Fırat Üniversitesi Deneysel ve Hesaplamalı Mühendislik Dergisi

T Bağlantılarda Deltoit Yarıçapının Çekme Yüküne Etkisinin Sayısal Olarak İncelenmesi

Mustafa ALBAYRAK[1]*

[1]Makine ve Metal Teknolojileri Bölümü, Malatya OSB Meslek Yüksekokulu, İnönü Üniversitesi, Malatya, Türkiye.
[1]mustafaalbayrak@inonu.edu.tr

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Öz

Bu çalışmada farklı deltoit yarıçaplara sahip kompozitlerden T şeklinde birleşimler tasarlanmıştır. Bu amaçla takviye elemanı olarak karbon elyaf dokuma kumaşlar tercih edilmiştir. Daha sonra bu kompozit T-eklemleri üzerinde çekme analizleri yapılmıştır. Deltoit yarıçapının yapının maksimum çekme kuvvetine ve hasar davranışına etkisi incelenmiştir. Analizler sonucunda kuvvet-deplasman grafiği ile birlikte her deltoit yarıçap için yapıda meydana gelen fiber çekme-basma hasarı görüntüleri elde edilmiştir. Hasar başlangıcı için Hashin hasar kriteri tercih edilmiştir. Aşamalı hasar analizinde hasar ilerlemesi için Malzeme Özelliklerinin Bozulması (MPDG) yöntemi kullanılmıştır. Deltoit yarıçapının 6 mm'den 12 mm'ye çıkarılmasıyla maksimum temas kuvveti yaklaşık %10 artmıştır. 18 mm'ye çıkarılmasıyla ise yaklaşık %20.11 yükseldiği belirlenmiştir. Flanşın ağ ile temas etmediği alt yüzeyinde geniş bir alana yayılan fiber basma hasarının baskın hasar tipi olduğu belirlenmiş ve deltoit yarıçapın artmasıyla bu hasarın azaldığı tespit edilmiştir. Deltoit yarıçapı arttıkça T bağlantılı kompozit yapının daha rijit malzeme davranışı sergilediği görülmüştür.

Anahtar kelimeler: T-bağlantıları, Deltoit yarıçapı, Karbon fiber, Sürekli hasar mekaniği, Malzeme özelliklerinin bozulması

*Yazışılan Yazar

İntihal Kontrol: Evet – Turnitin
Şikayet: fujece@firat.edu.tr

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Numerical Investigation of the Effect of Deltoid Radius on Tensile Load in T-joints

Mustafa ALBAYRAK [1*]

[1]Department of Machine and Metal Technologies, Malatya Organized Industrial Zone Vocational School, Inonu University, Malatya, Türkiye.

[1]mustafaalbayrak@inonu.edu.tr

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Abstract

In this study, T-shaped joints were designed from composites with different deltoid radius. For this purpose, carbon fiber woven fabrics were preferred as reinforcement elements. Then, tensile analyzes were performed on these composite T-joints. The effect of the deltoid radius on the maximum tensile load and damage behavior of the structure was examined. As a result of the analyses, fiber tensile-compression damage images occurring in the structure for each deltoid radius were obtained along with the load-displacement graph. The Hashin damage criterion was preferred for damage onset. Material Property Degradation (MPDG) method was used for damage progression in progressive damage analysis. By increasing the deltoid radius from 6 mm to 12 mm, the maximum contact load increased by approximately 10%, and by increasing it to 18 mm, the maximum contact load increased by approximately 20.11%. Fiber compression damage, spread over a wide area on the lower surface of the flange where it does not come into contact with the web, was determined to be the dominant damage type, and it was determined that this damage decreased with the increase of the deltoid radius. it was observed that as the deltoid radius increases, the T-jointed composite structure exhibits more rigid material behavior.

