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Experimental Determination of the Influence of Perforation of Adherend to the Adhesive Bond Strength

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Abstract: The growth of different types of industrialization technology led to the appearance of several types of effective adhesives with perfect intensity and durability that can be used with different types of joints. As a result, the adhesive properties and work conditions play an indispensable role in determining the kind of application for which the adhesive can be used. This study deals with the experimental work of two types of adherends, pereforation and non-pereforation adherents, with a specific focus on one type of adhesion. To conduct the examination, two types of standard tests, D2095–96 and D-1002-99, were used in the single lap and Butt joint tests, respectively, to accomplish all tests. The results show that the ability of the perforation surfaces to enhance the strength is better than the non-perforated adherent while maintaining the flexibility. Thus, the research conducted substantial points about these kinds of surfaces and recommended the essential points to choose the suitable type of adherend.

Keywords: MS polymers, Perforation adherents, Adherent surfaces, Butt-joint test, Single lap-joint test

Introduction

The bonding strength of adhesives has received considerable attention in recent decades due to advances in production processes across numerous disciplines. This field is expected to grow more in the future. The investigators (Al-Mayali, 2017; Mosa & Hamzah, 2022). This study employs butt and single-lap joint testing under quasi-static conditions to investigate the adhesive properties of hybrid polymers. The data show that MS Hybrid Polymers have both strength and flexibility. Experimental results prove the suitability of the adhesive for different applications based on its strength, elongation, and failure causes. (Alobaidi & Almuramady, 2022; Da Silva et al., 2006) We investigated the effect of bond thickness on the quality of the adhesive. The results demonstrated that the lap shear strength increases with increasing adhesive stiffness and decreasing bond thickness. (Naito et al., 2012) Demonstrates that adhesive thickness significantly affects tensile strength but not shear strength, giving information for optimizing joint design and performance in high-temperature circumstances. Work is done by (Kadioglu et al., 2015). The behaviour of a flexible adhesive and steel adherents was investigated utilizing a pendulum impact machine with a single lap joint (SLJ). The study found that lap joint strength improves during impact testing compared to quasi-static tests. Moreover, research conducted by (Banea et al., 2015) concluded that the inner adhesive layers are preferred for lower stress concentrations, whereas thicker layers may be more effective for ductile adhesive materials due to increased energy absorption in a larger volume. An experimental study by (Blackman et al., 2000) found that fracture energy is produced by the impact test using a high-speed hydraulic machine. Eventually, many investigators (Yohanes et al., 2020) analyzed the relationship between adhesive thickness and strength by employing the butt joint test. Previous

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research suggests that butt and single lap joints are effective tools for studying adhesive behaviour. Furthermore, quasi-static and dynamic loads can be employed successfully. As a result, this study aims to evaluate and describe the behavior of MS Hybrid Polymers adhesives in butt-joint and single lap-joint testing, both non-perforated and perforated. As a result, the research focused on how adhesives behave under semi-static pressure while maintaining their thickness.

Adhesive Material

Any process that bonds two solid materials together is known as adhesion. Adhesion technology has been used in many industrial applications, including coating materials, polymer mixes, adhesive joints, sandwich structures, and composites (Da Silva, Carbas, et al., 2009; Mosa et al., 2024). Modified-silane hybrid polymers were used as the adhesive in this work. These adhesives are widely used in many different industries, including manufacturing, automotive, and aerospace.(Alobaidi & Almuramady, 2023; Hayashida et al., 2015).

MS Hybrid Polymers

Japan developed the MS Hybrid Polymers technology almost 40 years ago. On the other hand, the Belgian company Soudal recognized the importance of this technology and has been manufacturing it for more than 30 years. Several advantages of this product are displayed for this type of adhesive, including high strength endurance of tensile and shear; furthermore, good flexibility with a cure period ranging from 3 to 24 hours (Pereira et al., 2013; Prolongo et al., 2006).

Table 1. General adhesive properties

Type of Adhesive	Ultimate tensile [MPa]	Viscosity	Density Mixture [g/cm^3]
Modified Silane Polymers	3.1	12000-55000	1.46

Figure 1. (a) Appearance of MS hybrid polymers, (b) Trade name and packaging of the adhesive

Adherend Material

Depending on the type of joint and the direction of the force, two types of samples were made using steel. This type is used to reduce substrate failure or plastic deformation in the bonded material; prudent to ascertain the kind of adherent before preparing specimens for testing(Alobaidi et al., 2023; Da Silva, Lopes, et al., 2009). A perforated plate is structural to investigate the method of connection between surfaces. Numerous tests have been employed with diverse possibilities for bond failure. when the adhesive layer and the adherend fail simultaneously, Adhesive failure occurs. Also, referred to as cohesive failure in the adhesive layer if the bond surfaces separate but the layer of adhesives remains on both sides (Azari et al., 2011; Mosa & Hamza, 2022). If the bond's strength is strong, the failure may occur in the adherend material, which is described as cohesive failure. Adhesive bond failures may involve two or more different kinds of failures. Figure 2 illustrates the patterns of adhesive bond failure(Marques et al., 2015; Oudah et al., 2023; Zhang et al., 2013).

