BAŞKENT UNIVERSITY
INSTITUTE OF SCIENCE AND ENGINEERING
DEPARTMENT OF DEFENSE TECHNOLOGIES AND SYSTEMS
MASTER OF SCIENCE IN DEFENSE PLATFORMS

EFFECTS OF REPAIR TECHNIQUES ON MECHANICAL PERFORMANCE IN COMPOSITE MATERIALS

BY

BEYZA NAZ KARADUMAN

MASTER OF SCIENCE

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ÖZET

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Günümüzde kompozit malzeme kullanımı oldukça yaygınlaşmış ve giderek de artmaktadır. Mukavemet ve hafiflik oranı avantajına sahip olan bu malzemeler, özellikle havacılık sanayi ve otomotiv sektöründe büyük önem kazanmıştır. Kompozit malzemelerin bu yaygın kullanımı sonrasında, malzemelerde dış etkenlerden dolayı meydana gelen hasarların tamiri de önemli bir araştırma konusu olmuştur. Bu çalışmada farklı onarım yöntemlerinin, malzemenin mekanik performansı üzerindeki etkileri incelenmiştir. Fazla yontma alanı yaratmamak ve hızlı bir onarım yöntemi bulmak için 20°, 30° ve 45° yontma açıları üzerinde çalışılmıştır. Ayrıca, daha sağlam bir çözüm bulmak için tek yönlü yontma ve çift yönlü yontma onarımının karşılaştırılması yapılmıştır. Numuneler karbon elyaf prepregten ve $[45/0/90/0/45]_{2s}$ oryantasyonuna sahip üretilmiştir. Farklı açılarda tek yönlü yontma ve çift yönlü yontma onarım konfigürasyonları ile hazırlanmış kompozit numunelere ASTM standartlarına göre, çekme, basma ve 3-nokta eğme testleri uygulanmıştır. Testler sonucunda elde edilen gerinim-gerilim eğrileri, 20° ile onarılmış numunelerin en yüksek dayanıma sahip olduğunu göstermiştir. Ayrıca çift yönlü yontma ile onarılmış numunelerin aynı açıda tek yönlü yontma ile onarılmış numunelere kıyasla daha yüksek kuvvetlere dayandığı tespit edilmiştir.

ANAHTAR KELİMELER: Karbon elyaf kompozit, onarım, tek yönlü yontma, çift yönlü yontma, mekanik performans

ABSTRACT

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EFFECTS OF REPAIR METHODS ON MECHANICAL PERFORMANCE IN COMPOSITE MATERIALS
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Today, the use of composite materials has become widespread and is increasing. These materials, which have the advantage of strength and lightness ratio, have gained great importance especially in the aeronautical industry and automotive sector. After this widespread use of composite materials, the repair of damages caused by external factors has also become an important research topic. In this study, the effects of different repair methods on the mechanical performance of the material were investigated. Scarf angles of 20°, 30° and 45° have been studied in order not to create too many scarf areas and to find a quick repair method. Also, a comparison of single scarf and double scarf repair was made to find a more robust solution. The samples were produced from carbon fiber prepreg and with the $[45/0/90/0/45]_{2s}$ ratio. Tensile, compression and 3-point bending tests according to ASTM standards were applied to composite samples prepared with single scarf and double scarf repair configurations at different angles. The stress-strain curves obtained as a result of the tests showed that the specimens repaired at 20° had the highest strength. In addition, it has been determined that the samples repaired with double scarf withstand higher forces compared to the samples repaired with single scarf at the same angle.

KEYWORDS: Carbon fiber composite, repair, single scarf, double scarf, mechanical performances

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Average cross-sectional area
ASTM D-3039	Standard Test Method for Tensile Properties Of Polymer Matrix Composite Materials
ASTM D-6641	Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using A Combined Loading Compression (CLC) Test Fixture
ASTM D-7264	Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials
b	Width
d	Depth
D	Deflection of the center of the beam
h	Specimen gage thickness
F^{cu}	Laminate compressive strength
L	Support span
L_g	Extensometer gage length
P	Load
P_f	Maximum load to failure
w	Specimen gage width
σ	Stress
σ_t	Tensile stress
σ_f	Flexural stress
ε	Strain
ε_f	Flexural strain
ε_i	Tensile strain
δ	Displacement
δ_i	Extensometer displacement at i^{th} data point

1. INTRODUCTION

Composites are a type of materials, which are formed by combining two or more materials to obtain required properties. Purpose of composite design is to achieve the desired properties with different materials and different combinations. Providing these possibilities is one of the biggest advantages of composites over traditional materials. These materials, which have the advantage of strength and lightness ratio, have gained great importance especially in the defense industry and automotive sector. In line with the widespread use of composite materials, the repair of damages caused by external factors has also been an important research topic.

Damage may occur in composites during service life or production due to mechanical and environmental conditions or accidental impacts [1]. If it is possible to make a durable repair to a damaged composite component, it is not preferable to replace that part with a new one for economic reasons [2]. The repair process is done to extend the service life of the damaged part and to increase its mechanical performance. It can be said that the main purposes of repair in composites are improvement and prevention of crack propagation and delamination. As a result of many experimental and analytical studies, many repair methods have been developed for different conditions, such as repair with mechanical fasteners and bonded repair.

Adhesively bonded joint application is a preferred method for composite repair, especially in aerospace applications, due to its design flexibility, greater fatigue resistance, and higher damage tolerance [3]. The adhesive repair method is a long-studied but still an evolving issue.

There are different types of bonded repair used for different situations, such as overlap, stepped and scarf repair. All of them have advantages and disadvantages. For example, overlap is a fast and effective solution [4]. Scarf repair is a method that takes some time but has a better load distribution and aerodynamic smoothness [5].

Adhesive repair techniques are used when damaged parts need to be repaired particularly and quickly. The first use of the adhesion repair method was in military aviation applications (see Figure 1.1.). Examples of these applications are repairs to cracked fuel vent holes in F-16s, cracks around holes in C-141 fleet, cracked joints of upper wing on B-52G/H models, and cracks in upper part of main fuselage of C-5A fleet.

Figure 1.1. Repair of an airframe with a patch [6]

There are many studies investigating the advantages and disadvantages of all these techniques. In this section, some of these studies will be discussed.

Kumar et al. [7] investigated the failure modes of repaired composite structures under tensile loading. In the research, they tested the epoxy adhesive and film adhesive (AF-163-2). In addition, the change in the tensile strength of the materials as a result of increasing scarf angles was defined by the finite element analysis method. Compared to large scarf angles, small angles showed higher strength under tensile load. Wang and Gunnion [8] found the strength of scarf joint at different angles in repaired composite structures and proposed a new design methodology accordingly. They investigated the effect of the scarf patch joint of stacked composite sheets on the tensile strength. Wang et al. [9] investigated the long shelf life, high mechanical performance and workability of materials to be used for rapid repair of war damage in composite aircraft structures. They evaluated the performance of adhesives and prepregs after storage at room temperature. As a result of research, they have seen that storing these materials for up to 15 months does not affect their performance when used. Wang et al. [10] investigated the repair and post-repair performance of a combat-damaged helicopter part. They compared the strengths of the undamaged part with the damaged and unrepaired part and the externally repaired part and supported their experimental results with finite element analysis. Caminero et al. [11] compared the tensile strength of carbon fiber reinforced polymer layers repaired by external patch and fill patch methods. They supported the experimental results with three-dimensional model analysis. To determine the location of damage in patch-repaired composite panels, they imaged the behavior of the panels with on-line damage analyzes and then compared them with off-line techniques. Wang and Gunnion [12] worked on the optimum shape to minimize the excess and undamaged areas of the material when using the scarf patch repair method. They used numerical methods and suggested optimum and near-optimal shapes according to chipping angles. Liu et al. [13] observed the tensile strength of patch-repaired thick composite plates and reached the maximum load capacity and damage mechanism. They developed a semi-analytical method. They argued that as a result of tensile loading, the modes of damage are seen as delamination in the adhesive-adhesive interface and in the base material. Breitzman et al. [14] investigated the effect of an auxiliary layer added to the repair zone of patch-filled composites. It was observed that the added patch slightly increased the hardness of the material under tensile load. They estimated the types of damage at the repair site by three-dimensional non-linear analysis and compared them with perforated and layer-by-layer repaired parts. They also studied the von Misses stress in the adhesive. Two-dimensional finite element analysis investigated the crack propagation behavior of the adhesive composite patch repaired material. Pinto et al. [15] performed tensile strength analysis on a three-dimensional model of filler patch repair in carbon-epoxy structures. Performing the finite element analysis method in software called ABAQUS, the team concluded that small chipping angles are more effective. Grabovac and Whittaker [16] used a carbon fiber composite patch technique to repair a fatigue crack in the hull of an Australian warship. Using the classical hand layup method, the duo interpreted the long-term and short-term adequacy of the repair technique. They argued that if applied properly, the carbon fiber exterior patch is a solution that works well. Kumari, Wang, and Saahil [17] observed the effect of repeated impact on repaired composite plates using the low velocity impact test. Composites repaired by the filler patch technique using the vacuum resin infusion method were subjected to the tensile test after low speed multiple impact tests and compared with the pure material. They said that the scarf repair restored 81.23% tensile strength. In addition, It was observed that the specimen that failed early in the tensile test received the highest dent damage in the low-velocity impact test. Zhang et al. [18] observed the behavior of metal materials repaired with composite filler patch at 4 different angles under tensile load. To support their observations, they used finite element analysis and found that the scarf angle affects the plastic behavior at the junction. They observed that the most important mode of damage was damage to the adhesive interface. Riccio et al. [19] analyzed the damage progression in the adhesive layer as a result of the three-point bending test to evaluate the stress distribution at the joints of repaired composites. Confirming the test results with numerical analysis methods, the team concluded that the voltage distribution of the scarf repair technique is better. Balakrishnan and Seidlitz [20] evaluated resin injection and scarf repair methods, which are widely used especially in the automotive industry. Using non-destructive technique for damage analysis and repair efficiency evaluation, the duo concluded that filler patching is a more complex process than the resin injection method and is used to repair larger parts. Xiaoquan et al. [21] used experimental and finite element methods to observe the damage distribution and maximum strength of adhesive scarf repaired carbon fiber reinforced plastic laminates depending on the scarf angle. They observed that as the scarf angle increased, the areas where the adhesive would be damaged decreased. Ahn and Springer [22] conducted experimental studies to determine the performance of fiber-reinforced laminated composites repaired with different repair techniques. Tensile tests were performed to determine the quality of composites repaired by filling, patching and stepwise patching techniques and to determine the efficiency of repair techniques. In addition, a mathematical model has been developed to calculate the damage loads of composites repaired by filling and patching methods, and this model has been compared and confirmed with experimental data. They observed that the type of wet-lay up repair material did not affect the failure load of the repaired composite and the variations of small scarf angles did not affect significantly the failure load. Truong et al. [5] used both experimental and numerical methods to investigate the damage under bending loads of composite laminates repaired by patch filling method. Different bending loads were applied to the repaired layers at different chipping angles and damage progression analysis was performed. Andrew et al. [23] observed the efficiency of the repair method by subjecting the glass epoxy composites, which they subjected to the weight drop test, to the impact test after they were repaired with kevlar. In addition to all these, after the impact test, they applied the compression test to both repaired and non-repaired subjects with impact damage and compared the results they obtained. They found that the compression strength of the repaired composite structures increased by 83% compared to the unrepaired ones. Tzetzis and Hogg [24] examined the effects of these uses on the adhesion toughness by pulling various films and curtains between the base material and the patch to improve the toughness of the adhesion surface in repairs made with adhesives of carbon fiber composites. Also in their other study, they evaluated the advantages of repair with vacuum assisted infusion technique [25]. Feng et al. [26] applied a tensile test to composites of different thicknesses repaired with a filling patch. Confirming the results obtained from the experiments with numerical methods, the team performed damage analysis. They observed that the effect of the repair did not vary greatly according to the thicknesses and was stable. Elaldı [27] conducted a study on rapid repair methods of composites. He has compared the performance of precured and co-cured patches in vacuum and autoclave. He also exposed the patched samples to moisture and tested at different temperatures, such as room temperature, 70°C and 100°C. As a result of the tensile and interlaminar shear strength tests applied to the samples, it has been seen that there is not much difference in the strength of the samples obtained by autoclave and vacuum methods. This means that the vacuum method can be a good alternative solution potential. In addition, the strength of the samples exposed to moisture and different test application temperatures decreased.