Keywords: T-joints, Deltoid radius, Carbon fiber, Continuum damage mechanics, Material property degradation

*Corresponging author

Plagiarism Checks: Yes – Turnitin
Complaints: fujece@firat.edu.tr

1. Introduction

In recent years, fiber-reinforced composite structures have been widely used in many areas, such as the marine, aviation, and space industries. Composites are lightweight and have high strength and rigidity. In addition, the fact that they can be produced in desired geometries and sizes and provide the intended strength properties by using different fiber/matrix components causes these structures to be widely used. Large fiber reinforced plastic (FRP) structures have many connection points in their topology due to design and manufacturing constraints [1]. The most important connection type applied in structural applications is the composite T-connection. T-joints are designed to meet bending loads in structures such as aircraft fuselage-wing connections, marine and road vehicles [2]. Thin-walled composite structures are used in some wing panels and fuselage sections of aircraft. These structures need to be strengthened with internal reinforcements, especially to increase buckling strength. The most suitable design for this is the T-shaped hardened connection. The purpose of the T-stiffener is to prevent buckling of the surface during wing loading [3]. Material and geometry changes have a significant impact on the stress distribution, damage mode and performance of T-joints [4]. Improper design of a connection increases the likelihood of structural damage or even disaster. Therefore, understanding the damage mechanism and mechanical behavior of composite joints is a very important issue [5]. When the static tests and analyzes performed on T-connected composite structures are examined: Trask et al. carried out studies on the damage mechanisms that occur in structures with laminated composite T-joint structures under tensile load. They investigated the effect of process-induced defects in the deltoid area on the damage load by focusing on the effect [6]. Philips and shenoi [1]. proposed an approach to evaluate the damage tolerance of fiber-reinforced composite structures in critical regions of single-wall T-joints. They examined the sequence of damage initiation and progression at T-joints under loading and boundary conditions and characterized the stress patterns in the connections under these loads. Khor et al. presented a new approach to improve the structural properties and damage tolerance of fiber-reinforced polymer composite joints by tufting using shape memory alloy (SMA) filaments. By strengthening the T-shaped connections made from carbon-epoxy composite material with thin SMA (Ni-Ti nitinol) tufts, they determined the ultimate load, ultimate displacement and absorbed energy capacity of the reinforced T connection [7]. Stickler and Ramulu produced cross-stitched T-joints using fiber splicing process and PR520 hardened epoxy resin and investigated their mechanical behavior. They carried out experimental and numerical analyzes under bending loading and carried out preliminary experiments under tensile loading [8]. Dharmawan et al. investigated the structural integrity and damage tolerance of typical composite T-joints found in ships constructed from glass fiber reinforced plastic. They determined the effect of T-joint geometry on strain distribution using finite element analysis [9]. Koh et al. conducted an experimental study on the effect of carbon/epoxy T-joints reinforced with z-pins on the structural properties and strengthening mechanisms. By increasing the volumes of z-pins, they determined the effects of T-connections on elastic stiffness, failure onset stress, ultimate strength, damage limit and absorbed energy capacity [10]. Heimbs et al. carried out a study on the mechanical behavior and damage status of T-joints under dynamic and static loads. They created a new reinforcement technique in the thickness direction using metallic arrow pins to increase the damage. They then performed T-bending tests on the composite connections to evaluate potential loading rate effects along with resistance and damage tolerance [11]. Yan et al. modeled T-joints from new generation 3D woven fabrics. Afterwards, they numerically investigated the mechanical behavior by performing tensile analysis. As reinforcement architecture, two new design models have been proposed that explain the weft yarn geometric properties based on the classification of production knitting patterns[12]. Barzegar et al. defined the adhesive region in the composite structure with a T-shaped profile and examined its behavior under bending load. They examined the changes in properties such as adhesive thickness, curve radius, etc. in the adhesive region they designed by using different adhesives [5]. Yang et al. investigated a new healing repair process for T joints by implanting a three-dimensional repairable polymer network using a fiber suture technique. For this, they sewed continuously repairable thermoplastic filaments into the T-junction to promote interlayer hardening as well as self-healing ability and examined its mechanical behavior under tensile load[13]. In this study, unlike the literature, T-shaped joints with different deltoid radius were designed from carbon-epoxy composite material. Then, by performing tensile test analysis on these structures, the effect of the deltoid radius on the maximum tensile load and the type of damage occurring in the T-shaped joints was determinate. As a result of the analyses, fiber tensile-compression damage images occurring in the structure for each deltoid radius were obtained and interpreted, along with the load-displacement graphs.