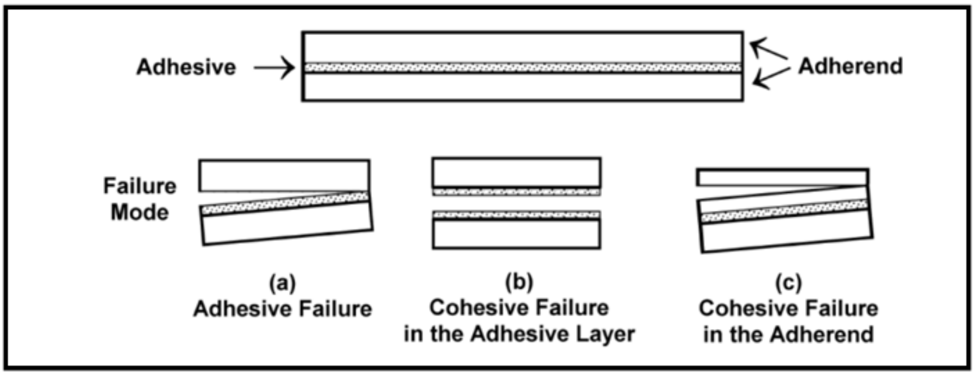


Figure 2. Failure modes of the adhesive bond (Koh et al., 2011; Yildiz et al., 2020)

Butt- Joint

Non-perforated Specimens

Tests of Butt-joint are often utilized in many sectors of transportation. The test specimens meet the ASTM standard (D2095- 96) (Alawsi et al., 2025). The specimen consists of two steel discs, each 40 mm in diameter and 3 mm thick, and contains an adhesive material., The specimen contains bonded material between them with an adhesive thickness of 3mm. Figure 3(a) illustrates the specimen size (Aradhana et al., 2020; Liao et al., 2013; Mosa & Hamzah).

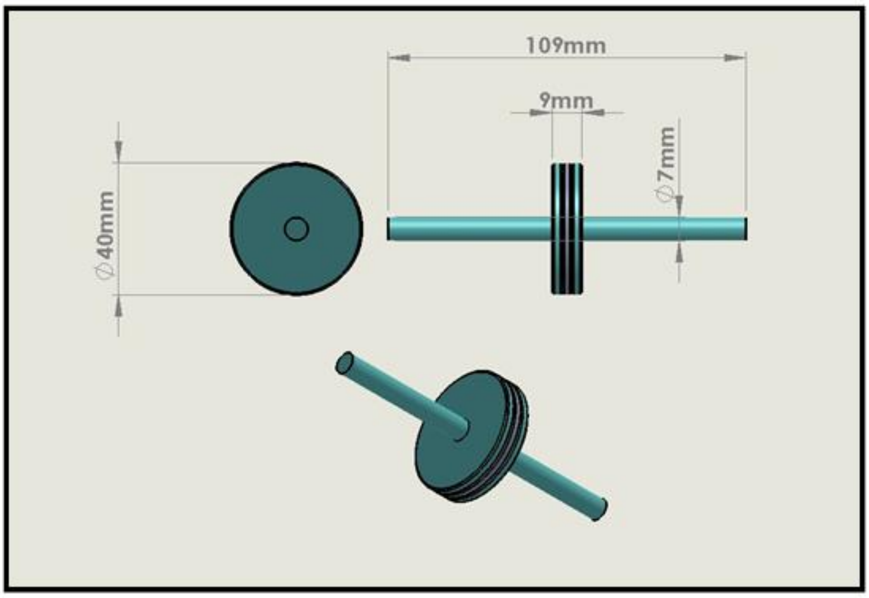


Figure 3. (a) Non-perforated butt-joint specimen

Perforated Specimens

Tests of Butt-joint are often utilized in many engineering applications. The test specimens meet the ASTM standard (D2095- 96). A perforated specimen has two disks with holes. The disks have a diameter of 40 mm, are constructed of steel with a thickness of 3mm, and have eight holes (Prolongo et al., 2006; Unuk et al., 2019). The diameter of the hole and the thickness of the hole are 3mm. Furthermore, adhesive material was placed between these discs, and the thickness of the adhesive was 3mm. Figure 4(b) depicts the dimensions of these specimens (Guilpin et al., 2019; Hussen et al., 2022; Kahraman et al., 2008).