1.1. Aim of the Thesis

The aim of the thesis is to make a scarfing angle and scarfing type recommendations for the quick, reliable and easy repair of damaged composite structures. As a result of the literature research, there has been not so much study in which single scarf and double scarf repair of composite materials and their comparison has been found in the studies carried out so far. In addition, the studies on the angles that the technician who will make the repair can work easily have been done very little and the tests applied are not detailed. Generally the angles studied for single scarf repair are mostly ideal angles less than 5°. Therefore, different scarfing angles and scarfing techniques were put into the studying agenda to propose a reasonably easy to apply, less time consuming and reliable enough repairing methodology for the composite parts that may not come to the depot level maintenance and to continue their use.

1.2. Scope of the Study

Within the scope of this study, composite specimens bonded at scarfed surfaces of 20°, 30° and 45° angles were produced. The performances of these samples under tensile, compressive and bending loads were investigated. In addition, in order to compare the mechanical performances of single scarf and double scarf repair methods, samples produced with 30° single scarf as well as 30° double scarf were fabricated and the same tests were applied. Thus, the relationship between the repair angle and scarfing technique and the performance of the repair was investigated.

2. COMPOSITE MATERIALS

2.1. Definition and History of Composites

Composite materials, which are formed as a result of the combination of more than one material, basically consist of reinforcing materials called fibers and supporting materials called matrix. When these materials come together, they do not blend and form a structure. The components that form the composite material do not lose their properties, they even complement each other's weaknesses. Components are more durable when they are together than as individuals.

The fibers used to produce composite materials can be natural or man-made. The most used fibers today are carbon, glass and aramid. The matrix used can be polymer, metal or ceramic. The most preferred matrix material is polymers such as epoxy resin. While the fibers increase the strength of the material against the applied force, the matrix holds the fibers together and protects them from environmental and external factors. In addition, the matrix ensures that the load is transmitted to the fibers, and the fibers allow the matrix to resist cracks and breaks.

Composites are increasingly popular and used in many sectors today. But composites are materials that have been used for a long time, and their earliest use dates back to ancient Mesopotamia around 3400 BC. They obtained plywood by combining wood strips at different angles. The composite concept has also been used for construction in the past years. Mud & straw and wood & clay mixtures are examples of this.

The first synthetic resin which can be converted from liquid to solid was developed between 1870 and 1890. In the 1930s, after some studies and developments for the resin, a patent was obtained for the unsaturated polyester resin, and then high performance resins began to be produced, including epoxy resin.

The modern composite age began with 'Bakelite' discovered by chemist Leo Hendrik Baekeland. The first commercial use of Bakelite was for the gear knob of Rolls Royce cars in 1917.

The first formation of the fibers used today occurred in the late 1930s, when the glass was drawn into thin threads. Strong and lightweight materials are produced by combining these glass fibers with synthetic resins.

The period when composite materials were most developed was during the World War II, because at that time, ways were sought to increase the durability of aircraft and sea vehicles while reducing the weight.

By the 1950s, composites were now widely used in trucks, sports cars, boats, and pipes. In these years, production techniques such as pultrusion and vacuum bag molding were also developed. The patent of carbon fiber, which provides advantages in many sectors, was taken in 1961 and then it began to be widely used in the aviation, automotive and marine sectors.

2.2. Advantages and Disadvantages

Today, the increase in the use of composites is due to many advantages it has. One of these advantages is about strength of the material. Composites are generally compared to metals in terms of strength. Looking at the strength-to-weight ratio, it is seen that they are one step ahead. Composites have high tensile strength.

The second important advantage is that they are light. Composites have perfect strength-to-weight ratio. Lightness is an important criterion, especially for transportation and aviation. Lightweight composites facilitate setup and reduce cost.

One of the most important advantages of composites is their design flexibility. With this feature, it is a material preferred by engineers, designers and architects. Complex designs can be produced easily thanks to ability to mold. In addition, durability and stiffness can be achieved in the desired direction with fiber orientations.

Composites have a long material life. When this feature is combined with the low maintenance requirement, composites become a preferred material for many applications. These materials are also resistant to chemical effects and heat. Therefore, it is widely used in outdoor and aviation applications that will be exposed to chemical and environmental effects.

2.3. Classification of Composites

Composite materials are classified in two ways according to the matrix material and according to the reinforcement elements.

The properties of composites classified according to reinforcement elements are explained below.

2.3.1. Fiber reinforced composites

Fiber reinforced composites formed by the composition of fine fibers and matrix (Figure 2.1.). Fibers increase the strength of the material, while the matrix holds them together. These fibers can be continuous (long) or discontinuous (short). Orientation of the fibers directly affects the strength of the structure. Placing the fibers parallel to each other provides high mechanical performance in the same direction, while it decreases in the vertical direction. The strength of the fibers used is directly proportional to the strength of the composite structure. As the length/diameter ratio of the fibers increases, the load transmitted through the matrix also increases.

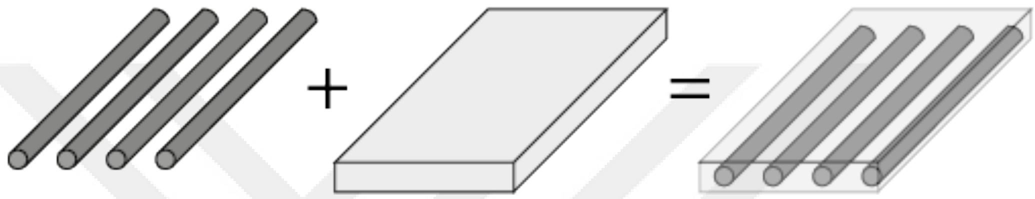

Figure 2.1. Fiber Reinforced Composite

2.3.2. Particulate composites

Composites in which the reinforcing material is in the form of particles in the matrix are called particulate composites (Figure 2.2.). These kind of composites are isotropic, that is, the properties of the material do not change according to its orientation. The strength of the material is depends on the hardness of the particles. The most widely used particulate composites are those with metal particles in a plastic matrix.

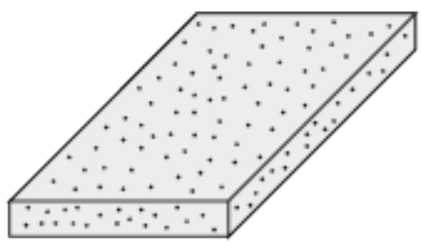

Figure 2.2. Particulate Composite

2.3.3. Hybrid composites

If two or more different fibers are in a same matrix, it is called hybrid composites (Figure 2.3.). It is developed to combine good physical and mechanical properties of conventional composites and smooth surface of micropyle composites. Hybrid laminates have better properties than conventional ones in terms of physical and mechanical performance. For example, the hybrid of aramid which is cheap, tough and has low compression strength and graphite which is expensive and has low toughness and high compression strength is better than graphite composite in terms of toughness and aramid composite in terms of compression strength.

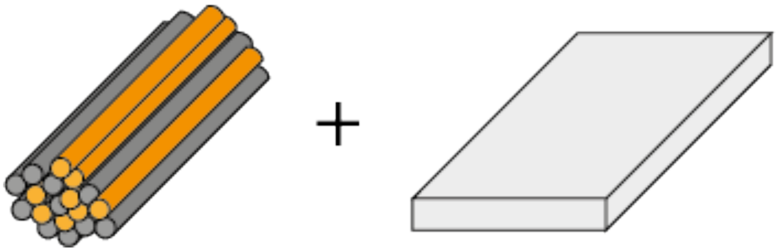

Figure 2.3. Hybrid Composite

2.3.4. Laminated composites

Layered composites, which are obtained by combining layers with different fiber orientations, are the most widely used composite type with many applications. Usually 0, 45, 90 degrees are used to achieve higher strength (Figure 2.4.). These composites are resistant to heat and moisture. With these layering process, corrosion and abrasion resistance, thermal expansion, strength and stiffness of the composite can be increase. Laminated composites, which are lighter than metals but strong enough, are widely used as surface coatings in the wing and tail assemblies of airplanes. Sandwich structures used as insulation materials are also an example of this composite group. This type of composite is used in the present work.

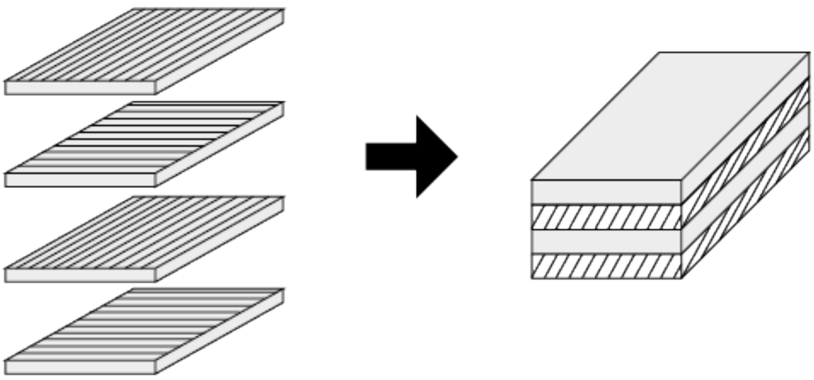

Figure 2.4. Laminated Composite

Laminated composites can be divided into 5 groups.

Symmetrical Laminate: A layer is symmetrical if the distances from the two opposite sides of a layer to the center are equal.

Balanced Laminate: In order for a composite plate to be balanced, the layers that make up the plate must have the same thickness and material properties, but have opposite fiber directions. For example, θ=30° if the fiber direction is θ=-30° in the layer array, or θ=0° if θ=90°.

Angle-Ply Laminate: If the fibers in a composite plate are oriented only at θ and - θ angles, this composite is angle-ply laminate.

Cross-Ply Laminate: When the fibers are only at 0° and 90°, it is called cross-ply laminates. They can be symmetrical or unsymmetrical.

Quasi-Isotropic Laminate: When the fibers are at 0°, 45° and 90°, it is called quasi-isotropic laminates. They can be symmetrical or unsymmetrical. For example, a 0º/-45º/+45º/90º laminate is quasi-isotropic as the material in the present work.

2.4. Usage of Composites

Today, composite materials are used effectively in many fields. Aviation is at the forefront of these sectors. Previously, it was used only in secondary structures, but now its use in primary structures, such as spars for wing, frames for fuselage and bulkhead, has increased [28]. For 40 years, from the 1960s to the early 2000s, the use of composites in aircraft did not exceed 20% of the weight of the structure [29]. Now, in Boeing 737 and A350 aircraft, the ratio of the use of composite material to their structural weight is approximately 50% [30]. In addition to being used as a structural material in aircraft and helicopters, composite materials are also used in interior design.

Composites, which are widely used in the defense industry, are not only used in aircraft but also as an armor material on many platforms. For example, helmets are made of aramid reinforced composite and armors are usually made of carbon reinforced composite.

These materials, which are also very preferred in space applications, can be seen in antennas, rockets and satellites. After the use of composites in space vehicles, the ranges have increased greatly due to both being light and reducing fuel consumption.

