ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

INVESTIGATION OF THE EFFECT OF RADIAL BOLT CONNECTIONS ON STRUCTURAL BEHAVIOR IN CYLINDRICAL CFRP BODIES BY FINITE ELEMENT ANALYSIS

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

SİLİNDİRİK CFRP GÖVDELERDE RADYAL CIVATA BAĞLANTILARININ YAPISAL DAVRANIŞA ETKİSİNİN SONLU ELEMANLAR ANALİZİ İLE İNCELENMESİ

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HAZİRAN 2025

Kubilay Sazan, a M.Sc. student of İTU Graduate School 511221118, successfully defended the thesis/dissertation entitled “INVESTIGATION OF THE EFFECT OF RADIAL BOLT CONNECTIONS ON STRUCTURAL BEHAVIOR IN CYLINDRICAL CFRP BODIES BY FINITE ELEMENT ANALYSIS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 30 May 2025
Date of Defense : 23 June 2025

To my family,

FOREWORD

I would like to express my heartfelt gratitude to my family, partner, and friends for their unwavering support throughout the process of writing this thesis. I am also deeply thankful to the Roketsan family—especially the colleagues and supervisors in the Mechanical and Structural Design Unit—for their continuous technical assistance and encouragement during this journey.

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June 2025

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ABBREVIATIONS

CFRP **:** Carbon Fiber Reinforcement Polymer
DOF **:** Degree of Freedom
IMU **:** Intertial Measurement Unit

SYMBOLS

W **:** Distance Between Bolts
D **:** Diameter of Holes

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INVESTIGATION OF THE EFFECT OF RADIAL BOLT CONNECTIONS ON STRUCTURAL BEHAVIOR IN CYLINDRICAL CFRP BODIES BY FINITE ELEMENT ANALYSIS

SUMMARY

Rockets are generally designed with cylindrical bodies to have more aerodynamically efficient performance. For this reason, more than one method is used to join bodies. Among these methods, the butt lap joint method is often preferred for rocket bodies to transfer load in material strength and shape connection. In this context, radial bolt connections are mostly preferred to limit 6 DOF. Bolt heads are hidden with special cut-outs to reduce aerodynamic drag in rocket bodies made of metals. However, this method causes deterioration of fiber integrity and reduction in structural stiffness in carbon fiber reinforced polymer (CFRP) material bodies.

Before the analyses on the cylindirical body, a tensile test model was performed on a simple plate model in order to verify the modeling on the ACP module. In line with this preliminary analysis, a tensile test study examining the bolt loading on a flat CFRP plate was taken as the basis. There are many studies on the subject mentioned in the literature. The selected study was preferred because it has the closest alignment to the stacking up model to be used in the main analyses.

The CFRP material plate was first modeled in the ACP module and the effect of the loading declared in the study was examined with static structural analysis. In the study, the accuracy rate of the analysis was increased by performing analysis on 2 models whose test results were shared. The error rate was obtained as 6.7% and 8.3%. The reason of this error is material characterization differences, mesh distribution and analyze modeling errors. Thus, it was shown that the analysis model worked correctly.

Under rocket maneuver, the effect of bending force acts as tensile and compressive force on the radial bolts. In this study, the effects of radial bolt connections and bolt head clearance depth on structural stiffness of two-cylinder structures made of CFRP under bending load were investigated. Analyses were performed in Ansys ACP module using the finite element method. The effects of different depth configurations on stiffness were compared in terms of stiffness. It was observed that the displacement and maximum stress were higher than the 1 mm bolt head discharge when there was no planar contact surface for the bolt head. It was observed that the bolt head deformed the bodies until it transferred the load to a flat surface. It is evaluated that this situation poses a danger to the flight of the rocket. On the other hand, it was determined that structural stiffness decreased with the deepening of bolt head cuts.

In the literature, CFRP and mechanical connection modeling have generally been examined with plates. In this study, it is aimed to provide a different perspective to the literature by through the analysis of cylindrical structures. In future studies, it is expected that the study will be detailed by adding flight conditions such as vibration and temperature to this connection area.

SİLİNDİRİK CFRP GÖVDELERDE RADYAL CIVATA BAĞLANTILARININ YAPISAL DAVRANIŞA ETKİSİNİN SONLU ELEMANLAR ANALİZİ İLE İNCELENMESİ

ÖZET

Roket ve füze sistemleri, kullancı tarafından talep edilen ana görev doğrultusunda tasarlanmaktadır. Bu ana görev gereksinimine göre, alt sistem gereksinimleri ortaya çıkmaktadır. Alt sistemler, hem elektroniksel hem de mekanik işlevlere sahip olabilmektedir. Bu işlevlere bağlı olarak alt sistemler, boyutlarına göre roket üzerinde bir bölge veya bir bölge içerisindeki küçük bir modül olarak paketlenebilmektedir.

Alt sistemler, işlevlerinin doğru yerine getirebilmeleri için üst sistem olan roketten bazı gereksinim taleplerinde bulunabilmektedir. Örneğin, roketlerde ivlenme hakkında veri üreten ataletsel ölçüm birimi (AÖB) güdüm içerisinde yer alan bir alt sistemdir. Ancak AÖB, doğru ölçüm verileri sunabilmek için roket sisteminden eksenelliğin bozulmamasını talep etmektedir. Bu sebeple, manevra altında gövdeler arasında oluşacak deplasmanın kalıcı olması eksenelliği bozarak AÖB'nin yanlış hesaplama yapmasına sebep olabilmektedir. Bu sebeple, gövdelerin katılığı doğrudan uçuşu etkileyen önemli bir parametredir.

Roketler, aerodinamik olarak daha verimli bir performansa sahip olmaları için genellikle silindir gövdelerden tasarlanmaktadır. Bu gövdelerin birleştirilmesi için literatürde birden fazla yöntem bulunmaktadır. Bu çalışma kapsamında, iç içe geçme bağlantı tipi üzerine çalışılmaktadır. Bu bağlantı tipinde, 6 serbestlik derecesinden 4 tanesi oluşturulan şekil bağı ile kısıtlanmaktadır. Geri kalan 2 serbestlik derecesi olan uçuş yönünde ayrılma ve rotasyon serbestlikleri de radial pin veya civatalar ile engellenmektedir. Bu çalışma kapsamında, roket gövdelerinin yapısal bağlantılarında radyal cıvata bağlantıları kullanılmaktadır.

Roketlerin uçuş safhasında maruz kalacakları yüksek sıcaklık ve yüklerden kaynaklı, çoğunlukla metal gövdeli tasarımlar tercih edilmektedir. Ancak, bu durum yapısal olarak ağırlığı arttırmaktadır. Ayrıca, açık lançerlerden yapılan roket atışlarında roketler doğrudan iklim koşullarına maruz kalmaktadır. Bu durumda metal gövdeli roketlerde paslanma durumu meydana gelebilmektedir.

Ağılık hafifletme ve açık atış gibi koşullar göz önünde bulundurulduğunda kompozit gövdelerin kullanımı önem arz etmektedir. Ancak, yukarıda bahsedildiği üzere yüksek yapısal dayanıklılık ve termal gereksinimlere göre tasarımın optimize edilmesi gerekmektedir. Bu çalışma kapsamında, yüksek katılık istenildiği için cam fiber ve yüksek maliyeti sebebiyle ise kevlar fiber malzemlerin seçimi tercih edilmemiştir. Bu doğrultuda, karbon fiber takviyeli polimer (CFRP) malzemesi seçilmiştir.

Metal gövdeli roketlerde, aerodinamik sürüklenmeyi azaltmak için radial cıvataların başları özel boşaltmalar ile gövdeye gömülmektedir. Ancak bu yöntem, CFRP malzemeli gövdelerde fiber bütünlüğünün bozulmasına ve yapısal katılığın düşmesine sebep olmaktadır.

Böylelikle çalışma kapsamında, CFRP'den üretilen iç içe geçen iki silindir yapının radyal cıvata bağlantıları ve cıvata başı boşaltma derinliğinin yapısal katılığa üzerindeki etkisi sonlu elemanlar yöntemi ile analiz edilmiştir. Analizler, civata başı gömülme derinliği 1 mm, 2 mm, 3 mm ve hiç boşlatma olmayacak şekilde 4 konfiügrasyon olarak gerçekleştirilmiştir.