2. Material Method

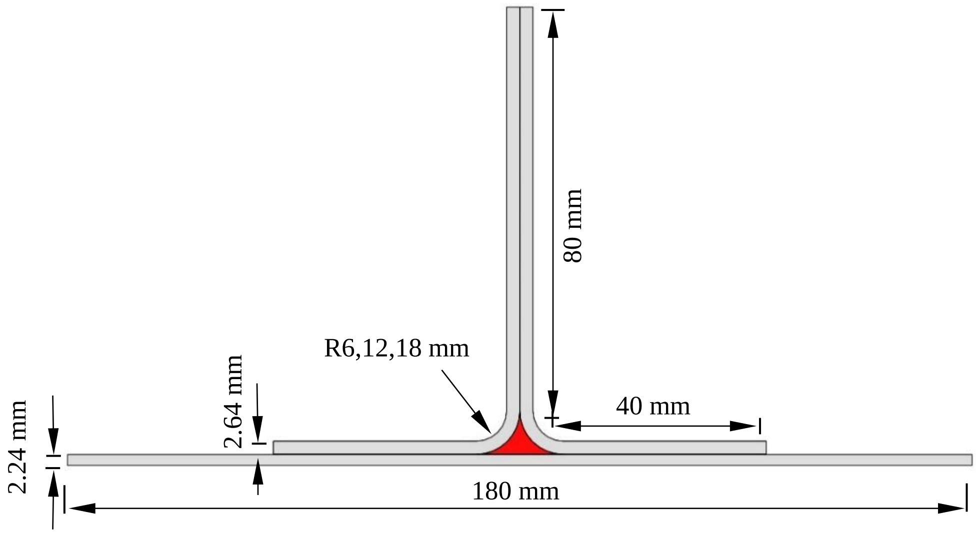

Figure 1. T-joint geometric dimensions.

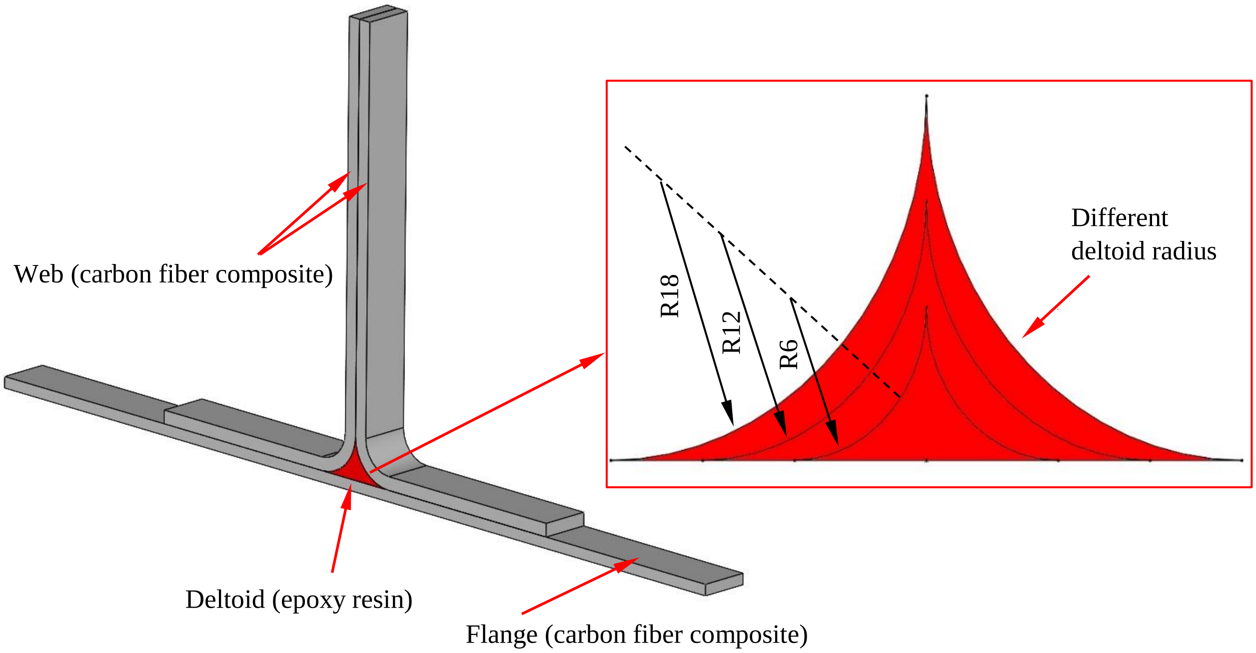

Figure 2. Design details for different deltoid radiuses.

