



**EXPERIMENTAL INVESTIGATION OF BEAM-  
COLUMN CONNECTIONS WITH DIFFERENT  
TAB CONFIGURATIONS IN STORAGE RACK  
SYSTEMS**

**Biemba BIEMBA**

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T.C.  
ATATÜRK UNIVERSITY  
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES  
DEPARTMENT OF CIVIL ENGINEERING

**EXPERIMENTAL INVESTIGATION OF BEAM-COLUMN CONNECTIONS WITH  
DIFFERENT TAB CONFIGURATIONS IN STORAGE RACK SYSTEMS**

(Depolama Raf Sistemlerinde Farklı Tırnak Konfigürasyonlarına Sahip Kiriş-Kolon  
Birleşimlerinin Deneysel Olarak İncelenmesi)

MASTER'S THESIS

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Yüksek lisans Tezi olarak Prof. Dr. Fatih Mehmet ÖZKAL ve Dr. Öğr. Üyesi Casim YAZICI danışmanlığında sunulan “Experimental Investigation of Beam-Column Connections with Different Tab Configurations in Storage Rack Systems” başlıklı çalışmanın tarafımızdan bilimsel etik ilkelere uyularak yazıldığını, yararlanılan eserlerin kaynakçada gösterildiğini, Fen Bilimleri Enstitüsü tarafından belirlenmiş olan Turnitin Programı benzerlik oranlarının aşılmadığını ve aşağıdaki oranlarda olduğunu beyan ederiz.

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## ABSTRACT

### MASTER'S THESIS

#### EXPERIMENTAL INVESTIGATION OF BEAM-COLUMN CONNECTIONS WITH DIFFERENT TAB CONFIGURATIONS IN STORAGE RACK SYSTEMS

**Biemba BIEMBA**

**Supervisor: Prof. Dr. Fatih Mehmet ÖZKAL**

**Co-Supervisor: Asst. Prof. Dr. Casim YAZICI**

**Purpose:** This thesis aims to experimentally investigate the structural behavior of beam-column connections with different tab configurations in storage rack systems. Steel storage rack systems are durable and modular structures used to store various goods and products safely in warehouses. The use of steel in the construction sector has increased over the years due to its advantages such as high strength, lightness, cost-effectiveness and sustainability. These systems generally consist of steel elements produced by the cold forming method and are designed to maximize the storage area, provide easy access to the stored products and carry heavy loads safely. In the thesis, the effect of tab configurations on the structural stability and load-carrying capacity of beam-column connections is investigated. These connections used in storage rack systems are of critical importance for the connection of beam-column and the safe transfer of loads. In engineering applications, tab configurations are generally found in three main types: bolted connections, boltless (tab) connections and welded connections. Each of these configurations exhibits different performance in terms of structural stability, stiffness, ductility and load-carrying capacity. This research experimentally investigates the moment-rotation curves of beam-column connections to understand the effects of tab configurations on structural performance.

**Method:** In this research, the moment-rotation behavior of beam-column connections used in steel storage rack systems with different tab configurations was investigated using the single cantilever test method. This method allows for the evaluation of the performance of beam-column connections under load by leaving one end of the beam free and fixing the other end to the column. A total of 18 test specimens were used in the experiments; these specimens consisted of different beam depths (120 mm and 140 mm) and different tab numbers (4 tabs, 5 tabs and 9 tabs). The flange and web wall thicknesses of columns and beams were selected as 1.5 mm for beams, 2.5 mm for columns and 3.0 mm for beam end connectors. The experimental setup was carried out under single loading, with the load applied to the beam at a distance of 40 cm from the connection point with the connector and at a constant loading rate. To evaluate the moment-rotation behavior of each specimen under different loading conditions, displacements were recorded with 2 displacement meters placed parallel to the beam direction on the connector and 1 displacement meter at the bottom point of the connector, also parallel to the beam direction. These displacement meters helped to calculate the moment-rotation relationship by measuring the displacement of the beam concerning the horizontal position. After the completion of the experiments, the collected data were meticulously processed and analyzed. Moment-rotation curves were created for each tab configuration and these curves were evaluated to understand the effects of the connections on load-carrying capacity and rotational rigidity.

**Results:** Experimental studies have shown that different tab configurations have significant effects on the structural behavior of beam-column connections. According to the test results, 9-tab configurations generally provided higher moment resistance and stiffness indicating that the connections were more resistant to the applied loads. The 9-tab configurations had higher moment capacity and significantly increased the load-carrying capacity of the connections. This configuration contributed to the safe carrying of the loads and resulted in stiffer and more

durable connections. On the other hand, 4-tab and 5-tab configurations, despite having lower moment capacity, positively affected the ductility properties of the connections. The 5-tab configurations, in particular, exhibited a balanced performance between ductility and stiffness, suggesting that they could be a suitable option for structures where moment resistance, stiffness, and ductility are critical. The experimental data also revealed the failure modes of different configurations; failure modes such as deformation of tabs and beam end connectors, yielding or fracture of tabs, and weld failure were identified as the main factors affecting the structural integrity of the connections.

**Conclusion:** The experimental analysis of moment-rotation curves performed within the scope of this thesis provided comprehensive results on the behavior of beam-column connections in steel storage racks. The findings revealed the main factors affecting the performance and reliability of the connections and provided important information for the design of more robust and secure storage rack systems. The 9-tab configurations provided higher moment resistance and stiffness, ensuring safer operation of the structure under critical loads. This configuration is considered to be an ideal option, especially for structures where moment resistance and stiffness are paramount. The 5-tab configurations were effective in increasing the overall performance of the storage systems by providing a balanced combination of moment resistance, stiffness and ductility. This suggests that the 5-tab configuration can be a suitable alternative for meeting certain structural requirements. Additionally, the experimental data revealed the effects of structural parameters such as beam depth on the performance of the connections; it was observed that beams with greater depth provided more bending resistance and therefore increased the moment capacity and stiffness of the connections. In conclusion, this thesis has provided important findings to understand the effects of different tab configurations of beam-column connections in storage rack systems on structural behavior and to improve the design of these systems. To ensure that storage rack systems are safer, more durable, and more efficient, tab configurations should be optimized and supported by advanced engineering analyses. The findings of this study have contributed to the design and engineering applications of storage systems, taking an important step toward increasing structural safety in industrial and commercial storage.

**Keywords:** moment-rotation curves, steel storage rack systems, beam end connectors, beam-column connections

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## ÖZET

### YÜKSEK LİSANS TEZİ DEPOLAMA RAF SİSTEMLERİNDE FARKLI TIRNAK KONFIGÜRASYONLARINA SAHİP KİRİŞ-KOLON BİRLEŞİMLERİNİN DENEYSEL OLARAK İNCELENMESİ

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**Amaç:** Bu tez, depolama raf sistemlerinde farklı tırnak konfigürasyonlarına sahip kiriş-kolon birleşimlerinin yapısal davranışını deneysel olarak incelemeyi amaçlamaktadır. Çelik depolama raf sistemleri, depolarda çeşitli mal ve ürünleri güvenli bir şekilde saklamak için kullanılan dayanıklı ve modüler yapılardır. İnşaat sektöründe çeliğin kullanımı, yüksek mukavemet, hafiflik, uygun maliyet ve sürdürülebilirlik gibi avantajları nedeniyle yıllar içinde artmıştır. Bu sistemler genellikle soğuk şekillendirme yöntemi ile üretilmiş çelik elemanlardan oluşur ve depolama alanını en üst düzeye çıkarmak, depolanan ürünlere kolay erişim sağlamak ve ağır yükleri güvenli bir şekilde taşıması amacıyla tasarlanmıştır. Tezde, kiriş-kolon birleşimlerinin yapısal stabilitesi ve yük taşıma kapasitesi üzerinde tırnak konfigürasyonlarının etkisi incelenmiştir. Depolama raf sistemlerinde kullanılan bu birleşimler, kirişlerin kolonlara bağlanması ve yüklerin güvenli bir şekilde aktarılması için kritik öneme sahiptir. Mühendislik uygulamalarında, tırnak konfigürasyonları genellikle üç ana tipte bulunur: bulonlu birleşimler, bulonsuz (tırnaklı) birleşimler ve kaynaklı birleşimler. Bu konfigürasyonların her biri, yapısal stabilite, rijitlik, süneklik ve yük taşıma kapasitesi açısından farklı performans sergiler. Bu araştırma, tırnak konfigürasyonlarının yapısal performans üzerindeki etkilerini anlamak için kiriş-kolon birleşimlerinin moment-dönme eğrilerini deneysel olarak incelemiştir.

**Yöntem:** Bu çalışmada çelik depolama raf sistemlerinde kullanılan kiriş kolon birleşimlerinin farklı tırnak konfigürasyonlarındaki moment dönme davranışı tek konsol test yöntemi kullanılarak incelenmiştir. Bu test yöntemi, kirişin bir ucu serbest bırakılırken, diğer ucu kolon ile sabitlenerek kiriş-kolon birleşimlerinin yük altındaki performansını değerlendirmeye olanak tanır. Deneylerde, toplamda 18 test numunesi kullanılmıştır; bu numuneler farklı kiriş derinlikleri (120 mm ve 140 mm) ve farklı tırnak sayılarından (4 tırnak, 5 tırnak ve 9 tırnak) oluşmaktadır. Kolon ve kirişlerin başlık ve gövde et kalınlıkları; kirişler için 1,5 mm, kolonlar için 2,5 mm ve kiriş ucu konnektörleri için 3,0 mm olarak seçilmiştir. Deneysel düzenek, tekil yükleme altında gerçekleştirilmiş ve yük kirişe konnektör ile birleşim noktasından 40 cm uzaklıktan uygulanarak sabit bir yükleme hızı ile uygulanmıştır. Her bir numune, farklı yükleme koşulları altında moment-dönme davranışlarını değerlendirmek amacıyla kirişin üst konumuna ve kiriş doğrultusuna paralel olacak şekilde konnektörden 2 deplasman ölçer ve kirişin altına kirişin doğrultusuna paralel olacak şekilde konnektörün alt noktasından 1 adet deplasman ölçer ile deplasmanlar kayıt altına alınmıştır. Bu deplasman ölçerler aracılığıyla, kirişin yatay konuma göre yer değiştirmesini ölçerek moment-dönme ilişkisini hesaplamaya yardımcı olmuştur. Deneylerin tamamlanmasının ardından toplanan veriler titiz bir işleme ve analize tabi tutulmuştur. Her tırnak konfigürasyonu için moment-dönme eğrileri oluşturulmuş ve bu eğriler, birleşimlerin yük taşıma kapasitesi ve dönme rijitliği üzerindeki etkilerini anlamak için değerlendirilmiştir.

**Bulgular:** Deneysel çalışmalar, farklı tırnak konfigürasyonlarının kiriş-kolon birleşimlerinin yapısal davranışları üzerinde önemli etkiler yarattığını ortaya koymuştur. Test sonuçlarına göre, 9 tırnaklı konfigürasyonlar genellikle daha yüksek moment dayanımı ve rijitlik sunmuş, bu da birleşimlerin uygulanan yüklere karşı daha dayanıklı olduğunu göstermiştir. 9 tırnaklı konfigürasyonlar, daha yüksek moment kapasitesine sahip olup, birleşimlerin yük taşıma

kapasitesini önemli ölçüde artırmıştır. Bu konfigürasyon, yüklerin güvenli bir şekilde taşınmasına ve birleşimlerin daha rijit ve dayanıklı olmasına katkıda bulunmuştur. Öte yandan, 4 tırnaklı ve 5 tırnaklı konfigürasyonlar, daha düşük moment kapasitesine sahip olmalarına rağmen, birleşimlerin süneklik özelliklerini olumlu yönde etkilemiştir. 5 tırnaklı konfigürasyonlar, özellikle süneklik ve rijitlik arasında dengeli bir performans sergileyerek, moment dayanımı, rijitlik ve sünekliğin kritik olduğu yapılar için uygun bir seçenek olabileceğini göstermiştir. Deneysel veriler, farklı konfigürasyonların göçme modlarını da ortaya koymuştur; tırnakların ve kiriş ucu konnektörlerinin deformasyonu, tırnakların akması veya kırılması ve kaynak kopması gibi göçme modları, birleşimlerin yapısal bütünlüğünü etkileyen başlıca faktörler olarak belirlenmiştir.

**Sonuçlar:** Bu tez kapsamında gerçekleştirilen moment-dönme eğrilerinin deneysel analizi, çelik depolama raflarındaki kiriş-kolon birleşimlerinin davranışı üzerine kapsamlı sonuçlar sağlamıştır. Bulgular, birleşimlerin performansını ve güvenilirliğini etkileyen temel faktörleri ortaya koyarak, daha sağlam ve güvenli depolama raf sistemlerinin tasarımı için önemli bilgiler sunmuştur. 9 tırnaklı konfigürasyonlar, yüksek moment dayanımı ve rijitlik sunarak, kritik yükler altında yapının daha güvenli bir şekilde çalışmasını sağlamıştır. Bu konfigürasyon, özellikle moment dayanımı ve rijitliğin ön planda olduğu yapılar için ideal bir seçenek olarak değerlendirilmektedir. 5 tırnaklı konfigürasyonlar ise, moment dayanımı, rijitlik ve sünekliğin dengeli bir kombinasyonunu sunarak, depolama sistemlerinin genel performansını artırmada etkili olmuştur. Bu durum, belirli yapısal gereksinimlerin karşılanmasında bu konfigürasyonun uygun bir alternatif olabileceğini göstermektedir. Ayrıca, deneysel veriler, kiriş derinliği gibi yapısal parametrelerin birleşimlerin performansı üzerindeki etkilerini de ortaya koymuştur; daha derin kirişlerin daha fazla eğilme direnci sunduğu ve bu nedenle birleşimlerin moment kapasitesi ve rijitliğini artırdığı gözlemlenmiştir. Sonuç olarak, bu tez, depolama raf sistemlerindeki kiriş-kolon birleşimlerinin farklı tırnak konfigürasyonlarının yapısal davranışları üzerindeki etkilerini anlamak ve bu sistemlerin tasarımını geliştirmek için önemli bulgular sunmuştur. Depolama raf sistemlerinin daha güvenli, dayanıklı ve verimli olmasını sağlamak için tırnak konfigürasyonlarının optimize edilmesi ve ileri mühendislik analizleri ile desteklenmesi gerekmektedir. Bu çalışmanın bulguları, depolama sistemlerinin tasarımı ve mühendislik uygulamalarına katkı sağlayarak, endüstriyel ve ticari depolama alanlarında yapısal güvenliği artırmaya yönelik önemli bir adım atmıştır.

**Anahtar Kelime:** moment-dönme eğrisi, çelik depolama raf sistemleri, kiriş ucu konektörü, kiriş-kolon birleşimi

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## INDEX OF ABBREVIATIONS AND SYMBOLS

<b>AISC</b>	: American Institute of Steel Construction
<b>ANSI</b>	: American National Standards Institute
<b>DEU</b>	: Double entry unity racks( DEU)
<b>EN</b>	: European Standards
<b>FEM</b>	: Federation of European Material Handling
<b>IBC</b>	: International Building Code
<b>ISO</b>	: International Organization for Standardization
<b>LIFO</b>	: Last-In, First-Out
<b>FEA</b>	: Finite Element Analysis
<b>FIFO</b>	: First-In, First-Out
<b>FILO</b>	: First In-Last Out
<b>RMI</b>	: Rack Manufacturers Institute
<b>SKUs</b>	: Stock Keeping Units
<b>SEMA</b>	: Storage Equipment Manufacturers Association
<i>bcb</i>	: beam-end-connector in bending and shear
<i>b-cwc</i>	: plates in bearing(upright web)
<i>b-bcb</i>	: plates in bearing( beam end connector)
<i>cwb</i>	: upright wall in bending
<i>cwc</i>	: upright wall in bearing
<i>cws</i>	: upright web in shear
<i>E</i>	: Elasticity modulus
<i>I</i>	: Second moment of inertia of the beam
<i>L</i>	: Length of the beam
<i>M</i>	: Moment
<i>M<sub>BU</sub></i>	: Ultimate moment of the beam end connector
<i>M<sub>CU</sub></i>	: Ultimate moment of the beam
<i>M<sub>U</sub></i>	: Ultimate moment
<i>M<sub>θ</sub></i>	: Design moment
<i>T</i>	: Tab
<i>tb</i>	: tab in bending
<i>t,cwc</i>	: upright Wall in bearing

- $\phi$  : Sway rotation equal to 0.02 Rad  
 $\theta$  : Rotation  
 $\theta_D$  : Ductility of the beam end connector



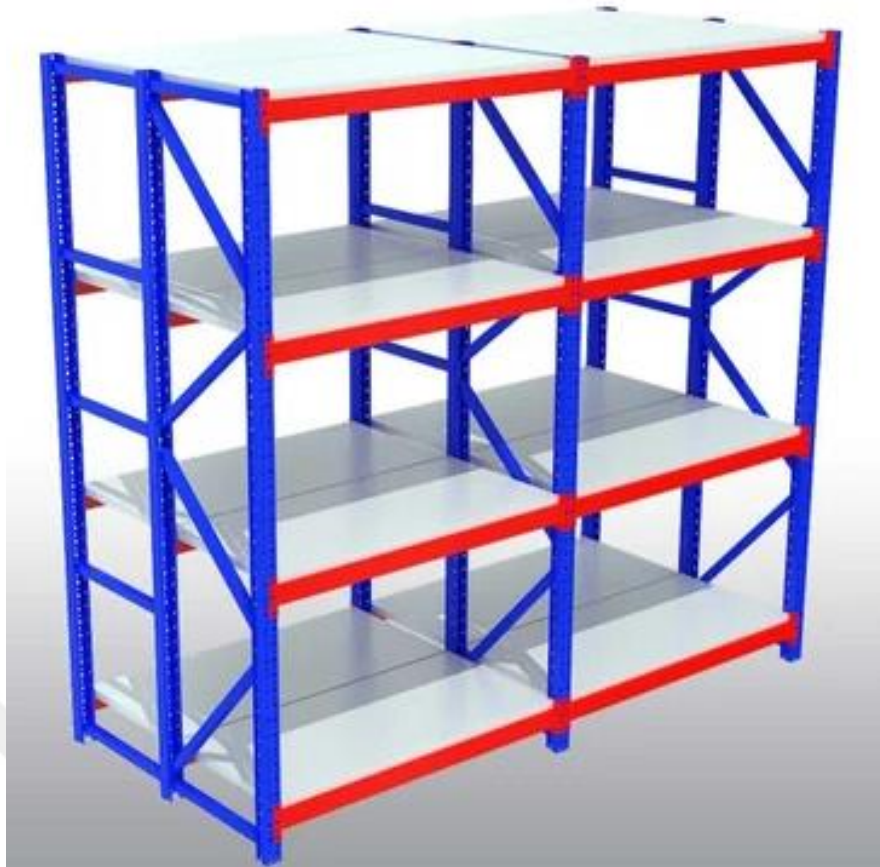
# INTRODUCTION

## Background

Cold-formed steel is commonly preferred in industries and warehouses due to its durability and strength to withstand heavy loads. Storage rack systems (Figure 1) play a crucial role in enhancing space utilization and facilitating economical material handling in industries and warehouses. They consist of various structural elements such as beams, columns, and beam end connectors. The behavior of beam-column connections influences the overall stability, load-carrying capacity, and safety of the storage rack system.

The design and performance of beam-column connections are critical factors in ensuring the integrity of storage racks, especially in situations where dynamic loads and static loads are concerned. Various connection configurations are used in steel storage racks such as bolted, boltless, and welded connections. Tabs serve as crucial load-transfer mechanisms between beams and columns. The configuration of tabs can impact the connection's resistance to shear forces, bending moments, and axial loads.

While design guidelines and standard codes provide recommendations for beam-column connections, the impact of different tab configurations on the behavior of beam-column connections in storage rack systems remains an area of active research. There is a need for a comprehensive investigation of the effects of varying tab dimensions on the performance of the connection. By investigating moment-rotation curves, this research aims to compare the moment-rotation curves of 4 tabs, 5 tabs, and 9 tabs connectors without changing any other dimensional parameter. Understanding how different tab configurations impact the moment-rotation response is vital for improving the overall robustness and dependability of storage rack systems. The test setup for this study will involve a single cantilever configuration subjected to monotonic loading.



**Figure 1.** A typical steel storage rack.

### **Purpose of the Thesis**

A deeper knowledge of how different tab configurations affect the structural behavior of beam-column connections is crucial in steel storage rack systems. Beam-column connections act as integral to the overall stability and load-bearing capacity of storage racks, a comprehensive study of their behavior leads to a full understanding of the following:

1. Design guidance practice
2. Connection performance for a better load distribution
3. High strength and energy dissipation and safety of racks
4. Reduce risks of failures, costs, and repair time in industries or warehouses.

Several researchers have investigated the behavior of beam-column connections but a few have conducted experimental investigations on the behavior of beam-to-column connections specifically with different tab configurations. This research aims to conduct an experimental investigation on moment-rotation curves of different tab configurations of beam-column connections. The main purpose is to conduct an experimental investigation into the moment-rotation curves of beam-column connections specifically focusing on connectors with various tab configuration storage rack systems. This research aims to explore the behavior of various connectors that possess distinct tab configurations. By performing strict experimental

tests and later analyzing the results, the aim is to identify the most effective and advantageous combination model among the connectors. Through a comprehensive comparison of their performance, this thesis intends to contribute valuable insights into the design and implementation of enhanced storage rack systems.



## THEORETICAL FOUNDATIONS

### Storage Rack Systems

Steel storage racks are commonly used in warehouses and industries, they are crucial in these sectors and their main function is to provide easy access to goods stored on pallets before distribution to consumers. The structural integrity of these systems is directly dependent on the behavior of beam-column connections which connect horizontal beams and vertical columns. To understand the performance of beam-column connections, it's necessary to guarantee the safety and dependability of storage rack systems under various loading conditions. According to Hancock *et al.* the industrial sector employs a variety of steel storage rack types such as selective pallet racks, drive-in and drive-through racks, push-back racks, cantilever racks, mobile racks, and mezzanine racks.