Bu analizlerin sonucu olarak, mühendislik tasarım pratiğine göre civata kafası boşaltması olmayan konfigürasyonun fiber yönelimini en az deforme etmesi sebebiyle en yüksek katılığa sahip olacağı beklenmektedir. Ancak bu analizler çerçevesinde, düz civata kafasına silindirik gövde teması olacağı sebebiyle, yüksek gerilme yığılmaları görülmesi beklenmektedir. Bu duruma bağlı olarak, boşlatma olmayan konfigürasyonun beklenenin aksine en yüksek dayanım içeren konfigürasyon olmadığı iddia edilmektedir.

Analizler için öncelikle tanımlanan katı model mesh atılarak Ansys ACP modülüne aktarılımıştır. ACP içerisinde katmanlandırma çalışması yapılarak statik yapısal analiz modülünde yükleme bilgileri, temas bölgeleri ve sınır koşulları tanımlanmıştır. Ayrıca civatalar da kiriş elemanı olarak başka bir geomeri modülünde modellenmiş ve aynı statik yapısal modüle gömülmüştür. Civata kafasının gövdeye etkisi, kiriş elemanın nodları ile temas alanındaki nodlar arasındaki temas tanımlaması ile yapılmıştır.

Analizler öncesinde, ACP modülü üzerindeki modellemeyi doğrulamak amacıyla basit bir model üzerinde çekme deneyi modellemesi yapılmıştır. Bu ön analiz doğrultusunda, düz bir CFRP plaka üzerindeki civata yüklemesini inceleyen çekme testi çalışması temel alınmıştır. Literatürde belirtilen konu üzerine birçok çalışma mevcuttur. Seçilen çalışma ise, asıl analizlerde kullanılacak katmanladırma modeline en yakın dizlime sahip olması sebebiyle tercih edilmiştir.

CFRP malzemeli plaka, öncelikle ACP modülünde modellenmiş ve statik yapısal analiz ile çalışmada beyan edilen yüklemenin etkisi incelenmiştir. Ek olarak, çalışmada beyan edilen 2 farklı numune üzerinde analiz çalışması gerçekleştirilerek analizin doğruluk oranı arttılmak amaçlanmıştır. Temel alınan çalışmada, 0.254 mm deformasyon görüldüğü beyan edilmektedir. Analizler kapsamında ise 0.271 ve 0.233 deformasyon miktarları tespit edilmiştir. Hata oranı ise %6.7 ve %8.3 olarak elde edilmiştir. Bu hatanın kök nedeni olarak ise, malzeme karakterizasyon farkları, ağ yapısı ve modelleme yanlışları oluşturmaktadır.

Asıl analizlerin sonucu olarak, maksimum gerilme, toplam deformasyon miktarı ve en yüksek kompozit elemanın geri dönülemez hasara uğradığı üst civatanın etki alanındaki hasara uğrayan eleman miktarı elde edilmiştir. Elde edilen sonuçlar üzerinden şu çıkarımları yapmak mümkündür,

Civatalar ve silindir gövde arasındaki temas yüzeyi sebebiyle, hiç boşaltma olmayan konfigrasyonda elde edilen gerilme (903.79 MPa), 1mm boşaltma olan konfigürasyona (792.01 MPa) göre yüksek çıkmaktadır. Bu durum, gevrek bir yapıda olan matris elemanı yani polimer malzeme için çatlak oluşumuna sebep olma ihtimaline sahiptir. Özellikle yüksek uçuş süresine sahip görevlerde, bu gerilme yığılmasına bağlı çatlak oluşumu ve ilerlemesi görülmesi ihtimali bulunmaktadır.

Maksimum gerilme keza 1 mm'lik konfigürsayondan 2 mm'lik konfigürasyona geçerken de azalmaktadır. Ancak, 2 mm'lik durumda civataların temas ettiği alandaki gerilme yoğunluğu artmaktadır. Bu duruma bağlı olarak, daha fazla elemanın yapısal bütünlüğü bozulmakta ve katılık düşmektedir.

Civata gömülme derinliği artışı na bağlı olarak, deliksiz konfigürasyon ile 1 mm arasında % 6,2 katılık kazancı söz konusu iken, 1 mm'den 2 mm'ye geçerken % 25.7 ve 2 mm'den 3 mm'ye geçerken % 23 katılık kaybı gözlemlenmiştir.

Manevra yükünün davranışından kaynaklı, civatalara etkiyen yük dağılımı civata pozisyonlarına göre değişmektedir. Yükün etki ettiği z ekseninde en üstte kalan civata en yüksek çekme yüküne maruz kalırken, en altta kalan civata ise en yüksek basma yüküne maruz kaldığı görülmüştür. Bu bağlamda, maksimum gerilme ve gerinimler bu civatalarda gözlemlenmiştir.

Bükme yükünün nötral eksenine yaklaştıkça, o bölgedeki civatalarda yük oluşmadığı tespit edilmiştir.

Civatalara etkiyen yükün dağılımı doğrudan manevraya yönüne bağlı olarak değişmektedir. Bu sebeple, tasarım aşamasında manevra yönü detaylıca tanımlanırsa civata bölgelerinin dayanımları da detaylıca tasarlanma imkanına sahip olmaktadır. Katman kalınlıkları, fiber oryantasyonu ve civata tipi manevranın detaylandırmasına bağlı olarak değiştirilebilecek parametrelerdir.

Literatürde CFRP ve mekanik bağlantı modellemesi genellikle plakalar ile incelenmiştir. Bu çalışmaya en benzer olan çalışmalar kapsamında ise, kompozit basınçlı silindir tank uygulamaları bulunmaktadır. Bu çalışmada silindirik yapıların bükülme kuvveti altında incelenmesiyle literatüre farklı bir bakış açısı kazandırılması amaçlanmaktadır. Ayrıca, literatürdeki birçok uygulamada modelleme kabuk eleman olarak yapılmıştır. Bu yönü ile çalışma literatürdeki katı eleman modellesi ile de farklı bir yere sahiptir.

Analizlerin modellemesi kapsamında, bazı dinamikler basitleştirilmiş olup, bazı varsayımlarda bulunmuştur. Bu durumlar sebebiyle gerçek koşullardan uzaklaşılmıştır. Örneğin modelleme kapsamında, uçuş sırasında ortaya çıkacak aerodinamik ısınmanın malzeme dayanımına etkisi, titreşimin bağlantı bölgesindeki etkisi ve irtifa değişiminden kaynaklı azalan dış basınç etkisi gibi etkilerin olmadığı varsayılmıştır. Civataların dişlerinin doğrudan kompozit gövdeye açılan dişlerden destek aldığı düşünülmüştür. Bu sebeple, yük altında dişlerin sıyırmadığı ve civataların gövdesinde yapısal olarak deformasyon olmadığı kabul edilmiştir. Ek olarak modelleme mentalitesi olarak, süperpozisyon yöntemi kullanılmıştır. Bu yöntem ile sadece bağlantı bölgesine odaklanılmış olup yapı daha küçük bir halde analiz edilmiştir.

Bu çalışmanın analiz temelli olması sebebiyle, analizlerin detaylandırılması ve test edilerek doğrulanması gibi birçok gelecekte yapılabilecek çalışma için temel niteliği taşımaktadır. Gelecek çalışmalarda ise bağlantı bölgelerine etki eden titreşim, sıcaklık değişimi ve şok gibi gerçek uçuş koşullarının da eklenerek analizlerin detaylandırılması düşünülmektedir. Ek tasarım çalışması olarak, deliklerde vida zırhı (helicoil) uygulaması yapılması ve bu uygulamanın civata dayanımına etkisi incelenebilir. Böylelikle varsayım miktarı da azaltılabilir. Ek olarak, yapılan bu analizlerin de gelecek çalışmalarda oda koşullarında bükme testlerinin gerçekleştirilmesi ve atışlı testler ile doğrulanması durumları da bulunmaktadır.

1. INTRODUCTION

Generally, systems that convert the high-energy fuel inside into gas by combustion reaction and pass it through a nozzle and thus produce thrust are called rockets (Sutton & Biblarz, 2016). The designs of rockets are formed according to the main mission decided upon in the conceptual design phase in line with the user's demand. Example of this design mission is, to shoot down an aircraft, hit a ballistic target, or destroy a tank target. Rockets consist of various subsystems in line with their main mission (Hongxing et al, 2023). Each subsystem is a mechanical or avionic subunit that performs a specific function so that the rocket can fulfill its main mission. As can be seen form Figure 1.1, depending on their sizes and functional requirements, subsystems can be located separately on the rocket or as integrated units to cover a specific area.

