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Patch Repair Analysis of Impact Damaged Glass Fiber / Epoxy Composite Tubes Operating Under Internal Pressure

İç Basınca Maruz Olarak Çalışan Darbe Hasarlı Cam Elyaf / Epoksi Kompozit Tüplerin Yama Onarım Analizi

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Abstract

Application of composite patches is a useful technique to repair damaged structures such as wind turbines, air vehicles, pressure tanks because of lightweight, flexible design, and low price, and have found a widespread application area in many more industries. To avoid excessive weight of the repaired region as well as unnecessary material consumption composite patches need to be optimized according to shape, size and material specifications. This paper introduces a numerical assessment of size and material effect in composite-to-composite patches having specific shape and material properties. Adhesively bonded round-tipped composite patch pieces are utilized to repair a quadrilateral puncture damaged cylindrical thin-walled hollow composite tubes loaded by internal pressure. Glass fiber / epoxy patches with five different kinds of stacking sequence and ten different sizes are numerically investigated to achieve the best composite patch solutions. Although the safety factor of repaired tubes enhances by increasing tip radiuses and hence their sticking area, it is found to be not sufficient to ensure that the patching process is completely safe because of the fiber orientation playing an important role on the factor of safety. The patches having $[0°]_4$, [0°, -45°,45°,90°], and $[0°,90°]_2$ stacking sequences and having adequate patch areas are found to be able to provide the safety value of "1.15" which is defined for normal safety class and below 5% coefficients of variation (COV) value in DNV's Offshore Standard (DNV-OS-C501).

Keywords: *Patch repair, Glass-fiber epoxy, Composite tubes, Pressure load*

Öz

Kompozit yama uygulaması, hafifliği, esnek tasarımı ve düşük fiyatı nedeniyle rüzgâr türbinleri, hava araçları, basınçlı tanklar gibi hasarlı yapıları onarmak için faydalı bir teknik olup daha birçok endüstride yaygın bir uygulama alanı bulmuştur. Onarılan bölgenin aşırı ağırlığından ve gereksiz malzeme tüketiminden kaçınmak için kompozit yamaların şekil, boyut ve malzeme özelliklerine göre optimize edilmesi gerekir. Bu makale, belirli şekil ve malzeme özelliklerine sahip kompozitten kompozite yamalarda boyut ve malzeme etkisinin sayısal bir değerlendirmesini sunmaktadır. Yapıştırılarak uygulanmış yuvarlak uçlu kompozit yama parçaları, iç basınçla yüklenen dörtgen şeklinde delinme hasarlı silindirik ince duvarlı içi boş kompozit tüpleri onarmak için kullanılmaktadır. Beş farklı istifleme dizisine ve on farklı boyuta sahip cam elyaf / epoksi yamalar, en iyi kompozit yama çözümlerini elde etmek için sayısal olarak incelenmiştir. Onarılan tüplerin güvenlik faktörü, uç yarıçaplarını ve dolayısıyla yapışma alanlarını artırarak yükselse de güvenlik faktörü üzerinde önemli bir rol oynayan fiber oryantasyonu nedeniyle yama işleminin tam güvenli olmasını sağlamak adına yeterli olmadığı bulunmuştur. $[0°]_4$, [0°, -45°,45°,90°] ve $[0°,90°]_2$ istifleme dizisine sahip ve yeterli yama alanlarına sahip olan yamaların DNV'nin Offshore Standardında (DNV-OS-C501) normal güvenlik sınıfı ve %5'in altındaki varyasyon katsayısı (COV) değeri için tanımlanan "1.15" değeri için güvenlik katsayısını sağlayabildiği bulunmuştur.

Anahtar Kelimeler: *Yama tamiri, Cam elyaf epoksi, Kompozit borular, Basınç yükü*

1. Introduction

It is a very common case that internal pressure pipes or tanks could be exposed some damaging cases such as impacts by piercing or cutting hard bits. If the material here is a plastic matrix composite, the issue gets more crucial because of high sensitiveness of plastics to impact loading. Sometimes it would be the only choice to replace the damaged component. However, repairing the material is usually more cost-efficient, easy, and practical way instead of a whole replacement if possible. Therefore, patch repair especially bonded composite technology has been widely utilized in restoring damaged structures for decades in various areas. Because of lightweight, flexible design, and low price, the bonded composite patches have found a widespread application area in wind turbines, air vehicles, pressure tanks and other related industries [1].

Being able to implement a reliable and efficient patch which provide the component to carry on its function just as a non-damaged one can be affected by multiple parameters. One of the factors regarded by researchers is the fitting method of the composite patch such as scarf, single-bonded and double-bonded repairs. Although it is regarded as the most common method, single bonded patch repair has some complications to be considered in design process [2]. The quality of single bonded patch repair is influenced by many parameters such as peel stresses, stress concentration factor (SCF), stress intensity factor (SIF), delamination, moisture absorption and so on [3-6].

To improve the performance of patch repair, it is required to develop some special methods which alleviates the adverse effects of the mentioned parameters. One of the methods usually applied to repairs is optimizing patch shape and geometry which could be effective ways to reduce stress intensity and concentration factors [7-8]. Brighenti et al. [9] tried to solve an optimal shape problem of patch repairs by using a genetic algorithm. Instead of regular square or rectangular patch, an optimal shape patch has reduced SIF and eventually increased mechanical properties by keeping the patch area constant. Also, a recent study was performed by Echer et al. [10] who applied fiber reinforced patches to locally damaged composite parts. The research was aiming to define optimum sized and fiber-oriented patches for conventional rectangular and elliptical geometries. It was proved that orientation of patch is not trivial even for simple and symmetric stacking sequence.

Thickness of the adhesive and shear modulus are regarded as other issues requiring optimization in patches. By means of using finite element method, Yala and Megueni [11] simulated composite patch and plates. For optimizing the repair operation, the effects of size and intrinsic properties of adhesive investigated. The results of the studies suggest that a realistic SIF should be around 8.38 MPa. $m^{-1/2}$. According to a different study by Abdelkader [12], thickness and shear modulus of the adhesive in addition to the lap width were found to be key factors to achieve a realistic optimization of bonding operation.