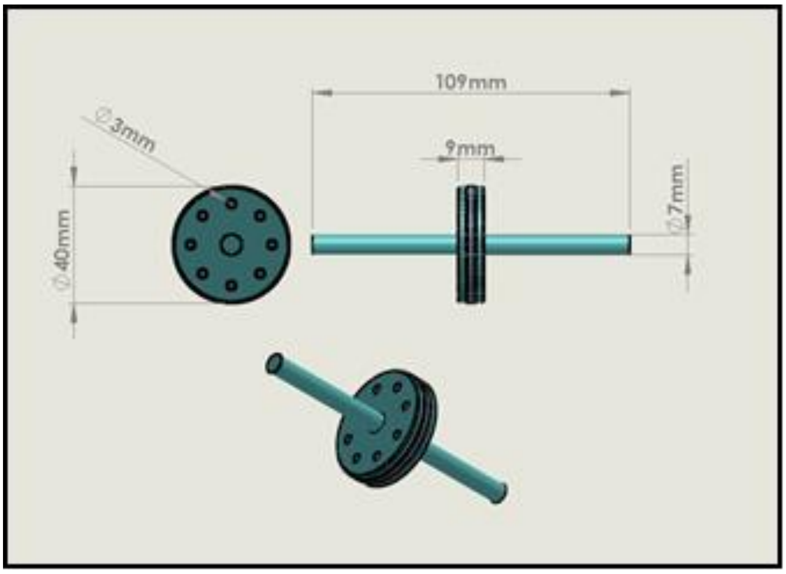


Figure 4. (b) Perforated butt-joint specimen

Single-Lap Joint Test

Non-perforated Specimens

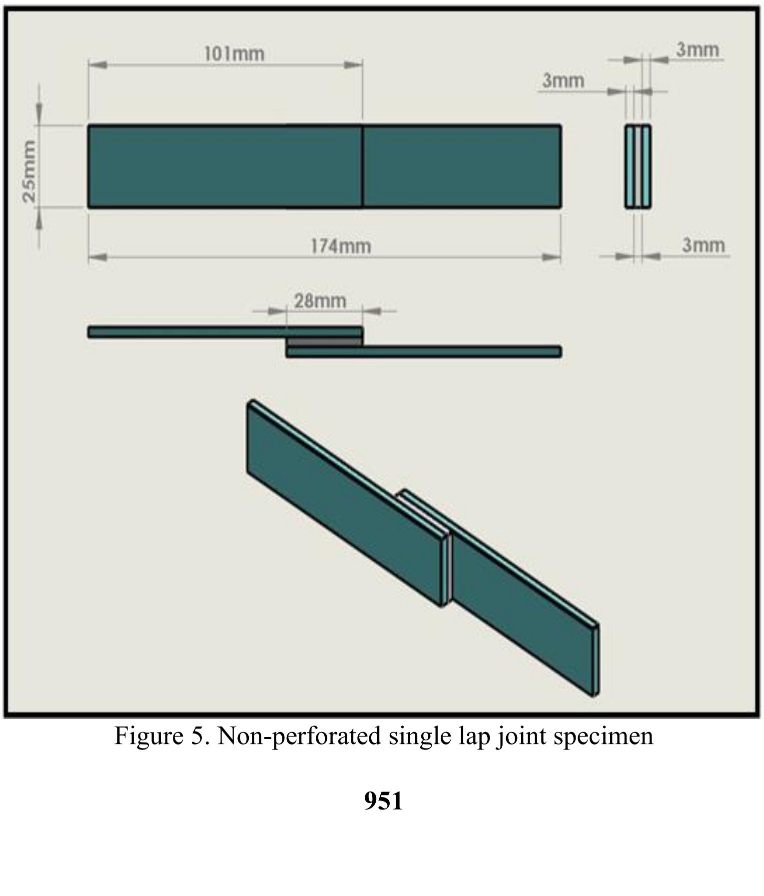


Figure 5. Non-perforated single lap joint specimen

In many industrial applications, testing is performed using a single lap joint. The specimen's single joint structure is compliant with ASTM Test Method (D-1002-99) (Unuk et al., 2019). Figure 5 displays the dimensions of the steel plates used in the shear test. However, the plate's length was 101 mm and its thickness was 3 mm. An adhesive 3 mm thick and 28 mm long was used to bind the two plates.

Perforated Specimens

A single lap joint has been used in many industrial applications. The specimens of a single joint structure are compliant with ASTM Test Method (D-1002-99) (Yildiz et al., 2020). Figure 6 shows the measurements of the steel perforated plates containing holes the number of three holes and used in the shear test. However, the plate's length was 101 mm, the thickness and the diameter of the hole was 3 mm. An adhesive of 3 mm thickness and 28 mm length was used to bind the two perforated plates.