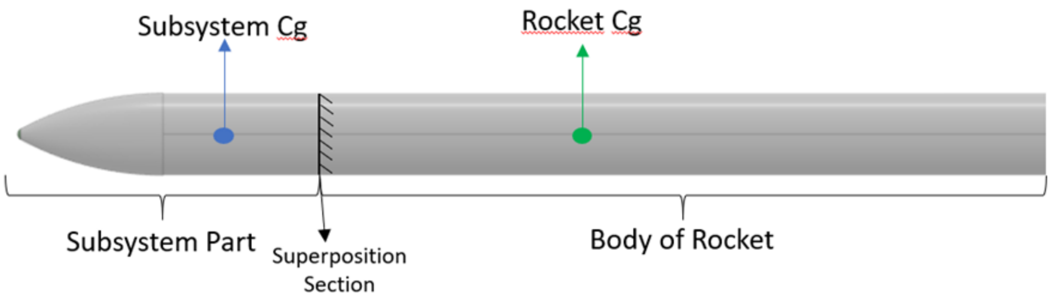

Figure 1.1 : Rocket Body and Subsystem.

Subsystems preferred in line with the main mission may demand special structural requirements from the rocket structural system. There are various methods used by rockets to calculate their own positions during flight. One of these methods, the Inertial Measurement Unit (IMU), produces information about the motion dynamics of the missile with the gyroscopes and accelerometers it contains. For example, in the case of using the Inertial Measurement Unit, the axiality must not be disrupted under the maneuver for the measured data to be meaningful (Fekete & Váradi, 2012). For this reason, it is critical for subsystems such as the IMU that the loading that occurs under the maneuver does not cause permanent damage between the bodies.

There are many methods in the literature for the connection methods of rocket bodies (Caywood, Rivello, & Weckesser, 1983). Butt connection which can be seen Figure 1.2 is one of these methods and is preferred in many applications. However, in this application, all the load flows in the form of tension and compression flowing to the bolts. It is also a difficult method for the integration of bodies. For this reason, it was not selected in this study.

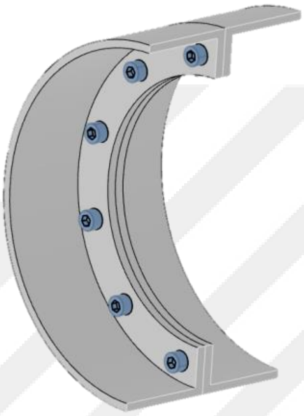

Figure 1.2 : Butt to Butt Joint Type.

In the study, the type of butt lap joint commonly used in rockets was preferred can be seen in Figure 1.3. Due to the shape connection they create, butt lap joints are frequently preferred in order to provide a safe and rigid connection in applications requiring high stiffness. The purpose of this connection method is to absorb the maneuver load with material strength and bolts.

Figure 1.3 : Butt Lap Joint Type.

In the butt lap joint, 4 out of 6 DoF are constrained by shape connections. The remaining 2 DoF are separation and moment on the flight axis. Bolts or pins are used to limit these 2 DoF in the flight direction. In these types of connections, radial bolts drilled along the body section are mostly preferred to provide ease of assembly. In the scope of this study, it was preferred to fix the bodies with radial bolts.

1.1 Purpose of Thesis

Different bolt types can be used in designs according to assembly requirements. Bolts are classified according to a series of features such as their heads, lengths, diameters, and thread types (Jack, 2013). In rocket designs, it is preferred to embed the bolt heads in the body in order to prevent extra drag.

According to Liu et al. (2022), bolt holes reduce the strength in CFRP structures due to fiber orientation disruption. In addition, embedding the bolt heads into the body will further disrupt the fiber orientation locally, further reducing structural stiffness and strength. This study examines the strain, stress, and structural integrity of fibers in the connection areas of a composite body with a wall thickness of 4 mm with different embedment amounts (1 mm, 2 mm, and 3 mm) and no embedment.

This study aims to investigate the effect of the shear and bending forces that a subsystem region will create under the maneuver to which the missile will be subjected, on the shear and bending forces that will occur in the connection area on the composite missile body. The maneuver to which the missile will be subjected is assumed to be 40 g.

1.2 Literature Review

Composite materials are widely preferred in the aerospace industry due to their high fatigue resistance, inherent strength and corrosion resistance (Afolabi & Olanrewaju, 2019). However, due to the more widespread use of composites in parts with very high area/wall thickness ratios, such as aircraft fuselages, composite analyses are mostly performed using the shell element method, assuming them to be flat plates (Son et al, 2013).

The most recent studies on cylindrical geometry specifically for composite materials focus on the characterization of composite fuel tanks (Gul, Xia, Gérard, & Ha, 2023). As mentioned above, there are studies in the literature on the effect of bolts on composite plate modeling (Barbero, 2013). These studies can be both on the performance of the bolts (Meram & Can, 2019) and the effects of the bolt on the plate are also examined (Fajri et al, 2024). However, no study has been found in the literature examining the loadings occurring in the connection areas of a rocket body made of composite material and in maneuver.

1.3 Hypothesis

According to engineering design practice, it is suggested that embedding radial bolt heads into the composite body may disrupt the fiber orientation, reduce the structural stiffness and weaken the connection areas of the bodies. However, this study proposes that the area where the bolt heads will be embedded will provide structural benefits such as preventing matrix cracking by distributing the load uniformly. Moreover, due to the nature of composite materials, concentrated high stresses create structural risks. Thus, this study hypothesizes that embedding bolt heads into the body will provide structural improvement in terms decreasing maximum stress in joint interface contrary to expectations.

2. MATERIAL

The usage of metal materials is a common practice due to high structural and thermal strength requirements in rocket designs (Khan, Ali, Gupta, Srivastava, & Kumar, 2025). However, advances in material technology have made the usage of composite materials increasingly common, especially in applications which requires weight reduction. In addition to the weight difference, the usage of metal materials can cause rocket systems which has no canister to be highly affected by environmental conditions and even rust in some cases (Choi & Jung, 2019). Special coatings and paints are used to reduce these effects and production costs increase. The choice of composite structures also prevents these situations. Although, composite materials are notable for their high specific strength, the use of these materials must design to meet high structural and thermal strength requirements. In this context, the usage of composite materials in rocket designs provides advantages over metal materials, but at the same time, the need to optimize the structural and thermal performance of these materials poses a challenge.

2.1 Material Characterization

Carbon fiber materials are quite suitable materials in terms of structural safety of rockets due to their high specific strength properties. However, due to the high production costs and certain performance deficiencies of other alternative materials, the usage of Kevlar and glass fiber materials is generally not preferred.

In this study, a material selection was needed that had been previously characterized. For this reason, MAT_162 UD material was selected. Table 2.1 shows the material properties of MAT_162 UD.

The main reason for material selection was the sensitivity to crack propagation, which is the subject of the study's hypothesis. Mr. Choi et al, state in their study that the material is a suitable material for modeling regarding the cause of damage (Choi, Kim, Park, & Lee, 2011). In addition, it is stated that it has a structure that can be followed regarding the progress of damage depending on the loading speed and that it is efficient as a test sample thanks to this structure. In this context, it is aimed to be a good sample material in case of future test studies due to the controllable structure of the material. On the other hand, other failure modes such as delimination, which are not examined in this study, are also suitable for investigation with this material.

Table 2.1 : Material Features of MAT_162 UD.

Young's Modulus X direction (GPa)	122.51	**Tensile Strength X direction (MPa)**	1835.4	**Shear Modulus XY direction (GPa)**	4.76
Young's Modulus Y direction (GPa)	8.4	**Tensile Strength Y direction (MPa)**	40.5	**Shear Modulus YZ direction (GPa)**	1.5
Young's Modulus Z direction (GPa)	8.4	**Tensile Strength Z direction (MPa)**	40.5	**Shear Modulus XZ direction (GPa)**	1.5
Poisson's Ratio XY	0.1	**Compressive Strength X direction (MPa)**	700	**Shear Strength XY direction (MPa)**	41.5
Poisson's Ratio YZ	0.2	**Compressive Strength Y direction (MPa)**	184.2	**Shear Strength YZ direction (MPa)**	55
Poisson's Ratio XZ	0.2	**Compressive Strength Z direction (MPa)**	184.2	**Shear Strength XZ direction (MPa)**	55

Tsai Wu criterion was used for fail analysis of the analyses. This is because the Tsai–Wu failure criterion is sensitive to the difference between tensile and compressive strengths, which affects its predictions under varying load conditions (Arruda et al, 2021). In addition, as stated in the hypothesis section, this study aims to obtain results especially on matrix cracking. Tsai Wu criterion also has a structure suitable for sensitive analysis on matrix properties (U.S. Department of Defense, 1996, p. 17).