Implementing a successful composite crack repair operation is depended on reducing the stresses generated at crack tips while transferring load between the separated crack sides through patch and adhesive [13]. This can be achieved by adjusting some specific parameters such as adhesive shear modulus, patch Young modulus and material thicknesses. By optimizing the weights of these factors, the best configuration can be determined to minimize SIF and to obtain long-lasting and efficient repair. Nevertheless, in case there is no other alternative option for the given parameters, the size of a patch could be the first determining factor to get an efficient patch design. In such a case, the main question is "what should be the optimum patch size for the given material, shape specifications?" While many previous studies have been concerned with determining optimum composite patch repair parameters such as adhesive type, stiffness of patch material, patch shape and patch thickness, the current paper introduces a different approach by trying to evaluate the optimum patch size for specific material and shape properties. Because an oversized patch results in excessive increase in weight of the patch region as well as unnecessary material consumption.

Within this context, the present paper gives a numerical assessment of size effect in composite-to-composite patches having specific shape and material properties. The repair operations to glass fiber reinforced epoxy composite pressure tubes that can be applied to all areas of the industry where high pressure liquid and gas transmission is concerned were examined. Epoxy based glass fiber reinforced cylindrical thin-walled hollow tubes having internal pressure were first intentionally damaged by opening a quadrilateral puncture. The damaged tubes were then repaired by using adhesively bonded round-tipped composite patch pieces.

2. Material and Method

A pressure tube with an inner diameter of 20 mm and 1 mm wall thickness is considered to have been damaged somehow by a hard cutting edge as a result of a dynamic impact load. As the tube material, a glass fiber / epoxy-based composite having 45˚ / - 45˚ fiber orientation according to the neutral axis is designed. Cylindrical members made of fiber reinforced plastic matrix composites are generally fabricated by filament winding process (Figure 1). The process is based upon winding the fibers on a rotating mandrel right after impregnating them in a resin bath [14]. The fiber winding angle can be set up basically by adjusting the angular velocity of the mandrel and linear speed of the fiber loader in axial direction. Finally, the epoxy matrix of the wounded tube is cured under a specific temperature to be able to reach its full strength.

The tube samples numerically analyzed here are exposed to a stable internal pressure of 10 MPa to evaluate the effectiveness of the patches with varied tip radiuses and areas. As defined in ASTM E2981-21 [15] the low-pressure filament wound composite vessels for carrying aerospace media have maximum allowable pressure of 3.5 MPa and high-pressure vessels for compressed gases have maximum allowable pressure of 70 MPa. With the internal pressure currently applied, the analyzed tubes can be said to be suitable for storing medium pressure compressed gases. The pressure tubes were selected as having 180 mm length, which is predicted to be sufficient to be able to assess efficiency of patches for selected geometry and sizes.

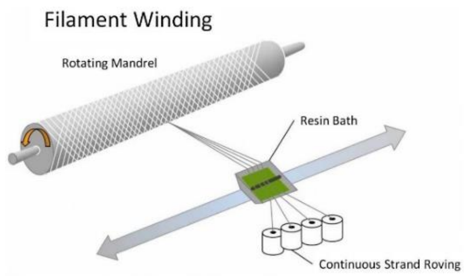

Figure 1. Schematic illustration of filament winding process [14]

Şekil 1. Filament sarma işleminin şematik gösterimi [14]

The glass filament wound composite tubes are made of four overlapping equal-thickness laminas having [45°, -45°,45°, -45°] fiber orientations. According to Standard Test Method for Measuring the Damage Resistance of a Fiber Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event, ASTM D7136 [16] the standard impactor geometry has a blunt, hemispherical striker tip. However, the standard recommends alternative appropriate impactors such as sharp striker tip geometries depending upon the damage resistance characteristics being examined. As seen in Figure 2, the models were intentionally fully perforated without bounce back so as to form a quadrilateral shaped slot by fixed dimensions to characterize the damage created by a sharp edge impactor. The mesh is configured automatically by the software. Because equivalent stresses are concentrated mainly at the slot circumference, this location is refined for obtaining more reliable solution.

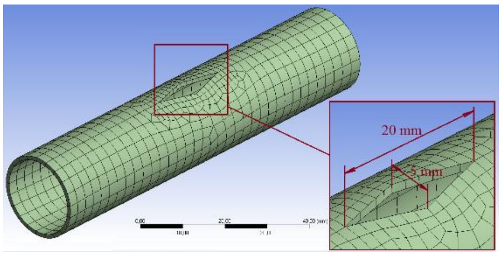

Figure 2. The dimensions of quadrilateral shaped slot on the specimen

Şekil 2. Numune üzerindeki dörtgen şeklindeki yuvanın boyutları

Afterwards the slots were repaired by using round tipped glass/fiber epoxy composite patches bonded adhesively to the specimens (Figure 3). The distance between the centers of two round tips at both side of the patch is fixed to 20 mm which is also equal to the whole length of damage slot. As regards to the radiuses of round tips (R), it is identified as a variable determining the applied composite patch areas having a direct impact on the effectiveness of the repair operation.

The selection of adhesive material is an important issue in adhesively bonded composite patch repair operations. Due to its long-lasting characteristic [17] LOCTITE EA 9466, an epoxy-based adhesive was selected and defined at the contact surfaces between patch and specimen. The mechanical property of the specified adhesive is given in Table 1. As an epoxy-based polymer adhesive, LOCTITE EA 9466 exhibits higher tensile modulus and strength in comparison to Polyurethane polymer and Silane-modified polymer-based adhesives [18].

The patch material is also composed of E-glass fiber / epoxy just like the repaired tube except for the orientation of the fiber reinforcements. As the repairing patch content, various types of reinforcing fiber angles are considered and analyzed as listed in Table 2. Moreover, the efficiency of each type of fiber-orientation was analyzed according to different R values representing the patch areas in Table 3.

