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RESEARCH ARTICLE

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Tensile Behavior of Steel Joints Implemented by Bolts and Adhesive

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Abstract: Joints are the weakest points of given mechanical structures. Therefore, multiple joining methods are applied, and joints are dealt with special care to extend the life of the structures. Hybrid joints are seen to improve the performance of the joints significantly, especially for composite–metal joints. The hybrid joints, as well as non-hybrid lap joints made of bolts and adhesive to join steel plates, were investigated in this article. The role of the joining method (hybrid and non-hybrid) and parameters (bolt number and overlap length) in the mechanical strength of the mild steel grade 300 joints were analyzed under tensile loading. Based on the experimental results, it was observed that an increase in the number of fasteners (bolts) increased the tensile strength of the joint if the shear stress on the bolt held its strength. In addition, an increase in overlap distance slightly decreases the tensile strength of the assembly. The assembly with both fasteners and adhesive (hybrid joint) had higher yield strength than the assembly using only fasteners, and the ultimate tensile strength was approximately the same for both joining methods.

Keywords: adhesive, fastener, tensile strength, hybrid joint

1. Introduction

Joining of metals is a very important step toward the fabrication of structural components, which can be broadly classified as mechanical, chemical, and thermal joining [1, 2]. Every joining method has its own design requirements and must consider characteristics such as operating environment, assembly efficiency, load conditions, maintenance, tensile strength, feasibility, and materials used [3, 4]. The most used joining method for temporary joining is fastening by bolts, which adds extra weight to the assembly. Welding is often a cost-effective way to join metals, which occurs at high temperature and thus induces stresses in parts and is not suitable for very thin sheet metals and materials with low melting points, such as aluminum. In those scenarios, joining by fasteners and adhesives is more practical [5]. Fasteners have been used for a long time in the engineering world, which is a popular choice where disassembly of the structure is required for maintenance purposes [6]. The mechanical joining between parts can be of various natures, such as with adhesive, fasteners, or a combination of these two [7, 8]. The main advantage of adhesive joints is that the adhesives add negligible weight to the assembly. There are a number of parameters that dictate the strength of the final joint, such as overlap length, bond line thickness, and spew fillet on adhesively jointed lap joints, as reported by Gavgali et al. [9]. Theoretically, it was predicted that an increase in overlap area increases the bond area, which should give stronger tensile strength to the assembly. The increase in the number of fasteners will increase the tensile strength of the assembly to some limit. However, an increase in the number of fasteners also increases the weight of assembly along with the cost of assembly as well.

In an adhesive joint, the adhesive is usually a toughened epoxy, and the adherends are mild steel, which is usually used in the production of car bodyshells. In such a case, during external loading, the steel yields at the loading points, away from the overlap region, and hence stops any additional growths in load without causing failure of the joint [9]. The bending moment is constant at the edge of the overlap when failure occurs and corresponds to the maximum bending moment the steel can sustain. This bending moment generates large plastic strains, and this initiates failure in the adhesive. In such cases, the strength is independent of the adhesive thickness, and an increase in adhesive thickness causes the joint overlap section to be stiffer, but the bending moment is still the same at the edge of the overlap [9]. For a lap joint under tension, the longitudi-

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nal stress from the direct load and the bending moment at the edge of the overlap region generate plastic strains when the steel suffers plastic deformation, and these cause failure in the adhesive [9]. The lap joint under tension is subtle to adhesive thickness. To reach the same stress level and plasticity of the steel adherend, as the bending moment increases, the smaller the stress due to tension. As the bond line thickness increases, there is an increase in the bending stress since the bending moment has increased. Therefore, the strength of the joint is reduced. At the thinnest bond line of 0.1 mm, there is very little difference in the strengths of the joints with and without a fillet, but at a bond line thickness of 3 mm, the strength of the square-ended joint is less than half of that with a 45° fillet [10]. Withstanding such challenges, the advantages of adhesive joints are as follows: (i) no extra weight to the assembly, (ii) protective layer against corrosion, and (iii) leak-proof performance than mechanical fasteners only. The disadvantages include failure of adhesive at high temperature and lower tensile strength compared to that of mechanical fasteners [10–12].