3. METHOD

Within the scope of this thesis, UD fabric was selected to have high strength in each axis due to the previously mentioned 40 g selection being independent of the loading direction. In this direction, it was aimed to obtain equal strength in each direction by selecting [0, 45, -45, 90] as the layer structure shown in Figure 3.1.

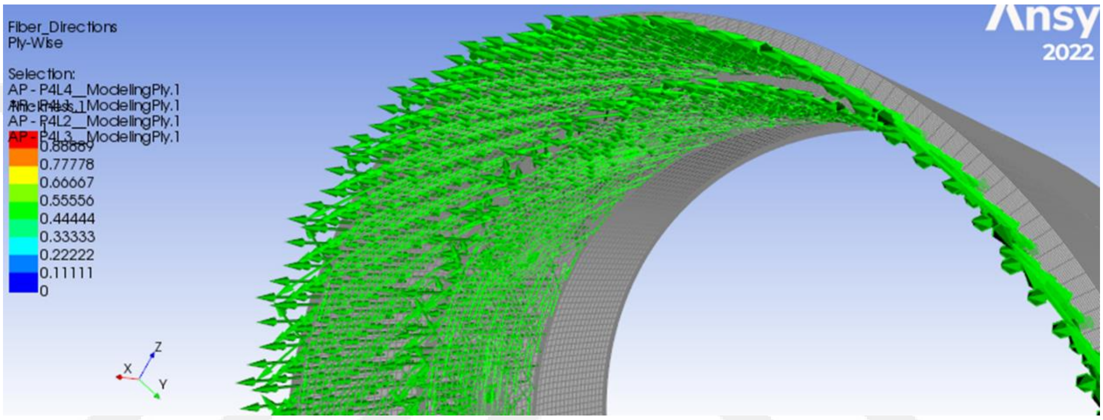

Figure 3.1 : ANSYS ACP Modelled Body and Fiber Directions.

The selected material information is defined in the material information section in the Ansys ACP (Advanced Composite Pre-Post) module. In the analyses performed, the basic mechanical properties of the material, young's modulus, Poisson ratio, shear modulus, tensile strength, compressive strength, shear strength, the modeling type will be layer-based and the failure criterion information are defined. The specified material properties are defined according to the x, y and z axes (xy, yz, xz for shear modulus).

Mesh quality directly affects the quality of the analysis results (Nemade & Shikalgar, 2020). The compatibility of the mesh distribution and dimensions with the geometry increases the quality of the results. As can be seen in Figure 3.2, the quadrilateral mesh element was preferred in this study (Mahran et al, 2017). The reason for this situation is that it softens the load transitions by increasing the number of nodes. In addition, the use of quadrilateral elements was preferred so that the analysis times would not be too long. By reducing the number of elements with the quadrilateral element, the analyses could be repeated more frequently (Franciosa et al, 2019).

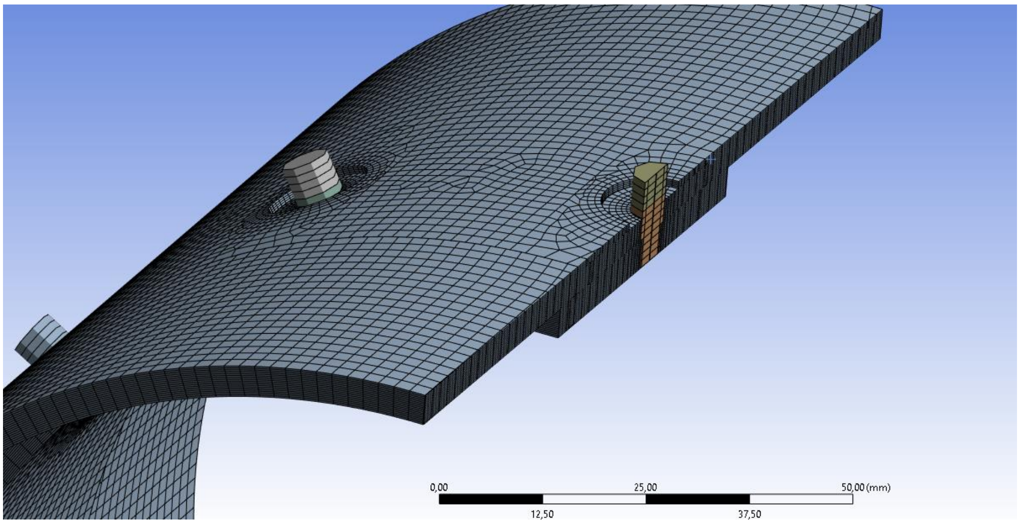

Figure 3.2 : Ansys Workbench Mesh and Layer Solid Model.

Since the analysis will focus on the hole perimeters, the mesh density around the holes must be fine which is shown in the Figure 3.3. Within the scope of the analysis, the surroundings of the holes were divided into equal parts as ± 6o. Mesh was also assigned as course mesh to the non-hole areas in between and the parts of the bodies outside the connection area. As the Figure 3.3 shows, 2 mm mesh size was preferred for flat parts. The mesh size was reduced to 0.35 mm around the holes. Since fiber agents are seen more around the holes, these areas were left with a larger mesh size.

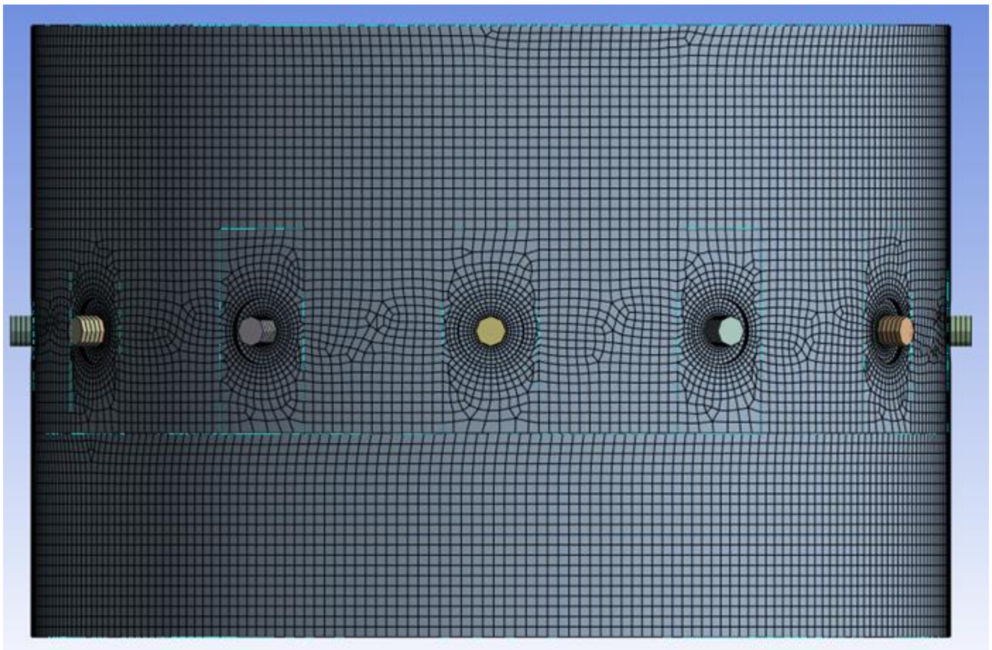

Figure 3.3 : Mesh Distribution Around Bolts.

The mesh distribution deteriorates towards the middle areas of the bolts as Figure 3.3 shows. No additional mesh improvement was required here. The purpose of this situation is that high stress concentration is not expected in those areas. For this reason, the focus was on the direct holes and their surroundings.

In addition to modeling the carbon fibers, the bolts are modeled as two different beam elements. The first beam element models the threaded area by defining the contact with the inner surface of the hole. The second beam element models the contact of the bolt head by defining the contact with the outer surface which can be seen Figure 3.4.

