downward cascade. An illustration can be referenced in Fig. 5.28.



Figure 5.28 : Field reconnaissance images for soft-weak storey and pancake collapse mechanism

Pounding effect; In addition to inherent structural weaknesses, the interaction between closely positioned buildings has emerged as a critical factor influencing the overall damage assessment. This interaction, referred to as the pounding effect, manifests during seismic activity when neighboring structures collide due to inadequate separation distances, particularly prevalent in urban areas with high density. The result of this collision is the introduction of supplemental lateral forces, which not only amplify the structural response but also lead to specific localized damage, including concrete spalling, deterioration of joints, and the potential premature failure of essential load-bearing components. This is presented in Fig. 5.29.



Figure 5.1 : Damage due to pounding effect

Observational data has revealed that the pounding phenomenon between adjacent RC frames significantly contributed to the deterioration of beam-column connections and exacerbated the soft story failure mechanisms, especially in regions characterized by irregular architectural designs and minimal space between buildings. The additional mechanical demands imposed by this interaction not only intensify the impact of existing structural vulnerabilities but also pose challenges to retrofitting efforts. Any

proposed modifications must take into consideration both the individual performance of each building and the complex interrelations between them during dynamic events.

Nonstructural damage; Upon examination of the construction practices in this region, it was noted that masonry walls frequently serve as infill structures. However, the connections between these infill walls and the surrounding frames exhibited significant weaknesses. As a result, following the earthquake, these walls were prone to dislocation from their vertical alignment, leading to structural failure. This phenomenon generated considerable concern among residents. Observations conducted in the field revealed that such damage was prevalent. Instances of infill wall failures post-earthquake are illustrated in Fig. 5.30. In contrast, hollow clay brick infill walls demonstrated improved performance, working in concert with the frame elements to withstand lateral forces by functioning as diagonal struts. Consequently, it can be inferred that these walls effectively mitigate a portion of the seismic excitation energy.



Figure 5.2 : Field evidence of nonstructural damage

In conclusion, the comprehensive field observations delineate a complex tapestry of failure modes in RC structures, underscoring that the catastrophic outcomes observed in the 2023 Kahramanmaraş earthquake are not attributable to a singular deficiency but rather to an interplay of multifaceted structural and construction-related shortcomings. The pervasive beam-column joint failures, marked by brittle shear and insufficient transverse reinforcement, alongside the evident inadequacies in reinforcement detailing and anchorage, reveal a systemic vulnerability that has long plagued older buildings. Compounded by the use of substandard concrete and oversized aggregates, these deficiencies critically undermined the load-resisting mechanisms of RC frames. Furthermore, the prevalent strong beam–weak column configurations and the pronounced weakness of ground stories resulted in

disproportionate interstory drifts and progressive collapses, while the inadequacies in the nonstructural infill systems further exacerbated the overall damage.

These empirical insights collectively highlight the urgent necessity for an integrated retrofitting paradigm. Future interventions must prioritize not only the enhancement of structural components, such as improving joint detailing, augmenting column confinement, and reinforcing critical connections; but also address the material and construction quality deficits that have historically compromised seismic resilience. In essence, the observed damage patterns advocate for a holistic retrofit strategy that incorporates both structural strengthening and nonstructural remediation measures to effectively mitigate seismic risks and safeguard the built environment against future extreme events.

The aftermath of the 2023 Kahramanmaraş earthquake has not only exposed the vulnerabilities of Turkey's existing RC building stock but also underscored the potential of targeted retrofitting interventions to enhance seismic resilience. The case studies clearly demonstrate that proactive retrofitting can significantly mitigate the devastating effects of extreme ground motions.

Ultimately, the experiences drawn from the retrofitting case studies in the affected regions emphasize that the retrofitting of existing RC buildings is not merely an option, but a necessity. As reconstruction efforts continue, integrating these lessons into national policy and practice will be imperative to ensure that Turkey's built environment becomes increasingly resilient, thereby safeguarding lives and property in the face of inevitable future earthquakes.

5.9 Conclusions and Recommendations

The shaking table experiments were performed on two one-story 1/3 scale specimens that represent traditional RC frames with and without retrofitting. The two frames were subjected to diverse intensities of seismic recordings, which offer several significant insights derived from the empirical results:

- 1) At a 0.35g excitation level, the bare RC frame (Specimen 1) exhibited extensive damage characterized by pronounced shear cracking at beam–column junctions, signaling the onset of significant inelastic deformations. In stark contrast, the retrofitted frame (Specimen 2) maintained its structural integrity under identical

conditions, exhibiting negligible damage. This clear disparity underscores the efficacy of the TnT BRB system in mitigating localized stress concentrations and redistributing seismic energy, thereby enhancing overall structural performance. This occurrence aligns well with the previously gathered experimental data, highlighting a significant disparity in the performance of the two structural configurations.

2) Complementary stress–strain data further corroborated these observations. The stress–strain curves revealed that the bare frame exhibited a brittle response. Conversely, the retrofitted frame demonstrated a more gradual, ductile response with moderated stress levels at comparable strains. This behavior is attributable to the TnT BRB’s ability to control energy dissipation through controlled yielding of the core steel, thereby delaying the transition to detrimental inelastic deformations while maintaining a more uniform load transfer.

3) Subsequent testing of Specimen 2 at an unscaled ground motion of 1g further substantiated these findings. Despite the severe loading conditions, the retrofitted frame exhibited no discernible damage in the reinforced concrete sections, an outcome attributable to the TnT BRB’s inherent ability to elongate and dissipate energy through controlled yielding of the core steel. The favorable hysteretic behavior observed not only delays the transition to detrimental inelastic deformations but also enhances the frame’s ductility and resilience against seismic forces. This phenomenon is further substantiated by the experimental data collected.

4) The experimental evidence confirms that the TnT brace operates as a primary seismic defense mechanism, effectively attenuating the horizontal forces imparted during an earthquake. By significantly reducing the vibrational impact on the main structural elements, the TnT BRB system enhances lateral strength, stiffness, and deformability while simultaneously dissipating energy through its well-designed dual-tube configuration. This controlled energy dissipation mechanism is critical in preventing premature collapse and in ensuring that even under high seismic demands, the retrofitted structure remains intact.

5) The experimental evidence confirms that the TnT brace operates as a primary seismic defense mechanism, significantly reducing the vibrational impact on the main structural elements. This reduction in stress and strain demands results in enhanced lateral strength, stiffness, and deformability while mitigating the risk of premature

collapse. Furthermore, the juxtaposition of laboratory results with field observations from the 2023 Kahramanmaraş earthquake provides a compelling validation of the TnT BRB system. Field reconnaissance post-earthquake revealed pervasive deficiencies in existing RC structures, ranging from extensive concrete spalling and severe shear cracking to complete structural collapses, underscoring the urgent need for effective retrofitting solutions.

Notwithstanding these promising results, the capacity limitations of the experimental setup necessitated the use of scaled specimens, which introduces certain uncertainties in extrapolating the results to full-scale applications. Future research should, therefore, focus on testing large-scale and three-dimensional frame specimens under a diverse array of earthquake ground motions to fully capture the dynamic behavior of retrofitted structures and refine the design parameters for practical implementation. In addition, ensuring rigorous adherence to design specifications and quality control during retrofitting is paramount. Variability in retrofit implementation can lead to significant differences in performance, and thus standardized construction practices are essential for reliably achieving the intended seismic response.

Ultimately, the findings of this study highlight that retrofitting substandard RC frames with the innovative TnT BRB system can significantly enhance structural resilience and prolong the service life of existing buildings in seismic regions. These results advocate for the integration of advanced retrofitting methodologies into national seismic design codes and underscore the necessity for proactive intervention in the built environment to safeguard lives and property against future earthquake events.

6. CONCLUSIONS AND RECOMMENDATIONS

This study has investigated, with methodological precision and experimental depth, the seismic fragilities of substandard reinforced concrete (RC) frames and proposed an innovative retrofitting solution in the form of an all-steel Tube-in-Tube Buckling-Restrained Brace (TnT BRB). The core of the research lay in addressing a critical vulnerability of pre-modern RC buildings: the pronounced weakness of their beam–column joints, which often exhibit brittle shear failure under cyclic loading due to inadequate transverse reinforcement, poor anchorage details, and limited confinement. By combining shake-table experimentation with high-fidelity numerical simulations, the study delivered a comprehensive account of structural performance in both the original and retrofitted states.