The great advantage in fuel consumption with the lightening of the weight is also an important issue for the automotive industry. That's why composite materials are also used in vehicles such as buses, trucks, trucks and especially Formula 1 vehicles. In the Formula 1 example, it is very important to find the most durable solution with the least weight for vehicles. Cars, which were previously made of aluminum, have started to be made of composite parts as it reduces weight. In addition, since the production of complex parts is easier with composites, the number of required parts has decreased.

It is very important that the weight is low in electric vehicles, so parts made of composite materials are used. An example of this is the fully electric BMW i3. The entire body of the car is made of carbon fiber [31]. It is also seen in the roof and body components of other BMW vehicles. Other sectors where composite materials are used are as follows;

- Construction
- Medical supplies
- Chemistry
- Production of sports equipment
- Production of musical instruments
- Robotics technologies

3. REPAIR OF COMPOSITE MATERIALS

3.1. Damages in Composites

Some types of damages on composites are given below, Figure 3.1 – 3.5.

3.1.1. Dent damage

If a damage is less than 2 millimeters when measured from the surface, it is called surface damage. This type of damage does not spread to the undamaged area, but delamination can occur if liquid seeps into the fibers.

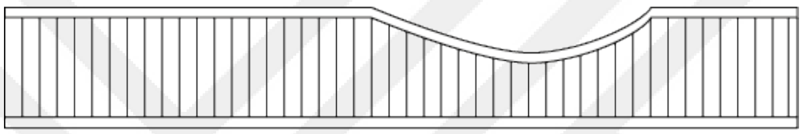

Figure 3.1. Dent Damage

3.1.2. Puncture damage

If both side has damaged, it is puncture damage.

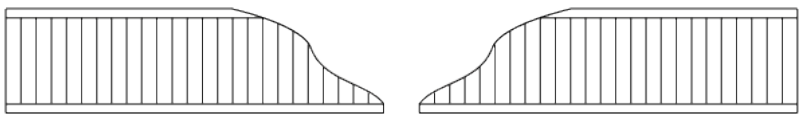

Figure 3.2. Puncture Damage

3.1.3. Laminate splitting

As a result of loading, cracks, dents and small holes may occur in the layers. Mechanical performance is affected by the length of cracks which is not through the full length of laminate.

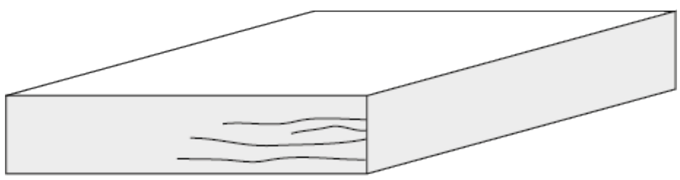

Figure 3.3. Laminate Splitting

3.1.4. Delamination

The separation of adjacent layers from each other is called delamination. It is the most common type of damage due to the low strength between the layers. Some of the causes of delamination are the effects that occur as a result of impacts by foreign objects, stress concentration in the discontinuity areas, wrong cure cycle process, dirt while layering laminates and defects caused by manufacturing.

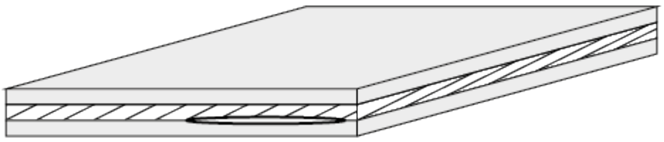

Figure 3.4. Delamination

3.1.5. Heat damages

Irreversible physical or chemical changes can occur in composites when they are exposed to high temperatures, and these changes are called heat damage. Cracks, disbonds, and delamination are examples for these physical changes. These damages are seen when the exposure temperature exceeds the glass transition temperature [32].

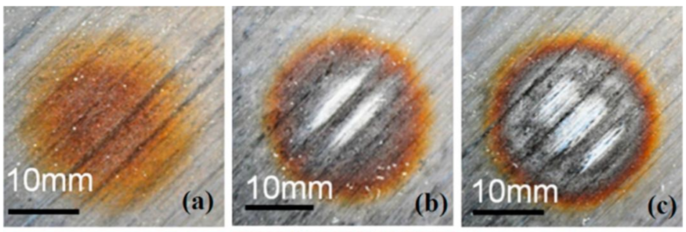

Figure 3.5. Heat Damage [32]

3.2. Aim of Repair

Repair is done to prolong the life and increase the performance of damaged or manufacturing defected components of various structures. As a result of experimental and analytical studies, many different repair methods have been developed. The conditions in which each developed technique is used are different. For example, the scarf method is used to meet the aerodynamic requirements, while bolted repair is used when there is a shortage of time.

3.3. Composite-to-composite repair methods

The main composite-to-composite repair methods are as follows.

3.3.1. Pre-preg repair

The abbreviation prepreg comes from the word "preimpregrated". This method of repair with fabric pre-impregnated with resin is often preferable because there is no need for resin mixing. Therefore, it can be said that it is a clean and easy repair method. It is generally preferred for the repair of large-sized parts.

3.3.2. Room temperature wet lay-up

It is one of the frequently used repair methods due to its many advantages. One of the biggest advantages is that the fabric to be used and the surface to be repaired can be easily adapted. In this method, no heating is done when fast curing is not required. The disadvantage of this method is its poor performance at high temperatures.

3.3.3. Elevated temperature wet lay-up

All the advantages of the room temperature wet lay-up method are also valid for this method but for elevated temperature wet lay-up, heat is needed. It can be a disadvantage for some situations.

3.3.4. Bolted repair

Mechanically fixed repairs increase the stress concentration due to drilling and weight, while deteriorating the aerodynamic profile of the structure. But the biggest advantage is that it is a faster and easier repair method compared to other scarf methods. Bolted repair is usually applied to thick panels but as the thickness increases, the stress of the bolt material also increases [33]. In this case, it will be a lighter and cheaper application than adhesive repair.

3.3.5. Bonded repair

Bonded repair is one of the most used repair methods, especially in aviation applications. It is used both as a permanent and temporary repair method. In this technique, stress concentrations are more regular and uniform [34]. Load transfer is also more efficient than repair with mechanical fasteners. As a result of all these advantages, it can be said that adhesive repair provides a high structural performance. Therefore, it is a highly preferred method especially in aviation applications.

Bonded repair requires high curing temperatures because the patch will replace the parent material which is usually prepreg material with a resin cured at temperatures between 120°C and 180°C.

For bonded repairs to be made outside the factory, portable tools are required for the curing process, such as vacuum bag and heat blanket. The portable mechanical device that controls this process is called a hot bonder. The bonders support 'out-of-autoclave or oven' processes.

There are many techniques for different requirements and conditions. The most commonly used adhesive repair techniques are given below.

3.3.5.1 Scarf repair

It is the most used method for the repairs made by adhesion. This repair technique is preferred when high bond strength and a smooth repair surface are desired. Generally, a ratio of 20:1 is preferred for scarf repair applied to large flat panels [35].

To repair the scarf, the damaged area is first removed from the base material. Afterwards, a patch with the same shape as the removed part is prepared. This patch can be the same or a different material as the main material, but generally the same material is preferred.

The biggest advantage of scarf repair is that it shows regular stress-strain distribution and shear stresses [36]. This reduces the possibility of delamination.

In addition, unlike repair methods such as external patching, it does not create protrusions or roughness on the applied surface. This satisfies the aerodynamic requirement, which is particularly important for aviation applications.

Scarf repair also has some disadvantages. One of these disadvantages is that it has a process that takes some time compared to other methods. Another downside is the removal of extra material while removing the damaged area to capture the angle.

Scarf repair can be applied in different ways. Single scarf is the most used type of them (Figure 3.6.). Double scarf is difficult to apply in some cases (Figure 3.7.). The details and construction stages of these methods used are explained in the following sections.

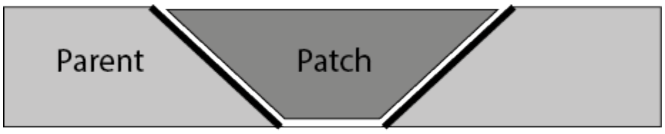

Figure 3.6. Single Scarf Repair

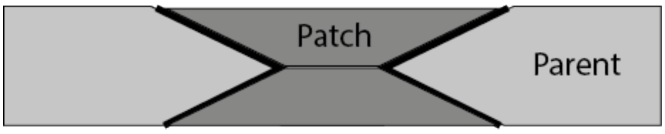

Figure 3.7. Double Scarf Repair

The reason why stepped scarf is preferred is the ease of observing the stress distributions. It can be applied as a single-sided and double-sided stepped scarf.

3.3.5.2 Overlap repair

It is an easier repair method than scarf repair because there is no need to remove material or to produce patches according to the shape of the removed material. It is generally suitable to be applied to thin components or skins. No major changes are made to the parent material.

It is frequently preferred because it takes less time and requires less complex equipment than other bonded repair methods, but it results in a lower repair strength recovery [5].

Since overlap repair, which is easy to perform, is made in the form of an external patch, it disrupts aerodynamics, unlike single scarf.

It can be applied in two ways as single side and double side overlap repair (Figure 3.8. – 3.9.). There are repairs where both scarf and overlap are used.

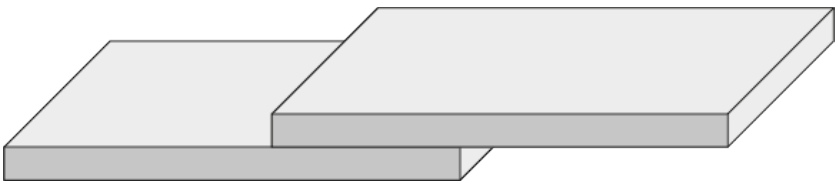

Figure 3.8. Single Side Overlap Repair

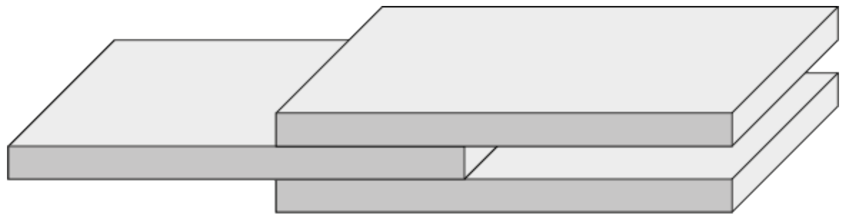

Figure 3.9. Double Side Overlap Repair

4. EXPERIMENTAL TEST

4.1. Production of Composite Laminates

In this thesis, VTP H 300 FCA 310 12KUD RC40 HS carbon prepreg (SPM Composite) is used to produce composite laminate. The properties of the prepreg material are in Table 4-1.

Table 4-1 Mechanical Properties of the Prepreg

3-Point Flexural Properties (ISO 178)		
Flexural Modulus	GPa	2,9-3,1
Max. Flexural Strength	MPa	125-135
Elongation at Flexural Strength	%	7-10

The prepreg material was laid in 20 layers with the $[45/0/90/0/45]_{2s}$ orientation. The plate is designed as symmetric and balanced to show quasi-isotropic properties and prevent the warpage after curing. While arranging the layers, the most commonly used angle orientations in aviation were taken into consideration.

After the hand lay-up process, the composite plates were cured in an autoclave at 120 degrees Celsius for 2 hours, following the manufacturer's recommended cure cycle. As a result of the composite production process, 4 plates with a thickness of 7.1-7.8 mm and 2 plates with a thickness of 3.6-3.9 mm, a total of 6 composite plates were produced. Half-thick plates have the $[45/0/90/0/45]_s$ orientation.