As a basis of the current numerical analysis, the default mechanical properties of the E-glass fiber / epoxy unidirectional composite lamina in the Ansys software are utilized for Finite Element Analysis (FEA) and listed in Table 4. Establishing a suitable finite element model, internal pressure analyzes were conducted to obtain numerical solutions. Among the specimen codes given in Tables 2 and 3, an optimum combination of patch repair was aimed to deduce from the analyses performed by applying constant 10 MPa internal pressure. It will be detected what fiber angle of patch is most convenient with the smallest patch area providing a reasonable factor of safety.

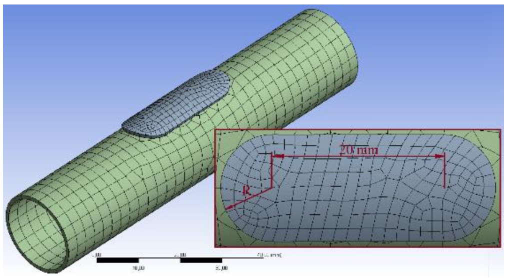

Figure 3. The dimensions of round tipped composite patch adhesively bonded on the specimen

Şekil 3. Numune üzerine yapıştırılmış yuvarlak uçlu kompozit yamanın boyutları

3. Results and Discussion

After practicing of 10 MPa pressure to the patch repaired specimen models having damage originated quadrilateral slot, various types of failure responses have been received according to the fiber stacking sequence and overlapping area of composite patches. While some patch geometries couldn't maintain the state of bonding connection with the base material, a certain number of them were able to carry out the repairing task within reasonable safety levels. In FEA a cohesive zone model was used to analyze the resistance of bonded contact between composite patch and defective composite tube surface.

By means of safety factor calculated by the software, it would be possible directly estimate which configuration of patch material and size is most appropriate for a repair operation. Besides that, the stress distribution locally detectable on the patch layers gives a strong feeling about which regions are more crucial to consolidate in composite patch repair.

The distribution of equivalent stress intensities because of pressure load applied inside the tube specimen of which patch type is described as A6 and made of merely zero-degree fibers reinforcing epoxy matrix is depicted in Figure 4. Considering the top scene of the patch having 6 mm tip radius, the peripheral form doesn't become deformed after loading. However, the central region of the patch gives an appearance of slight collapse due to high tensile stresses generated at the bottom side as seen on the reverse view of the repaired region. Although, this is the highest measured stress value for the entire body, no decomposition is visible at any part of the patch geometry just as the entire tube. The bond line region also maintains its integrity which implies that adhesive joint zone withstands being separated. As the tip radiuses is declined from 6 to 4 mm, the patch area reduces from 353.1 mm^2 to 210.3 mm^2 which also cause diminishing in bonded area.

Table 1. The typical mechanic properties of LOCTITE EA 9466 epoxy-based adhesive

Tablo 1. LOCTITE EA 9466 epoksi bazlı yapıştırıcının tipik mekanik özellikleri

Young's modulus (MPa)	Poisson's ratio	Shear modulus (MPa)	Max. normal contact stress (MPa)	Max. equivalent tangential contact stress (MPa)	Glass transition temperature (°C)
1718	0.33	645.86	32	5	62

Table 2. Patch types according to the stacking sequence

Tablo 2. İstif sırasına göre yama türleri

Patch code	A	B	C	D	E
Stacking sequence	[0°,0°,0°,0°]	[0°,45°, -45°,90°]	[45°, -45°,45°, -45°]	[0°,90°,0°,90°]	[90°,90°,90°,90°]

Table 3. Patch types according to the radiuses of round tips

Tablo 3. Kavisli uç yarıçaplarına göre yama çeşitleri

Patch code	1	2	3	4	5	6	7	8	9	10
Radius of round tips: "R" (mm)	2.7	3	3.5	4	5	6	7	8	9	10
Patch Area (mm^2)	130.9	148.3	178.5	210.3	278.5	353.1	433.9	521.1	614.5	714.2

Table 4. Elastic properties of unidirectional E-glass fiber reinforced epoxy composite lamina

Tablo 4. Tek yönlü E-cam elyaf takviyeli epoksi kompozit tabakanın elastik özellikleri

Density x 10^{-9} kg/m^3	Young's Modulus in dir. x (MPa)	Young's Modulus in dir. y (MPa)	Young's Modulus in dir. z (MPa)	Poisson's Ratio xy	Poisson's Ratio yz	Poisson's Ratio xz	Shear Modulus xy (MPa)	Shear Modulus yz (MPa)	Shear Modulus xz (MPa)
2	45000	10000	10000	0.3	0.4	0.3	5000	3846.2	5000

The stress variation in A4 type patch with 4 mm tip radius and zero-degree fibers is given in Figure 5. Unlike the situation in the patch type A6, the peripheral shape loses its linearity in patch type A4 and turns into a wavy form after the pressure applied. In this case, although the adhesion performance is not affected and no separation is also observed due to the reduction of the patch area, it is obvious that excessive stresses are generated at both ends of the patched area which reduces the overall safety of the repaired section. Reducing the area of adhesively bonded patch cause to increase in equivalent maximum stress as is also understood from the difference in top values between the patches represented as A6 and A4 modes given in Figure 4 and Figure 5, respectively.

To be able to sustain the joint its integrity, and withstand the applied load without separation, the post-loading contact status between repairing and repaired components should be investigated, carefully. Figure 6 shows the contact status detected under the patches having different sizes. The red colored regions in the picture represent sticking status which means that no tangential or normal relative displacement occur between the adjacent surfaces in 6 mm and 4 mm rounded tip patch repaired samples. Hence, it is possible to deduce from this solution that the bond of adhesion is preserved in almost all bonded areas for these samples. As concerns the orange and red colored areas, sliding and near contact statuses are the active contact cases at these points which refer to tangential and normal movements are measured between the bonded surfaces, respectively. However, such movements don't mean any adhesive failure for 6 mm and 4 mm rounded tip patch repaired samples (Figures 6-a and 6-b), since apart from the red areas, the reverse side of the patches are already empty due to the slot clearances, so the simulated motions are quite natural. For 3 mm and 2.7 mm rounded tip patch repaired samples, the damage case turns to be adhesive failure which is clearly seen in Figures 6-c and 6-d. Here the width in the narrowed areas of adhesive bond couldn't withstand the stresses arising from the internal pressure, resulting in explosion damage.