### Drive-In and Drive-Through Racks

Drive-in racks utilize a last-in, first-out (LIFO) storage configuration (Figure 2). These racks are high-density storage system that maximizes available space and height in the warehouses by eliminating the forklift operating aisles. Pallets are placed on continuous rails that extend deep into the rack, allowing forklifts to enter the structure and retrieve or place pallets. Drive-In and Drive-Through racks are specialized high-density storage solutions designed for homogeneous product storage. According to Rasmussen *et al.* drive-in racks use a last-in, first-out approach, while Drive-through racks offer a first-in, first-out arrangement.



**Figure 2.** Drive-in drive-through rack .

Advantages of drive-in and drive-through racks

- Maximum utilization of space: they have a high storage density that maximizes the available surface area and height and stores a large number of pallets.
- Simple and economical: it maximizes storage density and reduces costs.
- Configurable: it can be customized according to the height and depth of the rack making them adaptable for business.
- One or two aisles: it can eliminate the use of wide aisles for loading and unloading from front or back.
- Last-In-First-Out (LIFO) or first-in-last-out (FIFO) storage system.

#### Disadvantages of drive-in and drive-through racks

- Last in first out limits the selection of pallet goods.
- Poor accessibility to pallets that aren't at the front.
- Damage of goods due to poor handling: forklift can increase the risk and damage of racks due to poor handling.
- Easier to lose product if it's not well-managed

#### **Selective Racks**

1. Selective racks are a common and adaptable type of pallet racking system used in industries and warehouses (Figure 3). These racks are arranged in a single and double entry and designed to facilitate easy access to individual pallets. Based on Dubina *et al.* these racking systems are highly adaptable to narrow aisle configurations, standard setups, and deep-reach applications.



**Figure 3.** Selective pallet rack .

#### Advantages of selective pallet racks

- Easy selectivity: it provides direct access to every pallet and is easy to locate and retrieve every pallet without moving the other pallets.
- Compact storage system: due to its fast and simple loading and unloading selective racks are compatible with various types of forklifts.
- Reduce product handling: it reduces the risk of damage to products during storage and retrieval.
- Inventory control: it facilitates better inventory control by reserving each available space for a single unit load and a product.
- Accessibility: forklifts can easily maneuver the narrow aisle between selective racks by ensuring retrieval and storage operations.

#### Disadvantages of selective pallet racks

- Low storage space: the need for available space in warehouses limits selective racks.
- High storage costs: due to their lower storage capacity, selective rack storage costs per square meter are ultimately higher.
- Risk of damage: Pallet racking systems can be damaged by forklifts or other equipment if not used properly.
- Poorly suited for applications with high volumes; with limited stock-keeping units.

## Push-Back Racking Systems

Push-back racking systems offer an effective solution for achieving high-density storage with reasonable accessibility to multiple stock-keeping units (SKUs). This system operates on the Last-In-First-Out (LIFO) principle, where newly loaded pallets push existing ones further back (Figure 4). Similarly, when unloading, the pallet at the front is removed first. These racking systems incorporate inclined rails and sliding carts, enabling smooth movement of products.



**Figure 4.** Push back pallet rack .

### Advantages of push-back racks

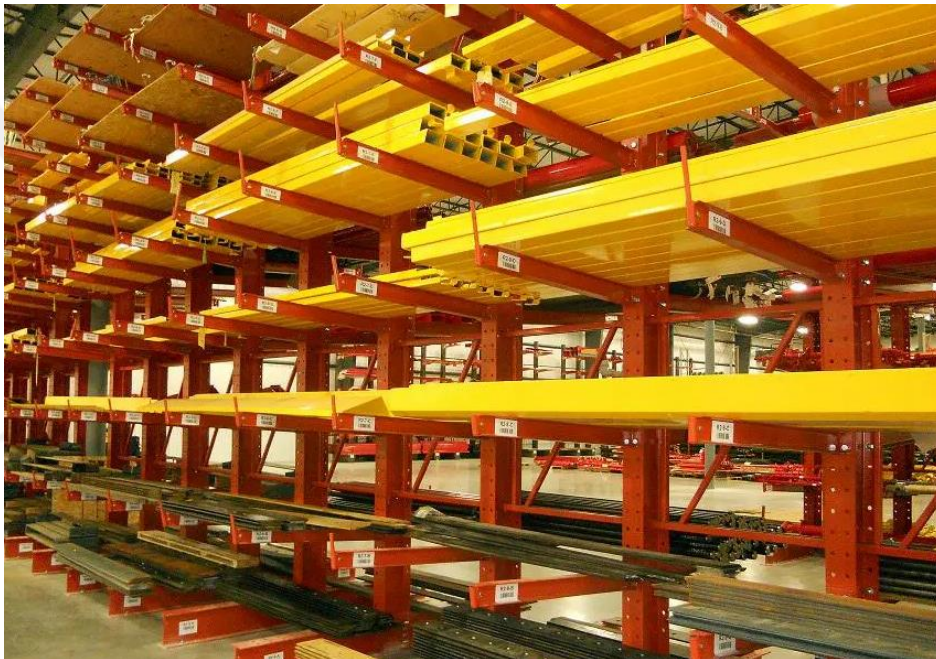
- High-density storage: it allows multiple pallets to be stored in a single bay.
- Improved safety: because forklifts don't enter the system, the columns are less exposed to damage.
- Time-saving: they require little to no maintenance
- FIFO inventory systems: it requires a first-in-last-out management system.
- Compatibility and adaptability

### Disadvantages of push-back racks

- Limited selectivity: only the pallets at the front can be easily accessible.
- The first in-last out (FILO) method is challenging to manage.
- Not suitable for large and heavy loads.
- Limited to 4-5 pallets deep.

## Cantilever Racking Systems

Cantilever racking systems are specifically designed to store long products and allow them to be removed without causing damage (Figure 5). They are designed to easily store and retrieve products with varying weights, lengths, and sizes. Cantilever racking systems do not require uprights, allowing for easy product accessibility and selectivity paired with high down-aisle density. The absence of uprights allows for clear product accessibility. Furthermore, cantilever racking systems exhibit a range of arm options by providing a full range of loading capabilities that can be customized to a storage application. Whether dealing with heavy-duty items or lighter loads, cantilever racking's adaptability accommodates a broad spectrum of inventory.



**Figure 5.** Cantilever racking system .

### Advantages of cantilever racking system

- It has a high storage capacity for products.
- Stored goods are easily accessible.
- Adjustable and customizable.
- Accommodates high capacity requirements.
- Increases vertical storage capacity.

### Disadvantages of cantilever racking system

- High cost compared to other storage options.
- Lower storage capacity.

- Requires a lot of floor space.
- Inefficient for storing palletized inventory.

### Flow Racking Systems

Flow racks also known as gravity racks, are a common choice for achieving high-density maximizing storage solutions for pallets in which loads move by gravity (Figure 6). Items are loaded at the upper end and retrieved from the lower end, utilizing a first-in, first-out (FIFO) system. The inherent design of flow racks facilitates automatic product rotation, synchronized with the continuous flow of loading and unloading. Gravity rollers form the core mechanism of flow racks enabling smooth movement of items. These rollers facilitate the movement of goods from one end of the channel to the other. Incorporated within the system are brakes or speed controllers, which regulate the pace of item movement. Dubina *et al.* an intrinsic advantage of flow racks lies in their self-powered operation, driven solely by the force of gravity. As a result, they do not necessitate electricity for their functioning.



**Figure 6.** Flow racking system .

#### Advantages of flow racking system

- It has high high-density storage system.
- It operates on the first-in first-out (FIFO) inventory management.
- It reduces labor costs.

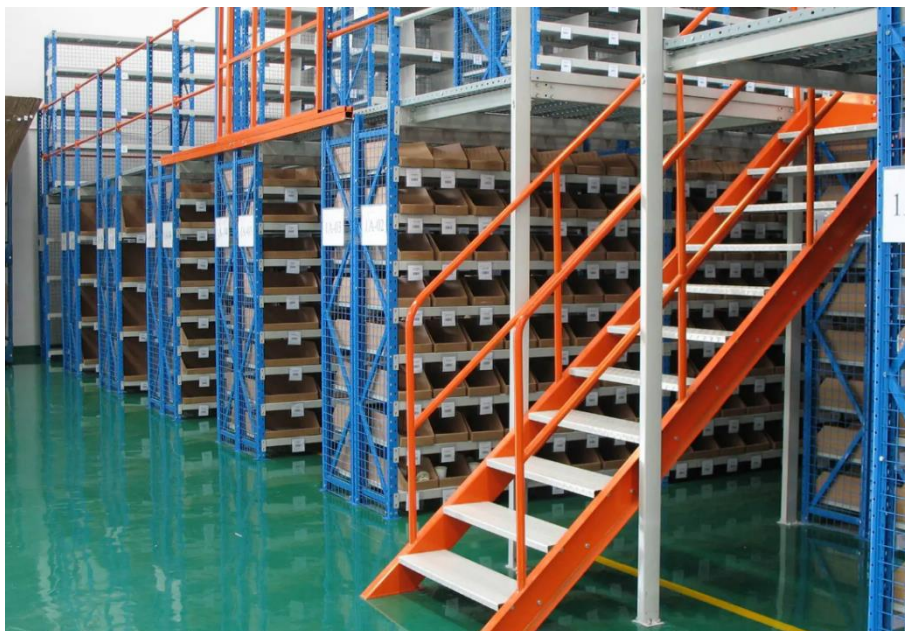
- Reduced safety risks.
- Can be customized.

#### Disadvantages of flow racking system

- More expensive than the other storage systems
- Require good pallet quality
- Require high maintenance
- Not ideal for first-in-first-out (FIFO) inventory

### **Mezzanine Racking Systems**

Mezzanine racking is also called pallet racking mezzanine or rack-supported mezzanine (Figure 7). The mezzanine racking system is to build an intermediate mezzanine on the existing workplace or rack to increase the storage space. They are suitable for accessing some lightweight and small-volume goods, and it is suitable for multi-variety high-volume or multi-variety small-volume goods. It is necessary to access the goods by hand, the goods are usually sent to the second or third floor by forklift, hydraulic lift, or elevator, then by light trolley or hydraulic pallet truck to a certain location. They usually use medium-duty or heavy-duty racks as the main body. The system typically consists of main rack structures and durable mezzanine floors made of materials like steel plates. The figure shows the mezzanine racking system.



**Figure 7.** Mezzanine racking system .

### Advantages of mezzanine racking system

- Increase space utilization
- Cost effective
- Versatile and bespoke
- Quick installation
- Reduced material handling

### Disadvantages of mezzanine racking system

- High cost
- Requires a lot of floor space

### Factors Affecting Storage Rack System Selection

Selecting the right pallet rack system for a warehouse or industry is crucial to maximizing storage space, improving efficiency, and increasing safety. Here are some factors to consider when selecting a pallet rack system highest rated cmms/eam .

1. **Storage density:** it should be designed to optimize available space, in warehouses or industries considering the height, width, and depth of pallets.
2. **Load capacity:** it should ensure that the rack system can support the weight, size, and shape of the product.
3. **Accessibility:** consider the frequency access for selective racks to reach the stored product or lower frequency for drive-in or push-back.
4. **Safety regulations:** they must meet the safety standards and regulations.
5. **Warehouse Layout:** the layout of the warehouse must be considered, including the location of the loading docks and, the size and shape of the building.
6. **Inventory Management:** need to understand the most appropriate rack system for inventory control that will be used to determine the right configurations in industries.
7. **Rack height:** the vertical space in the warehouse ceiling can hinder the height of the pallet rack, taller ceiling can increase storage density.
8. **Budget:** making a proper budget may play a vital role in the selection process for racks with different costs and rack maintenance.
9. **Future Expansion:** consider future growth by selecting a rack that can adapt to future expansions.

## Testing Standards of Beam-Column Connections in Racking Systems

When designing racking systems, it's essential to carefully study the relevant standards and codes that apply to your location and the intended use of the racking system. Compliance with these standards helps ensure the safety of personnel, the integrity of stored goods, and the longevity of the racking system. Below Table 1, Table 2, Table 3, Table 4, and Table 5 are some of the recognized code standards in the design of industrial racking systems.

**Table 1.** Rack Manufacturers Institute (RMI 2012)

Roles	Documents
Guidelines for rack design	Provide guidelines for Seismic design and load application.
Guidelines for rack testing	Provide information on load capacity, configuration, and safety factors.
Guidelines for rack installation	Designing efficient and safety consideration racking systems.
Guidelines for rack maintenance	Maintenance of industrial steel storage racks.

**Table 2.** Rack Manufacturers Institute (ANSI MH16.1 2012)

Roles	Documents
Guidelines for rack design	Provide design criteria and load factors of steel pallet racks.
Guidelines for rack testing	Provide procedures for testing beam-column connections.
Guidelines for performance criteria	Deformation, load-carrying capacity, and safety factors for steel pallet rack components.
Guidelines for material specification	Quality and specification materials in steel storage racks.
Guidelines for inspection and maintenance	Inspection, maintenance, and repair of pallet racks to ensure the safety of the structure.

**Table 3.** American Institute of Steel Construction (AISC 358-16 2016)

Roles	Documents
Focuses on seismic moment frames	Testing procedure via cyclic loading under seismic forces.
Guidelines for testing requirements	Monotonic and cyclic testing of beam-column connections.
Guidelines for Connection Classification	Categorizes connections into various classes based on the performance during testing.
Guidelines for performance factor	Provide parameters to measure energy dissipation in seismic regions.

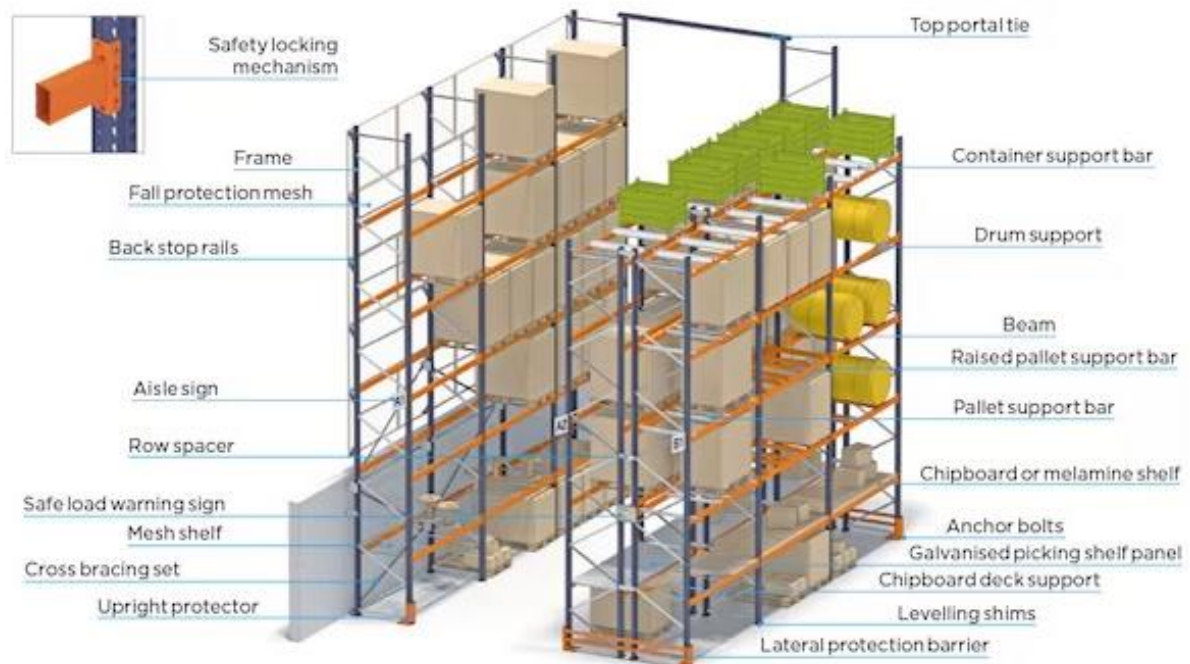
**Table 4.** Design of Steel Structures (Eurocode 3 EN 1993-1-8 2005)

Role	Documents
Guidelines for design methods	Provides design methods for bolted, welded, and moment-resisting connections.
Guidelines for loading	Cover seismic guidelines during the designing of components of the rack.
Guidelines for material considerations	Offers guides on selecting appropriate materials and their properties.
Guidelines for Analytical Methods	Offers methods for calculating the behavior and capacity connections under various loading conditions.

**Table 5.** Adjustable Pallet Racking Systems (EN 15512 2020)

Roles	Documents
Guidelines for the design	Design of adjustable pallet racking, drive-in racking, and cantilever racking systems.
Guidelines for calculation	Calculation of adjustable pallet racking systems with braced or unbraced.
Guidelines for safety	Safety of storage systems that work with handling equipment.
FEM 10.2.07 The Federation of European Material Handling (FEM)	Guideline for design, testing, materials, and installation racks.
IBC	Guideline for structural design, fire safety, and installation of steel pallet racks.
ISO 15629	Provide specifications for the design and testing of steel pallet racks.
SEMA Codes	Guideline for design, installation, and safety of rack components.

### Components of Rack Structure and Their Function



**Figure 8.** Components of rack structure .

## Frame

Save as vertical support and made of columns, bracings, and base plates (Figure 9). These features are critical to ensure the safety and performance of frames.

### Static Properties for Frame

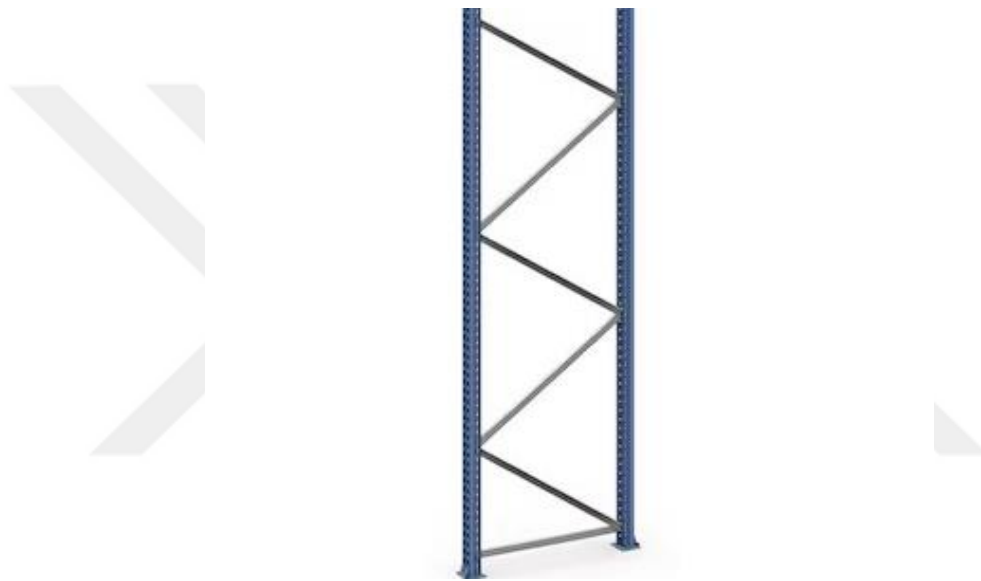
Strength: Must be resistant to high tensile, compressive and shear forces.

Stiffness: Provides resistance to deformation, increases stability.

Stability: Maintains structural integrity against horizontal loads.

Load Distribution: Uniform distribution of loads prevents overloading.

Rotational Resistance: Resists rotational movements.



**Figure 9.** Frame component .

## Beam

They are horizontal support that holds pallets or support shelvings on which goods are stored (Figure 10). The static properties of beams such as high strength, rigidity, moment resistance and wear resistance are critical to ensure the safety and performance of structures. As stated by Bernuzzi *et al.* these beams are typically designed in box, hat, or channel sections. They play a crucial role by providing both high moment capacity and adequate bending stiffness with the ability to handle bending forces.



**Figure 10.** Beam component.

## **Bracings**

These components act as horizontal and vertical support, enhance stability, and prevent swaying of pallet racking (Figure 11). In the cross-aisle direction, manufacturers in Australia and Europe often utilize bolted connections between the cross-aisle bracing and columns, whereas manufacturers in the United States typically utilize welded connections. Godley *et al.*. However, connections in the down-aisle direction are not braced, due to the lack of bracing in the down-aisle direction that enables quick access to stored goods Kozłowski *et al.* and Bajoria *et al.* .

### Sample Profiles for Bracing

These profiles are used to increase the stability of structures.

**Steel Bar (Rod):** High tensile strength, effectively carries tensile and compressive forces.

**Corner Profile (L-Section):** Provides high rigidity, effective for diagonal bracing.

**C Profile (Channel Section):** Light and easy to apply, carries tensile and compressive forces.

**Z Profile:** Ideal for light applications, provides two-way support.

**Rectangular/Square Hollow Section (RHS/SHS):** Resistant to both tensile and compressive forces.

**I-Profiles (Wide Flange Beams):** Suitable for carrying large structural loads with high moment strength.



**Figure 11.** Bracings .

### **Columns**

A vertical structure component that supports the weight and size of pallet racking. Columns in storage racks are typically made from cold-formed steel, although various profiles such as traditional hot-rolled profiles and tubular hollow sections can be utilized (Figure 12). According to Shah *et al.* the thickness of these columns generally varies between 1.5 mm and 3 mm which is relatively smaller compared to the overall height of the column. Due to the column's high slenderness and the presence of perforations, the critical elastic flexural and flexural-torsional (global) buckling loads of these columns are lower than those of unperforated columns, as noted by Cristopher *et al.* and Hancock *et al.* that the presence of perforations and the slender nature of columns impact their buckling behavior and the factors affecting the structural stability of the columns need to be considered during the design period.