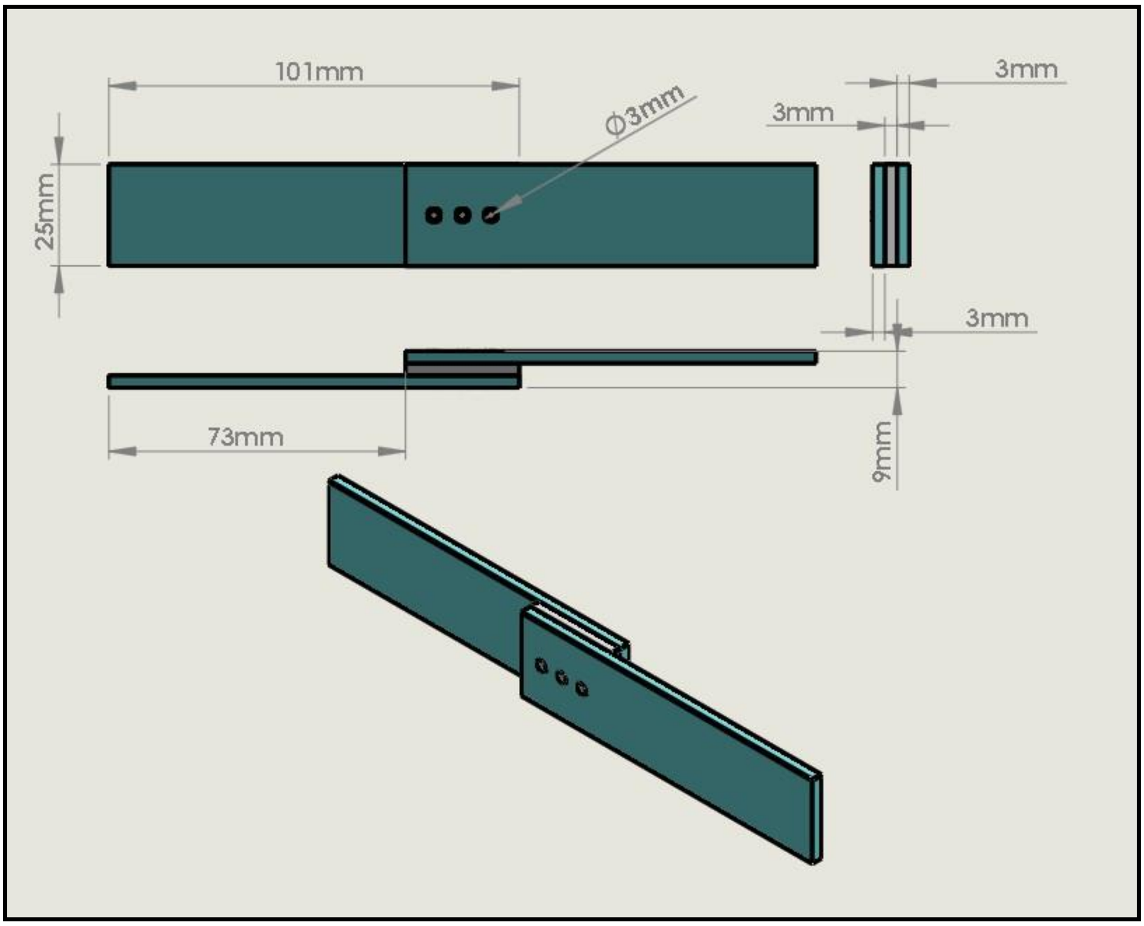


Figure 6. Perforated single lap joint specimen

Sample Manufacturing

The experiments were conducted using two types of samples: a butt-joint and a single-lap joint, with non-perforated and perforated adherends. Indeed, the CNC machine has been used to perforate the disks. We prepared a bolt and a tiny disc to make the Butt-joint specimens. After the disc was perforated, we cleaned and flattened the outer surfaces of the disc. Further, we are welding the bolt and a small disc. The sample was then painted to prevent it from oxidizing. The adhesive joint for a metal plate made of steel or aluminum is the most common because it is easy and efficient to manufacture, for example, of butt and single lap joints. In contrast, in both types of specimens (butt-off and single-lap joints), these devices were used to adjust the thickness of the adhesive layer. Furthermore, all of the samples were processed according to ASTM standards. Figure 7 illustrates all the procedures for preparing the adherent. All specimen dimensions must be changed to ensure that these tests produce reliable results. Furthermore, the same process was performed on the discs of specimens of a single lap joint.