4.2. Preparing of Specimens

The plates produced by the prepreg laying method were cut at 20°, 30° and 45° angles with a water jet machine (Figure 4.1.). While 2 plates were formed for every single scarf, 3 pieces of angled cut plates were prepared for the double scarf repair. Cut plate drawings are given in the image below, Figure 4.2 - 4.3.

Figure 4.1. The Picture While the Composite Plate Cutting with Robotic Water-Jet Machine

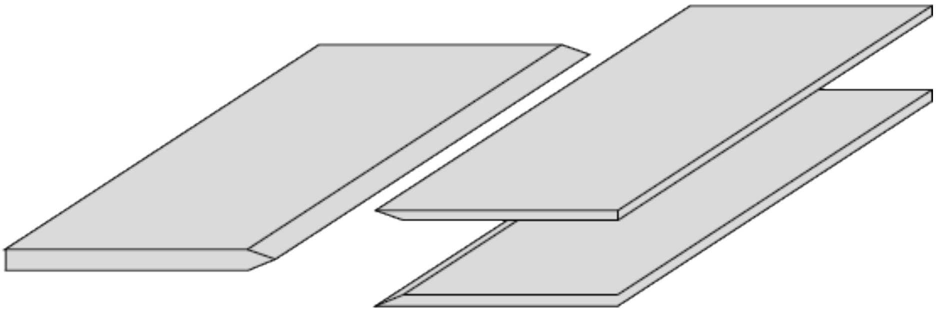

Figure 4.2. Double Scarfed Plate

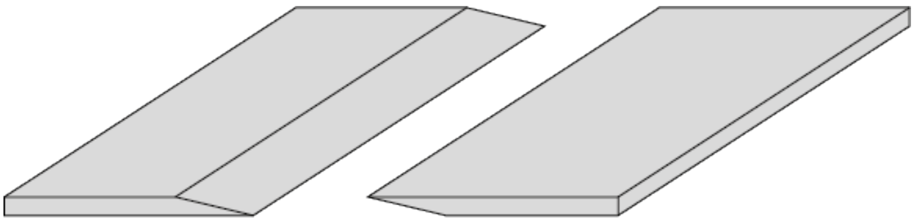

Figure 4.3. Single Scarfed Plate

The angled cut plates were then attached with film adhesive as parent and adherend material (see Figure 4.4.). The film adhesive used in this study is MTA 240, which is a product of Solvey company. This adhesive is an epoxy-based compound used in structural and semi-structural parts. Service temperature is from 70°C to 150°C. The advantage of this film adhesive is that it has a flexible cure range which is from 80° to 177°.

After the surfaces were cleaned, the bonding process was applied as recommended by the manufacturer and cured in an autoclave at 120°C for 1 hour. The surfaces to be bonded were cleaned of glycerin and no other solution was applied afterwards.

Figure 4.4. Bonded Composite Plates

A total of 60 samples which have dimensions given by the relevant ASTM standards for the tests to be made were extracted from the repaired composite plates with a water jet machine. Single scarf and double scarf sample drawings are given in Figure 4.5 and Figure 4.5.

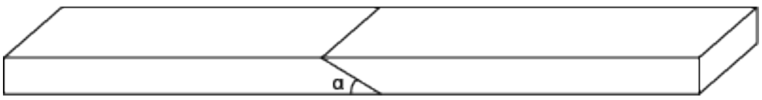

Figure 4.5. A Specimen Drawing Repaired with Single Scarf

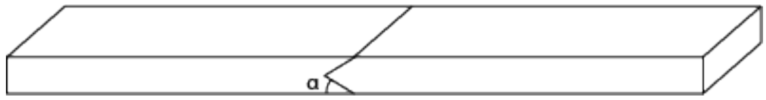

Figure 4.6. A Specimen Drawing Repaired with Double Scarf

Figure 4.7. Prepared Composite Samples

Repaired and prepared samples for mechanical tests are given in Figure 4.7. The inscriptions on the samples indicate the test type and repair configuration. The letters are written on the samples with the letters "T" for the tensile test, "C" for the compression test and "B" for the bending test. The numbers next to the letters represent the repair configuration. 2,3,4, and 0 indicate that specimens were repaired with 20°, 30°, 45° and double scarf, respectively.

4.3. Mechanical Tests

Mechanical tests were performed on the samples to compare the mechanical performances of different repair angles and joining configuration.

4.3.1. Tensile test

The tensile test applied to determine the ultimate tensile strength and elastic modulus of the samples was carried out in accordance with ASTM D3039. Samples were prepared with dimensions of 250 mm in length and 25 mm in width according to the standard (Figure 4.8.).

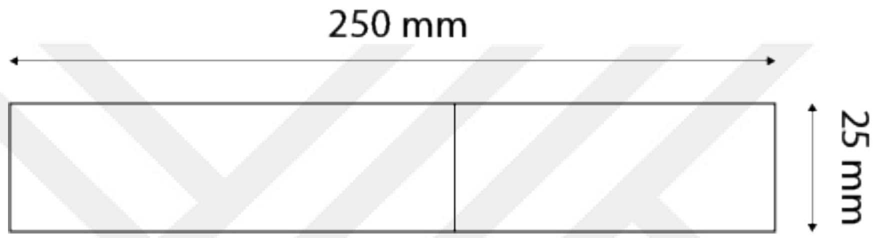

Figure 4.8. Dimensions of Tensile Test Specimen

Five samples were produced for each repair configuration. The tests were carried out at the appropriate temperature and at a cross-head speed of 2 mm/min (Figure 4.9.).

Figure 4.9. A Specimen Under Tensile Test

The tensile stress calculation method is given in the ASTM standard with the following equation.

$$\sigma_t = P/A$$

The tensile strain equation written in the standard is as follows.

$$\varepsilon_i = \delta_i / L_g$$

in the equations given above;

- P = Load (N),
- A = Average Cross-Sectional Area (mm^2),
- δ_i = Extensometer Displacement at i^{th} data point (mm),
- L_g = Extensometer Gage Length (mm)

4.3.2. Compression test

The compression tests applied to determine the compressive strengths of the samples were carried out in accordance with ASTM D6641. While performing the tests, the anti-buckling fixture mentioned in the standard was used. Sample dimensions were prepared to be 140 mm long and 12.7 mm wide (Figure 4.10).

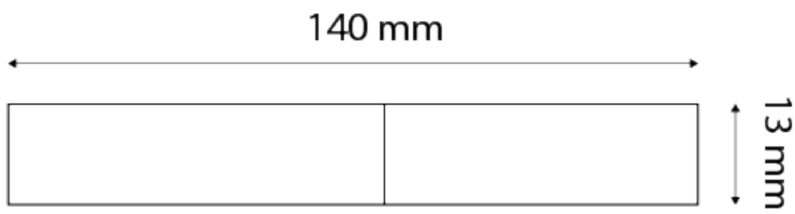

Figure 4.10. Dimensions of Compression Test Specimen

In Figure 4.11, compression test and anti-buckling fixture are illustrated.

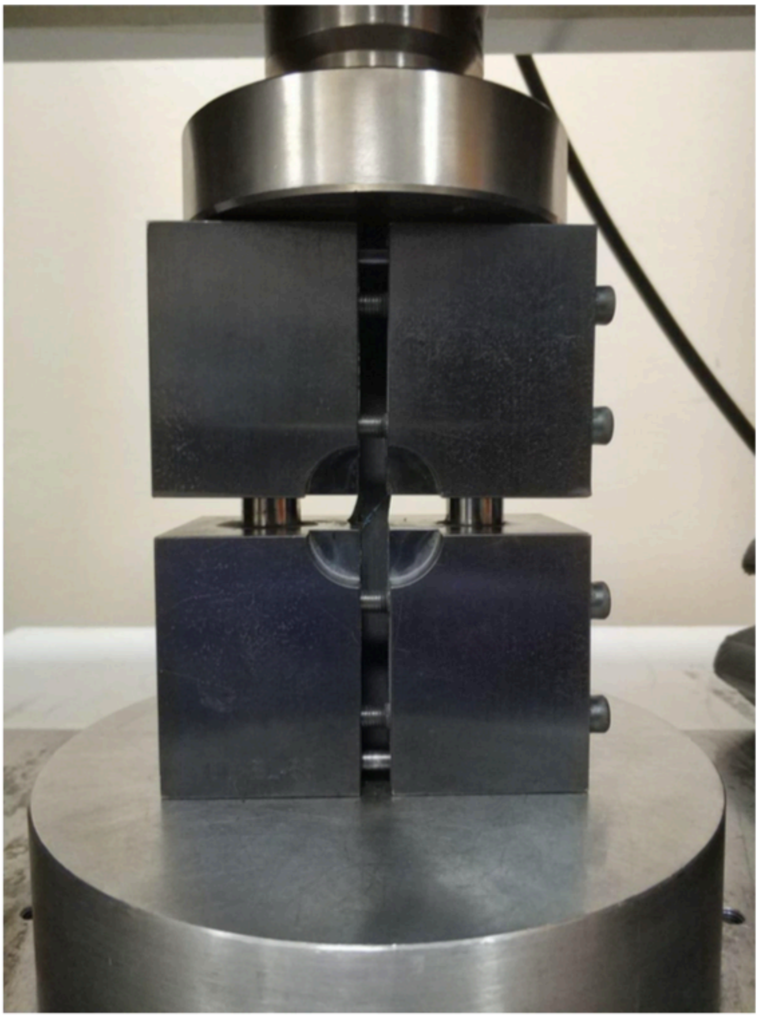

Figure 4.11. A Specimen Under Compression Test with Unti-Buckling Fixture

The tensile stress calculation method is given in the ASTM standard with the following equation.

$$F^{cu} = P_f / wh$$

The tensile strain equation written in the standard is as follows. In the equations given above;

- F^{cu} = Laminate Compressive Strength (MPa),
- P_f = Maximum Load to Failure (N),
- w = Specimen Gage Width (mm),
- h = Specimen Gage Thickness (mm)

4.3.3. 3-Point bending test

3-point bending test was applied to determine the bending characteristics of the samples. There are 2 ASTM standards for this test ASTM D790 and ASTM D6272. ASTM D790 standard was used in this study. Because ASTM D6272 is more about 4-point bending test. The tests were carried out on the MTS Servo hydraulic testing machine under the relevant conditions (Figure 4.12.). The dimensions of the samples prepared according to the standard are 13 mm wide and 142 mm long (Figure 4.13.).

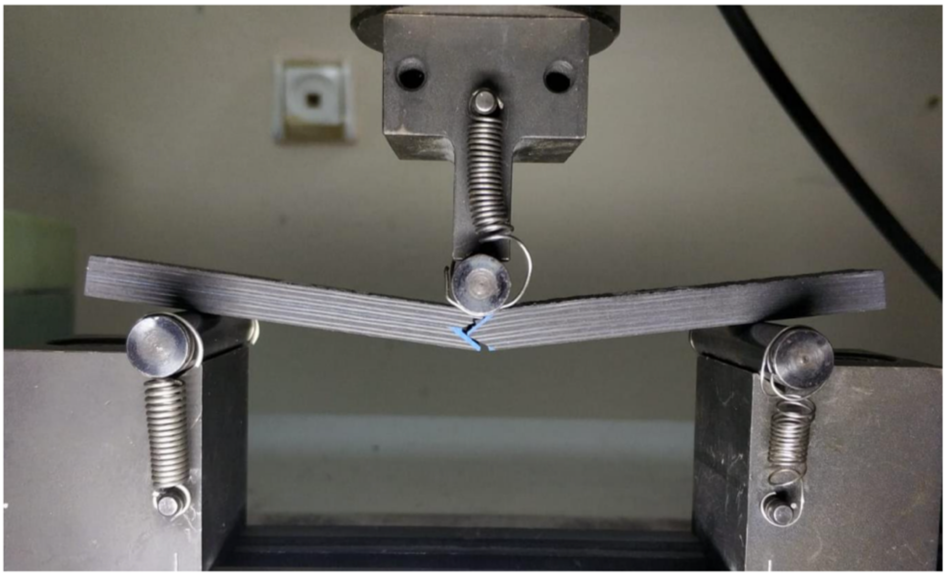

Figure 4.12. A Specimen Under Flexural Loading

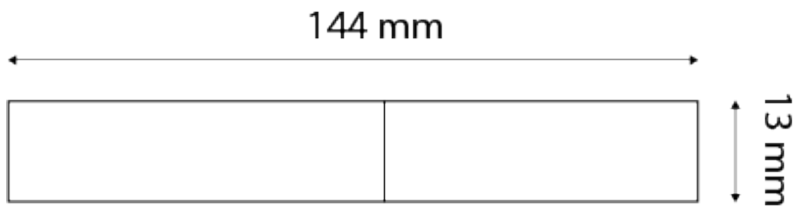

Figure 4.13. Dimensions of Bending Test Specimen

The flexural stress calculation method is given in the ASTM standard with the following equation.

$$\sigma_f = 3PL/2bd^2$$

The flexural strain equation written in the standard is as follows.

$$\varepsilon_f = 6Dd/L^2$$

in the equations given above;

- P = Load (N),
- L = Support Span (mm),
- b = width,
- d = depth,
- D = deflection of the center of the beam.