**Figure 12.** Column component.

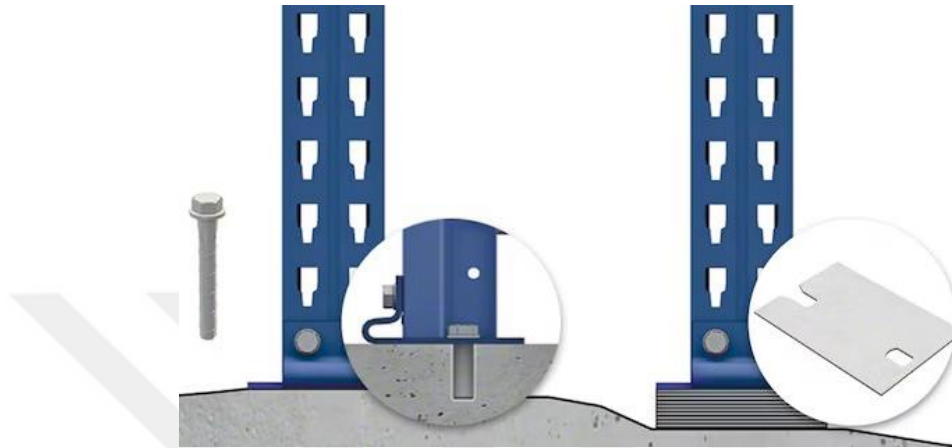
### **Suitable Column Profiles**

These profiles ensure strength, stability, and efficient assembly in storage rack systems.

- **Box Section :** High load capacity and torsional rigidity, ideal for strong, stable columns.
- **I-Profile:** Excellent bending resistance and strength-to-weight ratio for heavy-duty applications.
- **C-Profile:** Lightweight and easy to handle, suitable for light to medium loads.
- **Z-Profile:** Efficient material use and compact design, great for space optimization.

## Shims

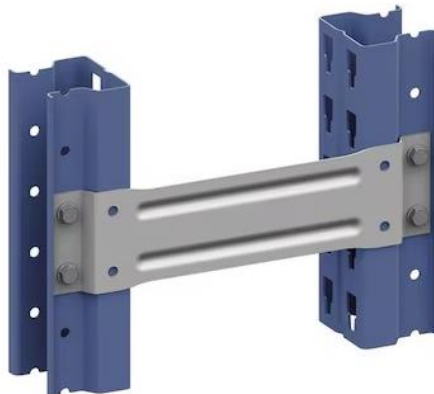
They are used when the columns are resting on uneven floors to ensure proper support. They are made of various materials such as wood, composite materials, metal, and plastic (Figure 13). Shims fill the gaps between the connecting elements, provide alignment and increase rotational rigidity. It has high load-carrying capacity, precise thickness and resistance to shear. By reducing stress concentrations, they improve connection performance.



**Figure 13.** Shims .

## Row Spencers

Row Spencers are used to join two uprights to give the pallet rack strength and steadiness (Figure 14). Row spacers increase the stability of the system by maintaining the distance between columns in racking systems. It has mechanical properties such as high compressive and tensile strength, bending resistance, ductility and rigidity. It should be resistant to corrosion and have high resistance to deformation.



**Figure 14.** Row spacer .

## **Baseplates**

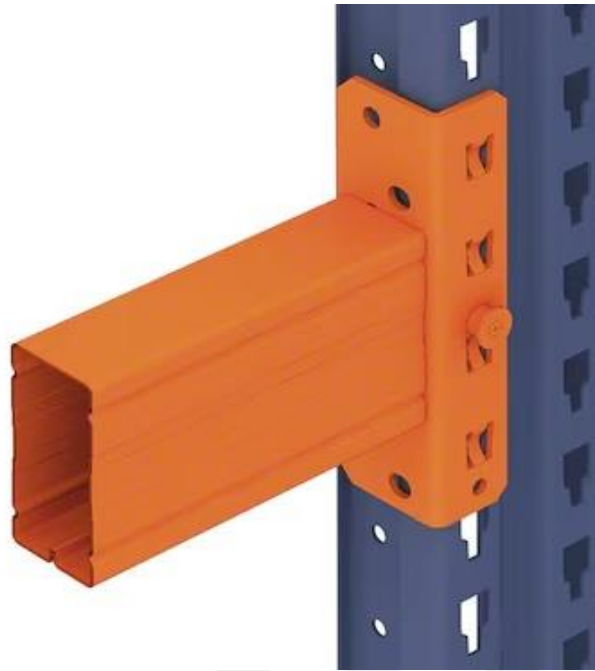
Godley baseplate connections play a vital role in ensuring the stability and overall performance of the rack structures and serve as anchors at the base of the upright (Figure 15). Base plates (anchor plates) provide the connection of structural elements to the foundation and generally have thicknesses ranging from 5 mm to 25 mm. High strength and stiffness reduce the risk of bending and deformation and they also provide protection against corrosion.



**Figure 15.** Base plate.

## **Locking Devices**

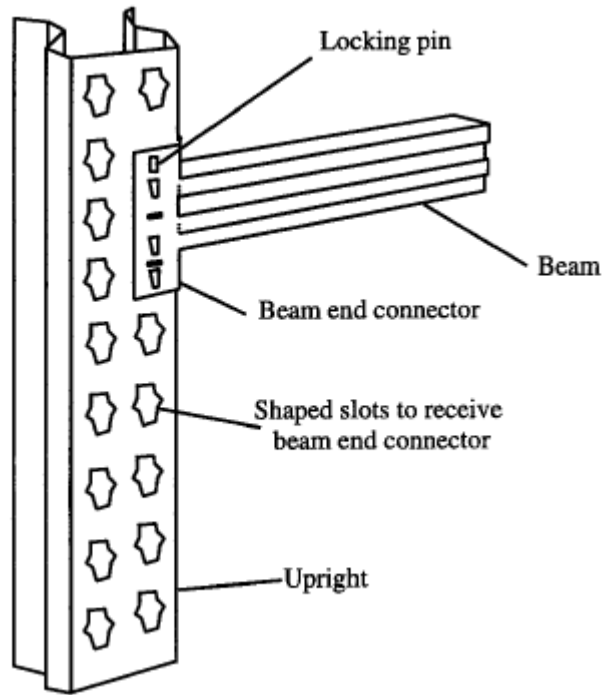
They prevent the beam from disengaging from the column's perforation (Figure 16). Locking devices have static properties such as high load carrying capacity, rotation and shear resistance, and wear resistance. These properties are critical to ensuring the safety and long life of the connections.



**Figure 16.** Locking devices .

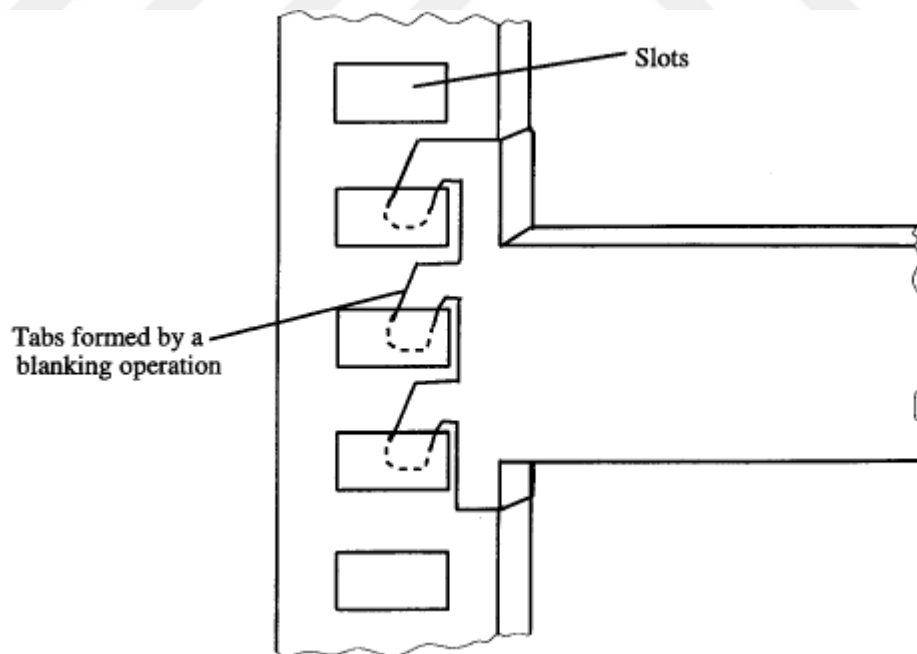
Beam-end connectors are boltless semi-rigid connections utilized in racking systems, beam-end connectors are welded to the beam manufactured from a hot rolled alloy of steel. They play a crucial role in beam-to-column connections, enabling the transfer of loads and ensuring the stability and integrity of a structural system. Typically, tabs are employed as connectors, which are inserted into perforations on the uprights with the aid of safety pins Markazi *et al.* the performance of storage rack systems depends on the efficiency of the beam end connector which provides support to the beam. As stated by Çirpici *et al.* beam-end connectors enable the disassembly and reassembly of beam-column connections in storage rack systems. Additionally, Merkazi *et al.* classified beam end connector design into the following categories, and conclusions were listed.

**Tongue and slot design:** It is the cantilevered tab which is formed and punched out the brackets, it has an integral tab, and when used, allows the beam end connector to establish contact with both the column's web and flange (Figure 17).



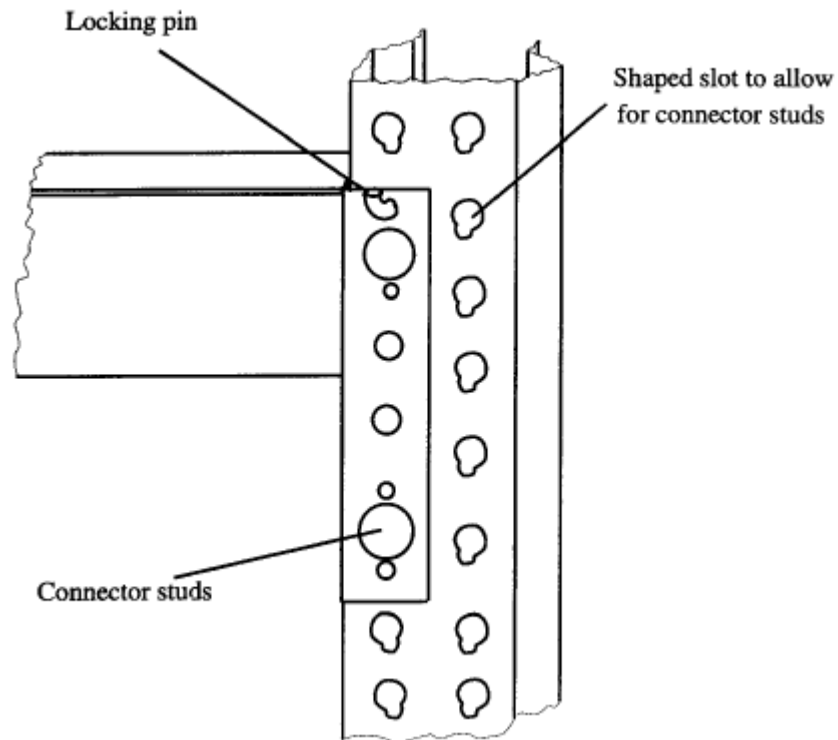
**Figure 17.** Tongue and slot design (Markazi *et al.* 1997).

**Blanking design:** Generates tabs based on the configuration of the upright, these tabs engage either parallel or perpendicular to the column web (Figure 18).



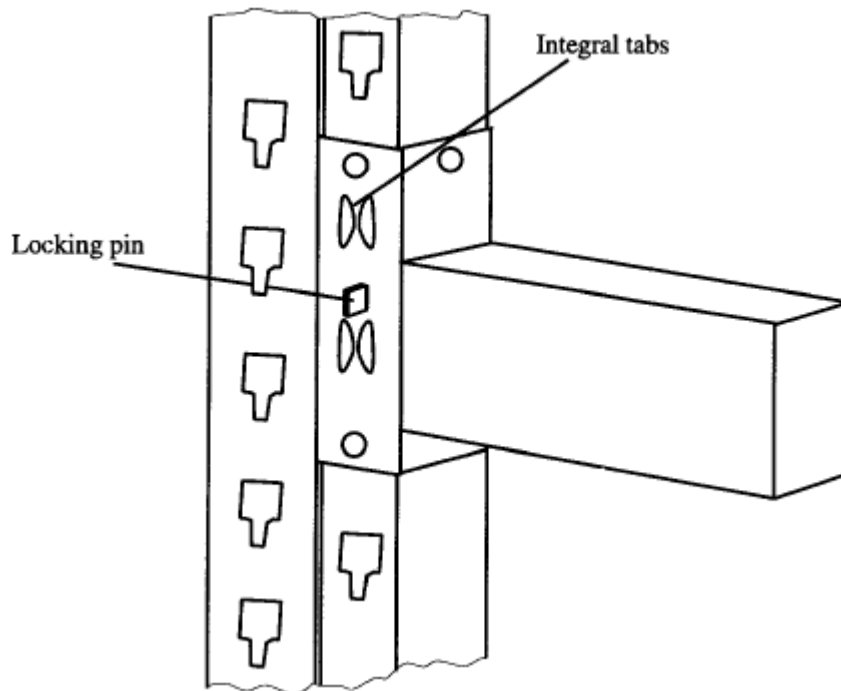
**Figure 18.** Blanking design (Markazi *et al.* 1997).

**Stud-incorporated design:** Here studs replace the tab used in the tongue and slot design, when in use the beam end connector makes contact with both column's web and flange (Figure 19).



**Figure 19.** Stud-incorporated design (Markazi *et al.*1997).

**Dual integrated tab design:** Tabs are formed and punched out of the bracket and remain attached to the bracket at two points. The beam end connector establishes contact with both the column's web and flange (Figure 20).



**Figure 20.** Dual-integrated tab design (Markazi *et al.* 1997).

Pekoz and Winter emphasized the effective utilization of steel pallet racks requires flexibility in the material constituting them for convenient adjustments and reconfiguration of rack elements as needed. Kozłowski and Ślęczka recommended cold-formed steel due to its peculiar structure. However, when racks have to support heavy loads, AS4084 permits the utilization of hot-rolled steel.

### **Tab Configuration in Steel Storage Racks**

In the construction of steel structures, critical decisions are made about the type of connections to be used. Tab configuration of beam-column connections plays a vital role in steel pallet racks as it impacts the behavior and performance of pallet rack structures in warehouses or industries. There are three main tab configurations commonly used in beam-column connections in steel storage racks such as bolted connections, boltless connections, and welded connections.

#### **Bolted Connections**

Bolted connections involve the use of bolts or nuts to connect structural members. There has been a notable development in the use of bolted connections in industries, research to clarify their behavior has been reported by Yin *et al.*, Rasmussen and Gilbert and Zhao *et al.*. It has been observed that to better understand the behavior of storage rack systems, experimental studies should be carried out on combination models where bolts and tabs are used together Figure 21.

##### Advantage of bolted connections

- Costs: it's less costly
- Easy to repair: easy to repair damaged
- Cheaper to ship
- Better for seismic consideration
- Customization /more flexible



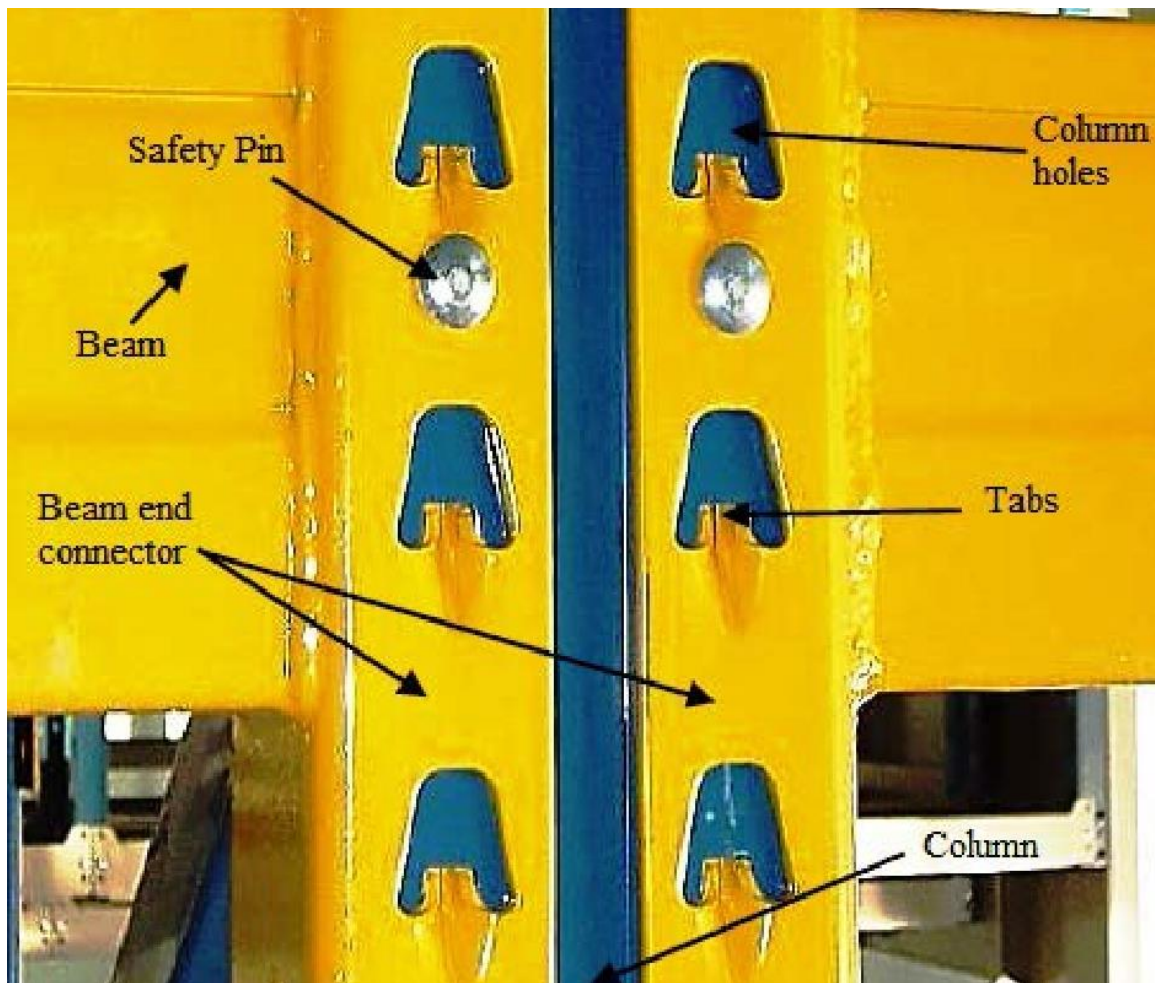
**Figure 21.** A typical bolted connection .

### **Boltless Connections**

These boltless connections are considered semi-rigid connections, this form of tab configuration involves the use of connectors that are welded at the end of the beam as reported by Shah *et al.* and Markazi *et al.* . These connectors have tabs that provide support to the connections of the structure (Figure 22). The loads on the beam are transferred to the connectors, and the loads on the connectors are transferred to the columns and from there to the ground through tabs.

#### Advantage of boltless connections

- affordability
- easy to assemble
- it's flexible
- it has high strength and durability
- it's easy to Access



**Figure 22.** A typical boltless connection (Shah *et al.* 2017).

### **Welded Connections**

As noted by Godley *et al.* cold-formed steel pallet racks are commonly used in industry, in the United States the upright is made by welding base plates and braces to the upright as discussed by Pekoz *et al.* (Figure 23).

Advantages of welded connection

- It has high strength
- It's a permanent part of the pallet rack
- Durability
- It's a safe and clean structure
- It requires less maintenance



**Figure 23.** A typical welded connection .

#### **Benefits of Tab connectors in Steel Pallet Racks**

- Easy to fabricate and assemble.
- Versatile to connect all the components of the rack structure.
- Resists fatigue and corrosion under various environmental conditions.
- High ductility to withstand seismic forces.
- It helps to maintain structural stability and integrity.

## **Common Tests Used in Beam-Column Connections of Steel Storage Racks**

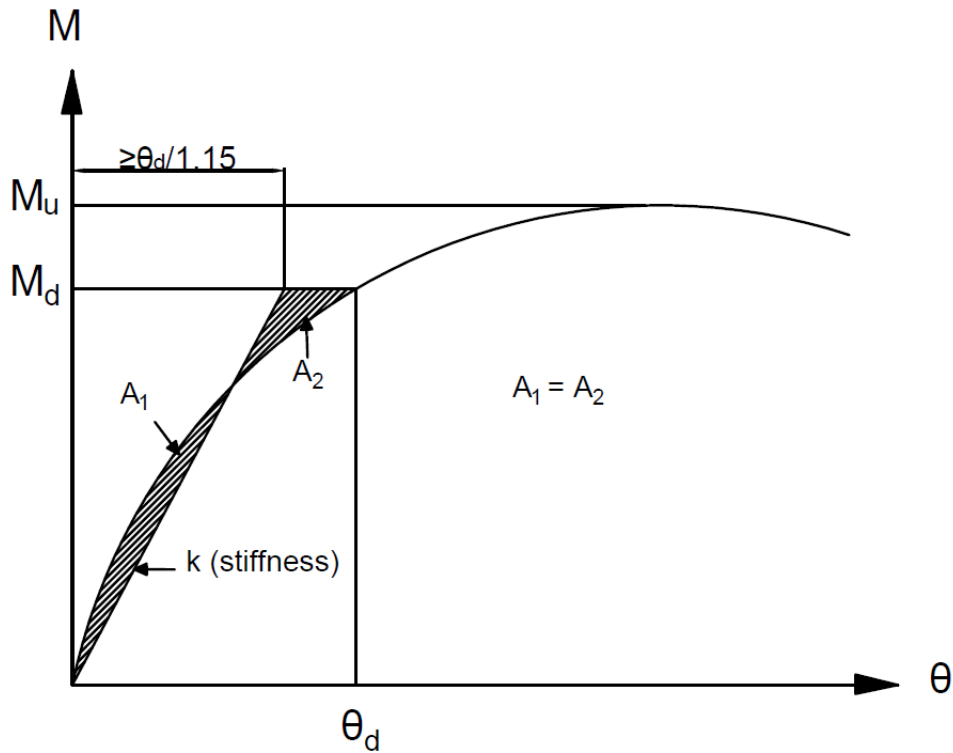
Before conducting experiments, it is important to thoroughly plan and design testing procedures to obtain accurate and meaningful results. This will help engineers understand the behavior and performance of beam-column connections in steel storage racks, ensuring structural integrity and safety in storage system designs. The following are the common tests used in beam-column connections of steel storage racks European Standard .