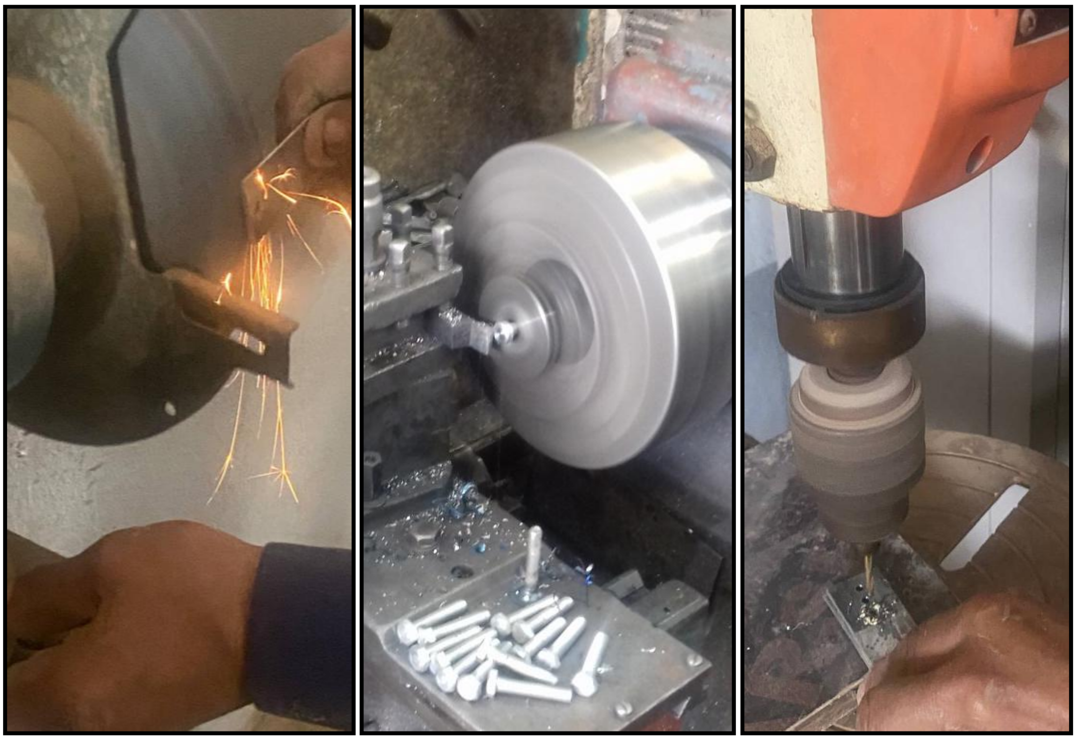


Figure 7. Adherent manufacturing

In this study, two types of experimental setups were used. A quasi-static test was used to measure all adhesion parameters for the 3 mm thick steel shown in Figure 8. Furthermore, handy auxiliary instruments were utilized to position and modify the specimens. The adhesive junction for a metal plate, such as steel materials, is the most common due to the ease and efficiency of manufacturing butt and single lap joints are simple and efficient. Numerous factors can impact the joint's strength, including adhesive type, bond layer thickness, and overlap length. The tensile and shear tests were performed on butt-off and single lap joint specimens. To make the Butt-joint examples, a bolt and a tiny disc were made, and the discs' outer surfaces were cleaned and flattened. After preparing the adherents, the adhesive was placed between the flat and perforated surfaces of the discs and plates at room temperature, 25-26 °C. Figures 9 and 10 display all of the procedures in preparing the specimens (butt-off and a single lap joint)

Figure 8. Regulate the specimens' thickness.

Figure 9. The specimens of butt-off

Figure 10. The specimens of a single lap joint

Procedures of Tests

In this work, a Universal Testing Machine (UTM) was employed to complete all tests, and a computer interface was used to control this machine (servo-hydraulic or servo motor system). The system merges all components, such as an encoder, extensometer, and load cells, to measure many parameters, including extension, load, and displacement, accurately. Three closed-loop systems in this machine operate a control system, with an accuracy of ±1% a besides the high-resolution data acquisition; moreover, the range of machine speed is from 0.02 to 490 mm/min. Figure 11 depicts the UTM used in the test (Arenas et al., 2013; Boutar et al., 2016). Figure 12 shows the configuration of the single lap-joint experiment. Furthermore, the setup for securing the butt-joint specimens using grip screws, aligning them with the loading axis. All experimental procedures were carried out at a constant force rate of 1 mm/min Indeed, the relation between load and elongation was recorded up to the failure of the specimen. This testing procedure was consistently applied across all specimen types at work (Carlberger & Stigh, 2010; Guilpin et al., 2019).