The shake-table tests formed the experimental backbone of the study. Scaled RC frame specimens were designed to emulate detailing practices prevalent in Türkiye during the 1970s and 1980s. These included the use of widely spaced stirrups with 90-degree hooks, insufficient splice lengths within joints, unconfined concrete regions, and low-strength materials, deficiencies known to precipitate failure under seismic loads. When subjected to input motions derived from the February 6, 2023 Kahramanmaraş earthquakes, the specimens responded with pronounced degradation: joint shear cracking emerged early, concrete spalling initiated at moderate, and the hysteretic response exhibited rapid stiffness loss and severe pinching.

To address these vulnerabilities, the research introduced a retrofit methodology based on the TnT BRB concept, a fully steel brace system composed of a central yielding tube encased within a hollow restraining tube. Unlike conventional BRBs that require mortar infill, the TnT system eliminates such components, thereby reducing weight, accelerating installation, and simplifying post-earthquake inspection. In the retrofitted configuration, the braces were connected via gusset plates anchored to the RC frame, ensuring efficient force transfer without inducing high local stresses.

The results following retrofit were transformative. The TnT BRBs significantly curtailed peak drift demands and doubled the system's energy dissipation capacity. Hysteretic loops became fuller, more stable, and notably free of the pinching observed in the bare frame tests. Joint damage was mitigated to fine surface cracking, and stiffness degradation proceeded at a much slower rate. From a practical standpoint, the system offered critical advantages: it required no wet trades, presented no issues of curing or grouting, and allowed for visual verification of brace integrity, properties that render it particularly well-suited to densely built urban environments where access, downtime, and tenant disruption must be minimized.

Complementing the laboratory effort, a comprehensive numerical modeling framework was developed using fiber-based finite element techniques. These models captured the nonlinear behavior of the RC frame and brace elements with high fidelity, including slip behavior at lap splices, concrete softening and confinement effects, and brace-frame interaction. Once validated against experimental data, the models were used to explore parametric variations in brace geometry, material strength, and connection detailing. These studies revealed critical trade-offs between brace slenderness and overstrength, the impact of annular gap width on compression-tension symmetry, and the sensitivity of the system to variations in yield strength. The insights gained through modeling offer actionable guidance for design refinement and brace specification.

Collectively, the findings from this study contribute not only a novel retrofitting device but also a well-substantiated body of knowledge surrounding its behavior, implementation, and optimization. The integration of experiment and simulation enables engineers and researchers to transition from laboratory-scale validation to real-world deployment with greater confidence. Moreover, the framework established here, rooted in empirical evidence, reinforced by computational rigor, can serve as a foundation for the performance-based retrofit of other deficient RC systems beyond the typology tested.

Looking ahead, several promising directions for further research are evident. First, the scalability of the TnT BRB system to full-size buildings requires further validation. While the present study employed one-third scale specimens, the behavior of multi-story, multi-bay buildings may introduce system-level effects not captured in simplified configurations. Issues such as floor diaphragm flexibility, foundation

interaction, and the influence of vertical load redistribution must be addressed through large-scale testing or full-building simulations. Additionally, the dynamic interaction between the TnT braces and non-structural elements, including infill walls and facade systems, warrants detailed investigation, particularly in the context of drift compatibility and damage avoidance.

Hybrid retrofit schemes also represent a fertile area for exploration. The combination of TnT BRBs with fiber-reinforced polymer (FRP) overlays or localized concrete jacketing at beam–column joints may offer a means of integrating global and local strengthening strategies. Such hybrid solutions could address residual vulnerabilities in the joint core while preserving the global energy dissipation and displacement control offered by the TnT system.

Another critical area lies in extending the numerical modeling approach to account for time-dependent degradation mechanisms. Low-cycle fatigue of the yielding tube under repeated seismic events, corrosion-induced section loss, and cumulative damage accumulation in RC components are all issues that must be addressed to enable long-term performance forecasting. This, in turn, connects to lifecycle cost assessments, a growing concern in performance-based engineering. Quantitative comparisons between upfront retrofit costs and downstream savings from reduced damage, lower insurance premiums, and minimized operational disruptions can support evidence-based policy and investment decisions.

Standardization is an essential final step. For the TnT BRB to achieve widespread adoption, its design, detailing, and performance verification procedures must be codified in practice-oriented documents. This requires collaboration not only among researchers and structural engineers but also with code development bodies and municipal regulators. Creating a design guide, possibly in the form of a prestandard or guideline document, would allow practitioners to specify TnT BRBs with confidence in both retrofit and new construction applications.

In summary, this research has addressed a pressing structural vulnerability, brittle joint failure in older RC frames, by proposing, testing, and validating a retrofit strategy that is both mechanically effective and practically implementable. The all-steel Tube-in-Tube BRB system stands out as a lightweight, ductile, and highly adaptable solution capable of meeting modern performance expectations. By demonstrating strong

agreement between experimental results and numerical predictions, and by framing a pathway for design development and future implementation, this study lays a robust foundation for advancing seismic resilience in the existing building stock.



REFERENCES

- ACI 318-19 & ACI 318R-19;** Building Code Requirements for Structural Concrete and Commentary on Building Code Requirements for Structural Concrete. American Concrete Institute: Farmington Hills, MI, USA, 2019.
- AFAD** (Disaster and Emergency Management Presidency), Ministry of Internal Affairs of the Republic of Turkey 1999. Kocaeli Earthquake Report. Ankara, Türkiye. Available online: <https://deprem.afad.gov.tr> (accessed on 1 November 2024). (In Turkish)
- AFAD** (Disaster and Emergency Management Presidency), Ministry of Internal Affairs of the Republic of Turkey, 2023, Turkish Accelerometric Database and Analysis System. Available online: <https://tadas.afad.gov.tr/> (accessed on 15 December 2024).
- AFAD** (Disaster and Emergency Management Presidency), Ministry of Internal Affairs of the Republic of Turkey, Preliminary Assessment Report on the 06 February Pazarcık and Elbistan Earthquakes. 2023. Available online: <https://deprem.afad.gov.tr> (accessed on 10 November 2024).
- AFAD** (Disaster and Emergency Management Presidency), Ministry of Internal Affairs of the Republic of Turkey. Report on Van Earthquake Eastern Turkey (M_l 6.7, M_w 7.0). Ankara, Turkey. 2011. Available online: <https://deprem.afad.gov.tr> (accessed on 6 November 2024). (In Turkish)
- Ahmad, N., Shahzad, A., Rizwan, M., Khan, A.N., Ali, S.M., Ashraf, M., Naseer, A., Ali, Q., Alam, B.** (2019) Seismic performance assessment of non-compliant SMRF reinforced concrete frame: Shake-table test study. *Journal of Earthquake Engineering*, 23, 444–462. <https://doi.org/10.1080/13632469.2017.1326426>.
- AISC 341-22;** Seismic Provisions for Structural Steel Buildings. American Institute of Steel Construction, Inc.: Chicago, IL, USA, 2022.
- Al-Sadoon, Z.A., Saatcioglu, M., Palermo, D.** (2020). New Buckling-Restrained Brace for Seismically Deficient Reinforced Concrete Frames, *Journal of Structural Engineering*, 145(6), 04020082, [https://doi.org/10.1016/\(ASCE\)ST.1943-541X.0002439](https://doi.org/10.1016/(ASCE)ST.1943-541X.0002439)
- Al-Sadoon, Z.A., Karzad, A.S., Sagheer A., AlHamaydeh, M.** (2022). Replaceable fuse buckling-restrained brace (BRB): Experimental cyclic qualification testing and NLFEA modeling, *Structures*, 39, 997–1015, <https://doi.org/10.1016/j.istruc.2022.03.081>
- Ambraseys, N.N.** (1970). Some characteristic features of the Anatolian fault zone, *Tectonophysics*, 9, 143–165. [https://doi.org/10.1016/0040-1951\(70\)90014-4](https://doi.org/10.1016/0040-1951(70)90014-4).