- ✓ Cantilever test ( monotonic and cyclic test)
- ✓ Finite element analysis
- ✓ Full-scale rack system testing
- ✓ Shake table testing
- ✓ Push-over test
- ✓ Portal frame test
- ✓ Component method test
- ✓ Thermal and fire resistance testing
- ✓ Compression and tension test
- ✓ Stub column test

## **Literature Review of Beam-Column Connections**

While tabs in beam-end connectors improve the rapid re-assembly of structures, the varying geometries and configurations of commercially available beam-end connectors constitute a challenge to establishing a generalized design approach for predicting the structural behavior of beam-end connectors. This challenge arises from their semi-rigid behavior, primarily attributed to the tab being hooked into the column, predicting the structural response through theoretical means is challenging. As a result, the commonly used design codes such as Australian Standards, European Standard, and RMI recommend conducting experimental tests on beam-end connectors to accurately predict their moment-rotation ( $M-\theta$ ) behavior. Beam-to-upright connections play a key in influencing the overall structural behavior of racks.

The initial rotational stiffness and the moment capacity are critical parameters in the moment-rotation relationship according to the European Standard. It defines rotational stiffness as a connection utilized for design purposes is established by determining the slope of a line originating from the origin. This line is positioned to isolate equal areas between itself and the moment-rotation curve, particularly below the design moment. This design moment is further adjusted for factors such as yield strength and material thickness (Figure 24).



**Figure 24.** Derivation of connector stiffness (Çirpici *et al.* 2022).

where;

$M$ : moment

$\theta$ : Rotation

$M_U$ : Ultimate moment

$M_\theta$ : Design moment =  $0.5 M_U$

Several literature have conducted studies on cold-formed steel connections, but very little research has been conducted regarding the investigation of beam-column connections. To analyze the performance of steel pallet racks of beam-column connections under monotonic loading, researchers have carried out both experimental and numerical investigations.

Markazi *et al.* conducted a comprehensive study in which they categorized beam-end connectors into four primary types. From their experimental finding, they examined various design parameters such as beam size, welding positions of the beam to the connector, and height ratio of the beam-end connector to the beam profile. In their research, they aimed at the characteristics of different types of beam-end connectors utilized in steel pallet racks. They emphasized that critical design parameters for steel pallet racks of beam-column connections

include the number of tabs on the connector, detailed geometry of the connector tabs, bracket design, and gauge of both the beam-end connector, column and profile of the column.

In another study, Markazi *et al.* conducted a numerical analysis of commercially available beam-end connectors and studied the structural behavior of beam-column connections using computational methods. Their conclusion highlighted that both experimental and numerical methods offered insight into the design criteria for connectors.

In 1997 Godley conducted a study to establish the demand for the ductility of beam end connectors and proposed the required minimum rotation of connectors that allows plastic design for beams. The formulated equations were for braced racks and unbraced racks, the plastic mechanism should be calculated as follows:

$$\text{For braced racks: } \theta = \theta_D = \frac{L}{6EI} (2M_{CU} - M_{BU})$$

$$\text{For unbraced racks } \theta_R = \phi + \frac{L}{6EI} (2M_{CU} - M_{BU})$$

where;

$L$ : Length of the beam

$E$ : Elasticity modulus

$I$ : Second moment of inertia of the beam

$M_{CU}$ : Ultimate moment of the beam

$M_{BU}$ : Ultimate moment of the beam end connector

$\theta_D$ : ductility of the beam end connector

$\phi$ : Sway rotation equal to 0.02 Rad

Sarawit and Pekoz conducted an experimental investigation by focusing on the column bases, beam-to-column connections, and members. The results showed that determining the average stiffness of connectors during frame sway and pallet loading improves accuracy in portal frame tests compared to cantilever tests for side sway behavior evaluation (Figure 25, Figure 26, Figure 27).

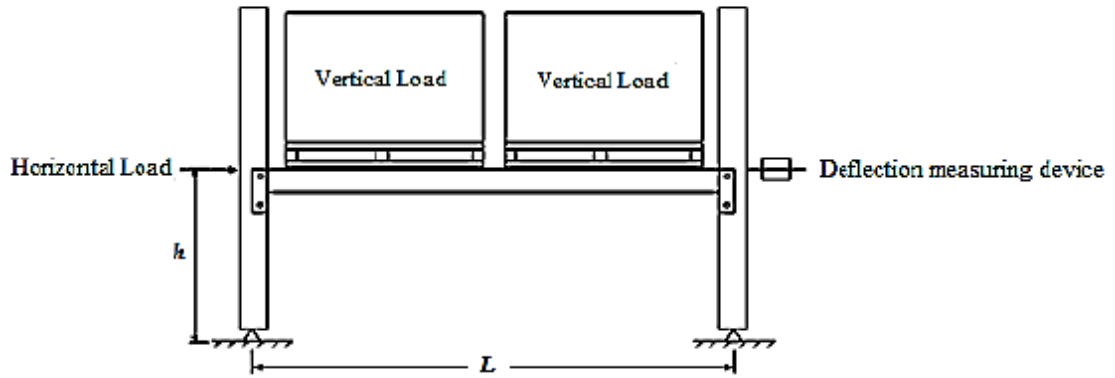


Figure 25. Portal frame test.

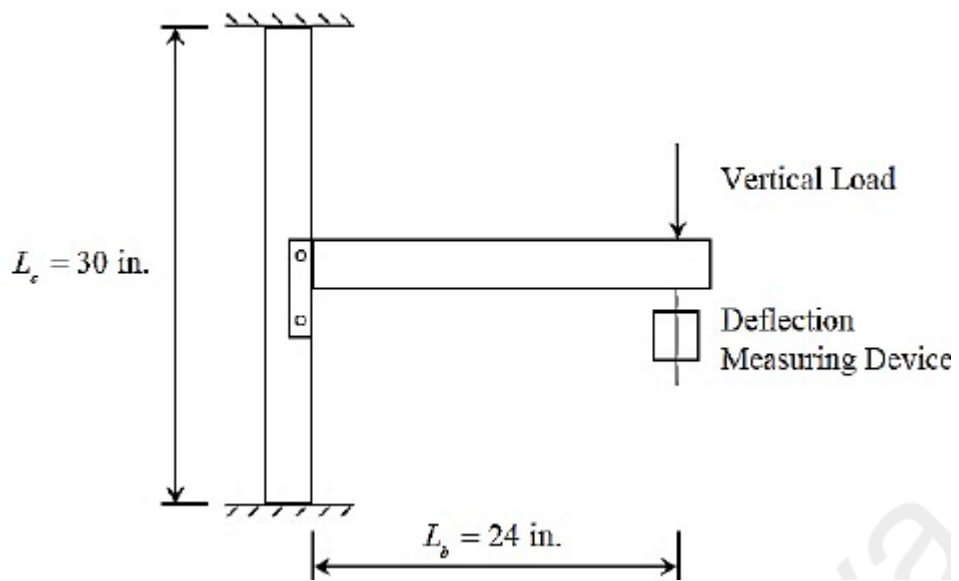


Figure 26. Cantilever test .

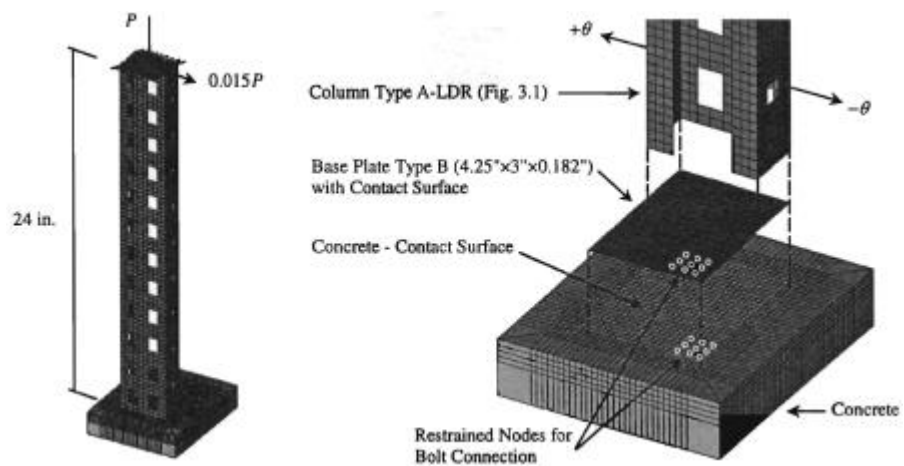
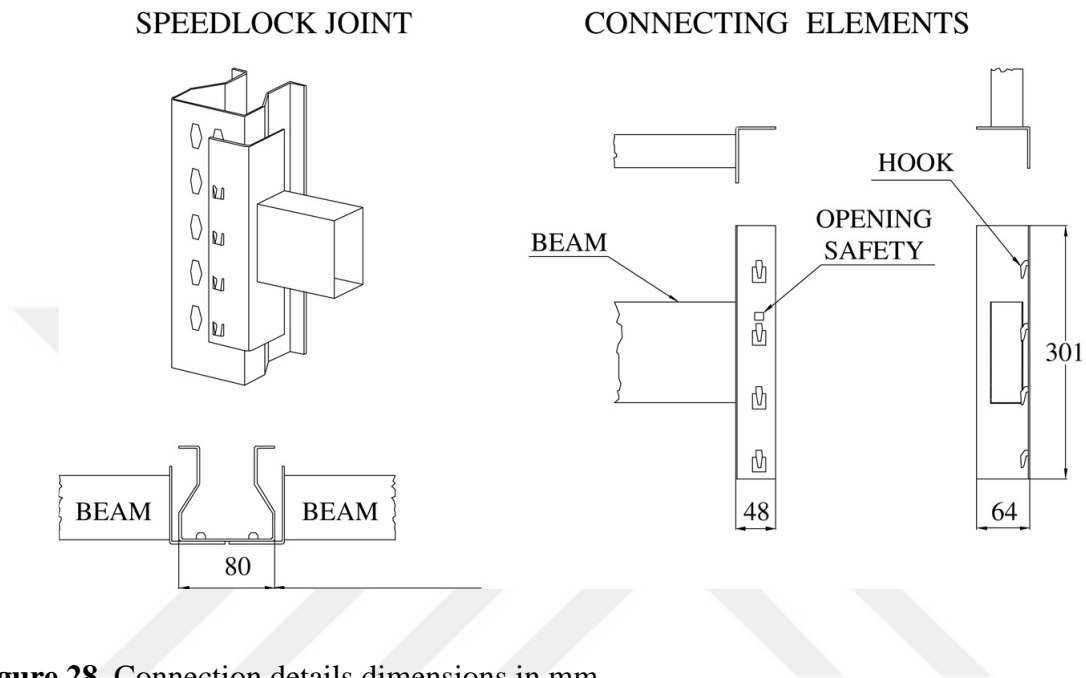


Figure 27. Column Base Finite Element Model .

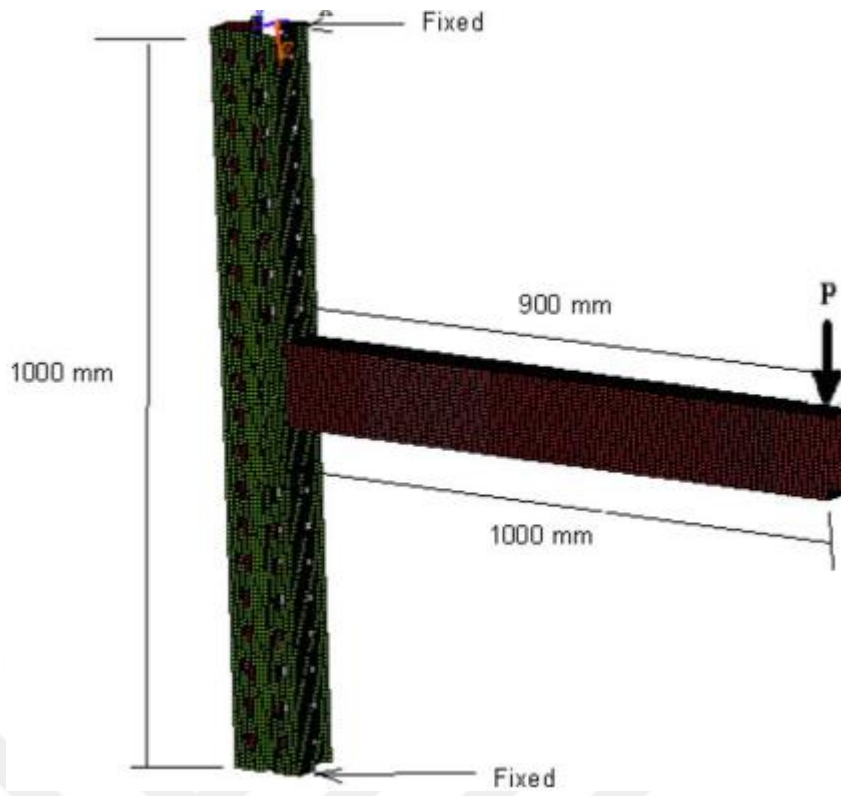
Aguirre researched experimental results of beam-column connections subjected to both static and cyclic loading conditions. Failure modes were observed during static and cyclic loading tests. This similarity indicates that the failure mechanism is primarily influenced by the performance of the tabs within the connection and the failure occurs at the beam segment (Figure 28). Additionally, when the beam failed, the tabs acted as protective mechanisms that prevented the critical failure of the column.



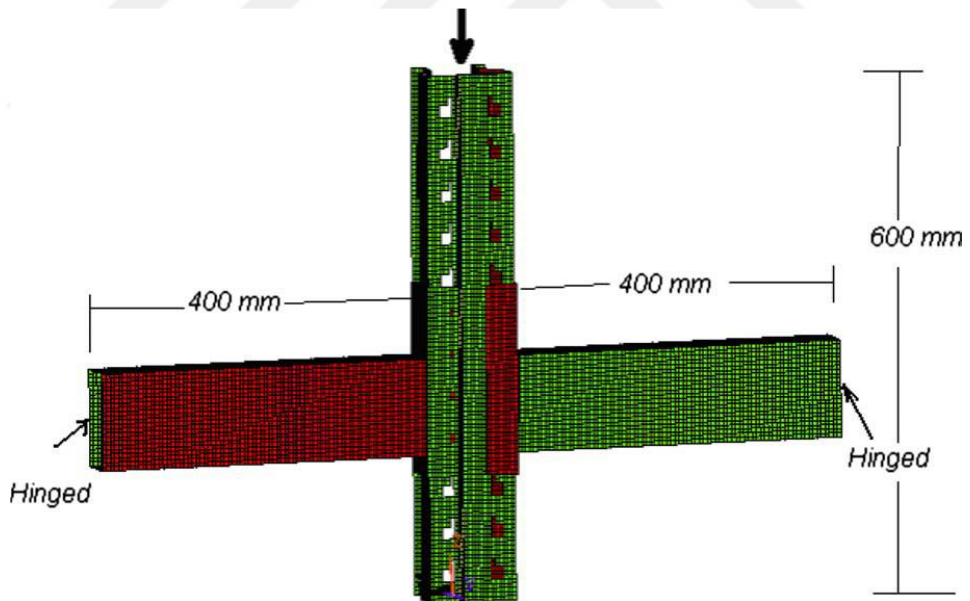
**Figure 28.** Connection details dimensions in mm .

Abdel-Jaber *et al.* carried out monotonic and cyclic tests on cantilever beam-column connections and portal frames. They observed flexibility of the stub beam has introduced errors of up to 4% in the moment-rotation relationships. Equations were introduced and the errors were subsequently corrected. The correction equations developed in this study were essential for assessing the rotational stiffness of beam-end connectors. The experimental results in this study enabled the moment at the connection and sways to be measured.

Bajoria and Talikoti investigated the flexibility of beam-column connectors in steel storage racks via single and double cantilever test methods. The connector in the double cantilever was subjected to three types of forces namely moment, shear, and the axial pull exerted by the beams as illustrated in (Figure 29, and Figure 30). The experimental results were compared with non-linear finite element analysis. The findings indicated that the double cantilever test method showed slightly better results in comparison to the results obtained from full-scale testing.

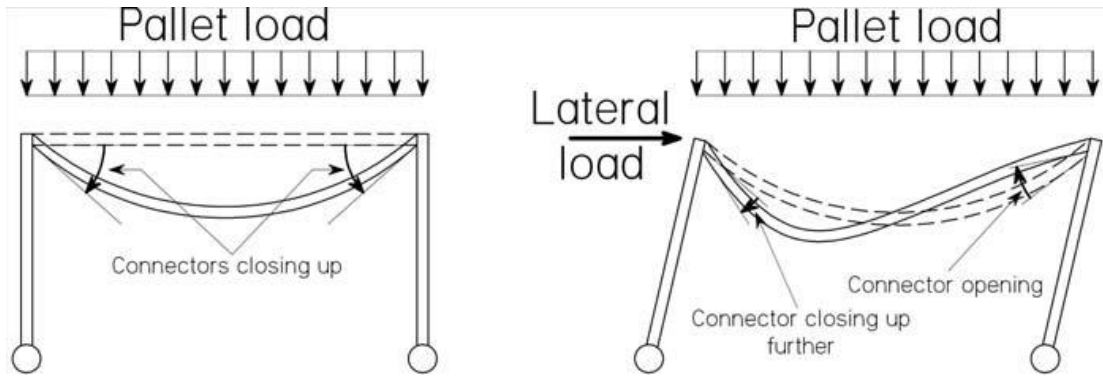


**Figure 29.** Finite element model of cantilever test .



**Figure 30.** Finite element model of double cantilever test .

Harris conducted both the cantilever test and portal test compared the two results from the experimental setups and observed that the connector stiffness values taken from the cantilever test were generally half of those obtained from the portal frame test. This was due to the closing-opening effect of the connector within the portal frame test (Figure 31).



**Figure 31.** Portal frame test deformation (a) application of pallet load and (b) application of lateral load

Sleckza and Kozlowski studied the component method to analyze boltless connections in steel storage racks (Table 7 and Table 8). They investigated five distinct types of joints and identified deformable components in the connections. The researchers derived equations to compute initial stiffness and moment resistance from the experimental results. Their conclusion highlighted that the component method enhanced the understanding of the structural behavior of boltless connections in steel storage racks.

**Table 6.** Comparison of Experimental and Numerical Initial Stiffness (Sleckza *et al.* 2007)

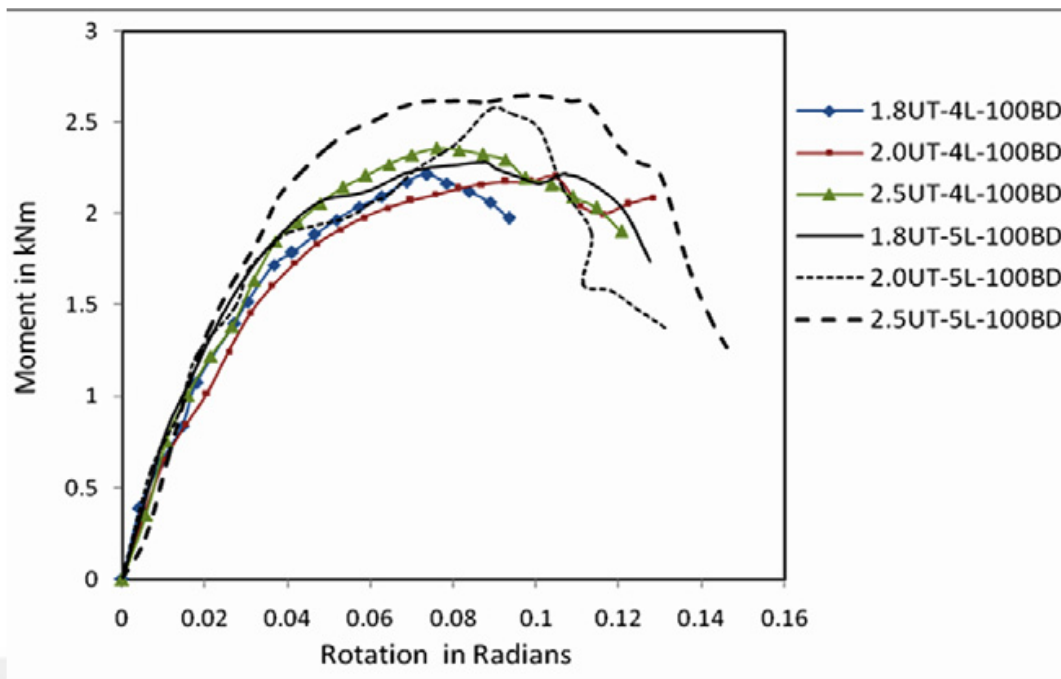
	Test results [KNm/rad]	Component method [KNm/rad]	Difference (component-test)/test [%]
Group “B”	139.40	98.2	-29.6
Group “C”	116.70	93.6	-19.8
Group “D”	71.35	93.3	-30.7
Group “E”	123.06	100.4	-18.4
Group “F”	96.15	95.3	-0.8

**Table 7.** Prediction of the Plastic Flexural Resistance and Comparison With Experimental Data (Sleckza *et al.* 2007)

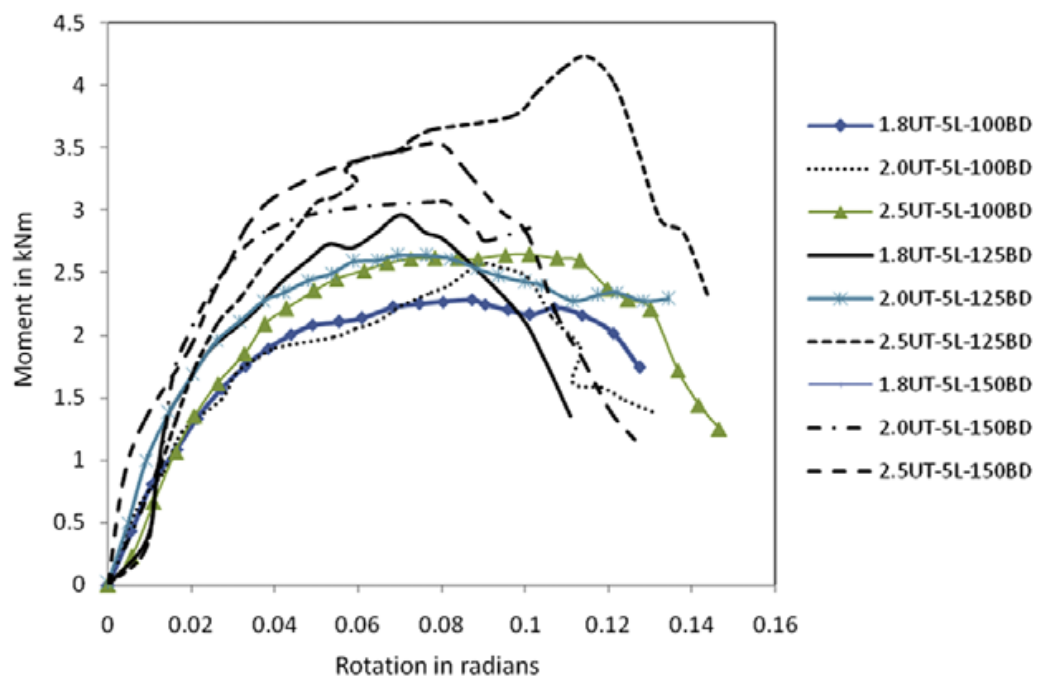
	Test results [KNm/rad]	Component method [KNm/rad]	Difference (component-test)/test [%]
Group “B”	3.19	2.95	-7.5
Group “C”	3.36	2.49	5.5
Group “D”	3.10	2.95	-4.8
Group “E”	3.20	3.13	-2.2
Group “F”	3.37	3.13	-7.1

Godley and Beale investigated the impact of looseness on the stiffness and load-bearing capacity of upright frames in pallet rack structures. Their investigation focused on how the looseness in the connections of the frames affects the overall structural behavior and they suggested that when analyzing and designing rack structures it's vital to account for the effects of looseness. They proposed that the initial out-of-plumb condition caused by the looseness should be considered.