The model whose dimensions are given in Figure 1 was designed to perform tensile analyzes on the T-jointed carbon fiber composite structure. Modeling in the design was done in the Solidworks program. Here, the Flange and Web parts are modeled at 10 mm width. T-joint design details for different deltoid radius are given in Figure 2. In this study, the effect of deltoid radius was examined. For this purpose, deltoid radius of 6mm, 12mm and 18mm were used, respectively.

2.1. Numerical analysis

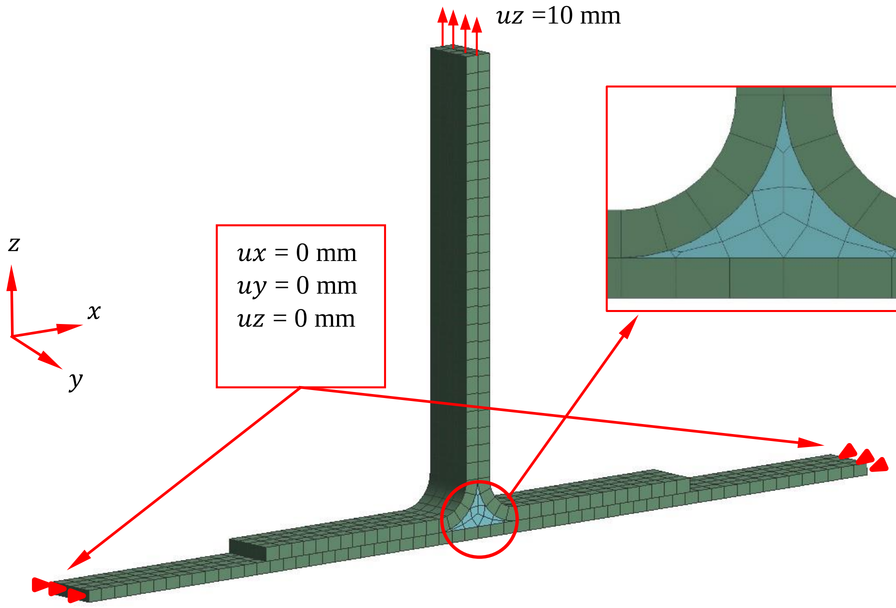

Figure 3. Finite element model of T-joint composite.

In the numerical part, the analyzes were carried out in the Ansys Workbench 2020R1 program. The Flange and Web parts that make up the T-joint were modeled as separate volumes and transferred to the Workbench program with the "Parasolid" extension. After the necessary material assignments were made, the solid models were divided into finite elements. Here, 8-node element type is preferred and Multizone mesh type is used. In the model divided into finite elements, the number of elements was determined as 5820 and the number of nodes was determined as 33175. The mesh structure of the finite element model are presented in Figure 3. The two side surfaces of the Flange model were selected as fixed supports and the web part was given a displacement in the z direction.

2.1.1. Damage model

Orthotropic properties of carbon fiber are presented in Table 1. In order to define the beginning of damage in progressive damage analysis, Hashin damage initiation criteria must be entered into the program. The hash initiation criteria include the following four damage initiation modes. Here the damage initiation indices are I_f^t ; I_f^c; I_m^t and I_m^c represent fiber tensile, fiber compression, matrix tensile and matrix compression damage, respectively. When any of these indices exceeds 1, damage onset occurs. Four different damage cases belonging to the Hashin criteria are evaluated according to the following formulas in Equations (1)-(4)

Table 1. Mechanical properties of carbon fiber reinforced composite [14].

Symbol	Properties	Value	Unit
ρ	Density	1500	kg/m^3
E_x, E_y	Elasticity modulus x and y direction	43.7	GPa
E_z	Elasticity modulus z direction	14.57	GPa
υ	Poisson	0.21	-
G_{xy}	Modulus of rigidity in xy plane	14.18	GPa
G_{yz}	Modulus of rigidity in yz plane	14.65	GPa
G_{zx}	Modulus of rigidity in zx plane	14.65	GPa

Fiber failure for tension ($\sigma_{xx} \geq 0$):

$$I_f^t = \left(\frac{\sigma_{xx}}{F_{xt}}\right)^2 + \alpha \left(\frac{\sigma_{xy}}{F_6}\right)^2 \quad (1)$$