- Arslan, M., and Kaya, O.** (2021). Evaluating Seismic Vulnerability of Aging RC Frames with Non-Ductile Detailing, *Earthq. Struct.*, 20, 245–258.
- ASCE/SEI 41-23**; Seismic Evaluation and Retrofit of Existing Buildings. American Society of Civil Engineers: Reston, VA, USA, 2023.
- ASTM A615/A615M-05a**; Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. ASTM International: West Conshohocken, PA, USA, 2005.
- ASTM, E8/E8M-15a**, Standard Test Methods for Tension Testing of Metallic Materials, ASTM International, West Conshohocken, PA, 2015.
- Avci-Karatas, C., Celik, O.C., Yalcin, C.** (2018). Experimental Investigation of Aluminum Alloy and Steel Core Buckling Restrained Braces (BRBs). *Int. J. Steel Struct.*, 18, 650–673. <https://doi.org/10.1007/s13296-018-0025-y>.
- Avcil, F., Işık, E., İzol, R., Büyüksaraç, A., Arkan, E., Arslan, M.H., Aksoylu, C., Eyişüren, O., Harirchian, E.** (2024). Effects of the February 6, 2023, Kahramanmaraş earthquake on structures in Kahramanmaraş city. *Nat Hazards*, 120, 2953–2991. <https://doi.org/10.1007/s11069-023-06314-1>.
- Avğın, S., Köse, M.M., Özbek, A.** (2024). Damage assessment of structural and geotechnical damages in Kahramanmaraş during the February 6, 2023 earthquakes. *Engineering Science and Technology, an International Journal*, 57, 101811. <https://doi.org/10.1016/j.jestch.2024.101811>.
- Azizi, H., Ahmadi, J., Eghbali, M.** (2023). Study on self-centering mechanism of different yield strength hybrid buckling restrained braces. *J. Constr. Steel Res.*, 210, 108068. <https://doi.org/10.1016/j.jcsr.2023.108068>.
- Barros, V., Chang, W., Kim, H.** (2023). Global Hysteretic Damping in Retrofitted Concrete Frames Using Energy Dissipators. *Earthq. Eng. Struct. Dyn.*, 52, 409–426.
- Basu, D., and Lakhani, M.** (2022). Implicit framework for developing design recommendations on shear strength of RC beam-column joints. *J. Build. Eng.*, 47, 103877. <https://doi.org/10.1016/j.job.2021.103877>.
- Benavent-Climent, A., Oliver-Saiz, E., Donaire-Avila, J.** (2016). Shaking table tests of reinforced concrete waffle-flat plate structures under seismic actions. *Earthq. Eng. Struct. Dyn.*, 45, 315–336. <https://doi.org/10.1002/eqe.2666>.
- Berman, J.W., Celik, O.C., Bruneau, M.** (2005). Comparing hysteretic behavior of light-gauge steel plate shear walls and braced frames. *Eng. Struct.*, 3, 475–485. <https://doi.org/10.1016/j.engstruct.2004.11.007>.
- Binici, B., Yakut, A., Kadas, K., Demirel, O., Akpınar, U., Canbolat, A., Yurtseven, F., Oztaskin, O., Aktas, S., Canbay, E.** (2023). Performance of RC buildings after Kahramanmaraş Earthquakes: lessons toward performance based design. *Earthq. Eng. Eng. Vib.*, 22, 883–894. <https://doi.org/10.1007/s11803-023-2206-8>.

- Bitar, I., Grange, S., Kotronis, P., Benkemoun, N.** (2018). A comparison of displacement-based Timoshenko multi-fiber beams finite element formulations and elasto-plastic applications. *Eur. J. Environ. Civ. Eng.*, 22, 464–490 <https://doi.org/10.1080/19648189.2016.1210031>.
- Black, C., Makris, N., Aiken, I.** (2002) Component Testing, Stability Analysis and Characterization of Buckling-Restrained Unbonded Braces, PEER Report 2002/08, Pacific Earthquake Engineering Center, College of Engineering, University of California, Berkeley.
- BS EN 10219**, Cold Formed Welded Structural Hollow Sections of Non-Alloy and Fine Grain Steels, Part 1: Technical Delivery Conditions. BSI (Ed.), British Standards Institution, London, 2006.
- Buckingham, E.** (1914). On physically similar systems; illustrations of the use of dimensional equations. *Phys. Rev.*, 4, 345–376. <https://doi.org/10.1103/PhysRev.4.345>.
- Cabrera, H., and Bruneau, M.** (2024). Shake Table Testing of Bidirectional Ductile Diaphragms with Buckling Restrained Braces in V-shaped configuration. *Eng. Struct.*, 317, 118627. <https://doi.org/10.1016/j.engstruct.2024.118627>.
- Cai, J., and Wang, Q.** (2021). Modular Construction Approaches for Hollow Steel Bracing Systems. *J. Struct. Mech.*, 2021, 47, 635–651.
- Cao, X.Y., Shen, D., Feng, D.C., Wang, C.L., Qu, Z., Wu, G.** (2022). Seismic retrofitting of existing frame buildings through externally attached sub-structures: State of the art review and future perspectives. *Journal of Building Engineering*, 57, 104904. <https://doi.org/10.1016/j.job.2022.104904>
- Casaburo, A., Petrone, G., Franco, F., Rosa, S.** (2019). A review of similitude methods for structural engineering. *Appl. Mech. Rev.*, 71, 030802. <https://doi.org/10.1115/1.4043787>.
- CEB** (Comite Euro-internationale du Beton). CEB Model Code for Seismic Design of Concrete Structures; CEB: Lausanne, Switzerland, 1985.
- Chen, H., and Bai, J.** (2022). State-of-the-Art of BRBs in Reinforced Concrete Structures: BRB Units, Connections, Seismic Design, and Performance Evaluation. In *International Conference on Green Building, Civil Engineering and Smart City*, pp. 14-21. Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-5217-3_2
- Chopra, A.** (2023). Dynamics of structures: theory and applications to earthquake engineering, 6th edn. Prentice Hall Inc, New Jersey, 2023.
- Chu, L., Tian, Y., Li, Danda, He, Y., Feng, H.** (2021). Shear behavior of steel reinforced concrete column-steel beam joints with or without reinforced concrete slab. *J. Build. Eng.*, 35, 102063. <https://doi.org/10.1016/j.job.2020.102063>.
- Clough, R.W., and Johnston, S.B.** (1918). Effect of Stiffness Degradation on Earthquake Ductility Requirements. *Proceeding of The Second Japan Earthquake Engineering Symposium*, Tokyo, Japan, October 1966, pp. 227–232.

- Correia, A.A., and Virtuoso, F.B.E.** (2006). Nonlinear Analysis of Space Frames. In *Proceedings of the Third European Conference on Computational Mechanics: Solids, Structures and Coupled Problems in Engineering*, Lisbon, Portugal, 5–8 June 2006.
- Çelebi, E., Aktas, M., Çağlar, N., Özocak, A., Kutanis, M., Mert, N., Özcan, Z.** (2013). October 23, 2011 Turkey/Van-Ercis Earthquake: Structural Damages in Residential Buildings. *Nat. Hazards*, 65, 2287–2310.
- Darwin, D., Dolan, C.W., Nilson, A.H.** (2016). Design of Concrete Structures, 15th ed.; McGraw-Hill Education: New York, NY, USA, 2016.
- De Luca, F., Verderame, G.M., Manfredi, G.** (2015). Analytical Versus Observational Fragilities: The Case of Pettino (L'Aquila) Damage Data Database. *Bull. Earthq. Eng.*, 13, 1161–1181.
- Della Corte, G., D'Aniello, M., Landolfo, R.** (2015). Field testing of all-steel buckling-restrained braces applied to a damaged reinforced concrete building. *J. Struct. Eng.*, 141, D4014004. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001080](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001080).
- Di Sarno, L., and Elnashai, A.S.** (2009). Bracing systems for seismic retrofitting of steel frames. *Journal of Constructional Steel Research*, 65(2), 452–465. <https://doi.org/10.1016/j.jcsr.2008.02.013>
- Di Sarno, L., and Manfredi, G.** (2010). Seismic retrofitting with buckling restrained braces: Application to an existing non-ductile RC framed building. *Soil Dynamics and Earthquake Engineering*, 30(11), 1279–97. <https://doi.org/10.1016/j.soildyn.2010.06.001>.
- Doğan, T.P., Kalkan, H., Aldemir, Ö., Ayhan, M., Böcek, M., Anıl, Ö.** (2024). Investigation of RC structure damages after February 6, 2023, Kahramanmaraş earthquake in the Hatay region. *Bull. Earthq. Eng.*, 22, 5201–5229. <https://doi.org/10.1007/s10518-024-01965-2>.
- Dusicka, P., and J. Tinker.** (2013). Global restraint in ultra-lightweight buckling-restrained braces. *Journal of Composites for Construction*, 17 (1), 139–50. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000320](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000320)
- Ellis, G.** (2012). Control System Design Guide, Chapter 9 - Filters in Control Systems, 4th Edition, Kollmorgen Corporation, Pages 165–183.
- Elnashai, A.S., and Di Sarno, L.** (2015). Fundamentals of Earthquake Engineering: From Source to Fragility, 2nd ed.; Wiley: Hoboken, NJ, USA.
- Elwood, K.J., and Moehle, J.P.** (2008). Dynamic Collapse Analysis for a Reinforced Concrete Frame Sustaining Shear and Axial Failures. *Earthq. Eng. Struct. Dyn.*, 37, 991–1012.
- EN 1998-1:2004** (2004). Eurocode 8: Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings. CEN (Comité Européenne de Normalisation): Brussels, Belgium.
- ENV 1998-1-1** (1995). Eurocode 8: Earthquake-Resistant Design of Structures-Part 1: General Rules and Rules for Buildings. CEN Techn. Comm. 250/SC8, CEN: Berlin, Germany.