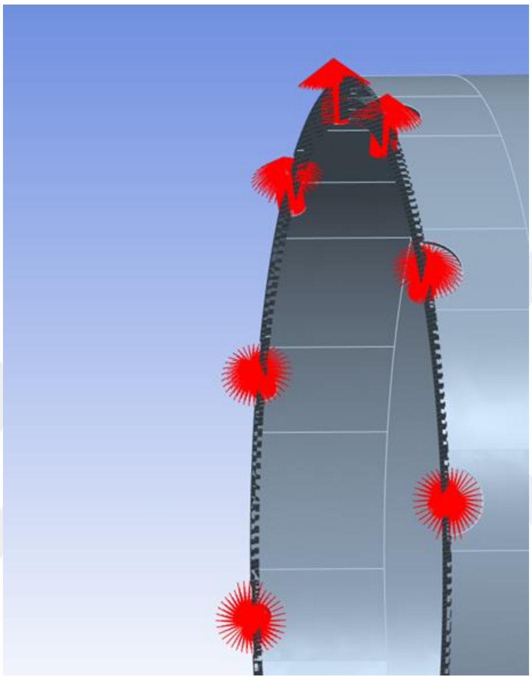

Figure 3.4 : Bolt Connection as Beam Elements of 1mm Clearance Sample.

In this study, the connection areas were examined by making them independent of the center of gravity of the rocket with the superposition method. With this method, a fixed support was selected and locked to a place close to the center of gravity of the body. On the other hand, a 24 kg load was applied from the center of gravity of the subsystem shown in Figure 3.5.

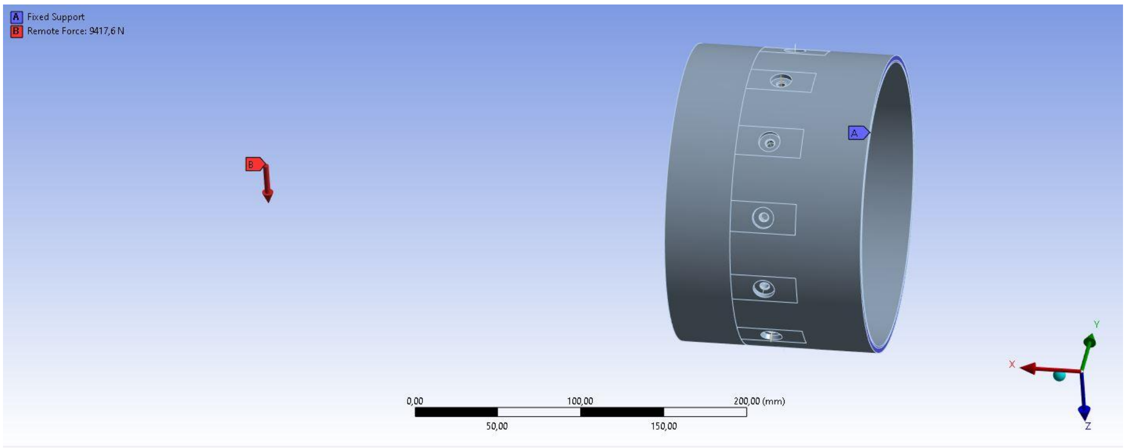

Figure 3.5 : Force and Support Assessment of 3 mm Clearance Sample.

3.1 Analysis Verification Method

Before the structural analysis of cylindrical composite bodies, an analysis study was carried out to review the accuracy of the analysis results. Within the scope of this study, a simple model with experimental data in the literature was studied. In the article published by Aktaş et al, a tensile test was performed on a plate made of carbon fiber (Aktas & Dirikolu, 2003). Within the scope of this study, the deformation around a pin is examined. As part of the study, samples with different W/D ratios are subjected to tensile tests until a D*0.04 deformation is observed. They also share the load values they obtained for different samples in a graph which shown in Figure 3.6.

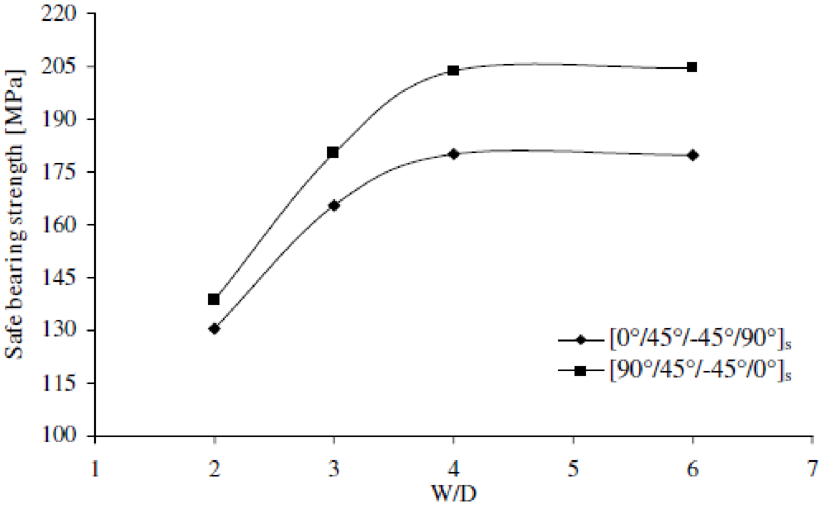

Figure 3.6 : Strength and W/D Ratio Graph of Samples (Aktas & Dirikolu, 2003).

Since the configuration selected within the scope of this thesis is [0, 45, -45, 90], this layer sequence was used in this analysis. In order to prove the higher accuracy of the analysis, 2 different configuration models with W/D ratios of 3 and 4 were selected. The hole diameter was selected as 6.35 mm, which is the same as in the study. The amount of deformation and the applied loads are shown in equation 3.1.

$$\text{Displacement (mm)} = \%\ 4 \times D = 0.04 \times 6.35 = 0.254 \qquad (3.1)$$

Layer alignment was first performed on the Ansys ACP module. Then, boundary conditions were assigned within the scope of the study as shown in Figure 3.7.

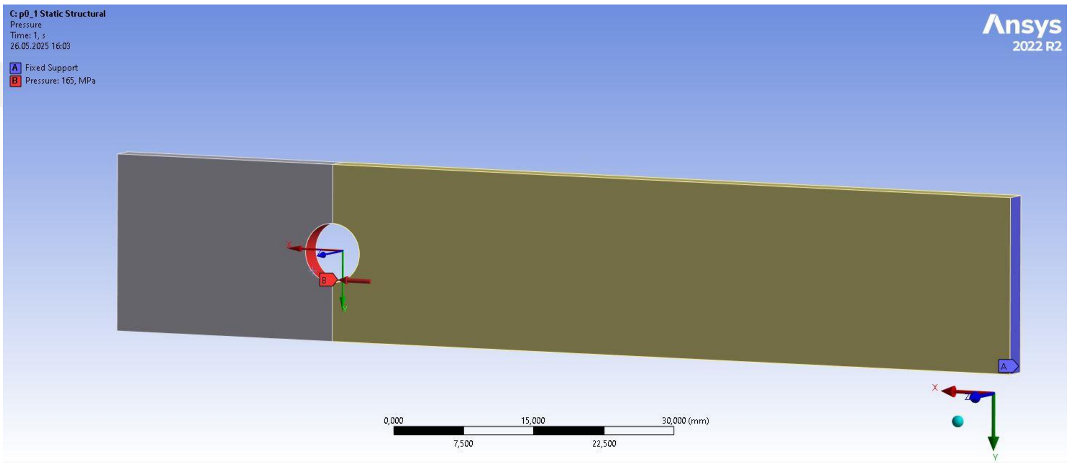

Figure 3.7 : W/D 3 Analysis Model.

Loading values selected from the graph in Figure 3.6 were applied to the relevant region in the plate. The stress values obtained for both configurations are shown in Figure 3.8 and the displacement values in Figure 3.9.