Figure 11. Universal testing machine

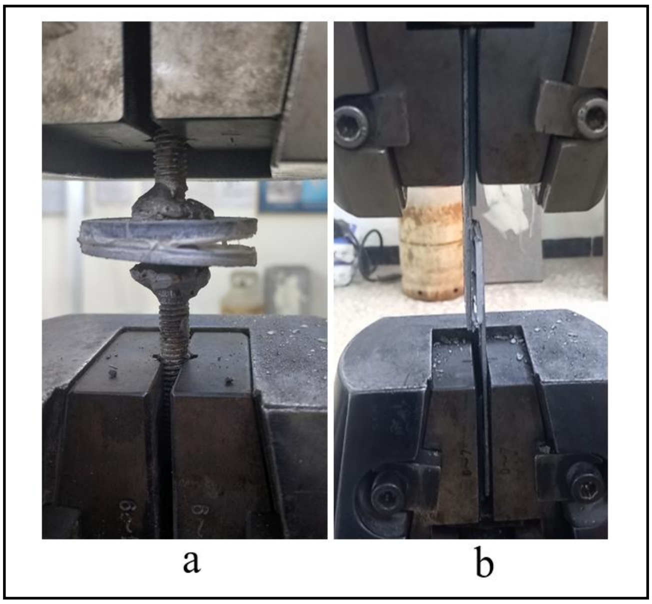
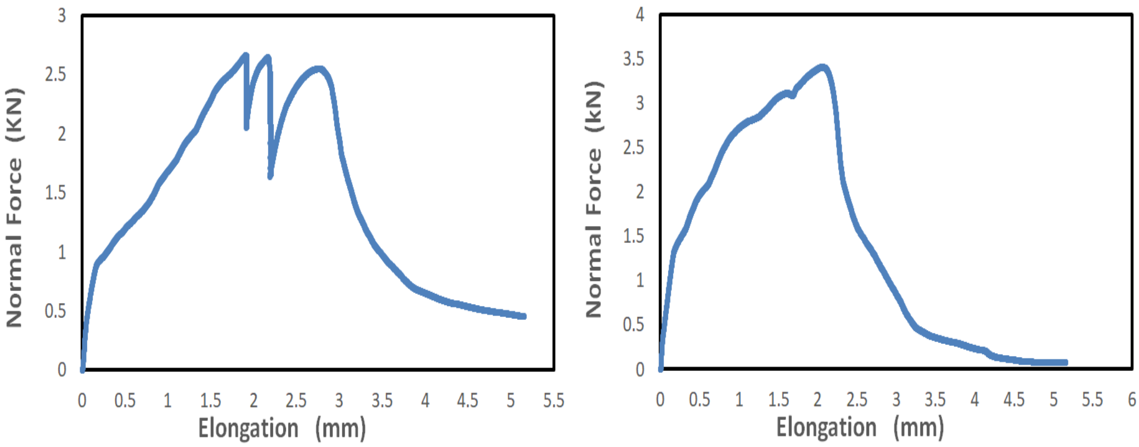


Figure 12. Quasi-static test (a) butt joint test (b) single lap joint test

Results and Discussion

The results of all tests (butt and single lap joints) were recorded visually after applying a quasi-static tensile load. After failure condition, the surface shape of both types of samples is displayed and highlighted within these plots; However, the average adhesive layer thickness for both types of joints across all samples remained at 2 mm. The first thing to note about the behavior of MS hybrid polymers in every test is that they are a clear, ductile adhesive. But in both butt joint testing, the tensile force of the MS Hybrid Polymers is the greatest at

28% of the single-lap joint. Figure 13 illustrates the relationship between the force and elongation of the two surfaces (perforated and non-perforated) of the Butt-joint specimen.



a **b**

Figure 13.Typical curve for the butt-joint specimen
(a) Non-perforated specimen (b) Perforated specimen

Due to the bonding materials and the adhesive layer of the perforated Butt-joint specimen having separated, the fracture surface. The mechanisms of adhesion and connection failure in both tests are depicted in Figure 14. These findings are consistent with the results of another study (Mosa & Hamza, 2022). This study demonstrated the tremendous bonding strength. However, this figure shows how the ductility of the hybrid MS polymers causes plastic bending, increasing their elongation.

Figure 14. The failure mode of a perforated butt-joint specimen

After analyzing the surface morphology shown in Figure 15, the cohesion failure pattern was evident in both Butt-joint tests. Furthermore, the adhesive failure mode has been extensively documented in some areas of surfaces. However, the morphology of the perforated Butt-joint specimen illustrates without doubt the strong bond between the two surfaces of the adherend as a result of perforations.