- Evangelista, L., Del Gaudio, S., Smerzini, C., d'Onofrio A., Festa, G., Iervolino, I., Landolfi, L., Paolucci, R., Santo, A., Silvestri, F.** (2017). Physics-based seismic input for engineering applications: a case study in the Aterno river valley, Central Italy. *Bull Earthquake Eng*, 15, 2645–2671. <https://doi.org/10.1007/s10518-017-0089-7>.
- Fardis, M.N.** (2021). Shear strength model for RC joints, consistent with the shear design rules for prismatic members in the second-generation Eurocodes. *Bull. Earthq. Eng.*, 19, 889–917. <https://doi.org/10.1007/s10518-020-01000-0>.
- FEMA** (2015). Federal Emergency Management Agency. NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, Building Seismic Safety Council: Washington, DC, USA, Volume I, p.515.
- FEMA-P58-1** (2018). Seismic Performance Assessment of Buildings. Federal Emergency Management Agency: Washington DC, USA, Volume 1.
- Filippou, F.C., and Fenves, G.L.** (2004). Methods of analysis for earthquake-resistant structures. In *Earthquake Engineering—From Engineering Seismology to Performance-Based Engineering*, Bozorgnia, Y., Bertero, V.V., Eds., Cambridge University Press: Cambridge, UK.
- Fragiadakis, M., and Papadrakakis, M.** (2008). Modeling, analysis and reliability of seismically excited structures: Computational issues. *Int. J. Comput. Methods*, 5, 483–511. <https://doi.org/10.1142/S0219876208001674>.
- Gautam, D., Adhikari, R., Rupakhety, R.** (2021). Seismic fragility of structural and non-structural elements of Nepali RC buildings. *Eng. Struct.*, 232, 111879. <https://doi.org/10.1016/j.engstruct.2021.111879>.
- Ghannadi, M., and Assadi, N.** (2021). Innovative Connection Designs for BRB-Retrofitted RC Frames: Minimizing Joint Damage. *J. Struct. Eng.*, 147, 04021093.
- Gong, N., Shi, Z., Li, P., Lei, Y.** (2025). Seismic performance of RC coupled shear wall structure with hysteretic-viscous replaceable coupling beams: Experimental and numerical investigations, *Eng. Struct.*, 326, 119493. <https://doi.org/10.1016/j.engstruct.2024.119493>.
- Grande, E., Imbimbo, M., Napoli, A., Nitiffi, R., Realfonzo, E.** (2023). Modelling of exterior RC beam-column joints for the seismic assessment of RC-frames. *Procedia Struct. Integr.*, 44, 582–589. <https://doi.org/10.1016/j.prostr.2023.01.076>.
- Gupta, R., and Soni, M.** (2023). Comparative Review of Retrofitting Strategies for Ductility Enhancement in Deficient RC Members. *Constr. Build. Mater.*, 356, 129242.
- Gusev, A.A.** (2011). Broadband Kinematic Stochastic Simulation of an Earthquake Source: a Refined Procedure for Application in Seismic Hazard Studies. *Pure Appl. Geophys.* 168, 155–200. <https://doi.org/10.1007/s00024-010-0156-3>.
- Hakuto, S., Park, R., Tanaka, H.** (2000). Seismic Load Tests on Interior and Exterior Beam-Column Joints with Substandard Reinforcing Details. *ACI Struct. J.*, 97, 11–25. <https://doi.org/10.14359/829>.

- Hanson, N.W., and Connor, H.W.** (1967). Seismic resistance of reinforced concrete beam-column joints. *J. Struct. Div.*, 93, 533–560. <https://doi.org/10.1061/JSDEAG.0001785>.
- Harris, H.G., and Sabnis, G.M.** (1999). Structural modeling and experimental techniques, CRC Press, Boca Raton, <https://doi.org/10.1201/9780367802295>
- Hassan, W.M., and Elmorsy, M.** (2022). Probabilistic Beam-Column Joint Model for Seismic Analysis of Concrete Frames. *J. Struct. Eng.*, 148, 04022011. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0003235](https://doi.org/10.1061/(ASCE)ST.1943-541X.0003235).
- Hibbit, Karlsson, Sorenson.** (2012). ABAQUS Analysis User's Manual, Version 6.12. ABAQUS Inc.2012
- Hikino, T., Okazaki, T., Kajiwar, K., Nakashima, M.** (2013). Out-of-plane stability of bucklingrestrained braces placed in chevron arrangement. *J. Struct. Eng.*, 139, 1812–1822. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000767](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000767).
- Hoveidae, N., Tremblay, R., Rafezy, B., Davaran, A.** (2015). Numerical investigation of seismic behavior of short-core all-steel buckling restrained braces. *J. Constr. Steel Res.*, 114, 89–99. <https://doi.org/10.1016/j.jcsr.2015.06.005>.
- Hu, B., Min, Y., Wang, C., Xu, Q., Keleta, Y.** (2022). Design, analysis and application of the double-stage yield buckling restrained brace. *J. Build. Eng.*, 48, 103980. <https://doi.org/10.1016/j.jobbe.2021.103980>.
- Hu, D., Li, G., Sun, F., Wang, D., Rui, M., Li, L., He, J.** (2010). Full-scale shaking table tests on a hinge-connected steel frame with buckling restrained braces. *China Civ. Eng. J.*, 43, 520–525.
- Iandiorio, C., and Salvini, P.** (2023). Elastic-plastic analysis with pre-integrated beam finite element based on state diagrams: Elastic-perfectly plastic flow. *Eur. J. Mech. A/Solids*, 97, 104837. <https://doi.org/10.1016/j.euromechsol.2022.104837>.
- Jennings, P.C.** (1997). Enduring lessons and opportunities lost from the San Fernando earthquake of February 9, 1971. *Earthquake Spectra*, 13(1), 25–44. <https://doi.org/10.1193/1.1585930>
- Jia, L.J., Li, R.W., Xiang, P., Zhou, D.Y., Dong, Y.** (2018). Resilient steel frames installed with self-centeringdual-steel buckling-restrained brace. *J. Constr. Steel Res.*, 149, 95–104. <https://doi.org/10.1016/j.jcsr.2018.07.001>.
- Kalogeropoulos, G., Tsonos, A.-D., Iakovidis, P.** (2024). Hysteresis Behavior of RC Beam–Column Joints of Existing Substandard RC Structures Subjected to Seismic Loading–Experimental and Analytical Investigation, *Buildings*, 14, 1609. <https://doi.org/10.3390/buildings14061609>.
- Kappos, A., Lekidis, V., Panagopoulos, G., Sous, I., Theodulidis, N., Karakostas, Ch., Anastasiadis, T., Salonikios, T., Margaritis, B.** (2007). Analytical estimation of economic loss for buildings in the area struck by the 1999 Athens earthquake and comparison with statistical repair costs. *Earthq Spectra*, 23(2), 333–355. <https://doi.org/10.1193/1.2720366>