As seen in Figure 7, despite the equivalent sized patch construction, the code C6 specimen with ± 45º oriented fibers could result in different stress accumulation regions from that with 0º oriented fibers. Although the equivalent maximum stress reduces from 104.71 MPa to 90.16 MPa associated with rising of the orientation angle, the peak center moves towards the slot extremes of the specimen. Switching of the stress concentration to the specimen side effects adversely the overall safety of the repaired specimen under the equivalent loading condition.

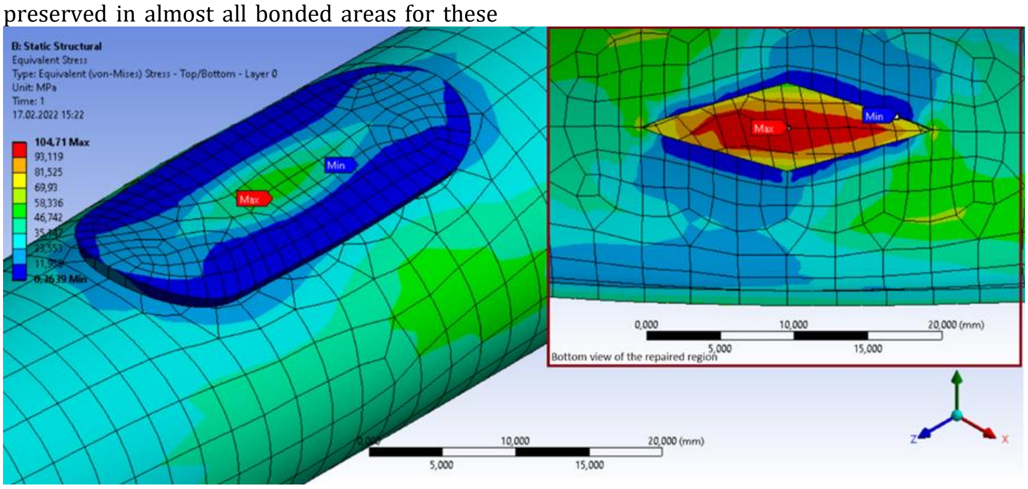

Figure 4. Equivalent stress distribution on patched up region of composite tube under internal pressure: Patch Code: A6

Şekil 4. İç basınca maruz kompozit borunun yamalı bölgesindeki eşdeğer gerilme dağılımı: Yama Kodu: A6

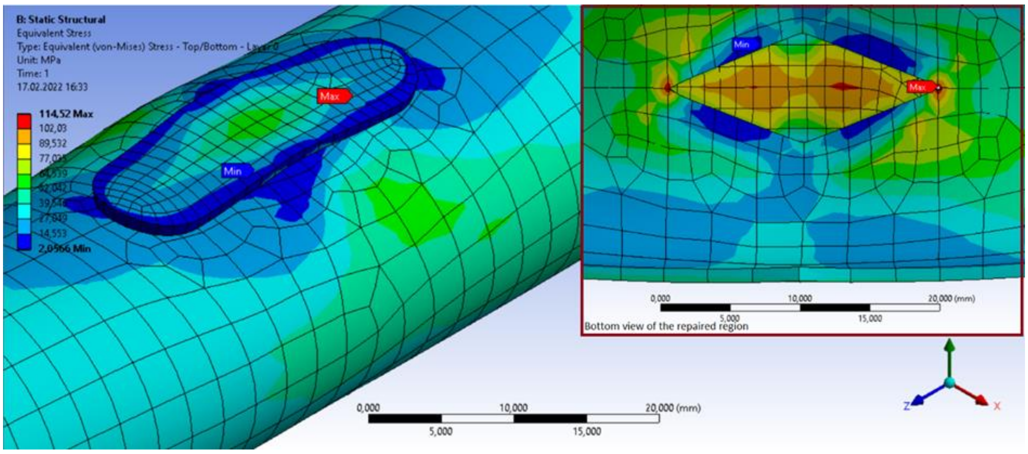

Figure 5. Equivalent stress distribution on patched up region of composite tube under internal pressure: Patch Code: A4

Şekil 5. İç basınca maruz kompozit borunun yamalı bölgesindeki eşdeğer gerilme dağılımı: Yama Kodu: A4

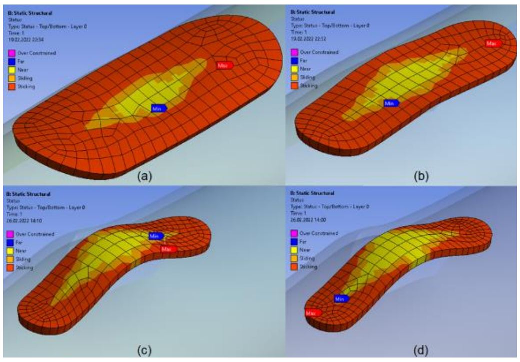

Figure 6. Bonded contact status between repairing patch and slotted specimen after applied pressure: Patch Code: a) A6, b) A4, c) A2, d) A1

Şekil 6. Basınç uygulandıktan sonra tamir yaması ile yarıklı numune arasındaki yapışma bağlantı durumu: Yama Kodu: a) A6, b) A4, c) A2, d) A1

Detailed information on the change in the safety parameter according to the size and orientation of the patches will be given in the following sections. On the other hand, the patch geometry almost maintains its linearity again except for the middle part just like as observed in code A6 specimen patch. When the patch radius is reduced from 6 mm to 4 mm for those having ± 45º oriented fiber, the patch geometry become crooked in the middle side after loading since the inflation of the tube on both sides under the patch had been hugely increased (Figure 8). Together with this extreme undulation, the maximum equivalent stress enhances by 46.8 % after reducing the patch area, however this rise was observed by only 9.4 % at the patches with 0º oriented fibers. The situation proves that fiber orientation constitutes an important role on getting the optimum patch size for composite-to-composite repair operations.