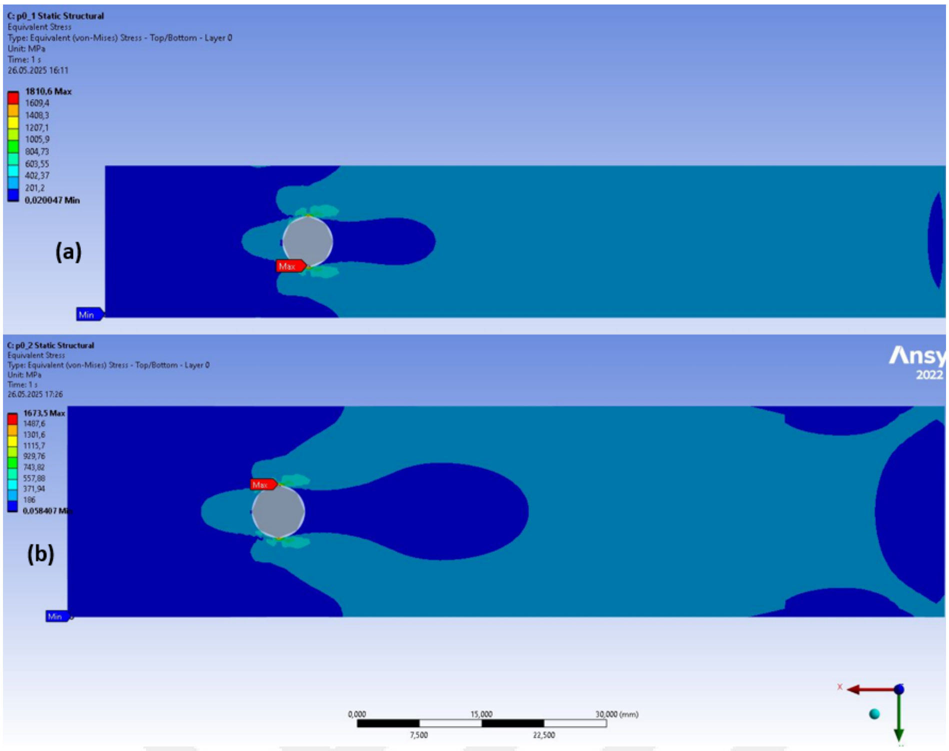

Figure 3.8 : (a) Stress Result of W/D 3 Configuration. (b) Stress Result of W/D 4 Configuration.

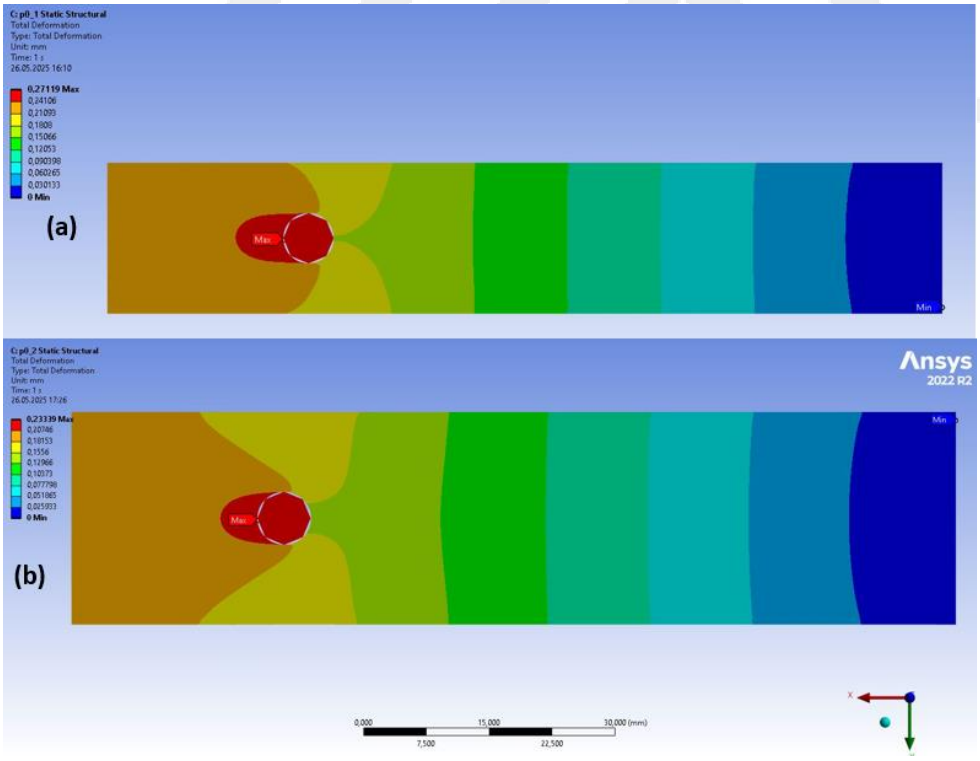

Figure 3.9 : (a) Displacement Result of W/D 3 Configuration. (b) Displacement Result of W/D 4 Configuration.

Error rates depending on displacement difference are shown in Table 3.1.

Table 3.1 : Displacement And Error Results.

	W/D 3	W/D 4
Deformation (mm)	0.271	0.233
Deformation Error Percentage (%)	6.7	8.3

It is considered that the errors in the analysis results are caused by factors such as insufficiently defined material information, boundary and environmental conditions. The error difference between the two analysis results is thought to be based on the mesh distribution, as shown in Figure 3.10.

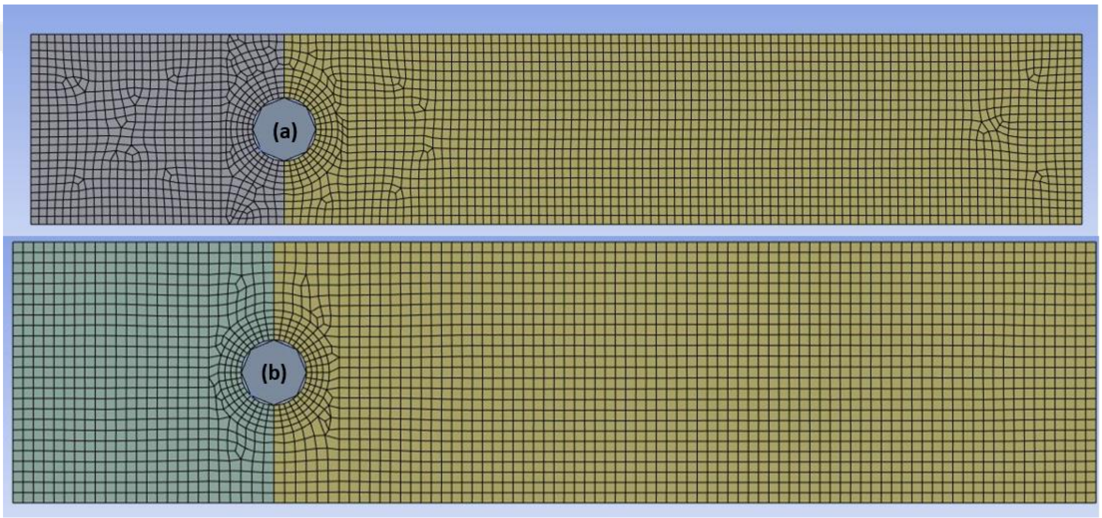

Figure 3.10 : (a) Mesh Distribution of W/D 3 Configuration. (b) Mesh Distribution of W/D 4 Configuration.

4. FINDINGS AND DISCUSSION

Within the scope of this study, analyses were performed on 4 different designs. The maximum stress, maximum deformation and the number of failing elements for the layer in contact with the bolt head are shared in Table 4.1.

Table 4.1 : Analyze Results for maximum stress, maximum deformation and the number of failing elements for the layer in contact with the bolt head.

Hole Depth	Max Stress (MPa)	Total Displacement (mm)	Max. Num. Hole Element Fails
No Hole	903.79	0,6054	108
1mm	792.01	0,568	73
2mm	720.7	0,714	82
3mm	953.94	0,8758	159

The information in Table 4.2 shows the change in body stiffness depending on the increase in hole depth in percent in the column in Table 4.1.

Table 4.2 : Comparisons of Deformation Change Percentage.

	No Hole to 1 mm	1mm to 2mm	2mm to 3mm
Deformation Change Percentage (%)	6,2	25,7	23,0

According to shared tables, it is possible to make the following outcomes,

Figure 4.1 Shows the stress values observed for the design without embedment for the bolt head is higher than the configuration with 1mm embedment. The reason for this situation is that the bolt head, which has a flat surface, crushes the cylindrical body until it absorbs the load. Since it first provides point contact with the surface it crushes, it causes very high deformation and fiber failure for local elements.