Figure 15. The failure mode of a non-perforated butt-joint specimen

Figure 16. Comparing these two types of surfaces, namely perforated and non-perforated surfaces, this study observed that an increase in the resistance to applied loads occurred in the perforated surfaces over the non-perforated surfaces, with an increase of 28% in the Butt-joint test. On the other hand, the study recorded that the amount of elongation in the two types of adherend is almost equal.

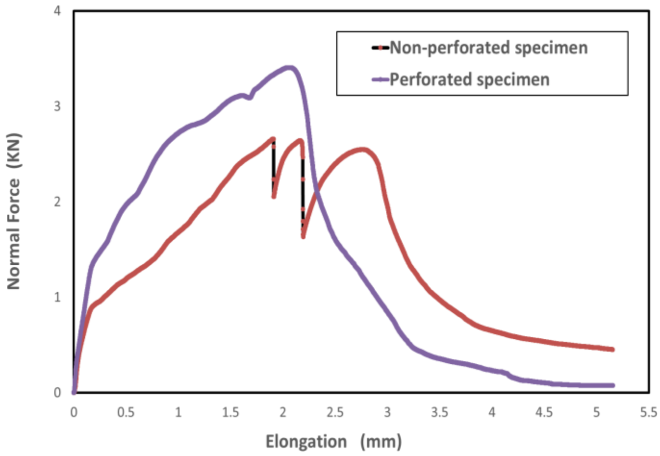


Figure 16.Typical curve for the butt-joint specimen

Figure 17 shows the increase in the adhesive resistance of the perforated surface to applied loads (3.406 KN) compared to the non-perforated sample (2.658 KN).

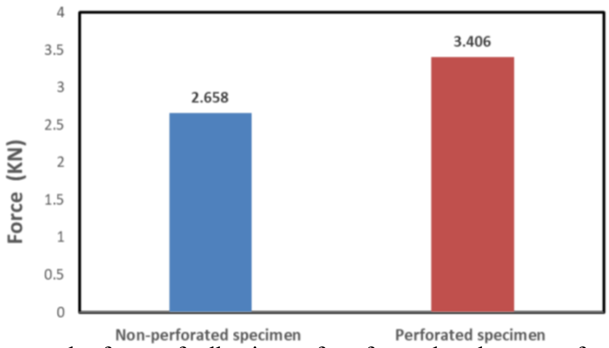


Figure 17. Comparison between the force of adhesives of perforated and non-perforated specimens in the butt-joint test

Figure 18 illustrates how the flexibility of MS hybrid polymers causes plastic bending Single-lap joint specimen and an increase in the tensile strength of the perforated surface by about 30% compared to the non-perforated surfaces. On the other hand, joint overlap exhibits the same ductility properties. Therefore, compared with two surfaces, the maximum elongation is 3.56 mm and 2.667 mm for perforated and non-perforated adherend, respectively.

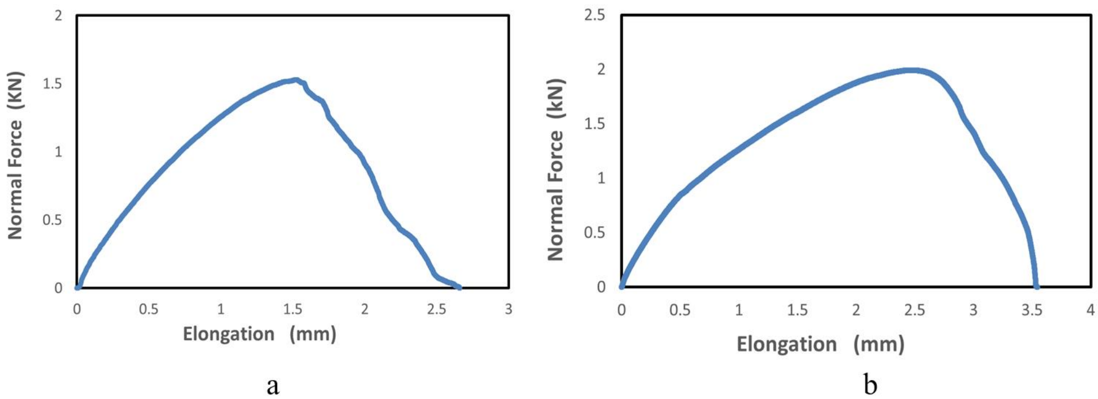


Figure 18. Typical curve for a single-lap joint specimen
(a) Non-perforated specimen (b) Perforated specimen

Figure 19 depicts the failure pattern after adhesion testing was a combination of surface bonding and cohesion patterns in the single-lap joint test.