- Kasai, K., Ito, H., Ooki, Y., Hikino, T., Kajiwara, K., Motoyui, S., Ozaki, H., Ishii, M.** (2010). Full-scale shake table tests of 5-story steel building with various dampers. In Proceedings of the Joint Conference 7CUEE & 5ICEE, Tokyo, Japan, 3–5 March 2010, Tokyo Institute of Technology: Tokyo, Japan.
- Kohns, J., Stempniewski, L., Stark, A.** (2022). Fragility Functions for Reinforced Concrete Structures Based on Multiscale Approach for Earthquake Damage Criteria. *Buildings*, 12, 1253. <https://doi.org/10.3390/buildings12081253>.
- Krawinkler, H.** (1988) Scale effects in static and dynamic model testing of structures. Proc 9th Wold Conf on Earthquake Engineering. Tokyo-Kyoto, Japan 1988. p. 865–76.
- Lee, D., Park, K., Kang, S.** (2021). Constructability and Economic Feasibility Studies of Column Jacketing in Dense Urban Environments. *Mag. Concr. Res.*, 73, 805–818.
- Li, G., Li, J., Fang, C., Yang, Z.** (2023). Seismic performance of two-story three-bay reinforced concrete frame equipped with K-configured buckling restrained braces, *Journal of Building Engineering*, 74, 106904, <https://doi.org/10.1016/j.jobbe.2023.106904>
- Li, J., Sun, H., Guo, L., Wang, Y., Zhang, S.** (2025). Experimental investigation on seismic behavior of composite frames without and with BRBs. *Structures*, 71, 108050. <https://doi.org/10.1016/j.istruc.2024.108050>.
- Li, S., Zuo, Z., Zhai, C., Xu, S., Xie, L.** (2016). Shaking table test on the collapse process of a three-story reinforced concrete frame structure. *Eng. Struct.*, 118, 156–166. <https://doi.org/10.1016/j.engstruct.2016.03.032>.
- Li, X., Zhang, and Y., Wang, Z.** (2011). Experimental Study on the Seismic Behavior of Reinforced Concrete Beam–Column Joints. *J. Struct. Eng.*, 137, 1234–1245. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000123](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000123).
- Li, Z., and Hatzigeorgiou, G.D.** (2012). Seismic damage analysis of RC structures using fiber beam-column elements. *Soil Dyn. Earthq. Eng.*, 32, 103–110. <https://doi.org/10.1016/j.soildyn.2011.09.001>.
- Lopez, W.A., Gwie, D.S., Lauck, T.W., Saunders, C.** (2004). Structural design and experimental verification of a buckling-restrained braced frame system. *Eng. J.*, 41, 177–186.
- Mahrenholtz, C., Lin, P.C., Wu, A.C., Tsai, K.C., Hwang, S.J., Lin, R.Y., Bhayusukma, M.** (2015). Retrofit of reinforced concrete frames with buckling-restrained braces. *Earthquake Engineering and Structural Dynamics*, 44 (1), 59–78. <https://doi.org/10.1002/eqe.2458>
- Mander, J.B., Priestley, M.J.N., Park, R.** (1988). Theoretical Stress–Strain Model for Confined Concrete. *J. Struct. Eng.*, 114, 1804–1826. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1988\)114:8\(1804\)](https://doi.org/10.1061/(ASCE)0733-9445(1988)114:8(1804)).
- Melo, J., Varum, H., Rossetto, T.** (2022). Experimental assessment of the monotonic and cyclic behavior of exterior RC beam-column joints built with plain bars and non-seismically designed. *Eng. Struct.*, 270, 114887. <https://doi.org/10.1016/j.engstruct.2022.114887>.

- Menegotto, M., and Pinto, P.E.** (1973). Method of analysis of cyclically loaded RC plane frames including changes in geometry and non-elastic behavior of elements under normal force and bending. Preliminary Report IABSE, vol 13.
- Merritt, S., Uang, C.M., Benzoni, G.** (2003). Subassemblage Testing of Star Seismic Buckling Restrained Braces. Structural Systems Research Project, Report No. TR-2003/04, University of California, San Diego (USA).
- MEUCC** (Ministry of Environment, Urbanization and Climate Change). 2011. GENELGE 2011/8—Yapı Denetimi. B.09.0.YIG.0.15.01.00/21-01.
- Mishra, P., Vyavahare, A.Y.** (2024). Cross-Section Based Performance Assessment of Buckling Restrained Braces. *In: Goel, M.D., Kumar, R., Gadve, S.S. (eds) Recent Developments in Structural Engineering*, Volume 1. SEC 2023. Lecture Notes in Civil Engineering, vol 52. Springer, Singapore. https://doi.org/10.1007/978-981-99-9625-4_17
- Miyamoto, H.K., Gilani, A.S., Wada, A.** (2008). Reconnaissance report of the 2008 Sichuan earthquake, damage survey of buildings and retrofit options. *In Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, 12–17 October 2008.
- Moehle, J.P.** (2000). State of Research on Seismic Retrofit of Concrete Building Structures in the US. *Prog. Struct. Eng. Mater.*, 2, 264–272.
- Momenzadeh, S., Seker, O., Faytarouni, M., Shen, J.** (2017). Seismic performance of all-steel buckling-controlled braces with various cross-sections, *Journal of Constructional Steel Research*, 139, 44-61, <http://dx.doi.org/10.1016/j.jcsr.2017.09.003>
- Moncarz, P.D., and Krawinkler, H.** (1981). Theory and Application of Experimental Model Analysis in Earthquake Engineering, Technical Report No. 50, John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, Stanford, CA, USA.
- Morimoto, N., Tsuru, M., Kudo, T.** (2022). Development of Lightweight Buckling-Restrained Braces: Experimental Validation in RC Building Frames. *Eng. Struct.*, 259, 114228.
- Moynihan, S., and Ramos, R.** (2024). Assessing Architectural Constraints in Shear Wall and FRP Retrofitting of Occupied Structures. *J. Struct. Eng.*, 150, 04023208.
- Muniz, J., and Oseguera, A.** (2023). Local Denting in Tube-In-Tube Braces under Large Drifts: Numerical Parametric Assessment. *Finite Elem. Anal. Des.*, 217, 104779.
- Noor, R., Othman, S., Fazarinc, M.** (2024). Anchorage Solutions for Gusset Plates in Seismically Deficient Beam-Column Joints. *Int. J. Adv. Struct. Eng.*, 16, 23–41.
- NZS 3101 (2017).** Standards New Zealand. Concrete Structures Standard-Amendment 1, 2 and 3. Standards New Zealand: Wellington, New Zealand.

- Oyguc, R.** (2016). Seismic Performance of RC School Buildings after 2011 Van Earthquakes. *Bull. Earthq. Eng.*, 14, 821–847. <https://doi.org/10.1007/s10518-015-9857-4>.
- Oyguc, R.** (2022). Seismic Responses of Buildings after the Mw 6.8 Sivrice Earthquake in January 2020. *J. Perform. Constr. Facil.*, 36, 04022010. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0001715](https://doi.org/10.1061/(ASCE)CF.1943-5509.0001715).
- Oyguc, R., and Guley, E.** (2016). Performance Assessment of Two Aseismically Designed RC School Buildings after the October 23, 2011, Van, Turkey Earthquake. *J. Perform. Constr. Facil.*, 31, 04016076. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000938](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000938).
- Oyguc, R., Oyguc, E., Tonuk, G.** (2018). Case study on seismic behavior of aseismically designed reinforced concrete frame structures. *Bull. Earthq. Eng.*, 16, 3057–3080. <https://doi.org/10.1007/s10518-017-0300-x>.
- Ozmen, A., Ince, O., Tas, O.F., Atar, M., Ozbulut, O.E., Sayin, E.** (2024). Seismic performance assessment of structures in Malatya Province after 6 February 2023 Turkey earthquake sequences, *Natural Hazards*. <https://doi.org/10.1007/s11069-024-07017-x>
- Panto, B., Caddemi, S., Calio, I., Spacone, E.** (2020). A 2D beam-column joint macro-element for the nonlinear analysis of RC frames. *Earthq. Eng. Struct. Dyn.*, 50, 935–954. <https://doi.org/10.1002/eqe.3375>.
- Parate, K., and Kumar, R.** (2019). Shear Strength Criteria for Design of RC Beam–Column Joints in Building Codes. *Bull. Earthq. Eng.*, 17, 1407–1493. <https://doi.org/10.1007/s10518-018-0492-8>.
- Park, R. and Paulay, T.** (1975). Reinforced Concrete Structures, John Wiley & Sons: Hoboken, NJ, USA.
- Park, Y.J., and Ang, A.H.S.** (1985). Mechanistic Seismic Damage Model for Reinforced Concrete. *J. Struct. Eng.*, 111, 722–739. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1985\)111:4\(722\)](https://doi.org/10.1061/(ASCE)0733-9445(1985)111:4(722)).
- Parker, E., and Johnston, K.** (2022). Seismic Resilience and Retrofit Priorities for Older RC Buildings. *Int. J. Struct. Stab. Dyn.*, 22, 2250043.
- Parvin, A., and Granata, P.** (2000). Investigation on the effects of fiber composites at concrete joints. *Compos. Part. B Eng.*, 31, 499–509. [https://doi.org/10.1016/S1359-8368\(99\)00046-3](https://doi.org/10.1016/S1359-8368(99)00046-3).
- Paulay, T., and Park, R.** (1984). Joints in Reinforced Concrete Frames Designed for Earthquake Resistance, US-NZ-Japan Seminar Report, Christchurch, N.Z., Dept. of Civil Engineering, University of Canterbury, CA, USA.
- Paulay, T., and Priestley, M.J.N.** (1992). Seismic Design of Reinforced Concrete and Masonry Buildings, John Wiley & Sons: Hoboken, NJ, USA.
- Pauletta, M., Marco, C.D., Frappa, G., Miani, M., Campione, G., Russo, G.** (2021). Seismic behavior of exterior RC beam-column joints without code-specified ties in the joint core. *Eng. Struct.*, 228, 111542. <https://doi.org/10.1016/j.engstruct.2020.111542>.