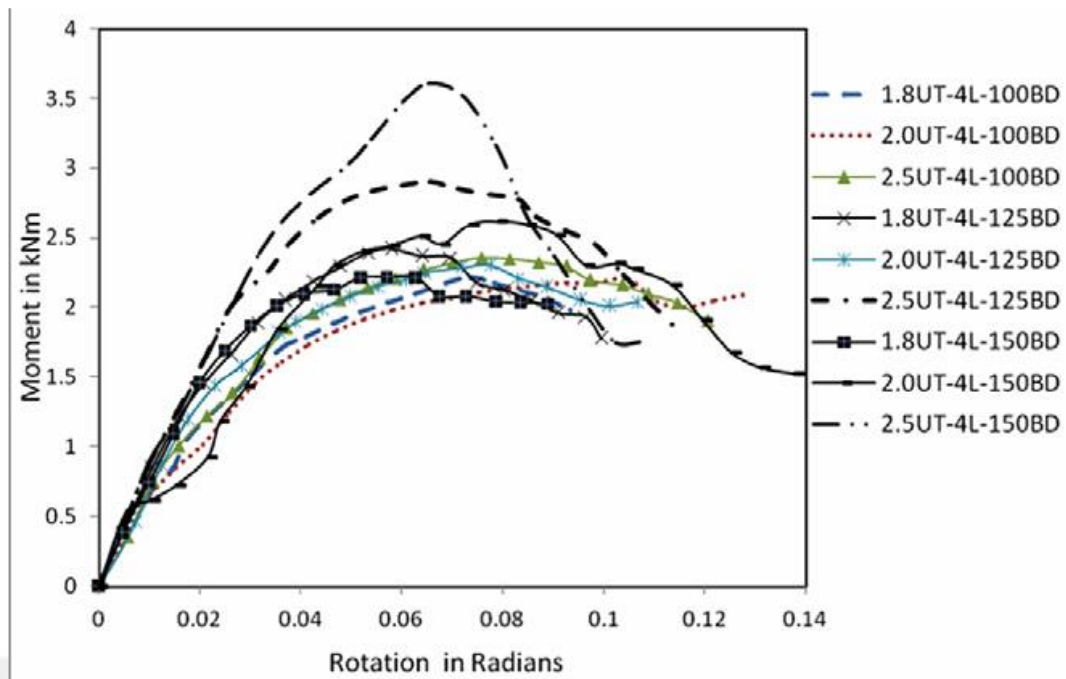
Prabha *et al.* conducted experiments using a double cantilever test method by varying the most influential parameters such as the thickness of the column, the depth of the connector, and the depth of the beam (Figure 32, Figure 33, Figure 34). Their findings showed that increasing the number of tabs significantly enhanced the stiffness and strength of the beam end connector. Furthermore, increasing the depth of the beam and the thickness of the column improved the strength and stiffness of the joint. In the same research probha *et al.* introduced two analytical models to calculate the stiffness of boltless semi-rigid pallet rack connections made from cold-formed materials. The first one was a polynomial model by the Frye-Morris approach and the second model was a power model. They concluded that the polynomial model effectively calculated the initial stiffness of the tested connections particularly within linear design parameters. The power model predicted the ultimate of the connection.



**Figure 32.** Effect of four and five-lipped connectors on the behavior (100 mm beam depth) (Prabha *et al.* 2010).



**Figure 33.** Comparison graphs for varying column thickness and beam depths for a 5L/C (Prabha *et al.* 2010).



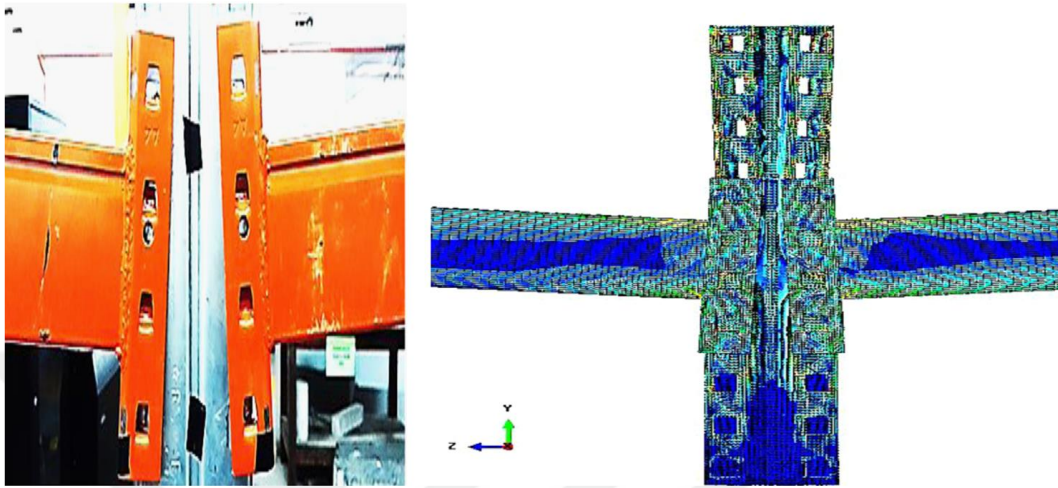
**Figure 34.** Comparison graphs for varying column thickness and beam depths for a 4L/C (Prabha *et al.* 2010).

In a study conducted by Zhao *et al.*, monotonic experimental tests were carried out to investigate the flexural behavior of connections under hogging loading conditions. The tests were performed under a single cantilever testing method. Various features of beam-column connections with different construction details were investigated. Several connections were examined, each having a distinct character such as the profile of the upright, the thickness of the upright, the connector, and the number of tabs in the connector. The study results highlighted that the failure mode of beam-column connections was influenced by the relative thickness between the upright and the beam-end connector.

Prabha *et al.* conducted a single cantilever and investigated the influence of the upright's profile and the thickness, depth of the beam, and connector on the moment-rotation behavior, and connection stiffness. Their findings concluded that connection performance was achieved by using a connector with several numbers of tabs, greater thickness, and improved profile of the upright and larger depth of the beam.

Shah *et al.* carried out a Finite Element (FE) analysis to understand the behavior of steel pallet racks of beam-column connections validated their experimental findings and investigated additional parameters. They examined the effects of parameters that weren't directly tested during their experiments. Their investigation concluded that increasing the size of parameters increased the stiffness of the connection at a higher rate as compared to the

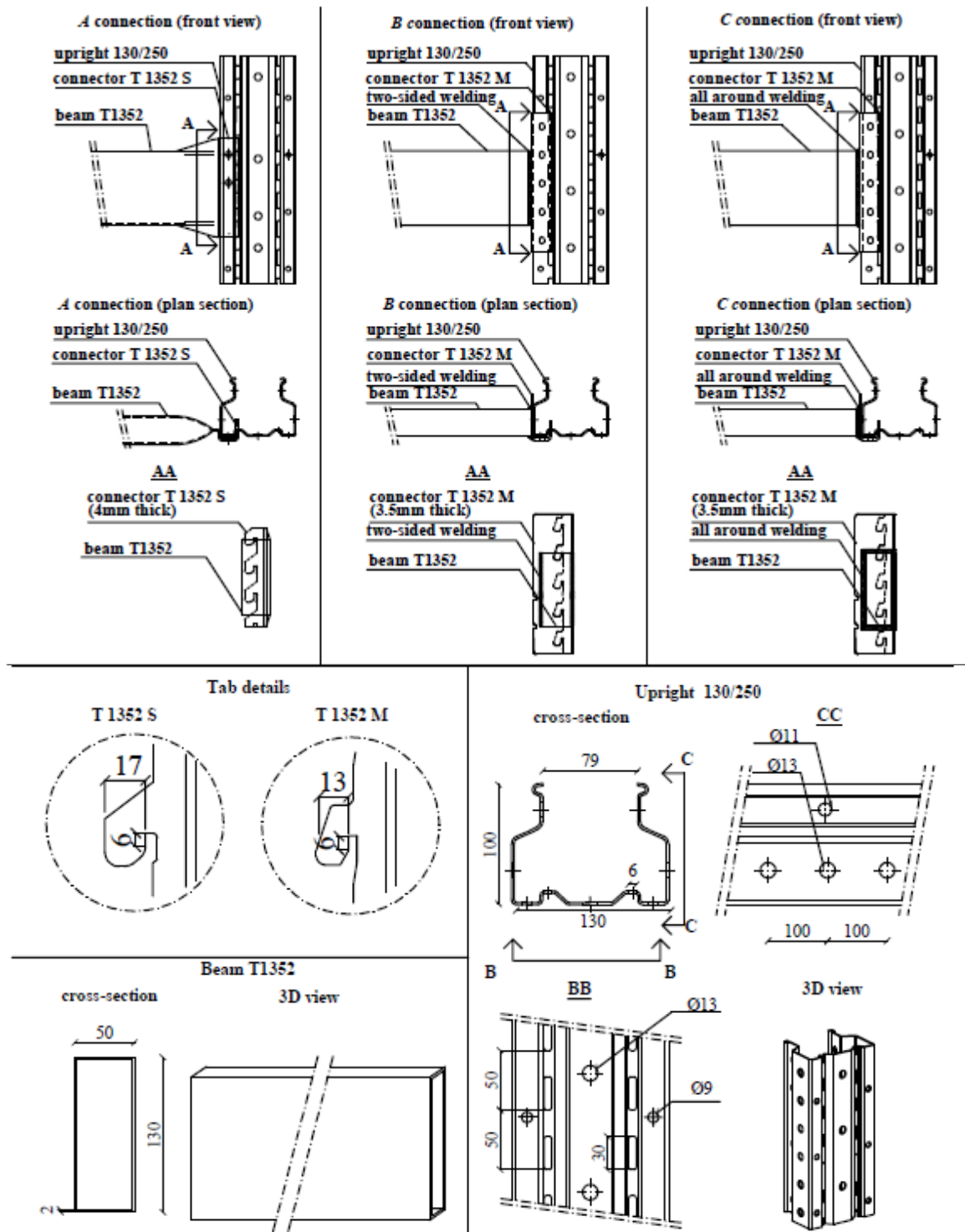
strength. This suggests that the elastic properties of beam-column connections in steel pallet racks are strongly dependent on their geometrical parameters (Figure 35). Shah *et al.* , conducted experimental tests on a steel pallet rack of beam-column connections, they explored influential parameters compared various stiffness design methods, and highlighted that the equal area method showed accurate results.



**Figure 35.** Experimental failure and FE analysis failure (Shah *et al.* 2016).

Yin *et al.* conducted experiments on monotonic and cyclic loading on speed-lock beam-to-upright connections by employing the cantilever test method. They examined both bolted and boltless connections and concluded that the presence of bolts helped the overall performance of the connection although it did compromise the speed-lock characteristic of the connection. They also considered two different configurations of weld beads between the beam and the end plate. The first configuration involved welds along both lateral sides of the beam, while the second involved welds around the entire perimeter of the beam. The experiments were carried out by both European standards and American regulations.

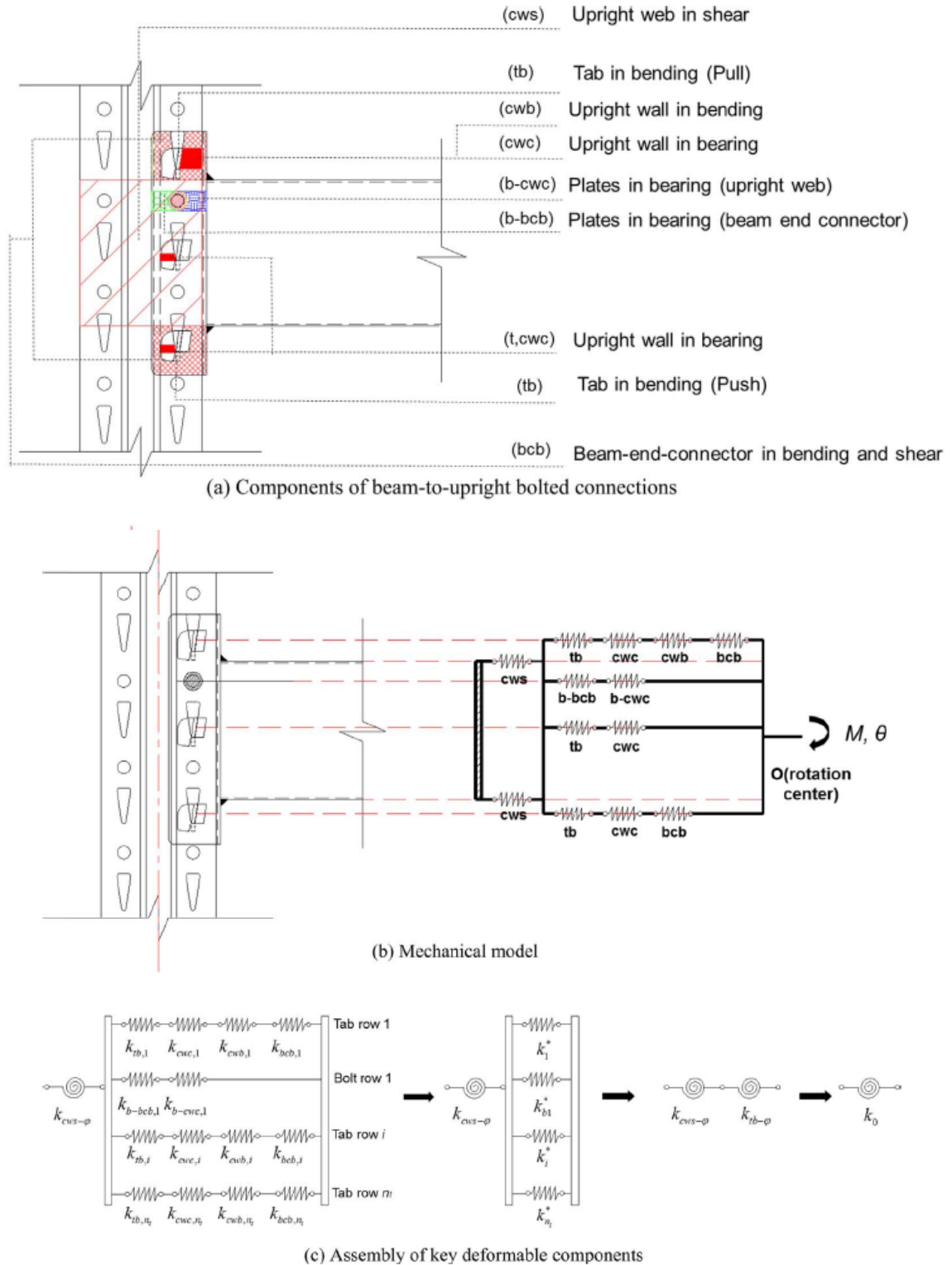
Gusella *et al.* compared the behavior of bolted and boltless connections of beam-column joints via monotonic and cyclic tests. The tested joints exhibited variations in terms of beam connector, number of tabs relative to the thickness of the upright and beam end connector, and additional bolts. The study focused on the main role of welding in the failure mode and significant pinching behavior in cyclic tests were identified. The results from the experimental test showed that the failure mode of connections depends on the weakest component of the joint. The failure mode of beam connector welding connection depends on the ratio between the thickness of the upright and the thickness of the tabs as well as the steel grade. Another research on monotonic and cyclic tests on beam end connectors was reported by Gusella *et al.* and the results were listed (figure 36).



**Figure 36.** Geometry and components of tested connection A and B (Gusella *et al.* 2017).

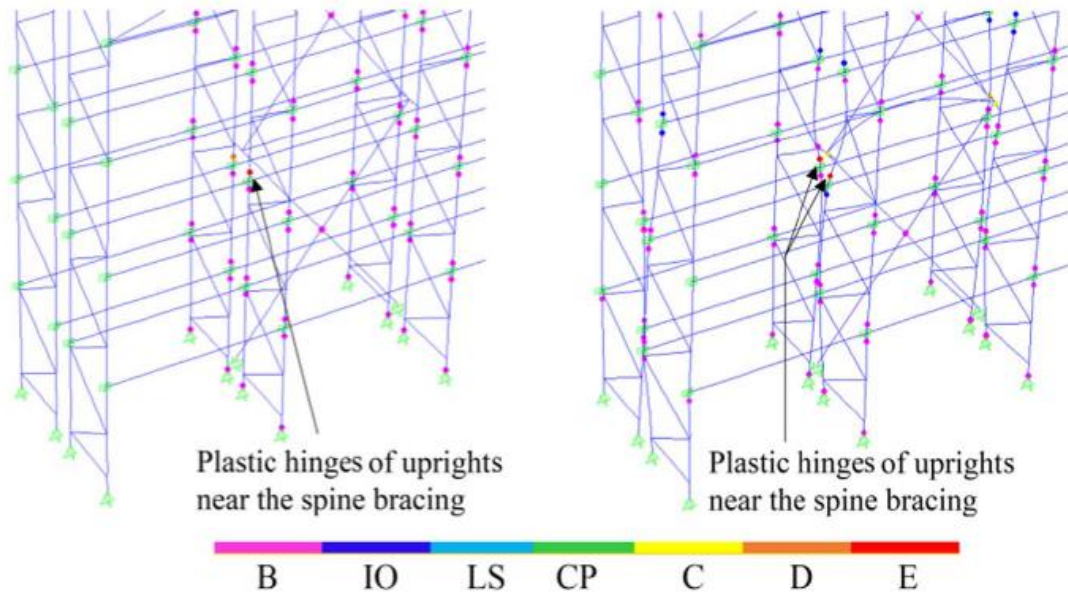
In 2018, Zhao *et al.* introduced a mechanical model based on a component method aimed at predicting the initial rotational stiffness of beam-to-column connections used in cold-formed steel racks. They discussed five basic deformable components contributing to the initial rotational stiffness of beam-to-upright connections. The components were tab in bending, upright wall in bearing, and upright wall in bending, beam-end-connector in bending and shear,

upright web in shear (Figure 37). The model provided a reliable means of calculating the rotational stiffness at the early stages of loading. Experimental tests were conducted leading to the conclusion that the proposed mechanical model effectively assesses the initial rotational stiffness of boltless connections within steel storage racks.



**Figure 37.** Mechanical model for bolted connections (Zhao *et al.* 2018).

Yin *et al.* investigated the seismic response of cold-formed steel storage racks with spine bracings using two types of connections: a speed-lock connection and a speed-lock connection with two bolts and full flange welding. Static elastic pushover analysis utilized speed lock connections (Figure 38). The objective of the study was to experimentally investigate how speed-lock connections impact the seismic performance of cold-formed steel storage racks with spine bracing. The effectiveness of bolts or welds contributed to reducing plastic hinges and damage in double-entry unity racks (DEU).



**Figure 38.** Formulation of plastic hinges in double entry unit (Yin *et al.* 2018)

Escanio *et al.* conducted an experimental and numerical study into the behavior of beam-column end connections. They evaluated the behavior, semi-rigidity, and influence of the geometric parameters on the stiffness of beam-upright-lipped connections. The experiment comprised three columns and four beam cross-sections. Through their study, they validated the numerical model of the beam to upright connection subjected to bending and concluded that the results of the numerical model exhibited a good correlation with the experimental results, with a maximum difference of 10% as indicated in (Table 8).

**Table 8.** Comparison of Experimental and Numerical Initial Stiffness (Escanio *et al.* 2020)

Prototype	EXP				NUM	
	Test 1	Test 2	Test 3	average	Init.Stiff.	Dif (%)
U1_2.0×B1_2.0	43.50	45.46	45.82	44.93	47.81	6.0
U1_2.0×B2_1.8	49.86	51.14	45.95	48.33	48.33	1.3
U1_2.0×B2_2.0	45.04	47.65	43.75	50.45	50.45	9.9
U2_2.0×B3_2.0	70.96	61.38	73.13	68.49	70.89	3.4
U1_2.0×B1_2.0	48.83	41.04	39.31	43.06	47.24	8.8
U1_2.0×B2_2.0	58.24	53.89	46.60	52.91	51.51	2.6
U1_2.0×B3_2.0	84.10	78.37	66.82	76.43	70.87	7.3

### Previous Studies on Moment-Rotation Curves of Beam-Column Connections

Moment-rotation curves show how a connection responds to applied moments in terms of rotation. The curves help to understand the connection's stiffness, strength, ductility, and overall behavior of the structure. Analyzing moment-rotation curves can reveal crucial information about the connection's ability to absorb energy, resist deformations, and distribute loads effectively. In the context of storage rack systems, where dynamic loads and potential impacts are common comprehending the moment-rotation behavior of beam-column connections becomes predominant. Moment-rotation curves are considered the most suitable representation of the connection's performance in pallet racking system. A typical moment-rotation curve comprises two distinct segments that correspond to different stages of connection behavior and they include both the elastic and yielding behavior. Commercially available beam end connectors commonly used in pallet rack structures, are categorized as semi-rigid connections.