5. RESULTS AND DISCUSSION

In this chapter, based on stress-strain curves constructed, results of tensile, compression and 3-point bending tests of four specimen groups are discussed.

5.1. Tensile Test

Carbon fiber reinforced composite specimens repaired with four different angle configurations were subjected to tensile testing in ASTM standards to determine their material properties.

The results from the tensile test are given in the stress-strain curves (see Figure 5.1-5.4). 5 samples were produced from each repair configuration in accordance with the standard. A total of 20 samples were tested. Tensile test specimens are coded as T2, T3, T4, and T0. The numbers next to the T represent the repaired angle. T2, T3, T4 and T0 are specimens repaired with 20°, 30°, 45° and 30°-30° (double scarf) respectively. 5 samples produced in accordance with the standard are expressed by writing numbers up to 5 next to the repair code. For example, 5 samples produced for T2 (samples repaired with 20°) were named T21, T22, T23, T24 and T25.

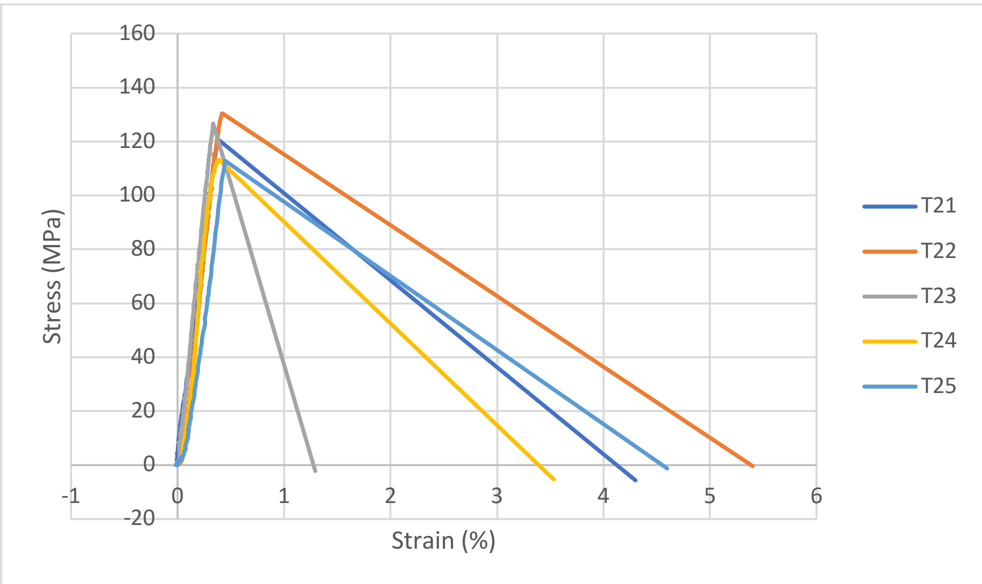

Figure 5.1. Stress-Strain Graph of the Specimens Repaired with 20° Angle Under Tensile Test

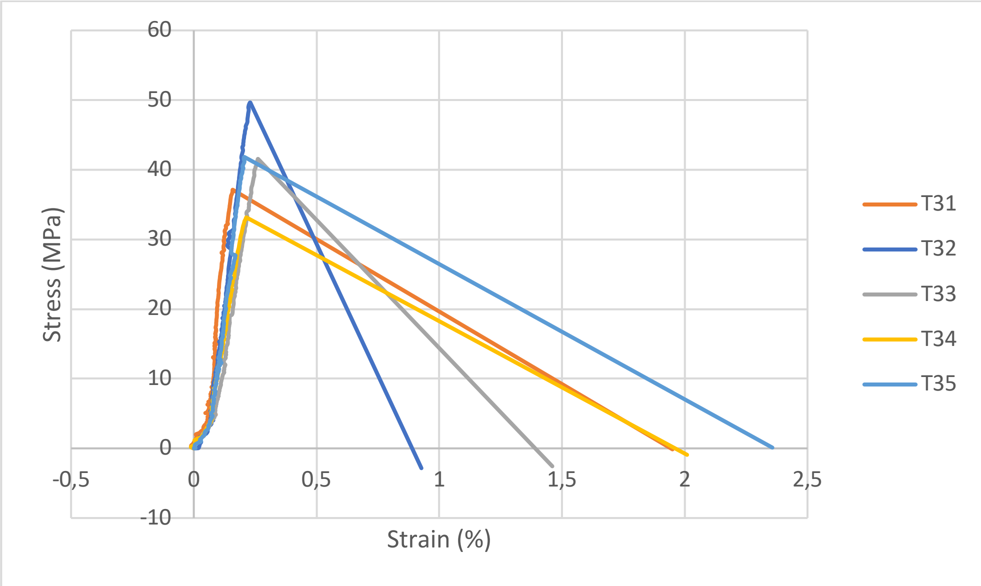

Figure 5.2. Stress-Strain Graph of the Specimens Repaired with 30° Angle Under Tensile Test

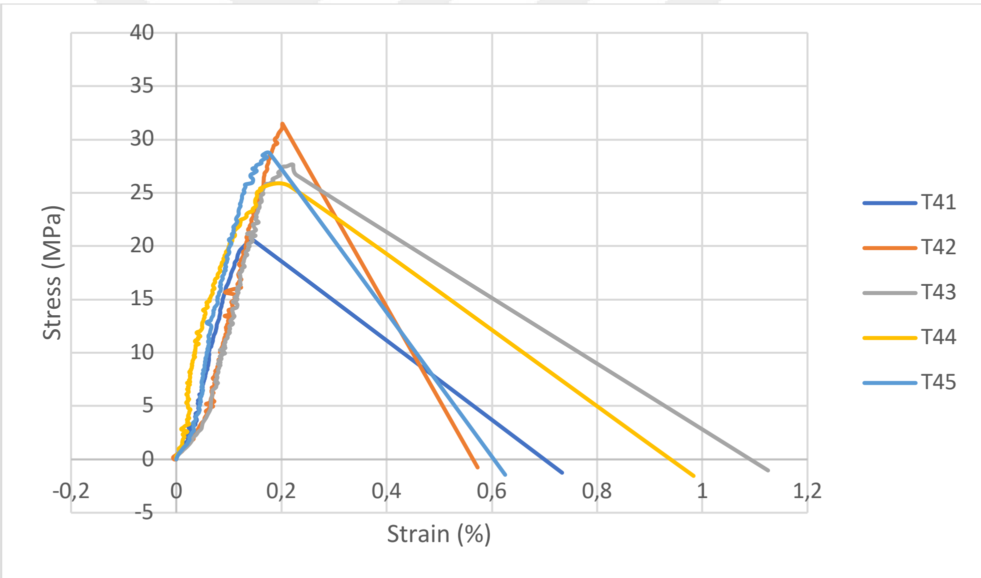

Figure 5.3. Stress-Strain Graph of the Specimens Repaired with 45° Angle Under Tensile Test

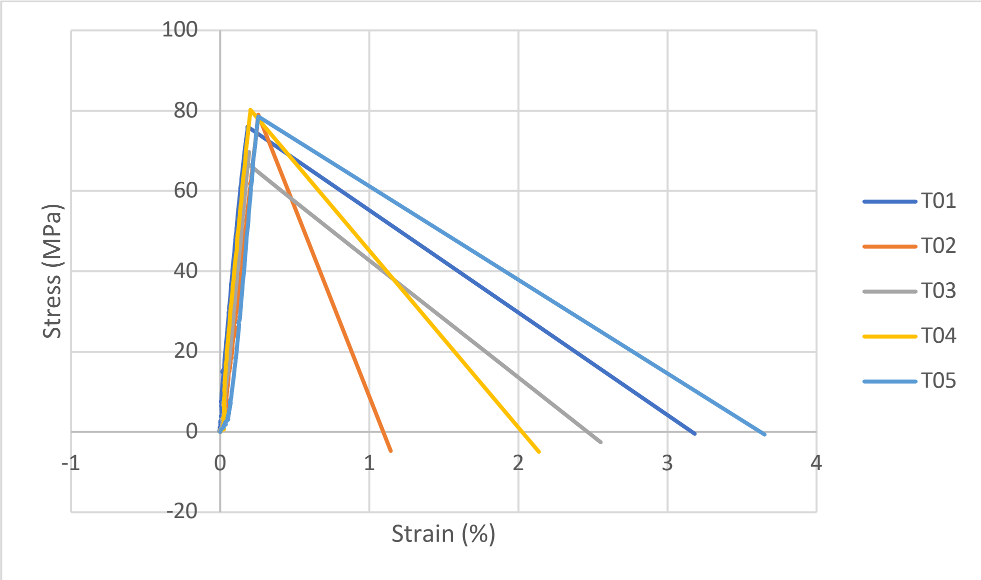

Figure 5.4. Stress-Strain Graph of the Specimens Repaired with 30°-30° Double Scarf Under Tensile Test

When looking at the graphics, the samples showing the highest tensile strength are the specimens that have been repaired with a 20° scarf angle. After the 20° single scarf configuration, the samples repaired with a 30° double scarf are the second most durable specimens. Samples repaired with single scarf and double scarf at 30° angle were produced to investigate the effects of bonding geometry on the mechanical performance of the repair. Considering the test results of these two groups of composites, the samples bonded with double scarf at 30° resisted higher stresses than the samples bonded with single scarf. When looking at the ultimate tensile strengths, the average of T0 samples is almost 2 times the average of T3 samples. While the thicknesses and adhesion surface areas of T0 and T3 samples are the same, only their joining geometries are different (Figure 5.5.).

Figure 5.5. Adhesion Surface Areas of Double Scarf (On the Left) and Single Scarf Repair (On the Right)

In the graphs drawn, the samples showed similar behavior under the applied tensile load. It can be seen that all of them has a sudden fracture or debonding from bonding surface.

The specimens with 45° scarf angle, which is the largest angle used for repair, showed the lowest strength under tensile force. From all these evaluated results, it can be seen that composites with the smallest repair angle showed the highest strength, while the samples with the largest repair angle showed the least strength. In this case, it can be said that strength of repair decreases while the repair angle increasing. This result supports the studies that have been studied for different angles before [37], [38]. This finding differs from them with a simple difference, which is their angles studied are much smaller than 20°.