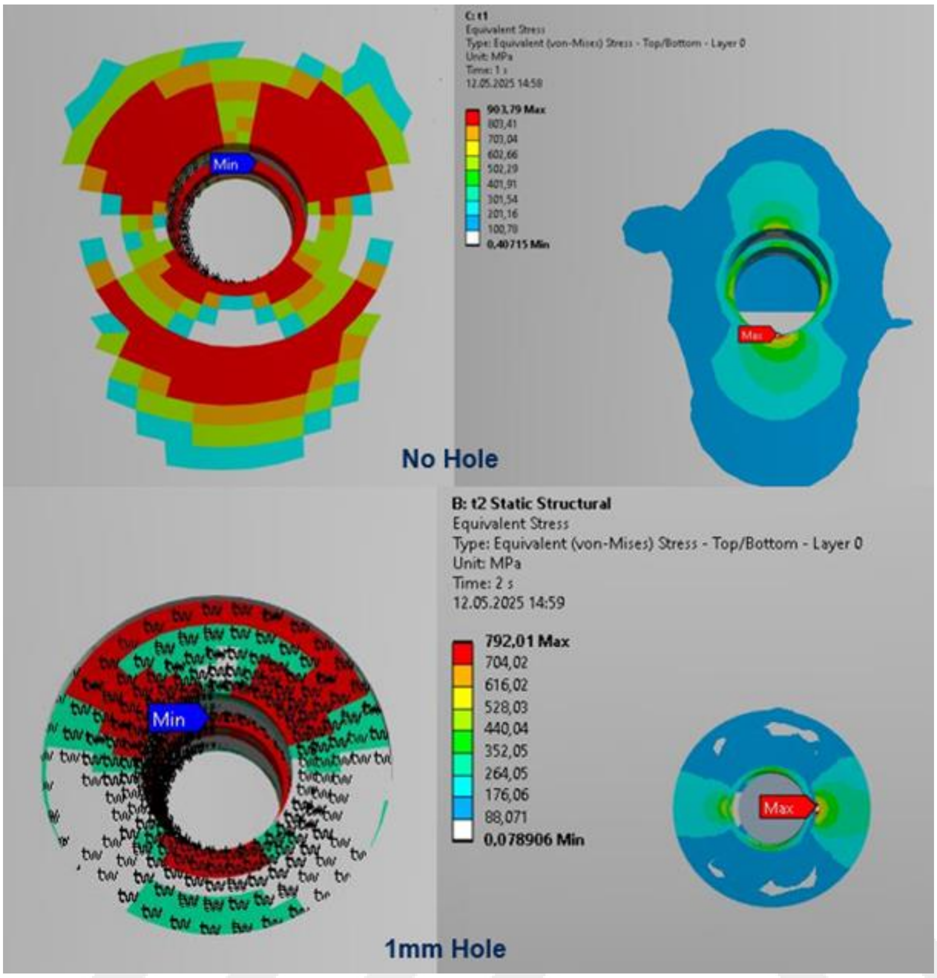

Figure 4.1 : Stress and Failure Around Top Hole for No Hole and 1mm Hole Analyzes.

This situation is considered to cause cracking in the matrix, which has a brittle structure. Due to this crack, crack propagation under vibration and shock is likely. This situation is especially critical in rockets with long flight times. It can cause the success of the flight and structural integrity to be compromised. Figure 4.2 and Figure 4.3 show the deformation and stress distribution of two different configurations.

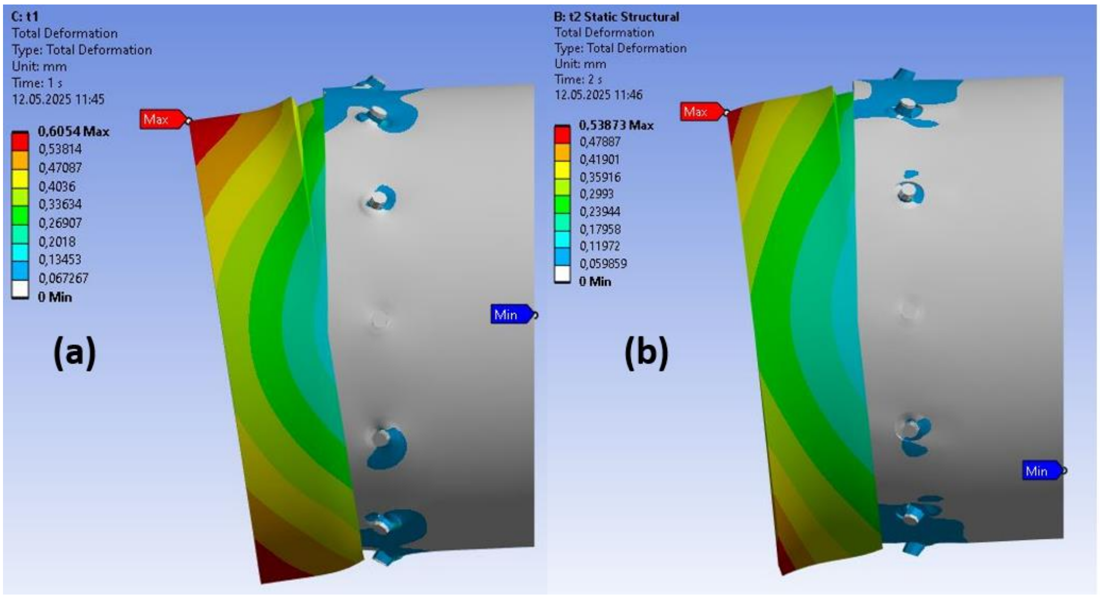

Figure 4.2 : (a) Displacement Result of No Hole Configuration with Auto Scale view. (b) Displacement Result of 1 mm Configuration with AutoScale.

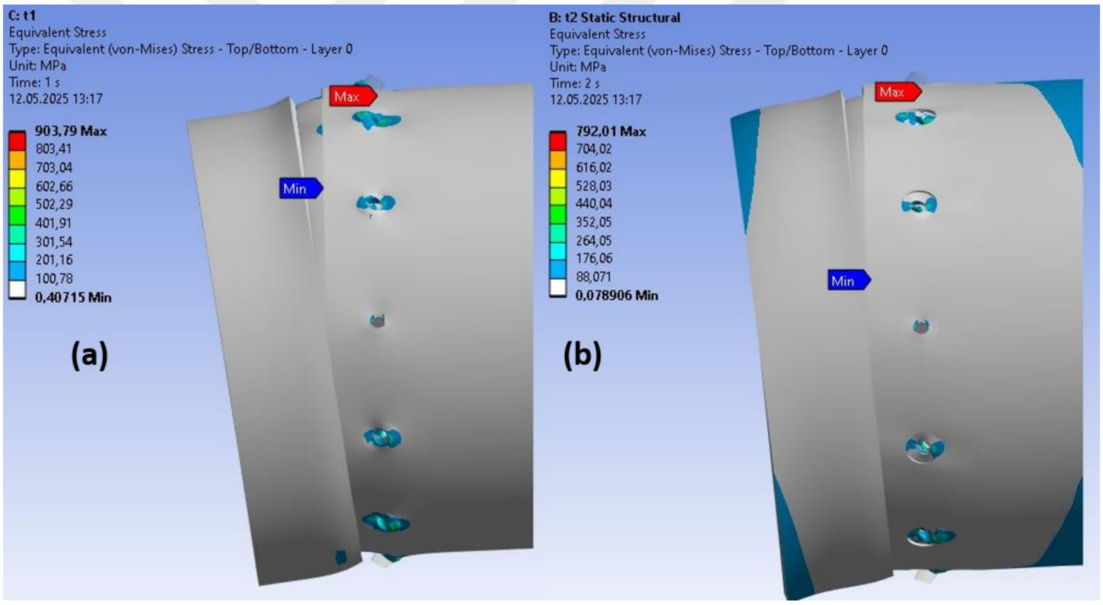

Figure 4.3 : (a) Stress Result of No Hole Configuration with Auto Scale view. (b) Stress Result of 1 mm Configuration with Auto Scale view.

As can be seen from Table 4.2 and Figure 4.4, the maximum stress decreases from 1 mm depth to 2 mm depth. However, the rigidity of the structure decreases as expected. The reason for this situation is that the stress density per unit area increases despite the decrease in the maximum stress. As can be seen from Figure 4.6, the element that acts in the area of effect increases for the bolt at the top, that is, the bolt that is subject to the highest tension.