Researchers have developed various approaches to predict the moment-rotation behavior of structural connections, the developed approaches are empirical, analytical, and numerical approaches.

- **Analytical Approaches:** Analytical models use mathematical formulations derived from theoretical principles, mechanics, and engineering concepts. This model often makes simplifying assumptions to describe complex behavior analytically. This method was first used by Beafoy and Moharram. The moment-rotation relationship of web cleat

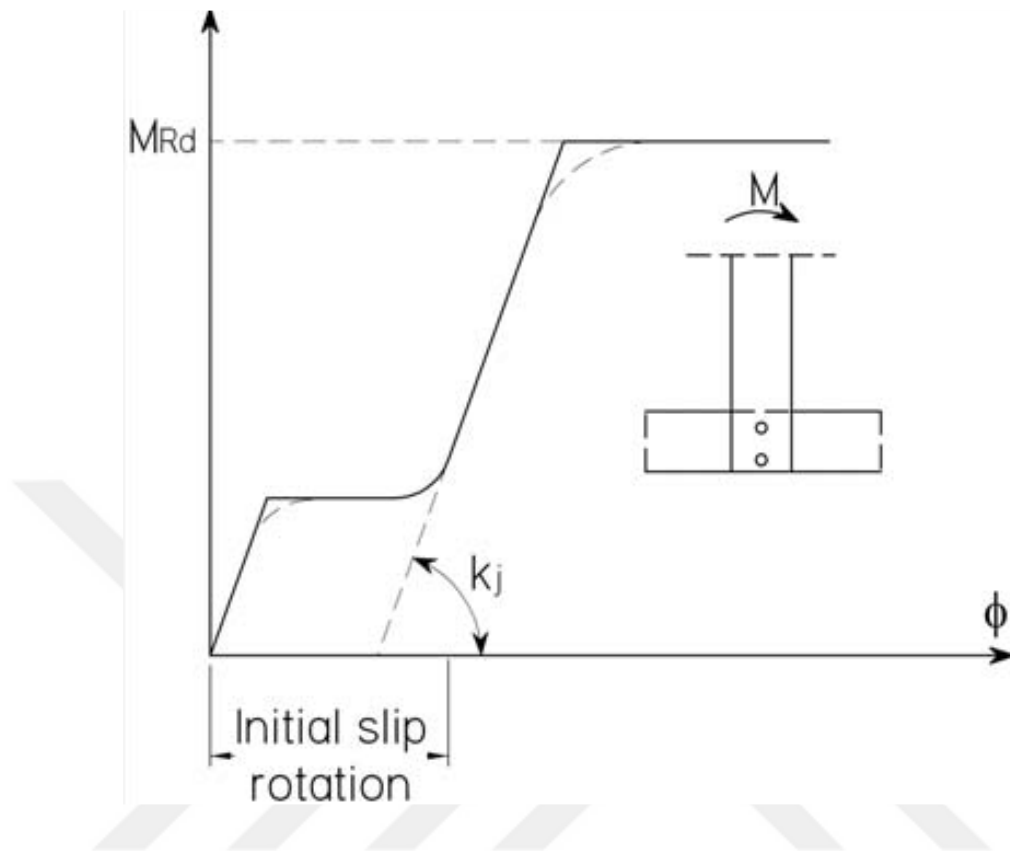
joints was determined. The experimental data associated with force-deformation characteristics of angle segments was used to provide insight into the fundamental mechanics of connection behavior and provide valuable information about the effects of various parameters on the moment to rotation. Analytical methods are typically used when a clear understanding of the fundamental behavior of connections is desired.

- **Empirical Approaches:** Empirical models are based on observed experimental data and practical observations. Empirical models rely on statistical relationships obtained from physical tests. Fry and Morris the authors introduced a specialized method to predict the moment-rotation characteristics of joints displaying odd-power behavior. It isolated the joint's behavior from the rest of the structure and assumed linear behavior for other structural elements. Krishnamurthy *et al.* proposed parametric studies for the moment-rotation relationship. Empirical models are particularly useful when experimental data is abundant and can be generalized to predict connection behavior in similar scenarios.
- **Numerical Approaches:** Numerical methods utilize computer simulations to model the behavior of connections. Finite element analysis (FEA) is a commonly used numerical technique in which complex geometries and loading conditions can be accurately simulated.

A study conducted by Cheng focused on the axial load behavior of cold-formed steel open sections, specifically in the context of their usage as load-carrying structural elements in storage racks. The objective of the study was to investigate the failure mode and axial load-carrying capacity of perforated columns commonly used in storage rack systems. He concluded that the primary failure mode for axially loaded perforated columns was local flexural-torsional buckling. He proposed an analytical expression to predict the axial load-carrying capacity of these perforated open section members.

Zaharia and Dubina research focused on the influence of axial loads in diagonal bracings on connection behavior and the subsequent impact of bolt slippage on truss deflections. They pointed out that while ignoring initial connection looseness might have been acceptable for structures primarily subjected to bending, it becomes crucial to address this issue in designs for slender structures like storage racks, where P- $\Delta$  effects(second-order effects ) are significant (Figure 39). This aligns with industry standards like those provided by the RMI and Australia

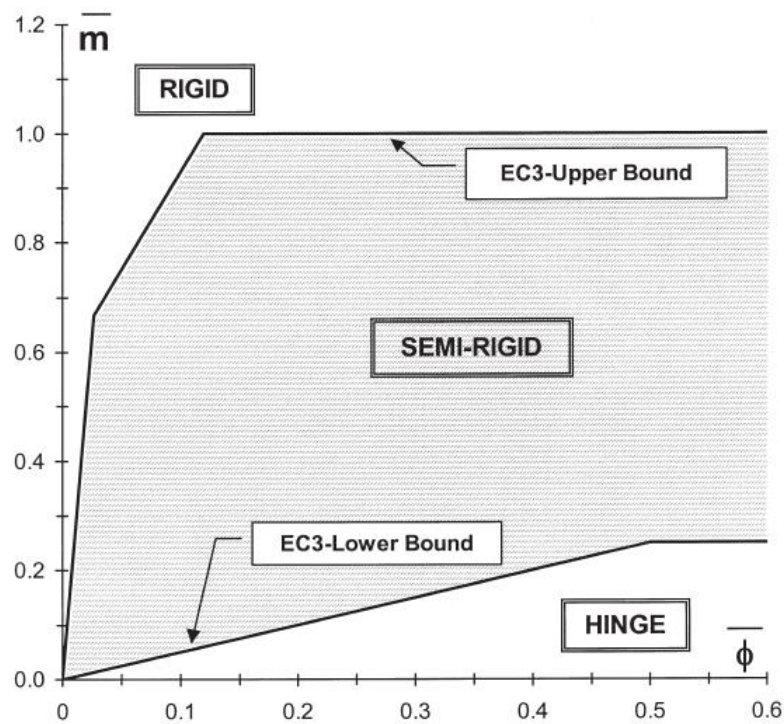
Standards emphasizing the importance of accounting for connection looseness to ensure the safe and accurate design of storage rack systems.



**Figure 39.** Moment-rotation curve for a bolted lap joint.

Chung *et al.* investigated the moment-rotation behavior of bolted moment connections in cold-formed steel structures considering connections using gusset plates between members as well as direct bolted connections. They concluded that moment connections among cold-formed steel members are structurally feasible and economical through rational design. Findings from Chung and Wong showed that bolted moment connections have proven their effectiveness in transferring moments between connected sections, facilitating efficient moment framing within cold-formed steel structures, and are viable and cost-effective Figure 40.





**Figure 41.** EC3 criterion for joint classification in unbraced steel frames .

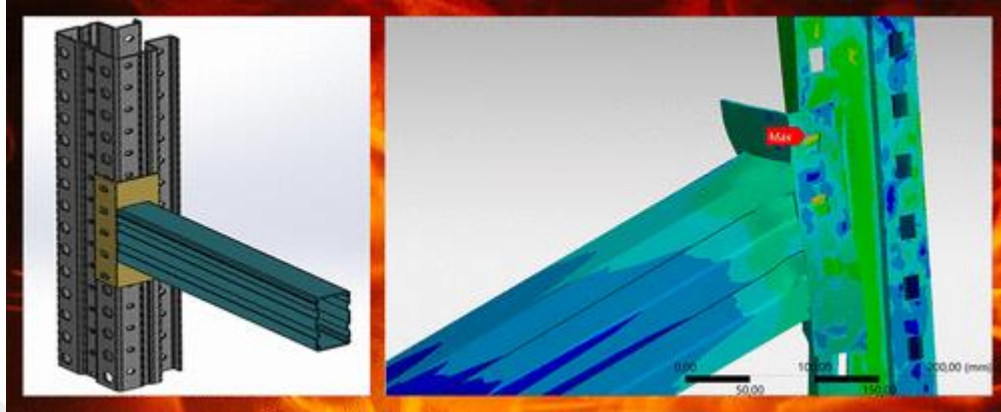
Rasmussen *et al.* conducted a portal test to investigate the behavior of bolted connections in drive-in and drive-through racking systems and concluded that tab connectors in bolted connections are feasible, economical, and provide moment resistance and stiffness to the pallet rack.

Cardoso and Rasmussen developed a finite element (FE) model for storage rack frames to study the moment-rotation behavior of upright pallet beam joints. Methodologies were introduced to integrate imperfections and clarify joint behavior in storage rack frames. A method was proposed to adjust cantilever test results to align with the observed initial stiffness from portal frame component tests and improve predictions in the FE model. The obtained results exhibited a good a satisfactory connection with the actual behavior of rack frames.

Dumbrava and Cerbu investigated the influence of both upright thickness and tab connector type on the rotational stiffness and the capable bending moment of the connection. The research comprised assembling a beam-connector-upright system by combining three types of beams with different box cross-section sizes, three uprights with different thicknesses of a section wall, and two types of connectors four-tab connectors and five-tab connectors. Monotonic hogging tests were conducted and results were concluded.

Çirpici *et al.* investigated the fire resistance of beam-to-column connections in storage racking systems using finite element analysis. They developed moment-rotation ( $M-\theta$ ) curves to evaluate the performance of intumescent-coated beams, uprights, and connectors. Using

ANSYS Workbench ( Figure 42), the study predicted temperatures of components with 1 mm thick coatings under standard fire conditions, aligning well with Eurocode 3. Structural analyses of nine models showed that the coatings effectively improved fire resistance, with full protection enhancing the moment capacity and stiffness of the connection by over 7%.



**Figure 42.** Transient thermal analysis system of ANSYS Workbench software (Çirpici *et al.* 2022).

In a subsequent experimental study, Dumbrava and Cerbu examined the impact of beam-end connector looseness in steel storage racks (Figure 43). The research revealed that the maximum corrections of 2.99% and 5.16% were necessary for the bending moment developed at the mid-point of the beam and for the maximum deflection, respectively. This indicates that connector type significantly influences the size of the correction.



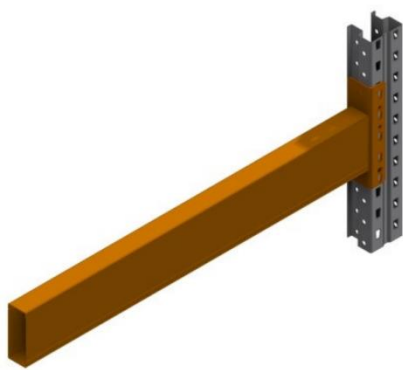
(a)



(c)



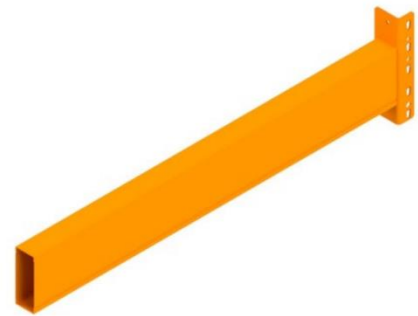
(e)



(b)



(d)



(f)

**Figure 43.** The main elements of the connections tested: (a,b) upright-connector-beam assembly, (c,d) upright, (e,f) beam with welded beam end connector.

Casim *et al.* investigated the influence of design parameters using a single cantilever test setup. The investigated design parameters were the wall-thickness of the column, height of the beam, vertical beam position on the connector, and installation of bolts to the connector. Results were concluded and an analytical model was proposed to investigate the behavior of beam-column connections in steel storage racks.

Table 9 shows the summary of previous experiments of beam-column connections.

**Table 9.** Summary of Beam-Column Connection Under Cantilever Test

Researcher(s)	Year	Experiment	Parameter investigated	Failure modes
Krawinkler et al	1973	Cantilever test	Geometry of connector tab	Deformation of tabs
Markazi et al	1997	Cantilever test	Geometry of connector tab	Deformation of tabs and columns, yielding of the beam end connector
Bajoria & Talikoti	2006	Cantilever and double cantilever test	beam-column connectors	Deformation of tabs
Ślęczka & Kozłowski	2007	Cantilever test	Beam-end connector	Deformation of tabs and columns, yielding of the beam end connector
Probha et al	2010	Double cantilever test	Depth of beam, depth of beam end connector, and thickness of column	Deformation of tabs and columns, yielding of the beam end connector
Zhao et al	2014	Cantilever test	Beam-end connector	Deformation of tabs
Probha et al	2015	Cantilever test	Upright profile and thickness, depth of beam and the connector	Deformation of tabs, Tearing of upright Yielding of the beam end connector
Yin et al	2016	Cantilever test	Beam-to-upright speed-lock connections	Cracks of the upper and lower welding area of the beam and beam-end-connector
Gusella et al	2018	cantilever test	The number of tabs, the relative thickness of the upright, and the beam-end connector	fracture of welding, yielding of tab, Deformation of connector
Dumbrava and Cebu	2020	cantilever test	upright thickness and tab connector	Deformation of tabs and connectors, tearing the upright

## **Key Differences Between This Study and the Existing Literature**

1. **Focus on Tab Configurations:** Unlike most studies that explore various connector types, this research specifically examines the moment-rotation behavior of beam-column connections with different tab configurations (4-tab, 5-tab, and 9-tab).
2. **Experimental Approach:** This research utilizes a unique experimental setup tailored to assess the specific characteristics of different tab configurations in storage rack systems, whereas many studies employ standard experimental methods like cantilever or portal tests.
3. **Material and Geometric Parameters:** This study investigates the distinct material properties and geometric configurations of beam-column connections in storage racks, which may not be a central focus in other studies.
4. **Detailed Moment-Rotation Analysis:** This study emphasizes analyzing moment-rotation curves, providing a more nuanced understanding of connection behavior compared to studies that primarily assess load-bearing capacity or failure modes.
5. **Comparison of Connection Types:** This research's specific comparative analysis among different tab configurations offers a unique perspective, contrasting with studies that typically focus on bolted versus boltless connections or general design parameters.
6. **Parameter Influence:** While other studies highlight general parameters affecting stiffness and strength, this research delves into how specific tab configurations distinctly influence overall performance, providing a focused examination.

## **Gaps in the Existing Literature of Beam-Column Connections of Steel Storage Racks**

- 1) **Fatigue performance:** due to repeated loading and unloading failure in steel storage racks can occur. More studies are needed to develop fatigue guidelines in pallet rackings to prevent the repeated loading and unloading of tested connections.
- 2) **Code standards and guidelines:** there's a need for further studies and expansion of code standards and guidelines in steel pallet racks.
- 3) **Seismic performance:** more tests on beam-column connections to understand how they can withstand seismic forces for tall pallet racks in warehouses. The influence of bolted, welded, and boltless connections on seismic performance must be investigated.
- 4) **Dynamic loading behavior:** dynamic loadings due to forklift operation must be considered in storage rack systems though a lot of studies focus on static loading. Failure modes due to dynamic loading must be studied.
- 5) **Environmental conditions:** more studies of beam-column connection on the effect of temperature or humidity must be conducted.

## MATERIAL AND METHOD

### Experimental Investigation

The experimental investigation of this study includes the following:

1. To experimentally investigate beam-column connections in steel racking systems and highlight the influence of tab connectors on the collapse mode and failure behavior of these connections.
2. To experimentally examine the moment-rotation curves of beam-column connections which are elements of storage rack systems and experimentally compare connectors with different tab configurations and determine the most advantageous combination model by comparing their performance.

### Test Specimens and the Test Methodology

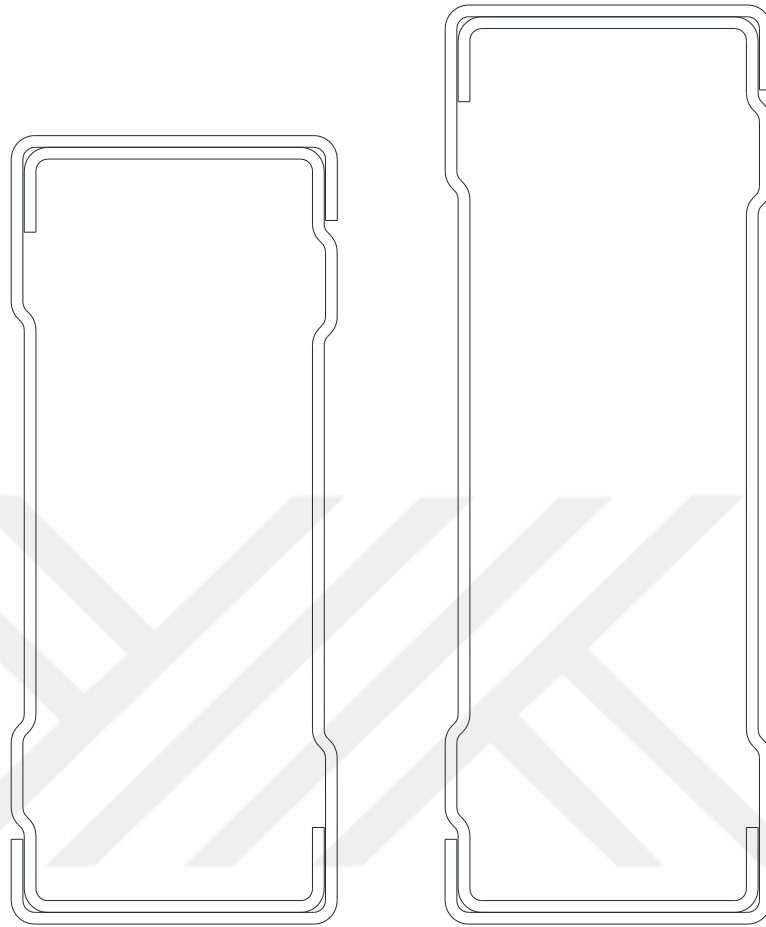
The specimens used in this study were designed to investigate the moment-rotation behavior of beam-column connections in storage rack systems specifically emphasizing the influence of the tab configurations on the beam-end connector. These specimens consisted of two different beam depths identified by the labels CC120 and CC140. Here, CC indicates a box beam made up of two nested C-lipped profiles while 120 and 140 signify the depths of the beams in millimeters. Both beams had a thickness of 1.5 mm. The geometry of the beam is shown in (Figure 44). In the experiment, a constant upright with a depth of 120 mm and thickness of 2.5 mm was used with the critical variation established in the beam end connector which had a thickness of 3.0 mm. Figure 45 indicates the geometric property of the column. For the CC120 beam, connectors with 4 tabs, 5 tabs, and 9 tabs configurations were utilized. Figure 46 indicates the geometric property of the beam end connector. Similarly, for the CC140 beam, connectors with the same tab configurations were used. Six sets of specimens as listed in were identified. Each set comprises three specimens, each distinguished by different combinations of beam depth, number of tabs in the beam end connector (4 tabs, 5 tabs, and 9 tabs), and a constant upright. A total of eighteen individual specimens were tested.

The main aim of this experimental test was to obtain moment-rotation curves for the tested joints. To accomplish this, a single cantilever test setup under monotonic loading Markazi *et al.* . The test apparatus was designed according to the standards of EN 15512 and ANSI MH16.1 for evaluating the behavior of the beam end connector. In this setup, a horizontal beam with a height of 800 mm was welded to the connector and braced on both sides of the beam's end to ensure stability and prevent sideways movement and twisting of the beam end while loading. A vertical column with a height of 760 mm was supported by plates welded on

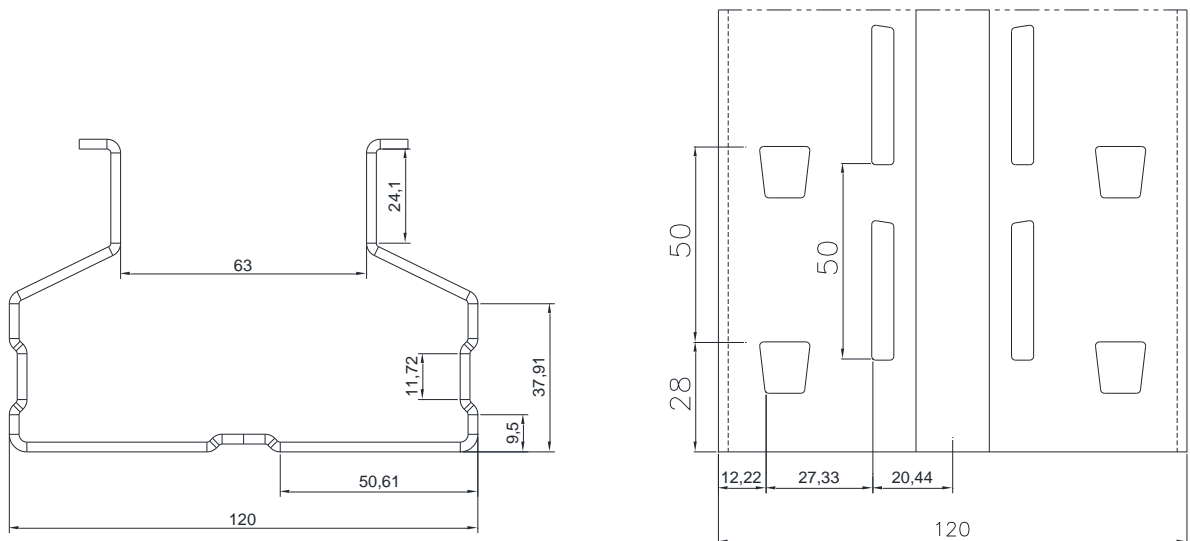
both sides and bolted to the reaction frame to create a fixed boundary condition as indicated in figure 47. The tabs of the beam end connector were engaged into the perforations on the column. Three LVDTs (Linear Variable Differential Transformers) were positioned on the beam end connector to measure and collect data. LVDT 1 and LVDT 2 were carefully mounted on the top side of the beam end connector near the beam-column joint to record vertical displacements or deformations during the test. LVDT 3 was positioned on the bottom side of the beam end connector to record vertical deformations from the opposing direction thereby offering vast deformation data as shown in figure 48. A load cell was perfectly incorporated connecting to the cantilever beam to ensure accurate measurement of the applied load. Monotonic loading conditions were carefully utilized, with the load gradually increasing at a specific point exactly 400 mm from the face of the column until the maximum load was reached and the connection failed. Deformation and load data were monitored, recorded, and carefully analyzed and the collected data was directly transferred to the databox. Figure 49 illustrates the single cantilever test setup.