Table 5-1 Average Tensile Strength and Elastic Modulus of Tensile Repaired Samples

Sample	Average Tensile Strength (MPa)	Average Elastic Modulus (GPa)
T2	120.78	36.65
T3	40.65	25.86
T4	26.78	19.32
T0	76.68	37.07

Average tensile strengths and elastic modulus of each repair configuration are given in Table 5-1. When the calculated elastic modulus values are examined, it is seen that the elastic modulus of the samples repaired with double scarf and 20° single scarf are very close to each other.

When the specimens ruptured after the test were examined, it was observed that cohesive failure occurred in T2, T3 and T4 specimens. Cohesive failure which is a desirable result is when the adhesive layer remains on both surfaces after rupture (Figure 5.6.). On the other hand, adhesive failure is observed when looking at the samples repaired with double scarf (Figure 5.7.). Failed composite specimens are given in Figure 5.8.

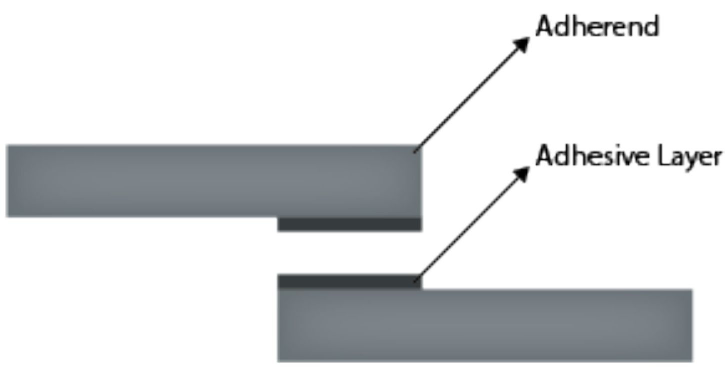

Figure 5.6. Cohesive Failure

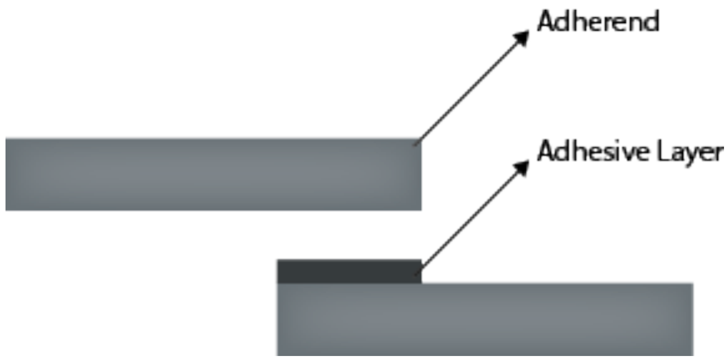

Figure 5.7. Adhesive Failure

Figure 5.8. Broken specimens repaired with 20° in (a), 30° in (b), 45° in (c) and double scarf in (d) after tensile test

5.2. Compressive Test

Carbon fiber composite specimens repaired with 20°, 30°, 45° and 30°-30° (double scarf) were subjected to compression load in accordance with ASTM D6641 standard to determine mechanical properties. As written in the standard, 5 samples of each repair configuration were produced. Samples coded C2, C3, C4 and C0 refer to samples repaired with 20°, 30°, 45° and 30°-30° (double scarf) respectively. Samples with the same configuration are named by placing numbers from 1 to 5 next to the configuration code, such as C21, C22, C23...etc.

Compression test results are given in the stress-strain curve (Figure 5.9.- 5.12.). When the graphs obtained after the test were examined, the specimens repaired at 20° were able to withstand higher compressive stresses than the others. The second durable repaired samples appear to be samples bonded with double scarf. When we compare the single scarf and double scarf configurations of 30°, the samples repaired with double scarf showed almost 2 times the strength of the samples repaired with single scarf. The compressive mechanical performances of the specimens repaired with 30° single scarf and 45° were close.

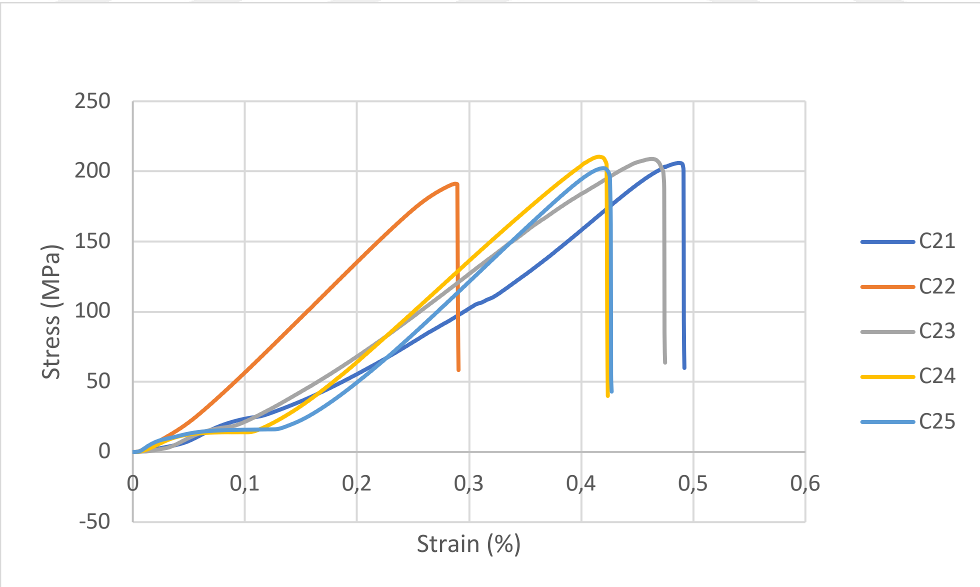

Figure 5.9. Stress-Strain Graph for the Samples Repaired with 20° Under Compressive Test

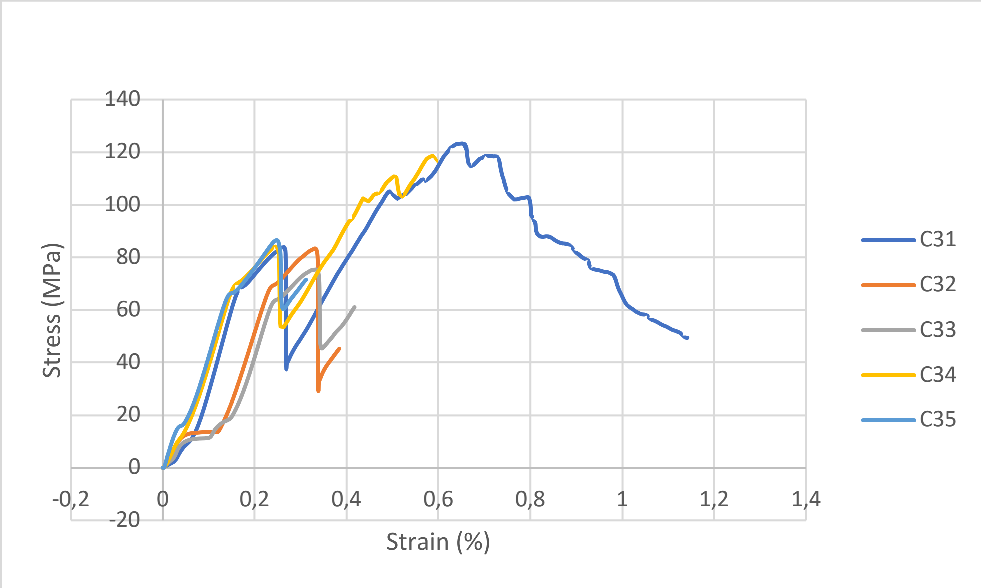

Figure 5.10. Stress-Strain Graph for the Samples Repaired with 30° Under Compressive Test

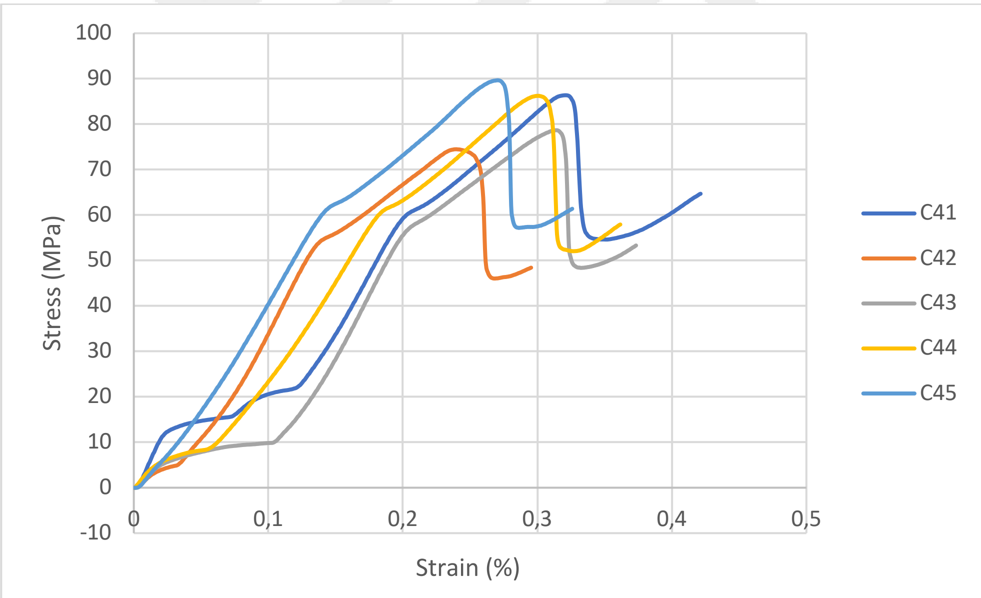

Figure 5.11. Stress-Strain Graph for the Samples Repaired with 45° Under Compressive Test

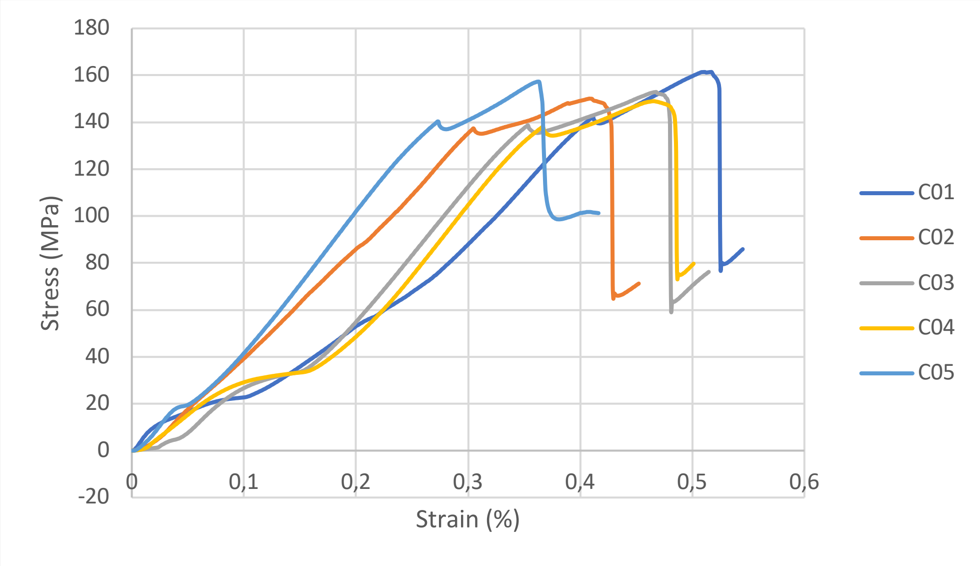

Figure 5.12. Stress-Strain Graph for the Samples Repaired with 30°-30° Double Scarf Under Compressive Test

As a result of the calculations made according to the test results, the ultimate compression strength of the samples was defined in Table 5-2. When the repair angles and average compression strengths are examined, it is seen that the compressive strength decreases as the angle increases, like tensile test results, which supports similar studies with small angles before. But, this observed reduction reported by Sivashanker [39] and Kumar et al. [40] who observed the performance of scarf repair with 0° to 5° angles.