Fiber failure for compression ($\sigma_{xx} < 0$):

$$I_f^c = \left(\frac{\sigma_{xx}}{F_{xc}}\right)^2 \quad (2)$$

Matrix failure for tension ($\sigma_{yy} \geq 0$):

$$I_m^t = \left(\frac{\sigma_{yy}}{F_{yt}}\right)^2 + \left(\frac{\sigma_{xy}}{F_6}\right)^2 \quad (3)$$

Matrix failure for compression ($\sigma_{yy} < 0$):

$$I_m^c = \left(\frac{\sigma_{yy}}{2F_4}\right)^2 + \left[\left(\frac{F_{yC}}{2F_4}\right)^2 - 1\right] \frac{\sigma_{yy}}{F_{yC}} + \left(\frac{\sigma_{xy}}{F_6}\right)^2 \quad (4)$$

Table 2. Orthotropic stress limit values of carbon fiber composite [14].

Symbol	Properties	Value (MPa)
X_T	Tensile strength in X direction	859
Y_T	Tensile strength in Y direction	859
Z_T	Tensile strength in Z direction	859
X_C	Compression strength in X direction	109.6
Y_C	Compression strength in Y direction	109.6
Z_C	Compression strength in Z direction	373.5
S_{XY}	Shear strength in plane $X - Y$	108.2
S_{YZ}	Shear strength in plane $Y - Z$	105.5
S_{XZ}	Shear strength in plane $X - Z$	105.5

Here σ_{ij} are the components of the stress tensor; F_{xt} and F_{xc} are the tensile and compressive strengths of a sheet in the longitudinal (fiber) direction; F_{yt} and F_{yc} are the tensile and compressive strengths in the transverse direction; F_6 and F_4 are in-plane and inter-layer shear strengths. α is the contribution of the in-plane shear stress according to this criterion and is taken as 0 in this study. In order to evaluate the damage initiation criteria in the composite structure, it is necessary to define the maximum stresses or strains that the material can tolerate before damage occurs. Stress limit values are presented in Table 2.

2.1.2. Damage evolution

MPDG was used for damage progression. Stiffness reductions used for the four damage cases in the study are given in Table 3.

Table 3. Stiffness reduction coefficients for the MPDG method.

Properties	Value
Reducing fiber tensile stiffness	0.46
Reducing fiber compressive stiffness	0.46
Reducing matrix tensile stiffness	0.4
Reducing matrix compressive stiffness	0.4

3. Results and Discussion

Tensile analyzes were performed on T-joined specimens made of carbon fiber reinforced composites. The problem was solved and evaluated according to the Material Property Degradation method for different deltoid radius. The effect of deltoid radius changes on the maximum load and damage type that the composite structure can carry was evaluated. Figure 4 shows the reaction load-displacement curve of the sample. Considering the graph, it was determined that the structure exhibited linear material behavior for all deltoid radiuses. However, it has been observed that as the deltoid radius increases, the T-jointed composite structure exhibits more rigid material behavior. Maximum contact loads for different deltoid radius are compared in Figure 5. When the graph is examined, the maximum contact load for R6 is determined as 121.86 N. For radius R12 and R18, these values are 133.15N and 146.36N, respectively. It was calculated that by increasing the deltoid radius from 6mm to 12mm, the maximum contact load increased by approximately 10%, and by increasing it to 18mm, it increased by approximately 20.11%. In their study, Trask et al obtained similar results by determining that the maximum contact load increased parallel to the deltoid radius. When the study is examined, Trask et al. performed tension pull-off test on the T-jointed structure they produced from carbon epoxy unidirectional pre-preg and according to the results they obtained: They determined that a 50% decrease in the deltoid area caused a 33% loss of strength in the structure. Fiber tensile and compression damage images occurring in the specimens for different deltoid radius are presented in Figures 6-8. A color scale appears next to the numerical damage images. Here, the red area indicates that the sample is damaged, and the blue areas indicate the undamaged parts of the sample. Fiber reinforced materials exhibit linear elastic behavior and their damage behavior is more complex than isotropic materials. Especially due to the brittle structure of damaged composites, fiber tensile damages can be observed in the damage area of the fibers carrying the main load under tensile load. When the fiber tensile damage images of all specimens were examined (Figure 6a-8a), fiber tensile damage was observed at each edge ends of the flange, which were kept fixed. However, fiber compression damages spread over a wide area were detected on the lower surface of the flange, where it did not come into contact with the web (Figure 6b). However, as the deltoid radius increased, fiber compression damage in this region was gradually reduced and even completely prevented (Figures 7b and 8b). This is related to ensuring continuity between web and flange a more linear geometry by increasing the radius value. In this way, the peak stress occurring in the web-to-flange transition connections are reduced [15].