CC 120

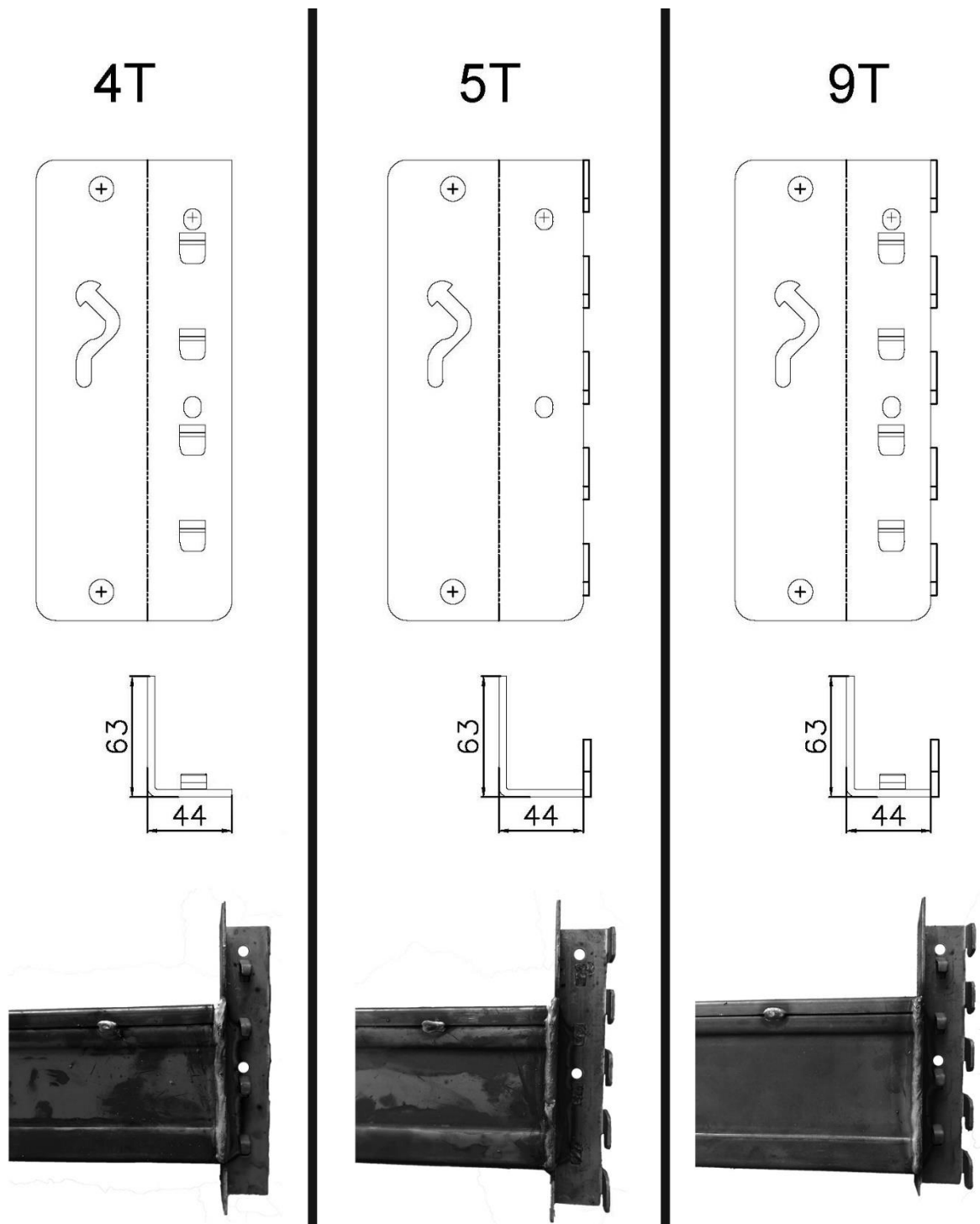
CC 140



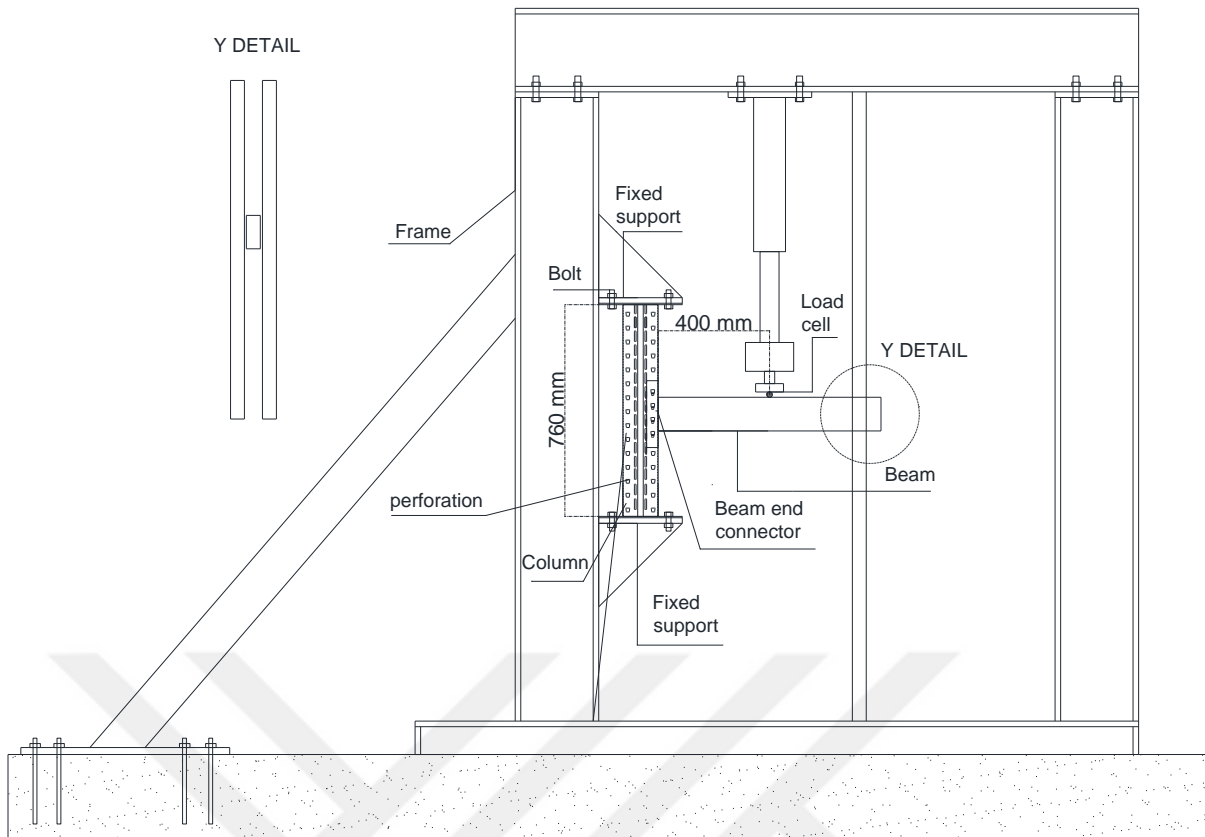
**Figure 44.** Geometrical details of the beams.



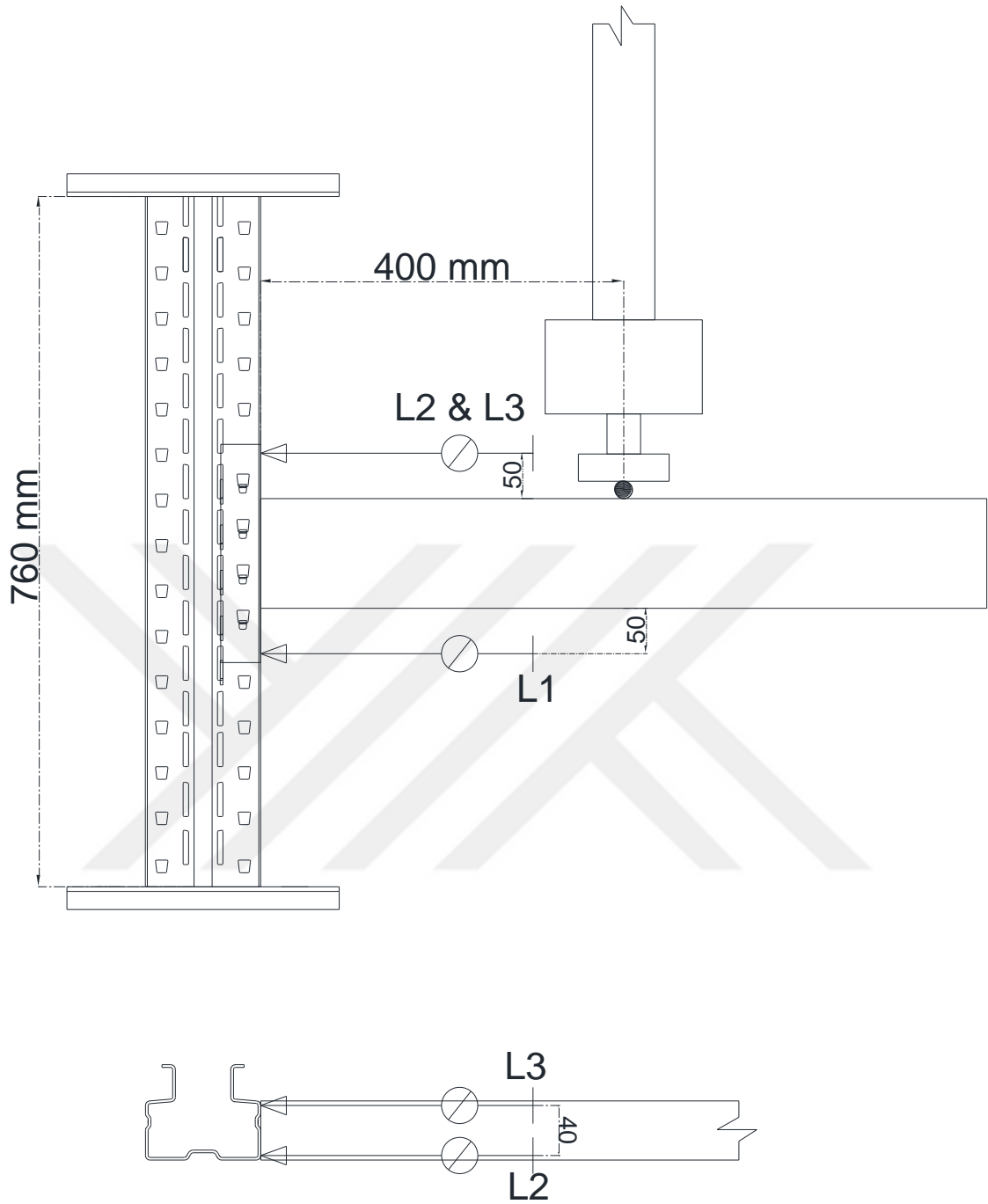
**Figure 45.** Details of the column.



**Figure 46.** Geometrical details of the beam end connectors.



**Figure 47.** Experimental setup designed for beam-column connection.



**Figure 48.** Test setup and locations of the displacement gauges.



**Figure 49.** Single cantilever test setup.

Table 10 summarizes the experimental setup focusing on beam-to-column connections in steel storage racks with different tab configurations. Six types of specimens were tested CC 120 and CC 140 beams each with 4T, 5T and 9T tab configurations. Each configuration was subjected to monotonic loading, where three specimens per setup were tested to ensure reliable results. The primary variable was the number of tabs, which directly affected the moment capacity, stiffness and rotational behavior of the connection.

**Table 10.** Specimens

Specimen	Loading protocol	Number of specimens	Variation
CC 120 – 4T	Monotonic	3	Tab number
CC 120 – 5T	Monotonic	3	Tab number
CC 120 – 9T	Monotonic	3	Tab number
CC 140 – 4T	Monotonic	3	Tab number
CC 140 – 5T	Monotonic	3	Tab number
CC140 – 9T	Monotonic	3	Tab number

## RESULTS

18 samples were subjected to monotonic loading to evaluate the behavior and failure modes of the connections. Understanding various failure modes the connections experienced during loading provides valuable insight into the design and performance of steel storage racks. The failure mechanisms in the beam-end connectors were observed and classified. Each sample was carefully monitored to identify specific points and types of failures that occurred.

### Failure Modes

Four failure modes were observed during the experimental investigation. These failure modes were categorized as follows: deformation of beam end connector (denoted as A), deformation of tabs (denoted as B), yielding or fracture of tabs (denoted as C), and welding break (denoted as D). As a result of monotonic loading, all 18 tested specimens experienced deformation in the beam end connector, primarily attributed to overloading. However, it was noteworthy that specimens CC120-9T and CC140-9T endured severe deformation compared to the other specimens. In these cases, the upper part of the connector separated from the column while the lower part of the connector remained intact with the column flange. Resulting from the gradually increasing load that widens the gap between the tension zone and the beam end connector. Failure mode A is illustrated in figure 50. For specimens CC120-4T and CC140-4T, the observed failure modes were A+B. This was due to the gradually increasing load causing the tabs to undergo plastic deformation. As a result, the three upper tabs in the tension zone completely deformed and disengaged, finally coming out of the column slots. It's important to note that no failure modes were observed on the beams and columns for all 18 tested specimens throughout the experiment. Figure 51 illustrates failure mode A+B.

Specimen CC120 5T and CC140 5T exhibited a failure mode attributed to A+C. This failure mode was characterized by the yielding or fracture of the three upper tabs located in the tension zone. The fourth and fifth tabs remain intact within the column slots and no failure mode was observed for the two tabs. It was observed that poorly designed tabs and connectors lead to high stress concentration especially affecting the three uppermost tabs causing yielding or fracture. To prevent stress concentrations on the tabs and connectors, proper engineering design codes must be considered. Figure 52 illustrates failure mode A+C.

In the case of specimens CC120 9T and CC140 9T, a failure mode characterized by A + C + D was observed, accompanied by significant deformation of the connector. These specimens experienced ongoing breakage of the beam end connector and yielding of the tabs due to loads exceeding their limits. The likely causes of the beam end connector breakage were

identified as improper welding techniques or inadequate weld size. Notably, the fracture of the upper tabs was the dominant feature in these specimens. Figure 53 illustrates failure mode A + C + D. Failure modes experienced by each test specimen during the experiment are shown in Table 11.

**Table 11.** Failure Modes of the Test Specimens

Number	Test specimen	Failure
1	CC120 -4T (1)	A+B
2	CC120- 4T (2)	A+B
3	CC120 -4T (3)	A+B
4	CC120 -5T (1)	A+C
5	CC120- 5T (2)	A+C
6	CC120- 5T (3)	A+C
7	CC120- 9T (1)	A+D
8	CC120- 9T (2)	A+C
9	CC120- 9T (3)	A+C
10	CC140- 4T (1)	A+B
11	CC140- 4T (2)	A+B
12	CC140- 4T (3)	A+B
13	CC140 -5T (1)	A+C
14	CC140 -5T (2)	A+C
15	CC140 -5T (3)	A+C
16	CC140- 9T (1)	A+C+D
17	CC140 -9T (2)	A+C+D
18	CC140-9T (3)	A+C+D



**Figure 50.** Failure mode A (deformation of beam end connector).



**Figure 51.** Failure mode A+B (deformation of beam end connector and deformation of tabs).



**Figure 52.** Failure mode A+C (deformation of beam end connector and yielding or fracture of tabs).

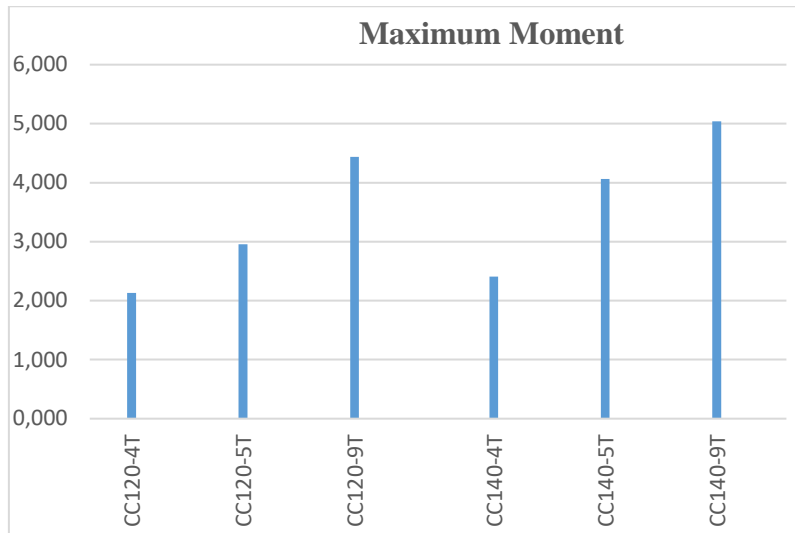


**Figure 53.** Failure mode A+C+D (deformation of beam end connector, yielding, and weld break).

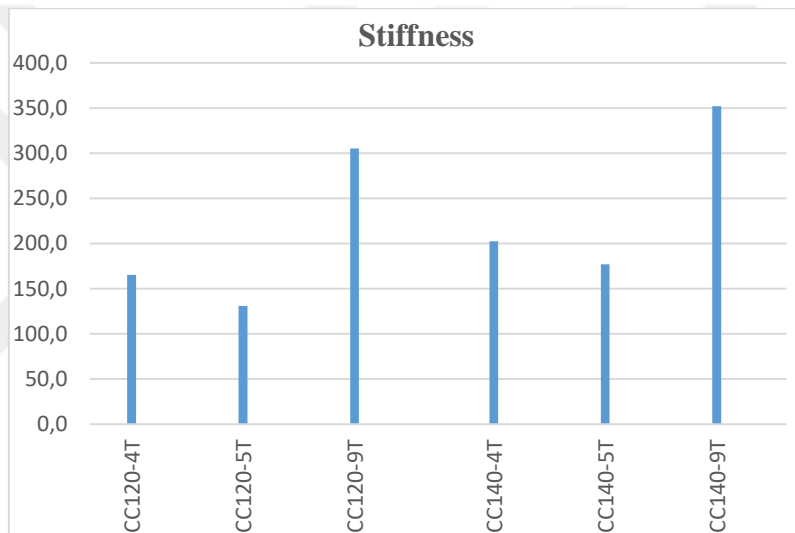
Table 12 and Figures 54-56 show the summary of experimental results for the maximum moment, stiffness, and ultimate rotation of beam-column connections in storage rack systems.