While the compression stress-strain curves of the specimens repaired with 20° give a typical graph, the behavior of the specimens repaired with 30°, 45° and double scarf under compression load is similar.

Table 5-2 Average Compressive Strength of the Repaired Composite Samples

Sample	**Average Laminate Compressive Strength (MPa)**
C2	206.39
C3	85.45
C4	87.94
C0	153.16

When we look at the failed samples after the test, a crack propagation from the joint center is seen in the repaired samples with double scarf, unlike the others (see Figure 5.13.). This is due to the difference in the joint geometry.

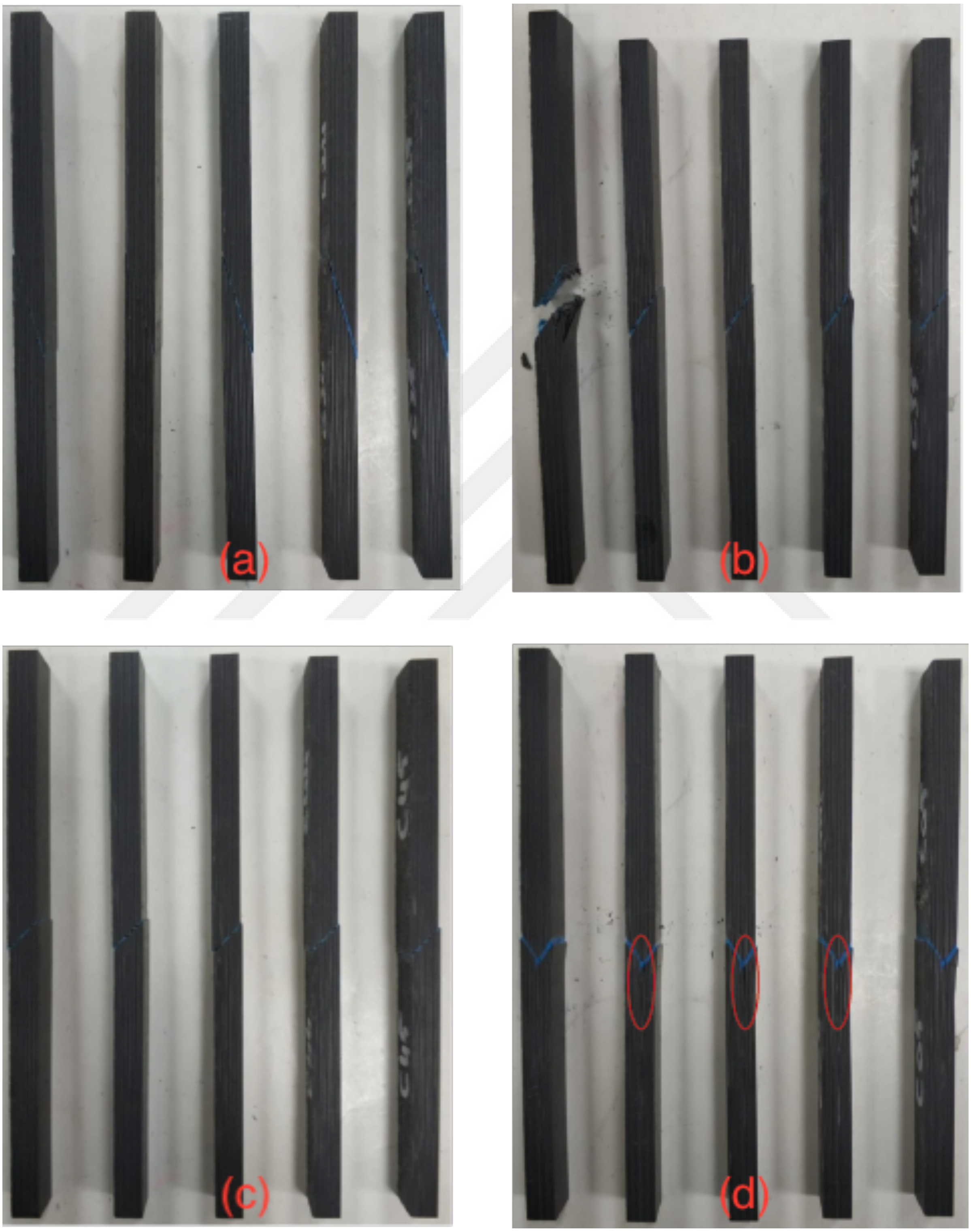

Figure 5.13. Failured specimens repaired with 20° in (a), 30° in (b), 45° in (c) and double scarf in (d) after compressive test

According to the stress-strain graph drawn, the specimen configuration with the highest average compressive strength is the specimens repaired with 20°.

When comparing double scarf and single scarf repair at 30° angle, the specimens repaired with double scarf were able to withstand higher compression stress. In addition, it is seen in the graphs of the samples with an angle of 20° that there was a sudden break after the maximum load.

5.3. Three-Point Bending Test

The specimens repaired with different angles and configurations were subjected to 3-point bending test in accordance with the procedure in ASTM D7264 standard. Five specimens produced for each repair configuration were tested to find their average flexural strength. The samples produced with 20°, 30°, 45° and double scarf were named as B2, B3 B4 and B0 respectively. Five identical samples produced from each repair type were named as configuration code +1,2,3,4,5, such as B21, B22, B23, ... etc.

The data obtained as a result of 3-point bending tests are given by drawing a stress-strain graph (Figure 5.14 - 5.17). When the graphs are examined, it is seen that the samples exhibit a linear behavior up to the first peak.

It can be seen from the strain values that specimens repaired at 45° tend to deform more than other specimens. On the other hand, specimens repaired with 20° withstand higher stresses than other specimens. In other words, specimens bonded with the smallest angle repair, 20°, are the repaired composites with the highest strength. The second most durable repaired composites are specimens bonded with double scarf. Their average bending strength is 570 MPa. It is almost half the average bending strength which is 1143 MPa of the specimens repaired at 20°. When 30° double scarf and single scarf repair were compared, samples repaired with 30° double scarf showed higher strength.

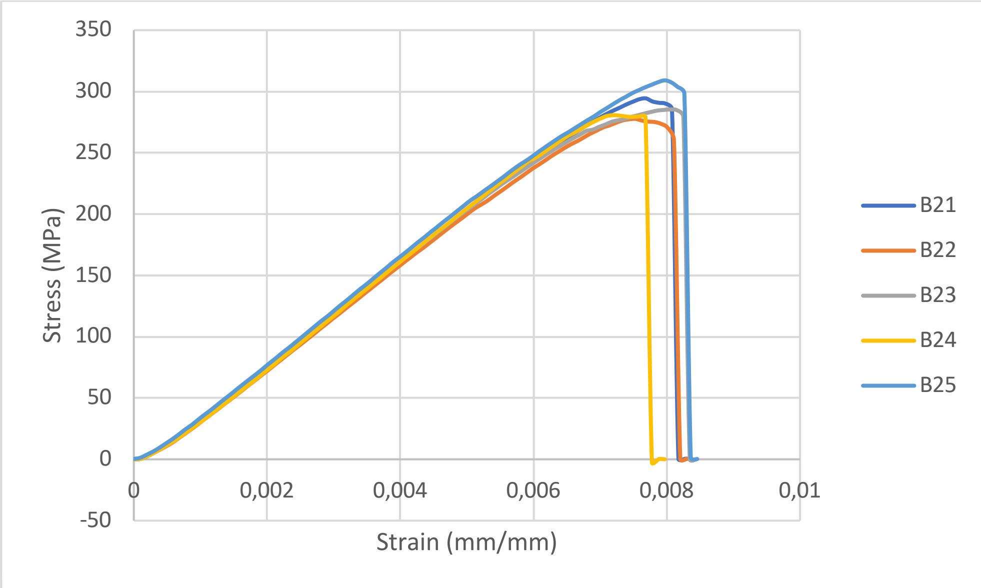

Figure 5.14. Stress-Strain Graph for the Samples Repaired with 20° Under Flexural Loading

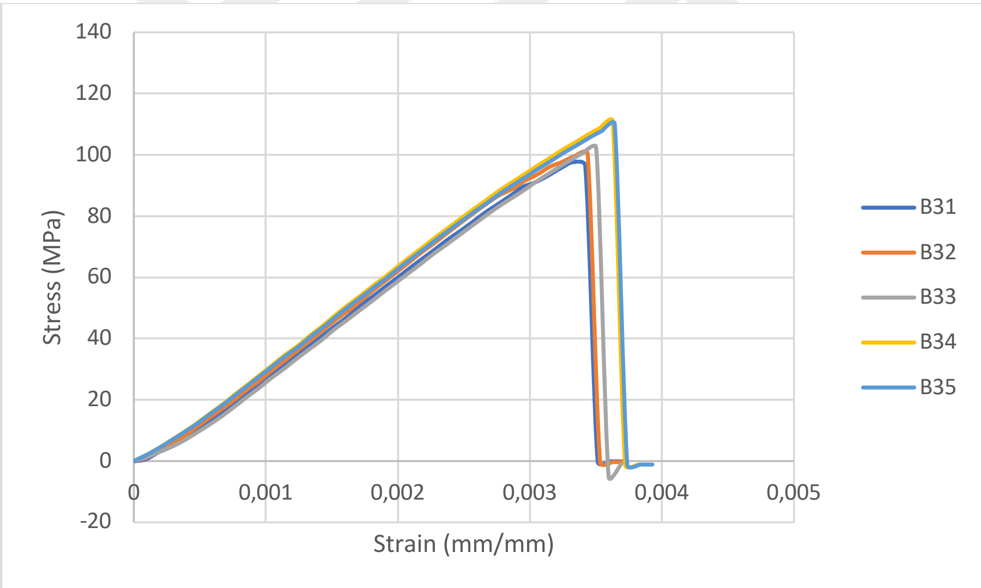

Figure 5.15. Stress-Strain Graph for the Samples Repaired with 30° Under Flexural Loading

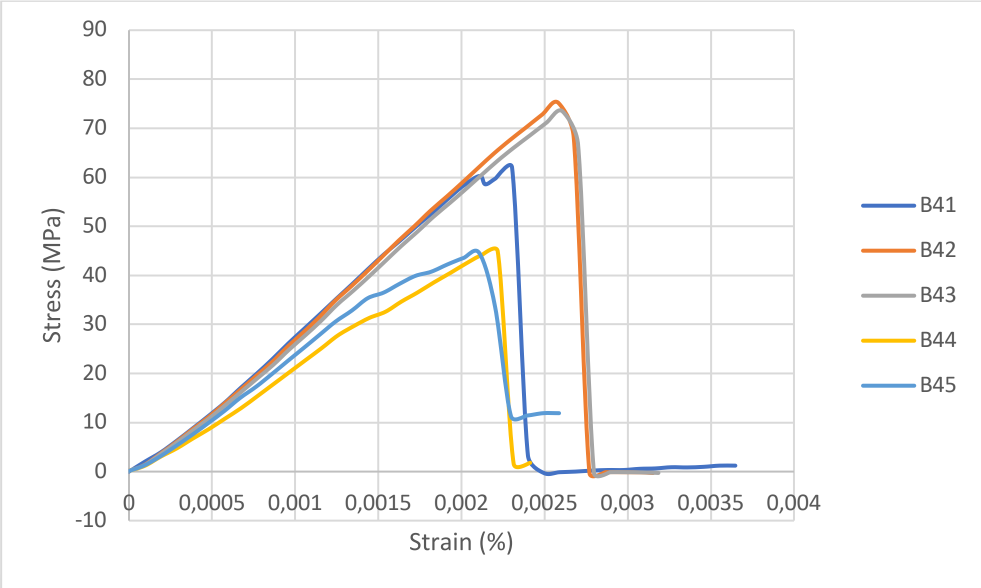

Figure 5.16. Stress-Strain Graph for the Samples Repaired with 45° Under Flexural Loading