The contact status between bonded surfaces doesn't change after internal pressure loading of ± 45º oriented 6 mm and 4 mm rounded tip patch repaired specimens as seen in Figures 9-a and 9-b. The state of sticking remains constant in red colored areas where the remaining orange- and yellow-colored zones stand for tangential and normal displacements between patch and substrate surfaces, respectively. As for the adhesive bond endurance of 3 mm and 2.7 mm rounded tip patch repaired samples in Figures 9-c and 9-d, those couldn't bear the given pressure load with insufficient patch bond wideness. Both relative tangential and normal movements are exhibited between the adjacent bonded surfaces.

The tangential and normal relative displacements can be distinguished by respectively orange- and yellow-colored areas partially overflowing from the red region. It appears that, an 8 mm wide patch is applicable and sufficient for 5 mm wide impact damage slot, not to observe adhesive failure in case of using the given shaped patch geometry.

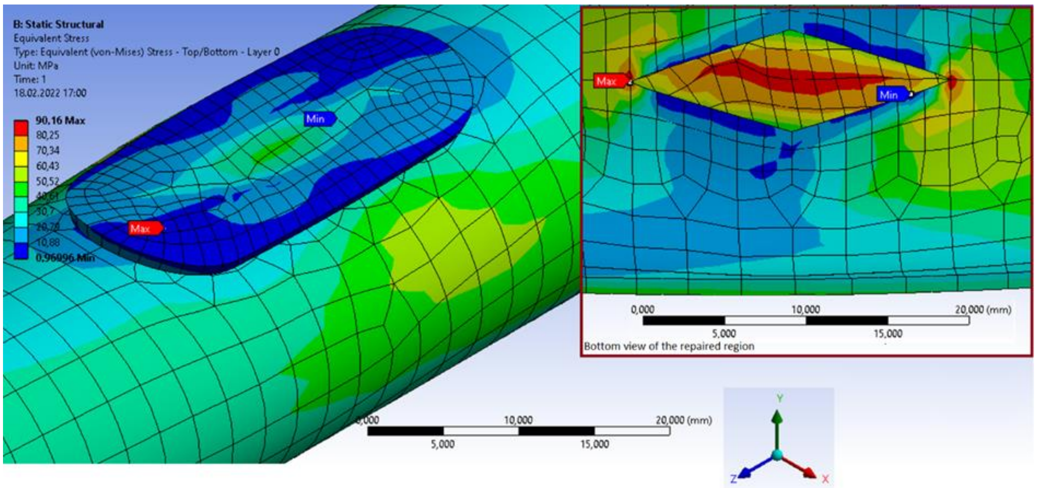

Figure 7. Equivalent stress distribution on patched up region of composite tube under internal pressure: Patch Code: C6

Şekil 7. İç basınca maruz kompozit borunun yamalı bölgesindeki eşdeğer gerilme dağılımı: Yama Kodu: C6

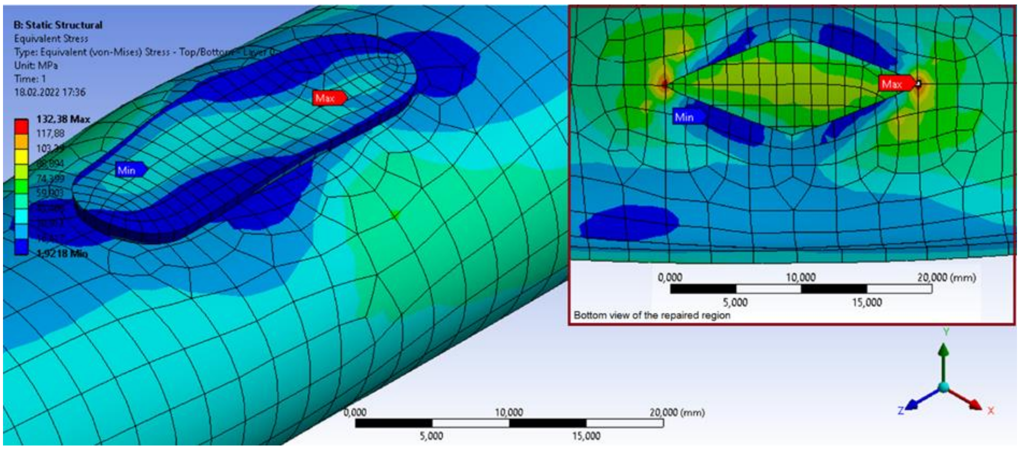

Figure 8. Equivalent stress distribution on patched up region of composite tube under internal pressure: Patch Code: C4

Şekil 8. İç basınca maruz kompozit borunun yamalı bölgesindeki eşdeğer gerilme dağılımı: Yama Kodu: C4

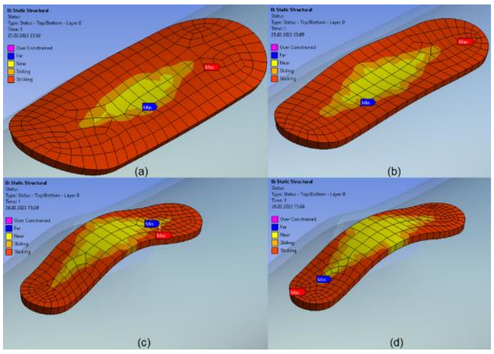

Figure 9. Bonded contact status between repairing patch and slotted specimen after applied pressure: Patch Code: a) C6, b) C4, c) C2, d) C1

Şekil 9. Basınç uygulandıktan sonra tamir yaması ile yarıklı numune arasındaki yapışma bağlantı durumu: Yama Kodu: a) C6, b) C4, c) C2, d) C1

For composite structures, safety factors are described in DNV's Offshore Standard (DNV-OS-C501) [19]. Although it is written for marine and offshore applications, the standard is valid and applicable to very large area of composite practices. DNV-OS-C501 specified the safety factors according to safety classes (low, normal, and high) which depends on the possible impacts of the failure [20]. The target annual probabilities of brittle failure for composites are defined in the standard as 10^{-4}, 10^{-5} and 10^{-6} for low, normal, and high safety classes, respectively. To obtain the target annual probability, the safety factor values are regulated. Another parameter affecting the safety factor is coefficients of variation (COV) which is calculated via dividing the standard deviation by the mean strength. Larger COV in structures yields to a necessity for greater value of safety factor. As given in Table 5, the enhancing effect of COV on safety factor is more ascendant relative to that of the safety class. This means that the material quality and the precision of the production method are determining an effective choice of safety factor.