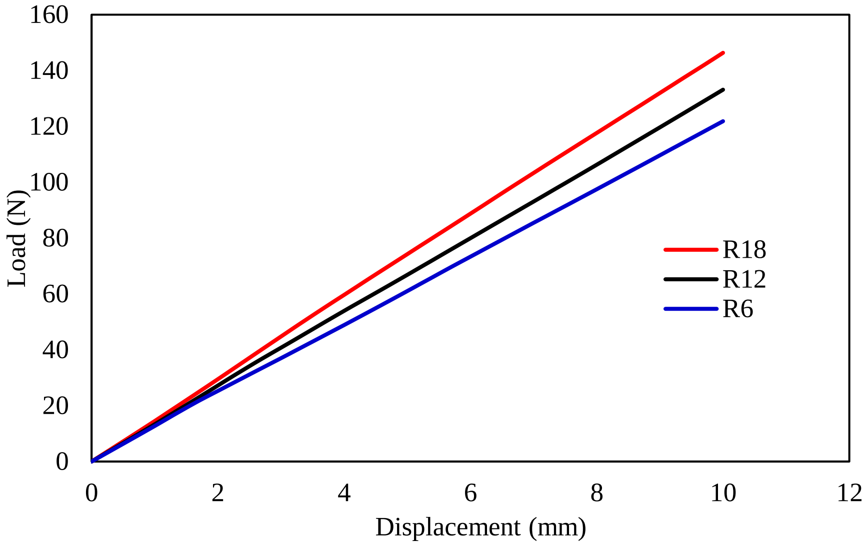

Figure 4. Comparison of load-displacement graphs for different deltoid radius.

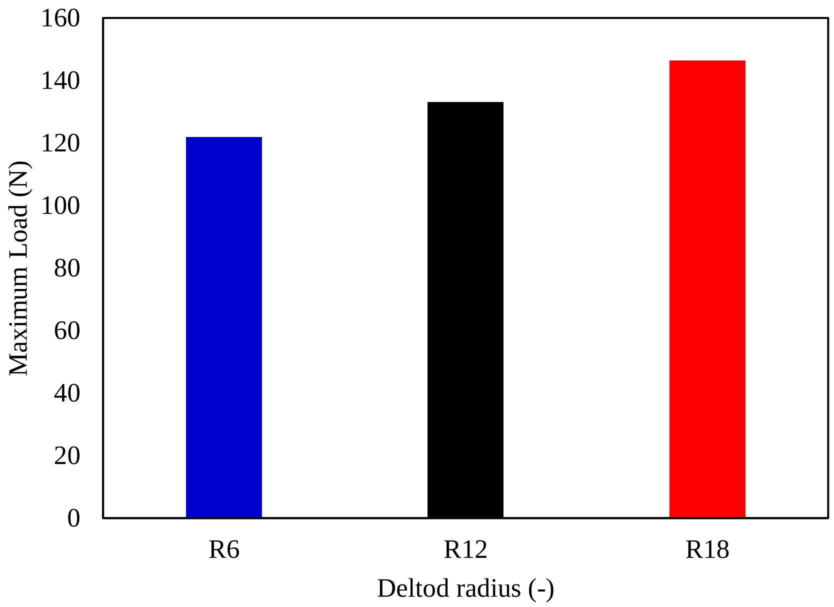

Figure 5. Numerical comparison of maximum load values.