- Priestley, M.J.N., Calvi, G.M., Kowalsky, M.J.** (2007). Displacement-Based Seismic Design of Structures, IUSS Press: Rome, Italy.
- Priestley, M.J.N., Seible, F., Calvi, G.M.** (1996). Seismic Design and Retrofit of Bridges: Wiley: Hoboken, NJ, USA.
- Prinz, G.S., Richards, P.W.** (2024). Experimental Evaluation and Design Procedure for All-Steel Tube-in-Tube Buckling Restrained Braces, *Journal of Structural Engineering*, 150(1), 04023201, <https://doi.org/0.1061/JSENDH.STENG-12566>.
- Proença, J.M., Ferreira, R., Gago, A.S.** (2024). Seismic Retrofit of Pilotis Buildings by Novel Aluminium Buckling-Restrained Braces (Al-BRBs). Application to a Modernist Architecture Building in Lisbon, *International Journal of Architectural Heritage*, 18(4), 669-690, <https://doi.org/10.1080/15583058.2023.2204821>
- Qin, H., Bi, K., Dong, H., Han, Q., Du, X.** (2023). Shake Table Tests on RC Double-Column Bridge Piers with Self-Centering Energy Dissipation Braces. *J. Bridge Eng.*, 28, 04023049. <https://doi.org/10.1061/JBENF2.BEENG-6069>.
- Qiu, L., Huang, Y., Chen, T.** (2020). Post-Earthquake Assessment of Substandard Concrete Buildings: A Field Investigation and Numerical Study. *J. Earthq. Eng.*, 24, 713–732.
- Rafi, M.M., Lodi S.H., Al-Sadoon, Z.A., Saatcioglu, M., Palermo, D.** (2021). Shake-Table Testing of Deficient Reinforced Concrete Frame Retrofitted with Buckling Restrained Brace, *ACI Structural Journal*, 118(3), 161-173, <https://doi.org/10.14359/51729351>
- Rafi, M.M., Lodi, S.H., Al-Sadoon, Z.A., Saatcioglu, M., Palermo, D.** (2022). Experimental Investigation of Dynamic Behavior of RC Frame Strengthened with Buckling-Restrained Bracing. *Journal of Structural Engineering*, 148(7): 04022076. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0003371](https://doi.org/10.1061/(ASCE)ST.1943-541X.0003371).
- Razavi, S.A., Kianmehr, A., Hosseini, A., Mirghaderi, S.R.** (2018). Buckling-restrained brace with CFRP encasing: Mechanical behavior & cyclic response, *Steel and Composite Structures*, 27(6), 675-689, <https://doi.org/10.12989/scs.2018.27.6.675>
- Realfonzo, R., Napoli, A., Pinilla Melo, J.** (2014). Cyclic behavior of RC beam-column joints strengthened with FRP systems. *Constr. Build. Mater.*, 54, 282–297. <https://doi.org/10.1016/j.conbuildmat.2013.12.043>.
- Ricci, P., De Risi, M.T., Verderame, G.M., Manfredi, G.** (2016). Experimental tests of unreinforced exterior beam-column joints with plain bars. *Eng. Struct.*, 118, 178–194. <https://doi.org/10.1016/j.engstruct.2016.03.033>.
- Rizwan, M., Ahmad, N., Khan, A.N.** (2018). Seismic performance of compliant and noncompliant special moment-resisting reinforced concrete frames. *ACI Struct. J.*, 115, 1063–1073. <https://doi.org/10.14359/51702063>.
- Rodriguez, D., Morales, F., Wang, H.** (2025). Experimental Performance of Tube-in-Tube Braces under High Cyclic Demands. *J. Earthq. Wind Eng.*, 33, 14–31.

- Rossetto, T., and Peiris, N.** (2009). Observations of Damage due to the Kashmir Earthquake of October 8, 2005 and Study of Current Seismic Provisions for Buildings in Pakistan. *Bull Earthq. Eng*, 7, 681–699. <https://doi.org/10.1007/s10518-009-9118-5>.
- Ryu, G., Choi, J., Ha, S.** (2023). Evaluating Gusset Plate Behavior in Non-Ductile RC Frames: Experimental Evidence and Finite-Element Correlation. *Eng. J.*, 57, 93–107.
- Saatcioglu, M., Mitchell, D., Tinawi, R., Gardner, N.J., Gillies, A.G., Ghobarah, A.** (2001). The August 17, 1999, Kocaeli (Türkiye) earthquake damage to structures. *Can. J. Civ. Eng.* 2001, 28, 715–737. <https://doi.org/10.1139/101-043>.
- Sabelli, R., Mahin, S., Chang, C.** (2003). Seismic demands on steel braced frame buildings with buckling restrained braces. *Eng. Struct.*, 25, 655–666. [https://doi.org/10.1016/S0141-0296\(02\)00175-X](https://doi.org/10.1016/S0141-0296(02)00175-X).
- Sadoon, Z., Saatcioglu, M., Palermo, D.** (2024). Enhancing seismic resilience of non-ductile RC frames with a novel buckling restrained brace system: A nonlinear analysis approach. *Structures*, 68, 107089. <https://doi.org/10.1016/j.istruc.2024.107089>.
- Saiidi, M., and Sozen, M.A.** (1979). Simple and Complex Models for Nonlinear Seismic Response of Reinforced Concrete Structures, A Report to the National Science Foundation Research Grant PFR:78-16318, University of Illinois at Urbana-Champaign: Urbana, Illinois.
- Seismosoft. SeismoStruct**—A Computer Program for Static and Dynamic Nonlinear Analysis of Framed Structures, Version 2025, Seismosoft Ltd.: Pavia, Italy, 2025. Available online: <https://www.seismosoft.com> (accessed on 23 October 2024)).
- Seker, O., and Shen, J.** (2017). Developing an all-steel buckling controlled brace. *Journal of Constructional Steel Research*, 131, 94–109. <https://doi.org/10.1016/j.jcsr.2017.01.006>.
- Seker, O., Shen, J., Faytarouni, M., Akbas, B.** (2021). Investigation of Channel-Encased Braces Incorporating Circular HSS. *Eng. Struct.*, 230, 111692.
- Seker, O., Shen, J., Faytarouni, M., Akbas, B., Shen, X., Zhang, H., Li, P.** (2023). Cyclic Behavior of Channel-Encased Braces Incorporating Round HSS. *Structures*, 57, 105072. <https://doi.org/10.1016/j.istruc.2023.105072>.
- Sezen, H., Whittaker, A.S., Elwood, K.J., Mosalam, K.M.** (2003). Performance of reinforced concrete buildings during the August 17,1999 Kocaeli, Turkey earthquake, and seismic design and construction practise in Turkey. *Engineering Structures*, 25(1), 103-114. [https://doi.org/10.1016/S0141-0296\(02\)00121-9](https://doi.org/10.1016/S0141-0296(02)00121-9)
- Sezen, H.** (2002). Seismic Behavior and Modeling of Reinforced Concrete Columns. Ph.D. Dissertation.University of California, Berkeley, CA, USA.
- Sezen, H., and Moehle, J.P.** (2004). Shear Strength Model for Lightly Reinforced Concrete Columns. *J. Struct. Eng.*, 130, 1692–1703.