**Table 12.** Summary of Experimental Results for the Maximum Moment, Stiffness, and Ultimate Rotation

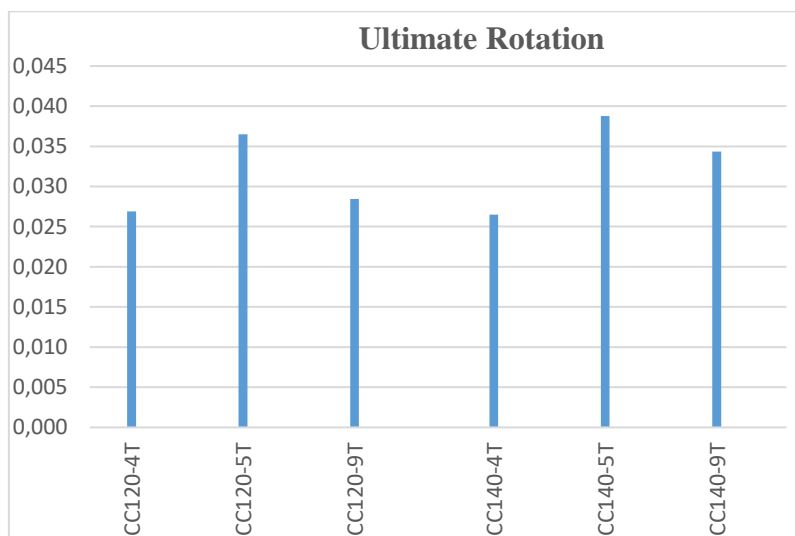
Specimen	Experiment	Max moment <i>kN.m</i>	Stiffness <i>kN.m/rad</i>	Max Rotation <i>rad</i>	Avg max moment <i>kN.m</i>	Avg stiffness <i>kN.m/rad</i>	Avg max rotation <i>rad</i>
CC120-4T	1	2.150	164.7	0.030			
	2	1.937	142.6	0.029	2.129	165.2	0.0027
	3	2.299	188.4	0.022			
CC120-5T	1	2.934	132.6	0.034			
	2	2.812	121.2	0.042	2.954	131.1	0.0037
	3	3.116	139.5	0.033			
CC120-9T	1	4.224	276.5	0.022			
	2	4.406	318.2	0.033	4.437	305.3	0.028
	3	4.680	321.2	0.030			
CC140-4T	1	2.372	201.1	0.027			
	2	2.327	185.9	0.029	2.409	202.4	0.026
	3	2.526	220.2	0.023			
CC140-5T	1	4.061	167.7	0.037			
	2	4.334	172.4	0.039	4.062	177.0	0.039
	3	3.792	190.9	0.040			
CC140-9T	1	4.911	345.9	0.041			
	2	4.863	328.3	0.025	5.040	352.0	0.034
	3	5.347	381.8	0.038			



**Figure 54.** Average maximum moment.



**Figure 55.** Average stiffness.



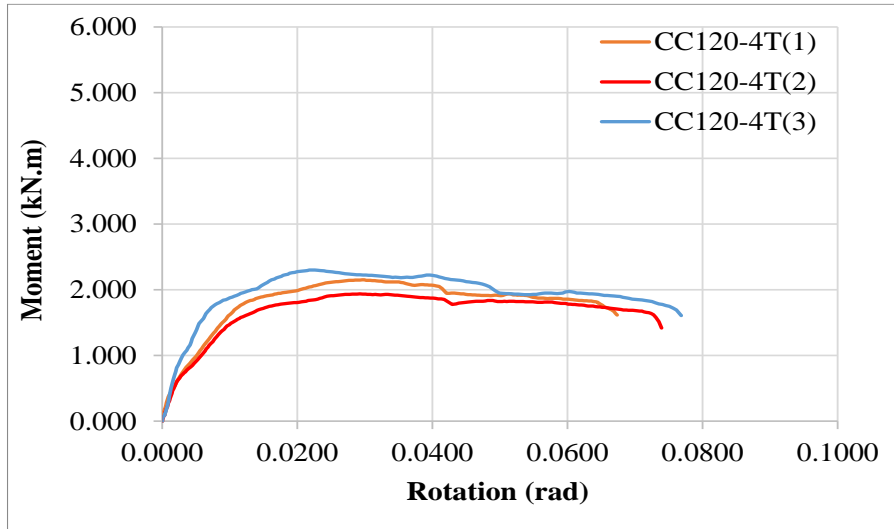
**Figure 56.** Average ultimate rotation.

## RESEARCH FINDINGS AND DISCUSSION

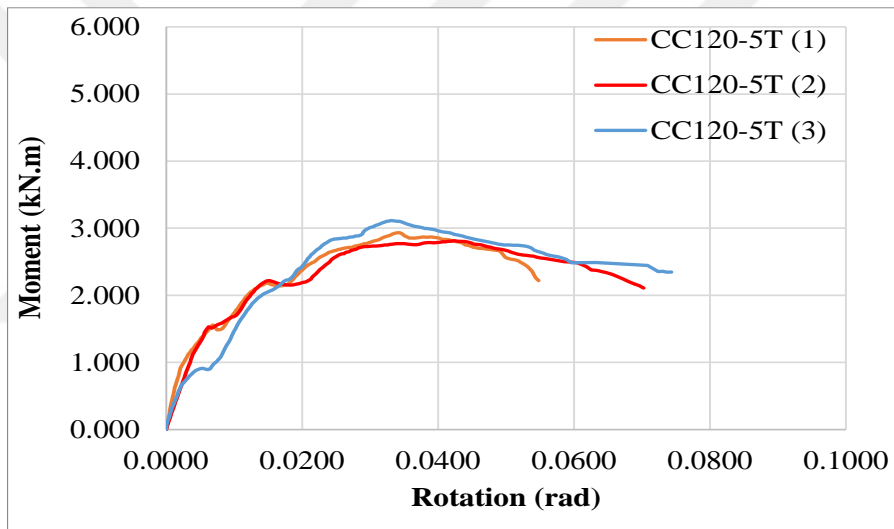
### Moment-Rotation Curves

The recorded displacement values from LVDTs were utilized to calculate the corresponding moments and rotations. The moment-rotation curves were calculated following the guidelines of EN 15512. The obtained results were then employed to calculate maximum moment, stiffness, and rotation capacity. Rotation capacity was calculated for the moment at which the maximum moment occurs. The calculated moments were plotted against the corresponding rotation. To calculate the initial stiffness EN 15512 suggests that the rotational stiffness of the connector shall be obtained as the slope of a line through the origin which isolates equal areas between it and the experimental curve, below the design moment corrected for yield and thickness. It is evident from the plotted moment-rotation curves that the connection exhibited linear behavior in the early stages of loading. After surpassing the yield point, the connections displayed non-linearity before reaching the ultimate moment capacity. This initial linear behavior can be attributed to the deformation experienced in the tested connections, a result of well-designed beams and columns. The subsequent non-linear behavior was observed due to yielding in the beam-end connector of the tested specimens. Figure 57-62 illustrates moment-rotation curves for tested specimens.

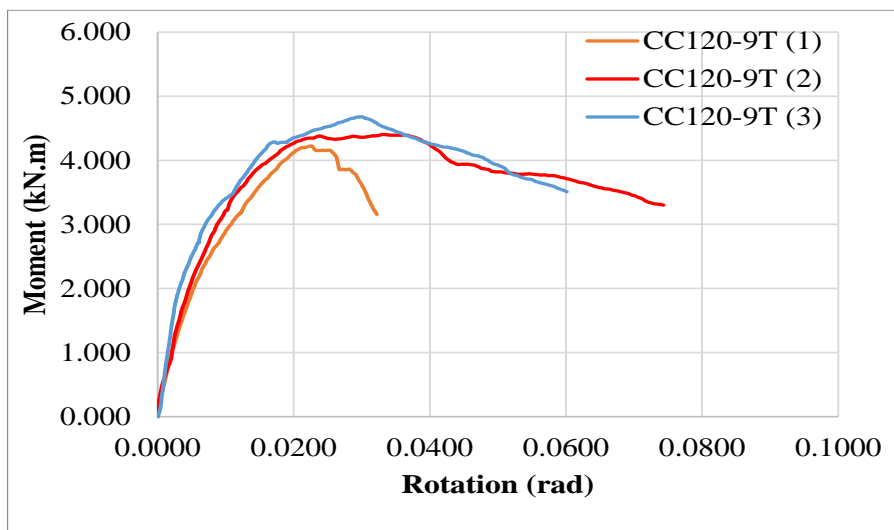
The maximum moment value was 5.347 kN.m for specimen CC140-9T (3) and the minimum moment value was 1.937 kN.m for specimen CC120-4T (2) as in (Table 12). The highest stiffness value was 381,8 kN.m/rad, achieved by specimen CC140-9T (3), and the lowest stiffness value was achieved by 121.1 kN.m/rad for specimen CC120-5T (2) as in (Table 12). The attained maximum moment and stiffness were attributed to the fact that work-hardening increased the material's strength and plastic deformation led to high stiffness in the specimen. Excessive deformation and yielding led to the formation of a plastic hinge in the specimens, resulting in low stiffness.



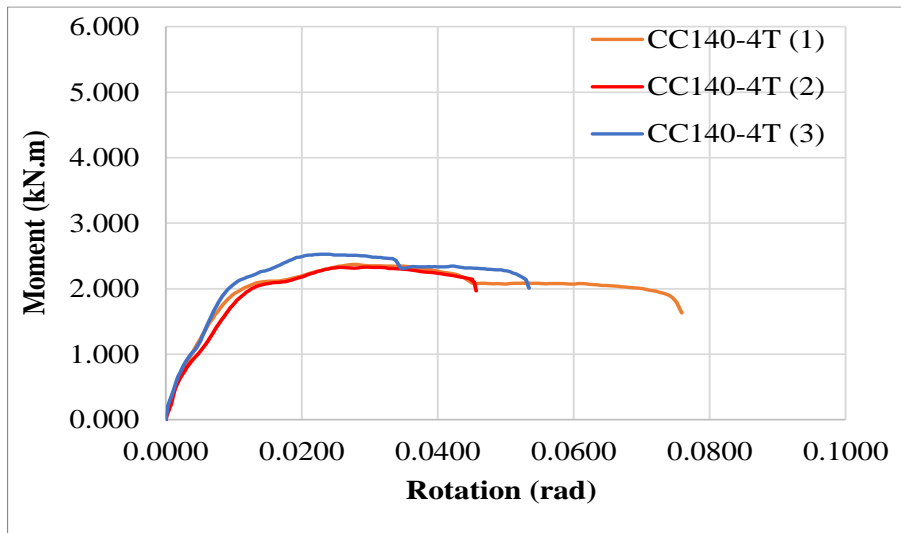
**Figure 57.** Moment-rotation curves for CC120- 4T.



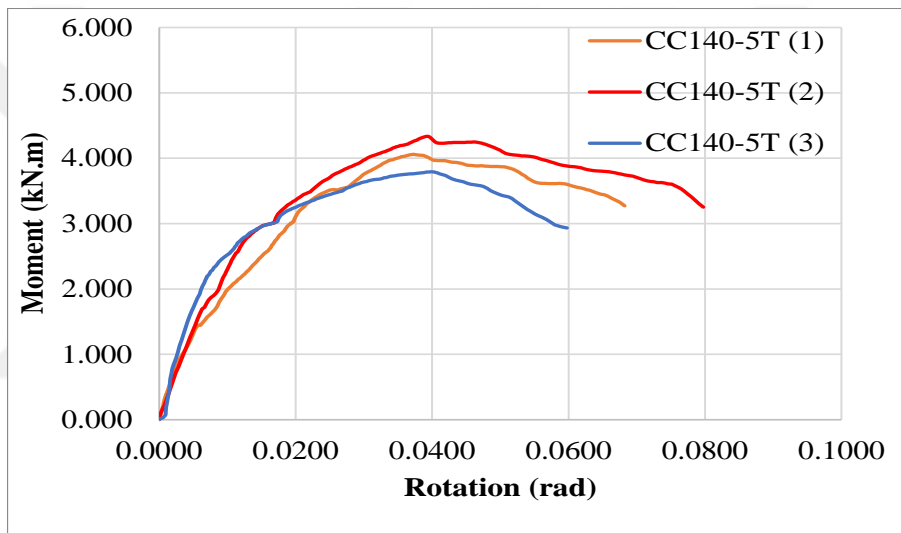
**Figure 58.** Moment-rotation curves for CC120- 5T.



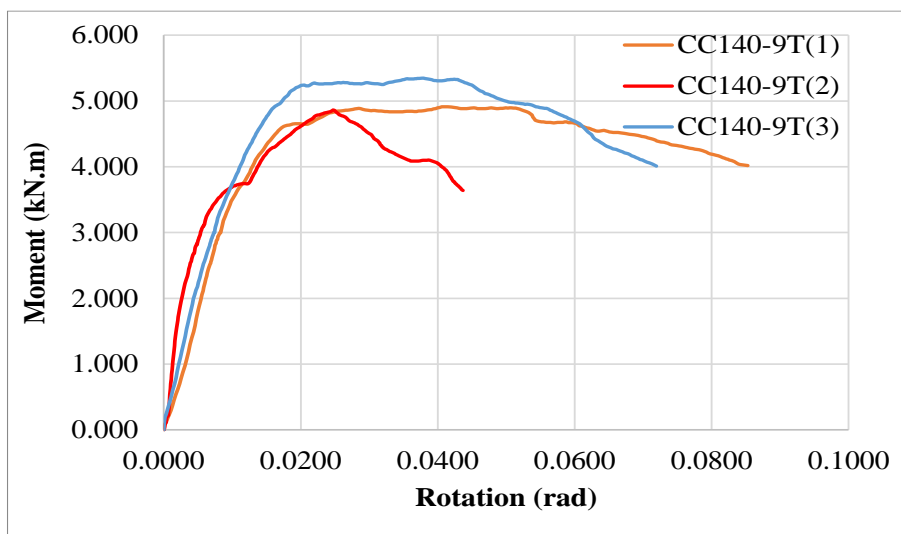
**Figure 59.** Moment-rotation curves for CC120- 9T.



**Figure 60.** Moment-rotation curves for CC140- 4T.



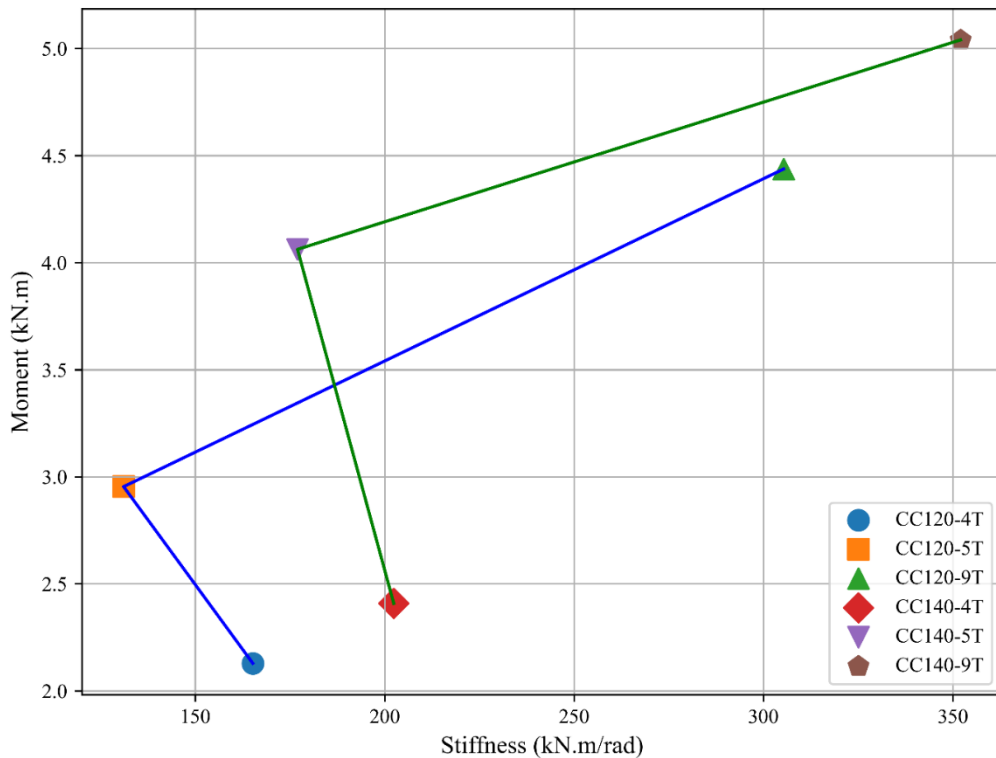
**Figure 61.** Moment-rotation curves for CC140- 5T.



**Figure 62.** Moment-rotation curves for CC140- 9T.

## Moment-Stiffness Relationship

The graph in (Figure 63) shows the relationship between stiffness (kN m/rad) on the x-axis and moment (kN.m) on the y-axis for different specimens (figure 63). The samples are categorized as CC120 and CC140 with different tab numbers (4T, 5T, 9T). Data points are shown with different symbols for each sample and trend lines for CC120 and CC140 are shown in blue and green, respectively.



**Figure 63.** Moment-stiffness relationship.

CC120-4T blue Lines (Circle): This specimen shows the lowest stiffness values with a maximum stiffness of just under 200 kN m/rad and a corresponding moment of approximately 2.5 kN.m, it shows a relatively linear relationship between stiffness and moment.

CC120-5T blue Lines (Square): It has similar stiffness to the 4T specimen but shows higher moment values reaching approximately 3 kN.m, the stiffness is approximately 150 kN m/rad, this is due to the added tabs providing improved load distribution and support, which enhances its moment capacity.

CC120-9T blue Lines (Triangle): This specimen has the highest stiffness and moment values among the CC120 group with stiffness values exceeding 300 kN m/rad and moment values close to 4.5 kN.m. This indicates a stronger and stiffer joint.

CC140-4T green Lines (Diamond): This specimen shows stiffness values of approximately 200 kN m/rad and a corresponding moment of approximately 2.5 kN.m, it has a similar trend as CC120-4T but has slightly higher stiffness and moment.

CC140-5T green Lines (Inverted Triangle): It shows higher stiffness compared to the 4T specimen, approximately 180 kN m/rad with a moment of approximately 4 kN.m. This indicates an improved joint stiffness with an increase in thickness.

CC140-9T green Lines (Pentagon): The 9T specimen has the highest stiffness and moment values in the CC140 specimen with stiffness values exceeding 350 kN m/rad and moment values approaching 5 kN.m indicating a very strong connection.

The graph in (Figure 63) clearly shows that both stiffness and moment increase with the thickness and the number of tabs in the specimen. CC140 specimens outperform CC120 specimens making CC140 specimens more suitable for applications requiring higher stiffness and moment capacity.

## **Effects of Design Parameters on Beam-Column Connections**

### **Effects of the tab count**

There's a slight decrease of -0.98% in the maximum moment for specimen CC120-4T, indicating that a 4-tab connector might result in a weaker connection in terms of moment resistance. CC120-5T exhibited an increase of 0.68% in maximum moment suggesting that a 5-tab connector contributes to a slightly stronger connection compared to a 4-tab connector. The most robust configuration was the CC120-9T configuration which exhibited a substantial increase of 5.04% in maximum moment indicating that the addition of tabs significantly enhances the moment resistance of the connection as shown in (Table 12) and (Figure 57-59).

In terms of stiffness, CC120-4T highlights a smaller increase of 0.30% suggesting a minor improvement in resistance to deformation. CC120-5T experienced a slight decrease of 1.13% in stiffness indicating that the 5-tab configuration exhibits a more flexible response. CC120-9T highlights a significant increase of 10.43% in stiffness. This indicates that the 9-tab connector contributes to a stiffer connection and improves the overall stability of the structure as shown in (Table 12) and (Figure 57-59).

Both CC120-4T and CC120-5T exhibit a significant decrease in maximum moment of -90.1% and -89.1% respectively, suggesting that the 4-tab and 5-tab have more brittle behavior with restriction to rotation deformation. There's a notable increase in maximum rotation of 27.27% in specimen CC120-9T, indicating that the 9-tab connector allows for more rotational

deformation before failure, providing a more ductile response as shown in (Table 12) and (Figure 57-59).

### **Effect of the beam depth**

CC140-4T experienced a moderate increase in maximum moment of 1.56% indicating that increasing the depth of the beam on a 4-tab connector contributes slightly higher moment resistance than CC120-4T. Increasing the depth of the beam from 120mm to 140 mm for the 5-tab connector had a minimal change in maximum moment of 0.02% indicating that CC140-5T improves the moment resistance over CC120-5T. A moderate increase in maximum moment of 2.63% for the CC140-9T connector, indicates that the 9-tab connector enhances moment resistance though the effect is less pronounced compared to CC120-9T as shown in (Table 12) and (Figure 60-62).

There's a notable increase of 1.48% in stiffness for specimen CC140-9T compared to CC120-9T. CC140-4T stiffness increased by 0.65% suggesting a minor improvement in resistance to deformation. CC140-5T had a significant increase of 5.58% which indicates that increasing the beam depth from 120 mm to 140 mm for a 5-tab connector substantially enhances stiffness better than the other configurations as shown in (Table 12) and (Figure 60-62).

CC140-5T configuration exhibits a significant increase of 5.41% in maximum rotation suggesting that increasing the beam depth enhances a more ductile response with increased rotational deformation before failure. Both CC140-4T and CC140-5T configurations show notable decreases of -3.70% and -17.07% in maximum rotation, respectively. Indicating more restricted rotational deformation and more brittle behavior as shown in (Table 12) and (Figure 60-62).

## CONCLUSIONS

This research was conducted to study the moment-rotation curves of beam-column connections in steel storage racks using a single cantilever test method. Six monotonic loadings were carried out according to EN 15512 standards. Various failure modes were identified in the study and the moment-rotation curves were drawn for analysis. The key parameters such as the maximum moment, stiffness, and ultimate rotation were compared in different configurations. The main objective of this research was to investigate the moment-rotation curves of different tab configurations of beam-column connections in steel storage rack systems. The following conclusions were drawn based on experimental investigations.

Four failure modes of the connection were identified and categorized as follows: (A) deformation of the beam end connector, (B) deformation of the tabs, (C) yielding or fracture of the tabs, and (D) weld failure. Prominent failure modes A and B highlight the importance of the beam end connector and tab behavior under loading. Specimens CC120-9T and CC140-9T exhibited a complex failure mode involving A, C, and D. This underlined the importance of welding techniques and appropriate weld size in configurations with larger numbers of tabs. This complexity shows that as the number of tabs increases, the demands on welding quality and technique also increase, and providing the appropriate weld becomes critical to prevent failure. Additionally, it was revealed that improper design of tabs and connectors leads to stress concentration affecting the uppermost tabs. Therefore, it is crucial to adhere to engineering design codes to ensure the overall integrity of steel storage racks.

The number of tabs in the connection substantially influences the behavior of beam-column connections in steel storage racks. The 9T configuration typically offers higher moment resistance and stiffness compared to 4T and 5T configurations. This distribution reduces the stress in each tab, thus increasing the connection's capacity to withstand applied moments. For both CC120 and CC140, the 9T configurations exhibit a significant increase in maximum moment. This implies that the additional tabs significantly increase the connection's capacity to resist bending moments

The 9T configurations steadily display a noticeable increase in stiffness, indicating that additional tabs contribute to a stiffer connection. Additionally, the 9T configuration offers a more ductile response due to higher maximum rotation values compared to the other tab configurations. This ductility is important for absorbing energy during loading and can prevent sudden failure. The 5T configurations for CC140 display a significant increase in both stiffness

and moment in addition to enhanced ductility. The improved ductility in the 5T configuration allows for better energy dissipation in dynamic loading conditions such as earthquakes

In summary, the experimental investigation of the moment-rotation curves revealed that for structures where moment resistance and stiffness are crucial, the 9T configurations may be preferred. This is due to their superior performance in distributing the load and resisting deformation. Moreover, For structures where moment resistance, strength, and ductility are critical, 5T configurations may be a suitable option that offers balanced performance with fewer tabs. Moreover, additional research and finite element analysis as well as optimization of tab configurations are required to better understand the behavior of beam-column connections in steel storage racks. This research is necessary to develop more efficient and safer design practices, ensuring that connections can adequately carry the loads they are subjected to without premature failure.



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