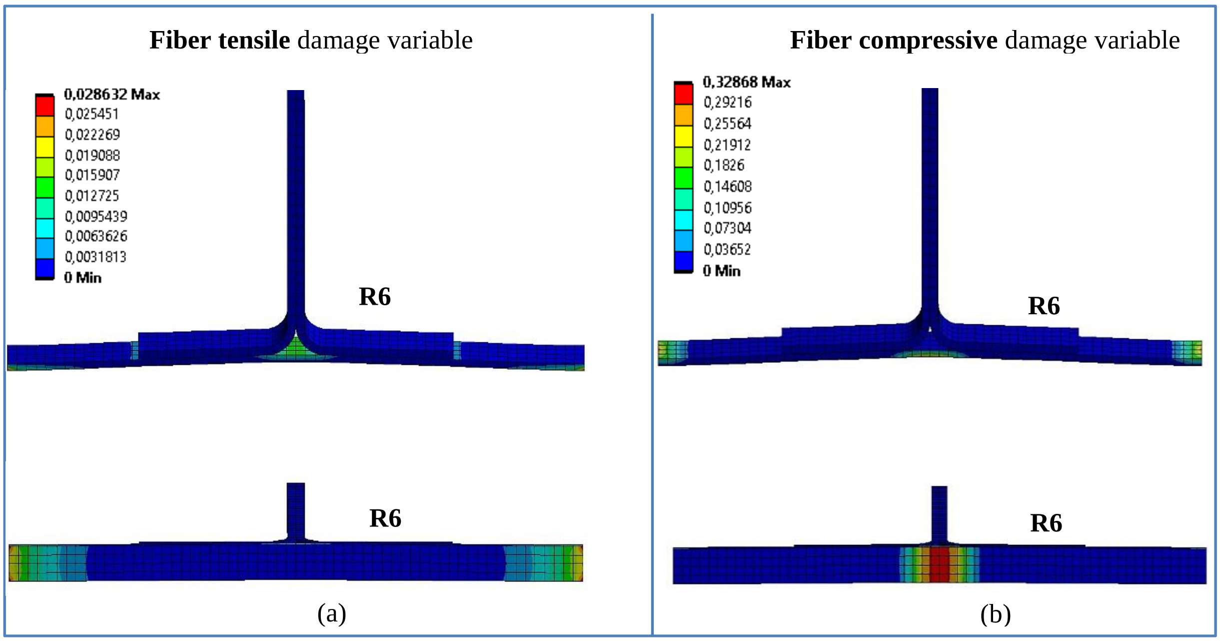

Figure 6. Comparison of (a) fiber tensile damage and (b) fiber compression damage images in the T-joint composite for specimen R6.

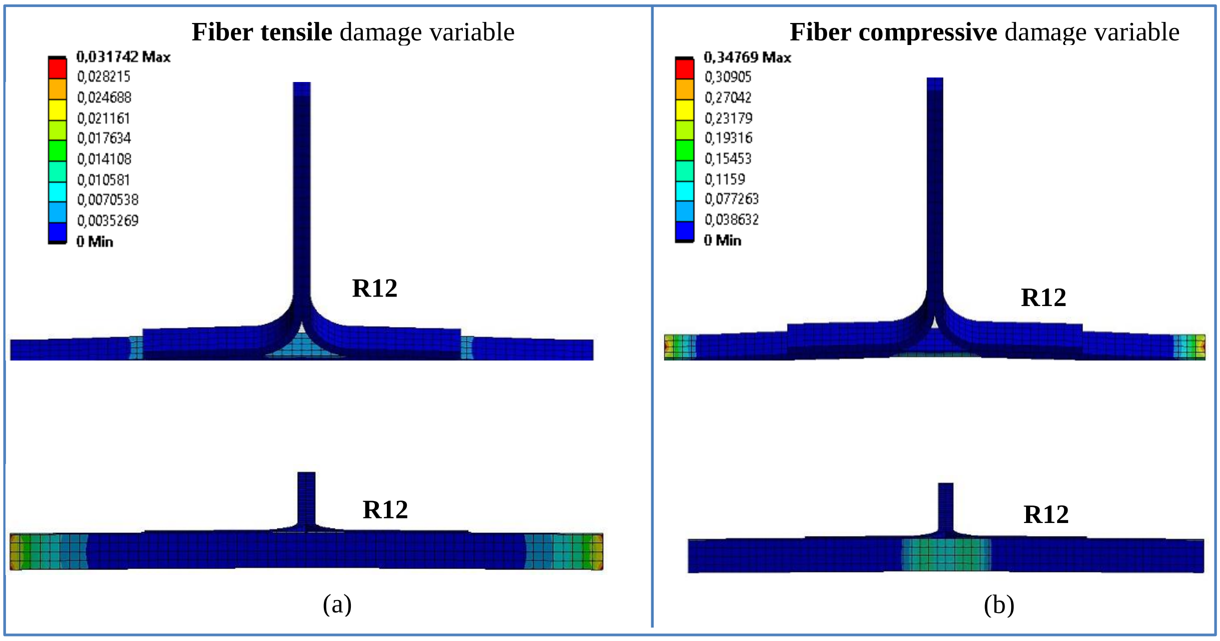

Figure 7. Comparison of (a) fiber tensile damage and (b) fiber compression damage images in the T-joint composite for specimen R12.