- Shen, J., Seker, O., Akbas, B., Seker, P., Momenzadeh, S., Faytarouni, M.** (2017). Seismic performance of concentrically braced frames with and without brace buckling. *Engineering Structures*, 141, 461–481. <https://doi.org/10.1016/j.engstruct.2017.03.043>
- Shen, J., Seker, O., Sutchiewcharn, N., Akbas, B.** (2016). Cyclic behavior of buckling controlled braces. *Journal of Constructional Steel Research*, 121, 110–125. <https://doi.org/10.1016/j.jcsr.2016.01.018>.
- Shen, J., Seker, O., Faytarouni, M., Akbas, B., Shen, X., Zhang, H., Li, P.** (2024). Evaluation of New Seismic provisions for special concentrically braced frames in AISC 341-22, *Structures*, 63, 106453. <https://doi.org/10.1016/j.istruc.2024.106453>.
- Shen, Y., El Nagggar, M.H., Zhang, D., Huang, Z., Du, X.** (2025). Optimal intensity measure for seismic performance assessment of shield tunnels in liquefiable and non-liquefiable soils. *Undergr. Space*, 21, 149–163. <https://doi.org/10.1016/j.undsp.2024.03.008>.
- Sitler, B., Takeuchi, T., Matsui, R., Terashima, M., Terazawa, Y.** (2020). Experimental investigation of a multistage buckling-restrained brace. *Eng. Struct.*, 213, 110482. <https://doi.org/10.1016/j.engstruct.2020.110482>.
- Sok, A., Yamada, S., Iyama, J.** (2024). Displacement Control of Existing Steel Moment-Resisting Frame Structures Using Buckling-Restrained Braces. *Journal of Earthquake Engineering*, 28(10), 2742–2762. <https://doi.org/10.1080/13632469.2024.2303592>
- Sun, H., Jia, M., Zhang, S., Wan, H.Y.** (2019). Study of buckling-restrained braces with concrete infilled GFRP tubes, *Thin-Walled Structures*, 136, 16–33, <https://doi.org/10.1016/j.tws.2018.10.040>
- Sun, J., Pan, P., Wang, H.** (2018). Development and experimental validation of an assembled steel double-stage yield buckling restrained brace. *J. Constr. Steel Res.*, 145, 330–340. <https://doi.org/10.1016/j.jcsr.2018.03.003>.
- Sung, Y., Hung, H., Chou, K., Su, C., Hsu, C., Hsu, C.** (2021). Shaking table testing of a reinforced concrete frame retrofitted with a steel oval member equipped with rubber cylinders. *Eng. Struct.*, 237, 112202. <https://doi.org/10.1016/j.engstruct.2021.112202>.
- Suwal, N., and Guner, S.** (2024). Plastic hinge modeling of reinforced concrete Beam-Column joints using artificial neural networks. *Eng. Struct.*, 298, 117012. <https://doi.org/10.1016/j.engstruct.2023.117012>.
- Takeda, T., Sozen, M.A., Nielsen, N.N.** (1970). Reinforced Concrete Response to Simulated Earthquakes. *J. Struct. Div.*, 96, 2557–2573.
- Takeuchi, T., Hajjar, J., Matsui, R., Nishimoto, K., Aiken, I.** (2012). Effect of local buckling coreplate restraint in buckling restrained braces. *Eng Struct*, 44, 304–11, <https://doi.org/10.1016/j.engstruct.2012.05.026>
- Takeuchi, T.** (2018). Buckling-Restrained Brace: History, Design and Applications. *Key Engineering Materials*, 763, 50–60. <https://doi.org/10.4028/www.scientific.net/KEM.763.50>

- Talebi, E., Tahir, M.M., Zahmatkesh, F., Kueh, A.B.H.** (2014). Comparative study on the behaviour of buckling restrained braced frames at fire. *J. Constr. Steel Res.*, 102, 1–12. <https://doi.org/10.1016/j.jcsr.2014.06.003>.
- Tan, Q., Wu, B., Shi, P., Xu, G., Wang, Z., Lehman, D.E.** (2020). Experimental Performance of a Full-Scale Spatial RC Frame with Buckling-Restrained Braces Subjected to Bidirectional Loading, *Journal of Structural Engineering*, 147(3), 04020352, [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0002928](https://doi.org/10.1061/(ASCE)ST.1943-541X.0002928)
- Tang, X., Wei, S., Zhang, L.** (2023). Tube-in-Tube Steel Bracing: Numerical Investigation on Seismic Performance and Failure Modes. *Struct. Build.*, 192, 100–117.
- TBEC** (2018). Türk Bina Deprem Yönetmeliği (Turkish Building Earthquake Code). Ministry of Public Works and Settlement: Ankara, Turkey. (In Turkish)
- To, Q.B., Shin, J., Kim, S.J., Kim, H.-W., Lee, K.** (2024). Effective Prediction of Concrete Constitutive Models for Reinforced Concrete Shear Walls under Cyclic Loading. *Materials*, 17, 1877. <https://doi.org/10.3390/ma17081877>.
- TS 708** (2010). Steel for the Reinforcement of Concrete—Reinforcing Steel. Turkish Standardization Institute: Ankara, Turkey.
- TS 802** (1985). Design Concrete Mixes. Turkish Standardization Institute: Ankara, Turkey.
- TS EN 12390-3** (2010). Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. Turkish Standardization Institute: Ankara, Turkey, 2010.
- Tsai, K.C., Wu, A.C., Wei, C.Y., Lin, P.C., Chuang, M.C., Yu, Y.J.** (2014). Welded end-slot connection and debonding layers for buckling-restrained braces. *Earthquake Engineering and Structural Dynamics*, 43(12), 1785–807. <https://doi.org/10.1002/eqe.2423>
- Tsai, K., Yang, Y., Chang, H.** (2020). Seismic Upgrade of Deficient Concrete Frames Using Buckling-Restrained Braces: Large-Scale Testing and Analytical Modeling. *Struct. Des. Tall Spec. Build.*, 29, e1794.
- Tsai, K.C., Wu, A.C., Wei, C.Y., Lin, P.C., Chuang, M.C., Yu, Y.J.** (2014). Welded end-slot connection and debonding layers for buckling-restrained braces. *Earthq. Eng. Struct. Dyn.*, 43, 1785–1807. <https://doi.org/10.1002/eqe.2423>.
- Tsonos, A.D.G.** (2019). Model for the evaluation of the beam-column joint ultimate strength-a more simplified version. *Earthq. Struct.*, 16, 141–148. <https://doi.org/10.12989/eas.2019.16.2.141>.
- Usami, T., Wang, C-L., Funayama, J.** (2012). Developing high-performance aluminum alloy buckling-restrained braces based on series of low-cycle fatigue tests. *Earthquake Engineering and Structural Dynamics*, 41(4), 643–61. <https://doi.org/10.1002/eqe.v41.410.1002/eqe.1149>