The safety factors of composite patched tubes under the equivalent loading conditions are graphically illustrated in Figure 10. It can be first inferred from the general appearance of curves that the stacking sequences of the patch materials are rather effective on the analytically identified safety factors. Each kind of fiber orientation give typical safety results for various patch tip radius values varying from 2.7 to 10 mm. Hence, increasing patch areas in connection with tip radiuses enhances the safety factor of repaired tubes. It is possible to say that these findings are consistent with those of the study by Meriem-Benziane et al. [21] in which pressure loaded pipes with longitudinal crack repaired by bonded composite investigated. Contrarily to the current paper, in this study, the crack length was increased by keeping the patch size constant. It was found that the safety factor is depended on the crack length and there is an inverse proportion between these variables.

Table 5. Recommended safety factors for static pressure burst in composites according to DNV-OS-C501 [20]

Tablo 5. DNV-OS-C501'e göre kompozitlerde statik basınç patlaması için önerilen güvenlik faktörleri [20]

Safety class / Probability of failure	COV ≤ 5%	COV= 10%	COV= 12.5%	COV= 15%
Low	1.11	1.28	1.41	1.60
Normal	1.15	1.40	1.62	1.96
High	1.18	1.53	1.86	2.46

The sample type E exhibits the lowest safety factors for all patch areas. Although the factor of safety calculated for sample E increases up to the level of 0.55 with ascending patch tip radiuses between 2.7 mm and 5 mm, it couldn't maintain rising and due to lying of its fibers just on the axial direction. The increase in the patch area is not sufficient to ensure that the patching process is safe. Also, the specimen C with ± 45º oriented fibers couldn't reach the safety region, although its safety factor is continuously increased with greatened patching areas. So, the composite patches having both merely axially or merely ± 45º oriented fibers are found to be not suitable and safe for repairing such types of slot damages in composite pressure tubes.

On the other hand, the patch types A, B, and D give reasonable safety solutions at least for enlarged patch areas. According to DNV-OS-C501, in Table 5 the safety factor for normal safety class is defined as 1.15 for the COV value is up to 5%. For specimen type B having 0/45/-45/90 oriented fibers, this safety value is met only by 9 and 10mm rounded tip patched specimens. Compared to type B, the specimen type D with 0/90/0/90 oriented fibers has higher safety factor values for the corresponding tip radiuses. Moreover, the specimen type D can meet the specified standard safety factor with 7, 8, 9, and 10mm patch tip radiuses.

The stress intensity factor (SIF) is regarded an important parameter determining the safety of crack damaged cylindrical structures [22]. Hence, the way to increase the safety factor could be possible by reducing the SIF as much as possible. Tasavori et al. [23] studied pressure vessels coated with composite laminate mounted on its outer surface. The results showed that the most reduction of SIF occurred in pressure vessels coated with 0º fiber orientation (in the hoop direction). These findings are in full agreement with the present study. In fact, among all sample types, the specimen type A with only 0º oriented fibers could reach the highest safety factor values for each patch tip radius. The normal safety class standard safety factor can be met by such type of composite patches with over 5 mm round tip radiuses. For the patch type with 0º oriented fibers, the safety factor is calculated as 1.16 at 6 mm radius and increases step by step with the increase of the patch radius. The safety factor could reach to the level of 1.59 as the highest value among all samples at 10mm patch radius. This value is also satisfying higher safety class and COV standard levels defined by DNV-OS-C501.

In many cases, the maximum stresses calculated on the loaded part by using FEA can give beneficial clues to observe the effect of various applied parameters on the loading case. As depicted in Figure 11 small patch areas leads to excessive stress concentrations on the body which could result in sudden load bearing interruptions. The patches smaller than 210.3 mm^2 area and 4 mm tip radius are exhibiting not a convenient stress distribution case for the current type patch shape in repairing tubular carriers containing pressured matter.

In terms of the fiber orientation, the lowest maximum stress values are calculated at the specimen type C with a patch material including ± 45º fibers. Although the safety factor of this material type doesn't satisfy the reliability conditions, the stress distribution seems to be more homogenous compared to the rest of the samples due to fiber orientation between principal stress directions. On the other hand, patch samples B and D with fibers oriented solely in tangential and axial stress directions exhibited almost overlapping maximum stress concentrations. In addition, the highest maximum stresses are observed in these samples among patches with large surface areas. Similarly, patch samples A and E with only unidirectional fibers produce overlapping maximum stress values for areas greater than 353.1 mm^2 (Patch Tip Radius: 6 mm). Hence, it can be inferred that the maximum stresses for all patch samples occur depending on the relationship of its fiber orientations with the axial and tangential directions.

Given the calculated maximum total deformation values (Figure 12), it is observed that the samples with patches smaller than 210.3 mm^2 areas (Patch Tip Radius: 4 mm) are again the most critical ones and deform excessively. This is probably because the dominant failure mechanism happening in these patch samples with such smaller areas is adhesive damage due to a narrower attachment width. As the patch areas are increased, total deformations decline to minimum values and reach to a plateau which is representing the maximum deformations mostly originated from adherent material instead of sticking. The fact that the maximum total deformations reach to its highest levels in the sample E which contains fibers merely in axial direction and perpendicular to the maximum principal tangential stress direction is another proof that this secondary plateau-like zone should be related to the deformations of adherent materials. It should also be noted for this region that the observed total deformation levels are compatible with safety factors calculated according to the material types, and there is an inversely proportional relationship between two variables.