Figure 19. Failure of the single-lap perforated joint specimen

On the other hand, experimental results for non-perforated single-lap joint specimens showed the interference link. In the end joint test, the surface morphology exhibits mixed mode (interface with cohesive failure), as shown in Figure 20.

Figure 20. The non-perforated single-lap joint specimen's mode of failure

Figure 21 compares two types of adherend (perforated and non-perforated surfaces) for the single-lap joint test. This study observed that an increase in the strength of applied loads takes place in the perforated surfaces over the non-perforated surfaces, with an increase of 30%. On the other hand, the study recorded a 25% increase in elongation in the perforated adherend compared to the non-perforated adherend.

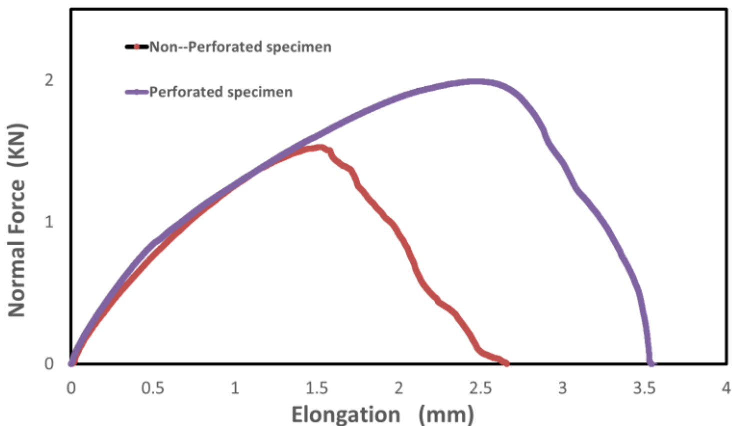


Figure 21. Typical curve for a single-lap joint specimen

Figure 22 shows the increase in the adhesive resistance of the perforated surface to applied loads (1.99 KN) compared to the non-perforated sample (1.528 KN).

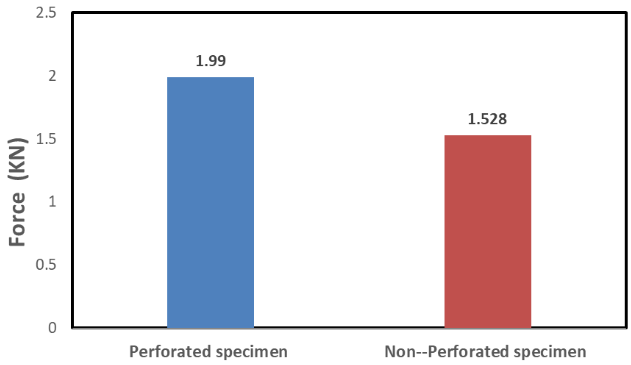


Figure 22. Comparison between the force of adhesives of perforated and non-perforated specimens in a single lap-joint test

Conclusions

Recently, all modern industries have generally relied on various types of adhesives in many applications, and there is expected to be an increase in demand for adhesives in the future. Therefore, the bonding agent must have high strength against shear and normal loads, as well as good elasticity with improved chemical, physical, and mechanical properties. Two types of adherend surfaces, perforation and non-perforation adherend, have been used in this work. Indeed, comparison between these adherends has been done by using quasi-static tests with two types of joints, butt and single lap joints, and using the MS Hybrid Polymers as adhesive. According to the main parameters such as load, elongation, and analysis of the behavior of the material, a comparison has been made, besides the study of the failure of specimens. The study concluded that the behavior of perforation adherend refers to high strength in the butt-joint test, and it is 28 % better than the non-perforation adherend with the same elongation. Also, the failure mode is cohesive failure in the adhesive layer for the butt joint and cohesive failure between the adherend and adhesive. On the other side, in the test of the single-lap joint test, the strength and elongation of adhesive in perforation adherend are higher than in non-perforation adherend by 30% and 25% respectively. Furthermore, the failure pattern is essentially a cohesive failure of the adhesive layer in both types of tests. The behavior of non-perforation adherend refers to good strength under normal and shear loads, and this adherend is less than the perforation adherend with the same ductility.

Recommendation

This study recommends examining other types of adhesives, such as epoxy and silicones. In addition, the study finds it necessary to change the surfaces used for bonding (surface of the adherend), for example, increasing their diameters or choosing other shapes or geometries.

Scientific Ethics Declaration

* I declare that the research work entitled Experimental Determination of the Influence of Perforation of Adherend to the adhesive bond strength, conducted by me under the supervision of Asst. Lect. Dr. Muhanad Hamed Mosa, was conducted strictly to the principles of scientific integrity and ethical conduct.

Conflict of Interest

* The authors declare no conflicts of interest.

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