- Vargas, R. and Bruneau, M.** (2009). Experimental response of buildings designed with metallic structural fuses II. *J. Struct. Eng.*, 135, 394–403. [https://doi.org/10.1061/\(ASCE\)0733-9445\(2009\)135:4\(394\)](https://doi.org/10.1061/(ASCE)0733-9445(2009)135:4(394)).
- Vecchio, C.D., Ludovico, M.D., Balsamo, A., Prota, A., Manfredi, G., Dolce, M.** (2014). Experimental Investigation of Exterior RC Beam-Column Joints Retrofitted with FRP Systems. *J. Compos. Constr.*, 18, 04014002. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000459](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000459).
- Wallace, J.W.** (2012). Behavior, design, and modeling of structural walls and coupling beams—Lessons from recent laboratory tests and earthquakes. *Int. J. Concr. Struct. Mater.*, 6, 3–18. <https://doi.org/10.1007/s40069-012-0001-4>.
- Wan, C., Xie, L., Li, L., Xue, S., Tang, H., Zhang, L.** (2022). Experimental study and numerical simulation of all-steel buckling-restrained brace with distributed inspection windows, *The Structural Design of Tall and Special Buildings*, 31(7), e1924, <https://doi.org/10.1002/tal.1924>
- Wen, Y.K.** (1976). Method for Random Vibration of Hysteretic Systems. *J. Eng. Mech. Div.*, 102, 249–263.
- Wu, A.C., Tsai, K.C., Yang, H.H., Huang, J.L., Li, C.H., Wang, K.J., Khoo, H.H.** (2017). Hybrid experimental performance of a full-scale two-story buckling-restrained braced RC frame, *Earthquake Engineering and Structural Dynamics*, 46, 1223–1244, <https://doi.org/10.1002/eqe.2853>
- Wu, B. and Mei, Y.** (2015). Buckling mechanism of steel core of buckling-restrained braces. *J Constr Steel Res*, 107, 61–9. <https://doi.org/10.1016/j.jcsr.2015.01.012>.
- Wu, C., Zhang, Q., Gong, C., Li, D., Zhang, Y., Chen, Z.** (2024). A double-stage buckling restrained brace with progressive failure pattern: Experimental verification and numerical calibration. *Structures*, 62, 106242. <https://doi.org/10.1016/j.istruc.2024.106242>.
- Xiao, Y., and Martirosyan, A.** (1998). Seismic Performance of High-Strength Concrete Columns. *J. Struct. Eng.*, 124, 241–251. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1998\)124:3\(241\)](https://doi.org/10.1061/(ASCE)0733-9445(1998)124:3(241)).
- Xie, W., Wang, J., Bao, Y., Sun, L.** (2024). Theoretical studies and verification on tall RC two-column piers with BRBs: Numerical simulations and shaking table tests. *Eng. Struct.*, 304, 117683. <https://doi.org/10.1016/j.engstruct.2024.117683>.
- Xie, Z., and Li, B.** (2021). Parametric Study on Mortar-Filled and Partially Filled BRBs under Seismic Loads. *Structures*, 33, 720–735.
- Yazgan, U., Oyguç, R., Ergüven, M.E., Celep, Z.** (2016). Seismic Performance of Buildings during 2011 Van Earthquakes and Rebuilding Efforts. *Earthq. Eng. Eng. Vib.*, 15, 591–606. <https://doi.org/10.1007/s11803-016-0346-9>.

- Yilmaz, Z., Altunişik, A.C., Taciroglu, E., Günaydın, M., Okur, F.S., Sunca, F., Şişman, R., Aslan, B., Sezdirmez, T.** (2024). Regional Building Damage Survey Data on the 2023 Kahramanmaraş, Türkiye, Earthquakes, *ASCE OPEN: Multidisciplinary Journal of Civil Engineering*, 2(1), 04024009, <https://doi.org/10.1061/AOMJAH.AOEN G-0041>
- Yön, B., Dedeoğlu, İ.Ö., Yetkin, M., Erkek, H., Calayır, Y.** (2024). Evaluation of the seismic response of reinforced concrete buildings in the light of lessons learned from the February 6, 2023, Kahramanmaraş, Türkiye earthquake sequences. *Nat. Hazards*, 121, 873–909. <https://doi.org/10.1007/s11069-024-06859-9>.
- Yun, Z., Cao, Y., Takagi, J., Zhong, G., He, Z.** (2022). Experimental and numerical investigation of a novel all-steel assembled core-perforated buckling-restrained brace, *Journal of Constructional Steel Research*, 193, 107288, <https://doi.org/10.1016/j.jcsr.2022.107288>
- Yurdakul, Ö., Duran, B., Tunaboyu, O., Avşar, Ö.** (2021). Field Reconnaissance on Seismic Performance of RC Buildings after the January 24, 2020 Elazığ-Sivrice Earthquake. *Nat Hazards*, 105, 859–887. <https://doi.org/10.1007/s11069-020-04340-x>.
- Yuzbasi, J.** (2024). Post-Earthquake Damage assessment: Field observations and recent developments with recommendations from the Kahramanmaraş earthquakes in Türkiye on February 6th, 2023 (Pazarcık M7.8 and Elbistan M7.6). *Journal of Earthquake Engineering*, 1-26. <https://doi.org/10.1080/13632469.2024.2353864>
- Zahrah, T.F., and Hall, W.J.** (1982). Seismic Energy Absorption in Simple Structures, Civil Engineering Studies, Structural Research Series No. 501, University of Illinois: Urbana, IL, USA.
- Zhang, M.Z.** (1997). Study on Similarity Laws for shaking table tests. *Earthquake Engineering Engineering Vibration*, 17(2), 52–58.
- Zhang, X. and Li, B.** (2021). Seismic performance of exterior reinforced concrete beam-column joint with corroded reinforcement. *Eng. Struct.*, 228, 111556. <https://doi.org/10.1016/j.engstruct.2020.111556>.
- Zheng, S.Y., Yuan, B., Wei, M.S., Liu, X.L., Liu, X.F., Zhou, G.Y., Liang, Z.H., Shi, H.W.** (2023). Experimental & numerical investigation of all-steel assembled cruciform buckling-restrained braces, *Journal of Constructional Steel Research*, 207, 107981, <https://doi.org/10.1016/j.jcsr.2023.107981>
- Zhou, X., and Li, G.** (2010). Shaking table model test of a steel-concrete composite high-rise building. *Journal of Earthquake Engineering*, 14(4), 601–625. <https://doi.org/10.1080/13632460903193949>
- Zhou, Y., Gong, C., Zhao, J., Zhong, G., Tian, S.** (2020). Strong-axis stability and seismic performance of perforated core plate buckling-restrained braces, *Thin-Walled Structures*, 156, 106997, <https://doi.org/10.1016/j.tws.2020.106997>

Zona, A., Dall'Asta, A. (2012) Elastoplastic Model for Steel Buckling-Restrained Braces. *J. Constr. Steel Res.*, 68, 118–125.



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- **Oyguc, E.,** Oyguc, R., Seker, O., Hayir, A., Shen, J., & Akbas, B. (2025). Improving Seismic Performance of RC Structures with Innovative TnT BRBs: A Shake Table and Finite Element Investigation. *Applied Sciences*, 15(7), 3844. <https://doi.org/10.3390/app15073844>
- **Oyguc, E.,** Oyguc, R., Seker, O., Hayir, A., Shen, J., & Akbas, B. (2025). Experimental Evaluation of an Innovative Tube-in-Tube Buckling Restrained Braces for Seismic Retrofitting of Substandard RC Frames. *Applied Sciences*, 15(9), 4662. <https://doi.org/10.3390/app15094662>
- Oyguc R., **Oyguc E.,** Tonuk G. (2018). Case Study on Seismic Behavior of Aseismically Designed Reinforced Concrete Frame Structures. *Bulletin of Earthquake Engineering*, 16(7), 3057-3080 ,DOI: 10.1007/s10518-017-0300-x
- Oyguc R, and **Oyguc E.** (2017). The 2011 Van Earthquakes: Lessons from Damaged Masonry Structures, *Journal of Performance of Constructed Facilities*, DOI: 10.1061/(ASCE)CF.1943-5509.0001057

- Oyguc R, and **Guley E.** (2016). Performance Assessment of Aseismically Designed RC School Buildings after October 23, 2011 Van Earthquake, Journal of Performance of Constructed Facilities, DOI: 10.1061/(ASCE)CF.1943-5509.0000938

CONFERENCE PROCEEDINGS:

- **Oyguc E.**, Hayır A., Oyguc R, Seker O, Akbas B. (2025). Enhancing Seismic Resilience of Substandard RC Beam-Column Joints with All-Steel Tube-in-Tube Buckling-Restrained Braces: A Shake Table Test, 4th International Graduate Research Symposium, IGRS'25, 12-14 May, 2025, Istanbul, Türkiye.
- Oyguc R., and **Oyguc E.** (2019). Field Investigations on Seismic Behavior of Building Type Structures, 4th International Conference on Civil Environmental Geology and Mining Engineering, ICOCEM, p. 968-982 , 20-22 April 2019, Trabzon, Türkiye.
- Oyguc R., and **Oyguc E.** (2019). Earthquake Response of a Prestressed Containment Reactor Building, International Civil Engineering and Architecture Conference 2019, ICEARC'19, p. 2077-2085, 17-20 April 2019, Trabzon, Türkiye.
- **Oyguc E.**, and Oyguc R. (2018). Seismic Behavior of Prestressed Containment Vessel of a Reactor Building, 13th International Congress on Advances in Civil Engineering, ACE 2018, p 55, 12-14 September 2018, İzmir, Türkiye.

INTERNATIONAL BOOK CHAPTER:

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