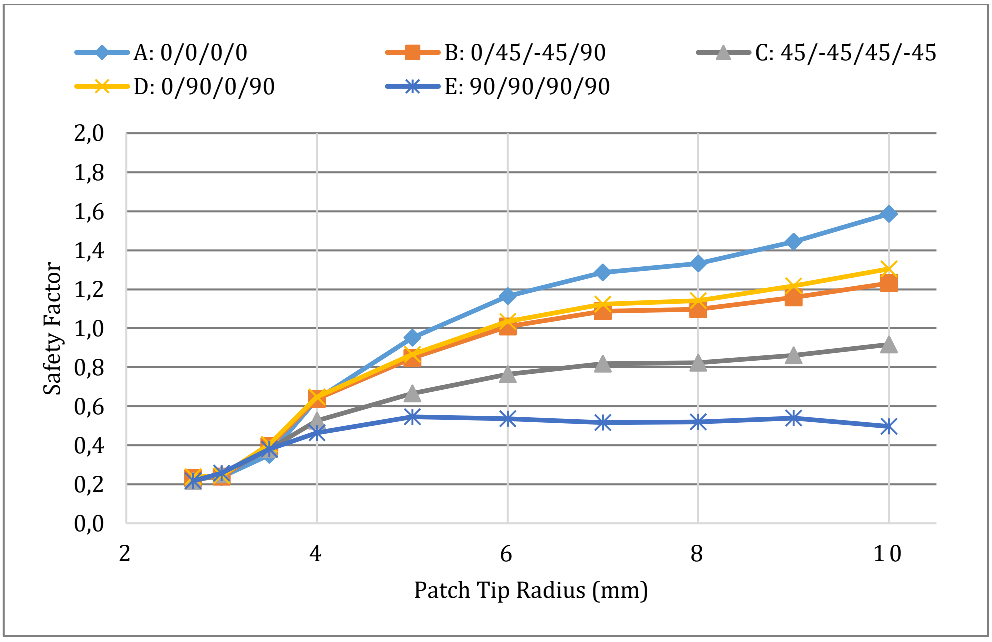

Figure 10. The factors of safety calculated for varied composite patch tip radiuses and patch fiber orientations

Şekil 10. Çeşitli kompozit yama uç yarıçapları ve yama fiber oryantasyonları için hesaplanan emniyet faktörleri

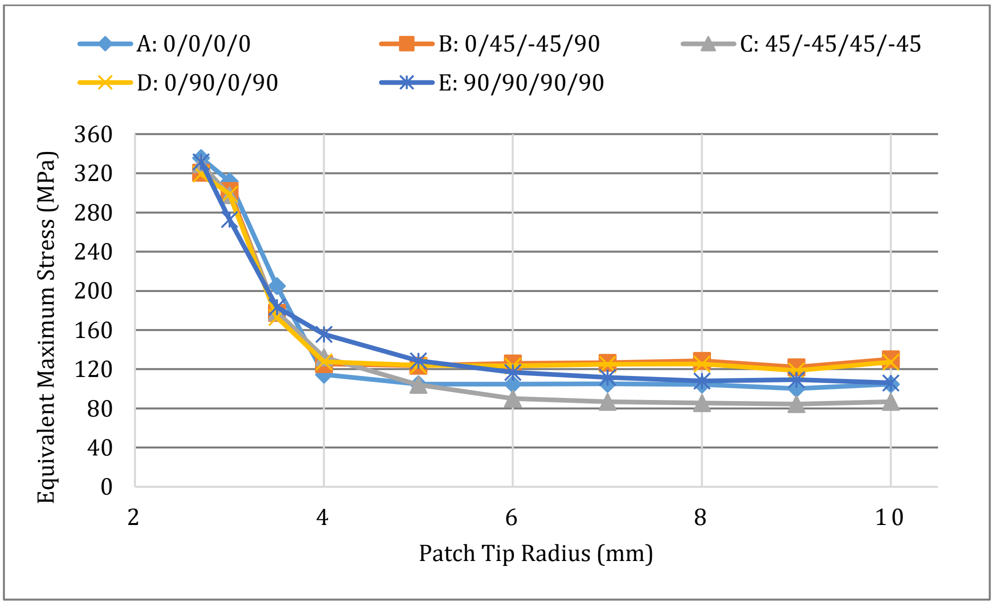

Figure 11. The equivalent maximum stresses calculated for varied composite patch tip radiuses and patch fiber orientations

Şekil 11. Çeşitli kompozit yama uç yarıçapları ve yama fiber oryantasyonları için hesaplanan maksimum eşdeğer gerilmeler

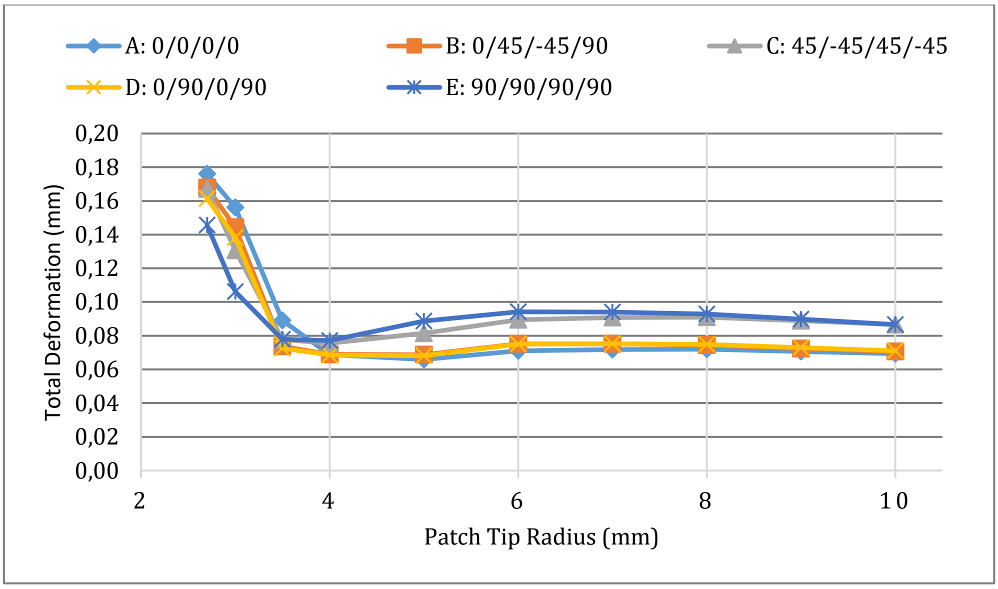

Figure 12. The total deformations calculated for varied composite patch tip radiuses and patch fiber orientations