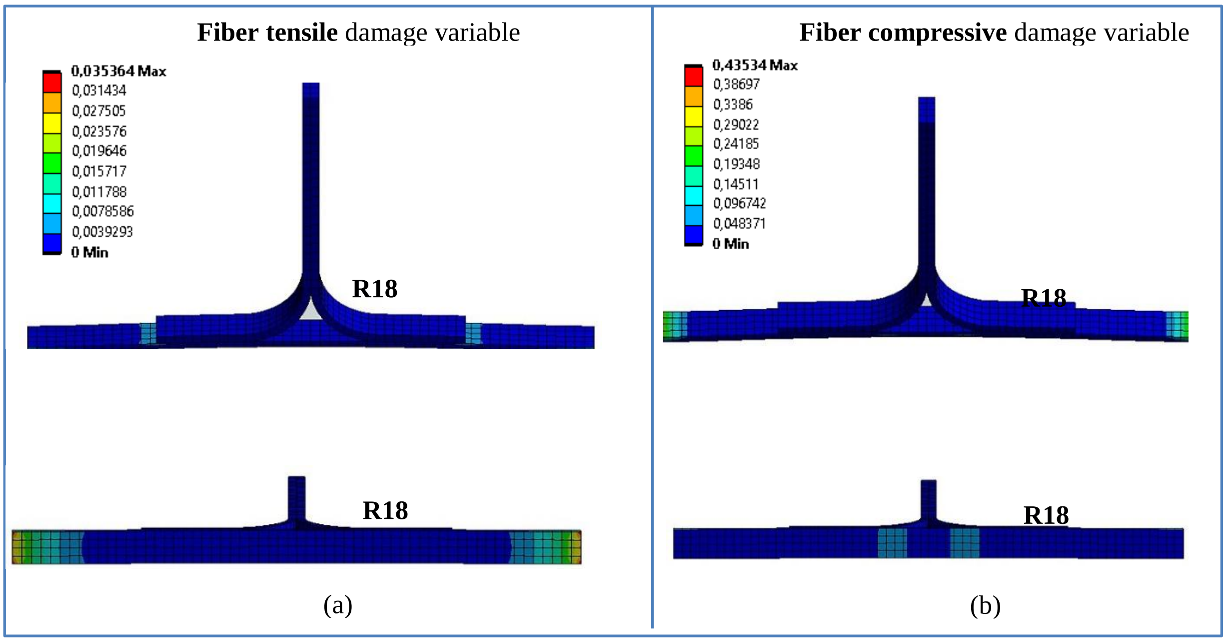

Figure 8. Comparison of (a) fiber tensile damage and (b) fiber compression damage images in the T-joint composite for specimen R18.

4. Conclusion

Tensile test analysis was carried out on T joints with different deltoid radius made of carbon-epoxy composite material, and the effect of deltoid radius on the maximum tensile load and damage behavior of the composite structure was examined. The results were compared and summarized as follows.

- By increasing the deltoid radius from 6 mm to 12 mm, the maximum contact load increased by approximately 10%, and by increasing it to 18 mm, the maximum contact load increased by approximately 20.11%.
- it was observed that as the deltoid radius increases, the T-jointed composite structure exhibits more rigid material behavior.
- With the increase in the deltoid radius, both higher contact loads were obtained in the structure and the peak stresses occurring in the web-flange transition connections were reduced as the continuity between the web and the flange provided a more linear geometry.
- It is recommended to increase the deltoid radius in the design of T joints, which is one of the most important connection types for structural applications. In this way, connections that are resistant to tensile load and less damaged are obtained.

5. Author Contribution Declaration

In the study carried out, Author 1 contributed to the formation of the idea, design and literature review, evaluation of the results, procurement of the materials used and examination of the results, and checking the article in terms of spelling and content.

6. Ethics Committee Approval and Conflict of Interest Declaration

There is no need to obtain ethics committee permission for the article prepared. There is no conflict of interest with any person/institution in the prepared article.

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