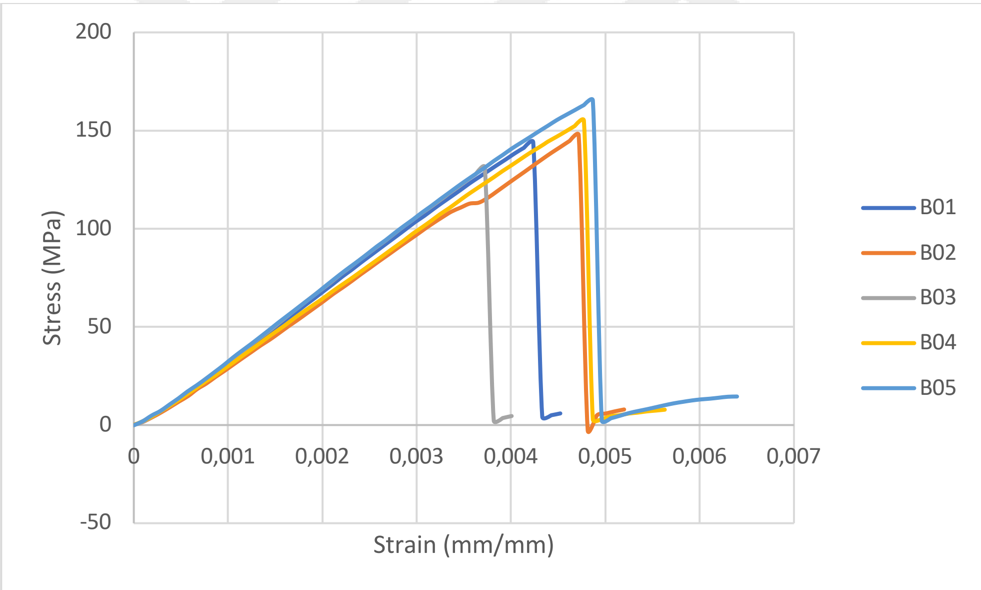

Figure 5.17. Stress-Strain Graph for the Samples Repaired with 30°-30° Double Scarf Under Flexural Loading

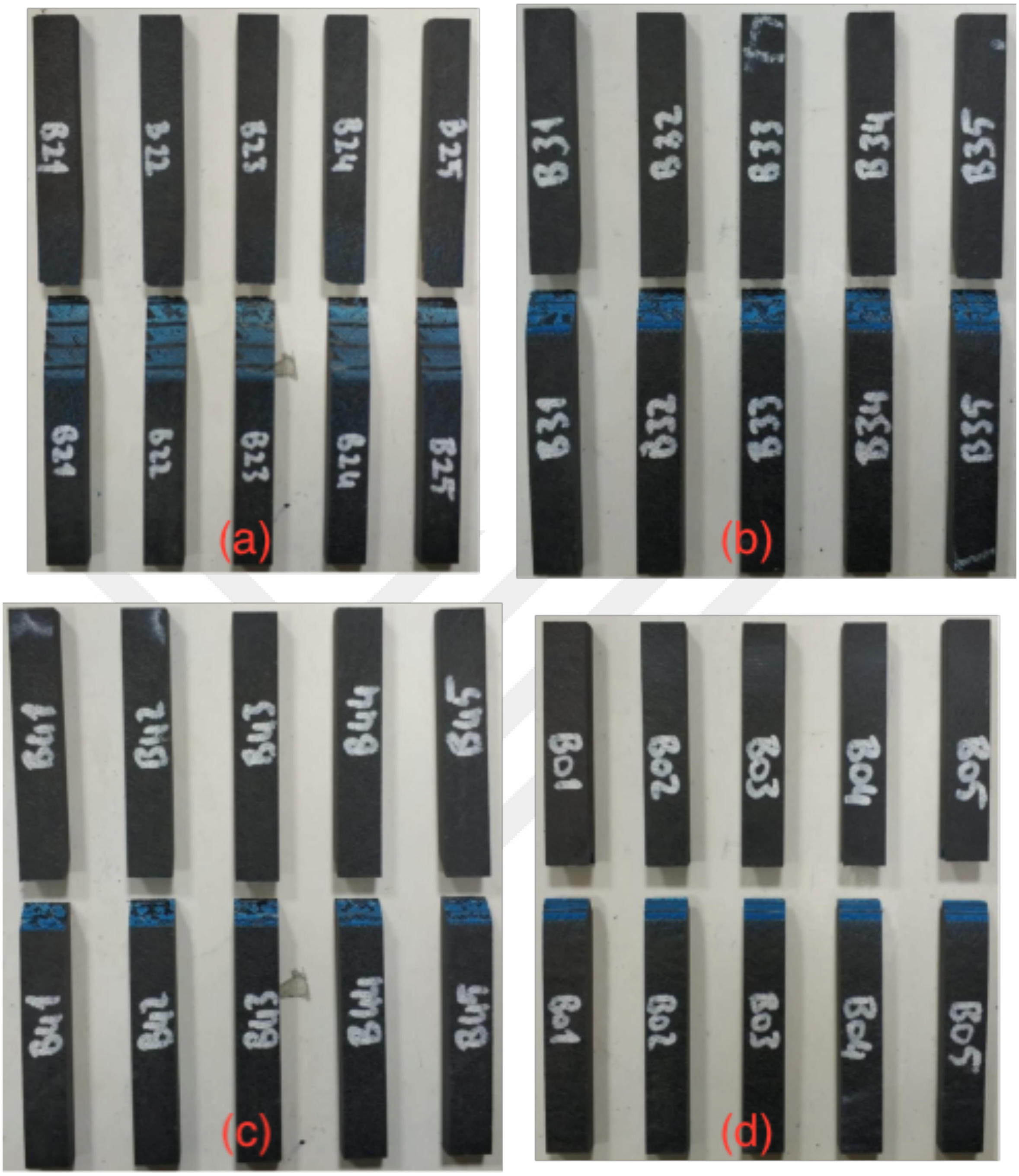

Figure 5.18. Fractured samples repaired with 20° in (a), 30° in (b), 45° in (c) and double scarf in (d) after bending test

When the interfaces of the broken specimens are examined, the specimens that the adhesive showed the best performance are the specimens that were repaired with 20°, is seen, moreover the specimens that show the most resistance are those (Figure 5.18).

It is seen that the average ultimate flexural strengths given in Table 5-3 are inversely proportional to the scarf angle. In other words, as the scarf angle decreases, the failure load increases. This supports the results of previous repair study of Campilho et al. [41] who worked with angles between 2°- 45° and revealed that smallest angle is most durable repair.

Table 5-3 Average Flexural Strength and Maximum Stroke of the Repaired Composite Samples

Sample	Average Flexural Strength (MPa)	Average Maximum Stroke (mm)
B2	289.46	2.31
B3	100.20	1.03
B4	55.17	0.68
B0	148.49	1.36

When the results of the three mechanical tests were examined, it was seen that the repair with the smallest scarf angle performed the best. As the scarf angle decreases, the adhesion surface on the parent and patch increases. It can be said that the performance of the repair increases in direct proportion to the expansion of the adhesion surface. This result is supported by previous similar studies. According to Xie et al. [37] scarfed the samples produced from carbon fiber fabric prepreg at 2°, 4° and 6° angles and used external plies for repair. As a result of the study, it was observed that the failure strength value of the 2° scarf repaired sample was higher than the others. Yoo et al. [38] compared repaired specimens with scarf ratios of 1/10 (5.7°), 1/20 (2.8°) and 1/30 (1.9°) with unrepaired specimens, and reported that specimens with 1/10 (5.7°) ratio had the lowest strength recovery rate. Kumar et al. [7], [40] reached the same conclusion in their studies with repairs performed at angles between 0° and 5°. In these studies in the literature, repairs were always performed at angles less than 10°. While the reduction of the scarf angle has a big advantage in terms of increase in the failure load, it also has some disadvantages. In order to repair with scarf patch with small angles, a very large area is removed from the parent material. While this causes the consumption of extra materials and times, it also increases the labor. It is also very difficult to work with such small angles in some situations where opportunities are limited, especially in non-factory for example field conditions. For all these reasons, it is aimed to change the repair angle. Therefore in this study, scarf angles of 20°, 30° and 45° were studied. While no big difference is observed between the performances of the 30° and 45° angled repairs, the performance of the 20° scarf angle repair appears to be approximately twice as good as the others.

In addition, as a result of the literature research, it has been determined that there is a lack of study about double scarf repair of composites. On the purpose of eliminate this deficiency, double scarf repair studies were carried out and examined in this study. In order to compare the joint configurations, both single scarf and double scarf repairs were made at 30°. As a result of the mechanical tests, it was seen that the double scarf combination made at 30° showed higher performance than the single scarf combination made at the same degree. In fact, double scarf repair performed with 30° gave results close to the performance of single scarf repair performed with 20°. This means that with double scarf repair, it is possible to achieve the performance of smaller angled single scarf repair. Thus, in cases where adhesively bonded double scarf can be applied, higher strengths can be obtained while scarfing less areas. However, double-sided access is required to apply the double scarf, which may not always be possible. This is a handicap of double scarf repair.

6. CONCLUSION

In this study, the mechanical performances of specimens adhered with different scarf angles and scarfing types under tensile, compression and bending loads were investigated according to ASTM standards. The motivation of this thesis is to investigate the angle and repair type that can be easily applied by technicians working with limited equipment for the repair of damaged composite structures that cannot come to factory maintenance. For this purpose, 20°, 30° and 45° angles were studied.

Experimental studies have revealed the following results:

- While single scarf repair consists of two parts, double scarf repair consists of three parts, which shows that single scarf repair takes less time than double scarf repair.
- According to the tensile test results, the strength of the repair decreases as the scarf angle increases. The strength of the double scarf repair is much higher than the single scarf repair performed at the same angle. On the other hand, when double scarf and smaller angle single scarf repair were compared the performance of single scarf was a little bit higher. In addition, sudden fracture was observed in the graphics of all samples. Cohesive failure was observed in samples with the highest strength at 20°.
- According to the compression test results, the smallest repair angle has the highest performance. When double scarf and single scarf repair performances are compared, it is observed that double scarf can withstand higher loads.
- As a result of 3-point bending tests, it is seen that the most durable samples are those that have been repaired at 20°. The samples repaired with 45°, which has the largest repair angle, show the least strength. The ultimate flexural strength of specimens repaired with 30° double scarf is almost twice that the strength of specimens repaired with 30° single scarf. All samples exhibited linear behavior under bending load.
- As a result all of these studies, the adhesively bonded double scarf joint seems more durable and advantageous than the single scarf joint. However, since double-sided access is required for double scarf repair, single scarf repair is recommended as a quick and easy repair solution.
- Among the single scarf combinations, the most suitable repair with the highest strength value is the repair with 20° angle joint. Adhesively bonded single scarf with

20° seems to be a suitable solution for a quick and durable but reliable repair, as it is easy to apply and also does not need to create a large scarf area as compared with previous low scarf angle studies in the literature.

6.1. Recommendation for Future Works

In this study, single scarf and double scarf comparisons were made in one angle. Double scarf repair can be studied from different angles to gain more information and understand the behavior of the double scarf.

The recovery rate can be calculated by performing an impact damage to the material and then repairing the double scarf. In addition, the effect of performance can be examined by performing the same process for single scarf repair and calculating the recovery rate of both.

As a continuation of this study, composite specimens repaired at similar angles can be modeled using the finite element method, and their behavior under tensile, compressive and bending loads can be observed and compared with the experimental results.

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