Şekil 12. Çeşitli kompozit yama uç yarıçapları ve yama fiber oryantasyonları için hesaplanan toplam deformasyonlar

4. Conclusion

Epoxy based patches having unidirectional and multi directional glass fiber reinforcements were used to repair the glass fiber / epoxy-based ± 45° fiber oriented cylindrical composite thin-walled tubes having a quadrilateral puncture defect. The effectiveness of these patches in repairing composite defected tubes were numerically investigated in terms of material type and patch sizes under a 10 MPa internal pressure load. According to the findings related to the current study, the following conclusions listed below are considered more important and prominent:

- Looking at the stress distribution in patch repaired region on composite tubes, it is obvious that reducing the area of adhesively bonded patch cause to increase in equivalent maximum stress and conveys the top stress point from the patch center to the corners of repaired geometry.
- From the contact status analyses, it is found that an 8 mm wide patch is adequate for 5 mm wide impact damage slot, in order not to observe adhesive failure in case of using the patch shape currently investigated.
- Increasing patch areas in connection with tip radiuses enhances the safety factor of repaired tubes. However, it is found be not sufficient to ensure that the patching process is safe. The fiber orientation of composite patches also plays an important role on the factor of safety.
- According to the safety value of “1.15” defined in DNV-OS-C501 for normal safety class and COV is up to 5%, the patches having $[0°]_4$, [0°, -45°,45°,90°], and $[0°,90°]_2$ stacking sequences give reasonable safety solutions at least for adequate patch areas.
- In designing composite patches for tubes, for all patch areas, the maximum safety factor can be achieved by employing 0° fibers oriented along the tangential direction. Furthermore, the safety factor of this type of material meets high safety class and COV=10%.
- The maximum stresses for all patch samples occur depending on the relationship of its fiber orientations with the axial and tangential directions.
- Since the most probable dominant failure mechanism happening in the currently analyzed patches smaller than 210.3 mm^2 areas (Patch tip radius: 4 mm) is adhesive

damage due to narrow and insufficient attachment width, these patches are found to be the most critical ones and deform excessively.

4. Sonuç

Cam elyaf / epoksi esaslı ± 45° elyaf oryantasyonlu silindirik kompozit ince cidarlı dörtgen delinme hasarlı tüplerin tamirinde tek yönlü ve çok yönlü cam elyaf takviyeli epoksi matrisli yamalar kullanılmıştır. Bu yamaların hasarlı kompozit tüplerin onarımındaki etkinliği, 10 MPa iç basınç yükü altında malzeme türü ve yama boyutları açısından sayısal olarak incelenmiştir. Mevcut çalışmaya ait bulgulara dayanarak, aşağıdaki sonuçların daha önemli ve belirgin olduğu düşünülmektedir:

• Kompozit borularda yamayla onarılan bölgedeki gerilme dağılımına bakıldığında, yapıştırılan yamanın alanının azaltılmasının eşdeğer maksimum gerilmede artışa neden olduğu ve en yüksek gerilme noktasını yama merkezinden, onarılan geometrinin köşelerine doğru ilerlettiği açıktır.

• Yapışma bağlantı durumu analizlerinden, incelenen yama şeklinin kullanılması durumunda yapıştırıcı hasarının görülmemesi için 5 mm genişliğindeki bir darbe hasarı yarığı için 8 mm genişliğinde bir yamanın yeterli olduğu görülmüştür.

• Uç yarıçaplarına bağlı olarak artan yama alanları, onarılan boruların emniyet faktörünü artırmaktadır. Ancak bu yama işleminin emniyeti olmasını sağlamak için yeterli görülmemektedir. Kompozit yamaların fiber oryantasyonu da güvenlik faktörü üzerinde önemli bir rol oynar.

• Normal güvenlik sınıfı ve %5'e kadar COV için DNV-OS-C501'de tanımlanan "1.15" güvenlik değerine göre, yamalar $[0°]_4$, [0°, -45°,45°,90 °] ve $[0 °,90 °]_2$ istifleme dizileri, en azından yeterli yama alanları için makul derecede emniyetli çözümleri sağlamaktadır.

• Tüpler için kompozit yamalar tasarlarken, tüm yama alanları için maksimum güvenlik faktörü, teğet doğrultu boyunca yönlendirilmiş 0° fiberler kullanılarak elde edilebilir. Ayrıca bu tip bir malzemenin emniyet faktörü, yüksek güvenlik sınıfını ve COV=%10'u karşılamaktadır.

• Tüm yama numuneleri için oluşan maksimum gerilmeler, elyaf oryantasyonlarının eksenel ve teğet yönlerle ilişkisine bağlı olarak ortaya çıkmaktadır.

• Hâlihazırda analiz edilen 210,3 mm^2'lik alanlardan (Yama uç yarıçapı: 4 mm) daha küçük yamalarda meydana gelen en olası baskın hasar mekanizması, dar ve yetersiz yapışma bağlantısı genişliğinden kaynaklanan yapışkan hasarı olduğundan, bu yamalar en kritik olanlardır ve aşırı deforme olurlar.

5. Ethics committee approval and conflict of interest statement

There is no need for an ethics committee approval in the current article.

There is no conflict of interest with any person/institution in the current article.

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