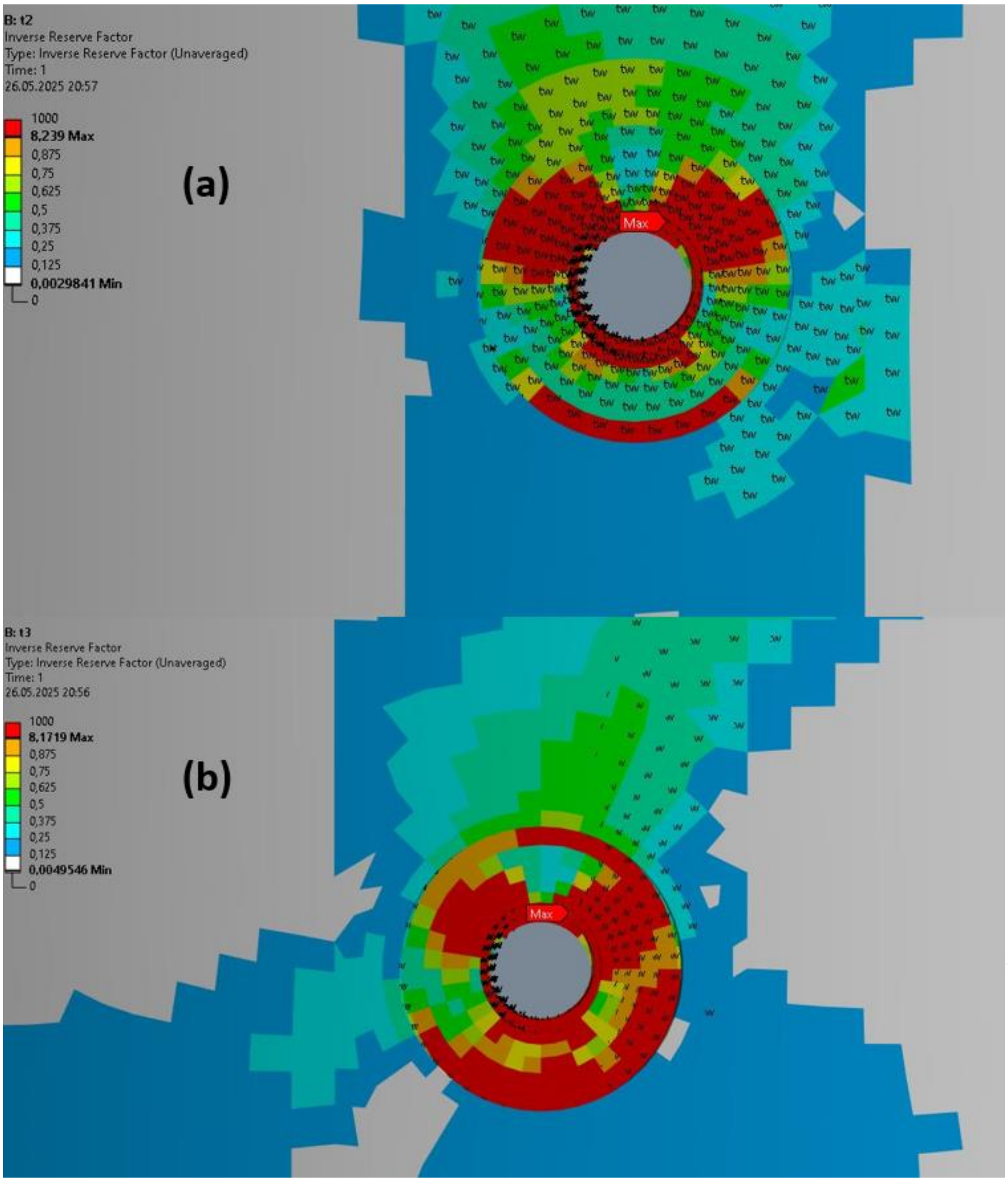

Figure 4.4 : (a) Fail Behavior of 1 mm Configuration For Top Bolt Area. (b) Fail Behavior of 2 mm Configuration For Top Bolt Area.

As the bolt head embedment depth increases, although an aerodynamically efficient structure is formed, it has been observed that the stiffness decreases by approximately 18.3% for each mm of depth. When we plot the changing deformation due to the decrease, the graph shown in Table 4.2 can be obtained.

As can be seen in Figure 4.5, the bolt tensions decrease as the approaches the neutral axis of the bending force. If the rocket's stiffness requirements were not directed towards maneuver in all directions, the amount of unloading in the bolts in the regions close to the neutral axis could be increased.

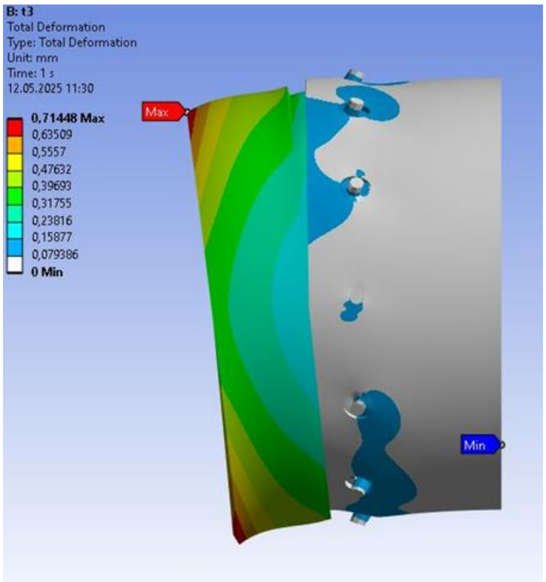

Figure 4.5 : Displacement Result of 2 mm Configuration with Auto Scale view.

Finally, if the desired maneuver in different direction is defined differently in the design requirements, there is not the same that the depths of the holes of embedment bolt head be the same as can be seen in Figure 4.6. In addition, incorrect assembly in the designs can be prevented in this way.

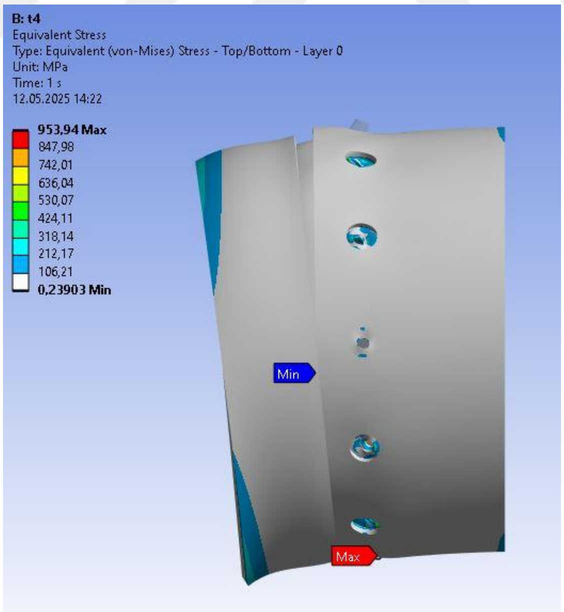

Figure 4.6 : Stress Result of 3 mm Configuration with Auto Scale view.

5. CONCLUSIONS AND RECOMMENDATIONS

Composite materials are frequently used in applications such as aircraft which weight reduction is required. The sizes of composite structures used in aircraft are extremely high compared to their wall thickness. This situation causes, modeling and analysis are examined on flat plates for these structures. Within the scope of this study, the analysis of mechanical joint methods for a cylindrical body is a first in the literature.

Although radial bolted connection type provides ease of assembly for rocket designs, the drag caused by bolt heads is of critical importance. On the other hand, the use of radial bolts creates drag due to bolt heads and therefore they must be embedded in the body. In composite material bodies, embedding bolt heads creates an average of 18.3% stiffness loss for each mm of discharge.

5.1 Assumptions

In the analyses, it was assumed that the bolts did not fail under load, there was no stripping on the threaded surfaces, there was no assembly clearance for antennas, sensors or other structural parts in in the bodies. the load assumed as static force. These assumptions cause the analyses to deviate from the real.

It is assumed that these fuselage structures are not exposed to real flight conditions. In this context, aerodynamic heating, low pressure conditions and engine vibration that will occur during flight are not included in the analysis. It is evaluated that all these conditions will directly affect the material and structural strength.

5.2 Suggestions

Rockets heat up excessively during the flight condition and enter low-pressure envelopes. In further studies, it is possible to study how high temperature affects this stiffness, the behavior of the body under low pressure, and the manufacturability, sustainability and pricing of this structure.

As explained in the results in Section 4, the tensile and compressive forces acting on the holes decrease as they approach the neutral axis. If the maneuverability can be detailed in the design phase, the layer thickness can be increased regionally. In addition, a safer design can be achieved by changing the bolt diameter depending on the maneuver and expanding the area of effect to which the load will be transferred.

It is obvious that extra thickening in bolt areas, regardless of bolt diameters, will be effective in terms of design stiffness. However, the desired weight reduction criterion should not be forgotten when starting the design.

5.3 Future Works

Within the scope of future studies, it is considered that the analyses will first be verified by testing them on real samples produced. In the following processes, it is possible to add the real flight conditions such as temperature change, temperature shock, flight/transport vibrations and pressure changes due to flight to the analyses verified by tests and to elaborate the analyses.

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