A combination of the above two joints is the hybrid joints that are used in several engineering areas (automation, aeronautics, naval industry, etc.) for joining sheet metals and dissimilar materials in body/ fuselage/surface components because of their properties that are superior to those found in single joints (which are adhesively bonded, mechanically fastened, or welded) [13, 14]. According to Maggiore et al. [15], hybrid joints lead to the combination of a welded or mechanical joint (riveted, screwed) with an adhesive. These hybrid joints are of great technological attention as they permit to combine and, in several cases, to enhance the individual effects of each kind of joint [4]. The properties of these joints will depend not only on the nature and properties of the adhesive but also on the mechanical system used [16], on the compatibility of the design, on the sequence, and on the conditions used for making the hybrid joints [17]. Hybrid joints have also been reflected in the repair and improvement of damage tolerance [18]. However, temperature change induces stress buildup when different materials are joined together in a hybrid joint. It also changes the behavior of adhesives, that is, brittle at low temperatures and strength reduction at high temperatures [19]. In general, adhesive is used in assembly where very less tensile strength is required, whereas fasteners are used where high values of tensile strength are required. Both fasteners and adhesive are used in structure where leak-proof components are needed, like ships, airplanes, etc.

There is much research in the literature to investigate the behavior of different types of joints of different material systems [20]. Those explain the advantages, disadvantages, and mechanisms of joints among different materials [21–23]. It was noted that there is no study to investigate the effect of different parameters, such as overlap area and fastener number for the hybrid joints (adhesive and bolt) of steel. These are very important to reduce the cost of joints and improve the efficiency in specific engineering applications.

Thus, the objective of the present research was to investigate the role of adhesive, fastened, and hybrid joints on the tensile properties of the joint assembly. In addition to that, the role of joining variables such as overlap area and number of fasteners in assembly on tensile strength was also addressed. The present work has significant applications in practical engineering, as the joining of metal components is inevitable to construct big structures, such as airplanes, submarines, ships, power plants, etc. Therefore, the outcome of the present work can be taken as reference when there is a need to select the number of bolts in the assembly, accurate method of joining to assemble the parts, deciding the overlap area in single lap joint for the different joining methods.

2. Materials and Methodology

Mild steel grade 300 (AS3679/AISI 1020) slab with dimensions of 6000 × 25 × 5 mm was the workpiece material. The composition and mechanical properties of the material can be found in Table 1 [24]. The computerized numerical control wire electrical discharge machine was used to fabricate the specimens of desired dimensions. The specimens were machined at constant conditions (such as on/off-peak current, speed and feed of wire travel, etc.) to maintain a similar surface finish. In this case, the average arithmetic surface roughness (Ra) of the joining surfaces was 10 µm.

Table 1
Elemental composition and mechanical properties of mild steel grade 300

Elemental composition (wt. %)		Mechanical properties	
C	0.25	Tensile strength (MPa)	480
Mn	1.6	Yield strength (MPa)	380
Si	0.5	Density (kg/m^3)	7850
P	0.04	Young's modulus (GPa)	200
Fe	balance	Shear modulus (GPa)	80

A lap joint is also called an overlap joint, in which the two members overlap each other to make an assembly. A full lap joint is a joint when the material with two thicknesses joins, resulting the joint which is combined thickness of two materials, whereas in the half-lap joint, material is removed from both the thicknesses to make the thickness of thickest material. Normally, the same thickness of material is used for half-lap joints as shown in Figure 1.

Araldite, a two-part epoxy adhesive, was used to make a single half-lap joint between two mild steel plates with a thickness of 1 mm. The glue has a tensile modulus of 1700 MPa, lap shear strength higher than 20 MPa, and elongation at break 10%. The schematic of the joint is shown in Figure 1. Araldite falls within the high-strength group of adhesives, which plays the prime role in the joining and strength of a structure. A maximum bond strength of 26 MPa was achieved after 3 days of bonding. Heating the bond at 40°C–100°C while curing can increase the cure rate and final strength of the bond. Consistency was maintained in applying and curing glue on the joining surface. A torque wrench was used to tighten the M3 fasteners to the 3 Nm recommended torque.

For mechanical joining, M3 bolt and nut fasteners were used, where 3.4 mm holes were produced to insert the bolts. In this investigation, experiments were done by increasing the number of bolts from 1, 2, 3, and 4 to join two specimens. The torque wrench was used to apply a specific torque to the fasteners to prevent the overtightening of the bolts. In this experiment, a torque wrench was used to tighten the M3 fasteners with an applied torque of 3 Nm as recommended with a tolerance of ± 6% [25].

An Instron 250 kN tensile testing machine was used to measure the tensile properties of the joints at ambient conditions. The stress-strain curves were generated, and mechanical properties such as ultimate tensile strength, proof stress, strain, and % elongation were calculated by the system. No slip was experienced in any of

Figure 1
Schematic of the joint: (a) standard dimensions, (b) top view of flat specimen, (c) top and front view of fastened specimens with M3 bolt and nut, and (d) front view of adhesively bonded specimens

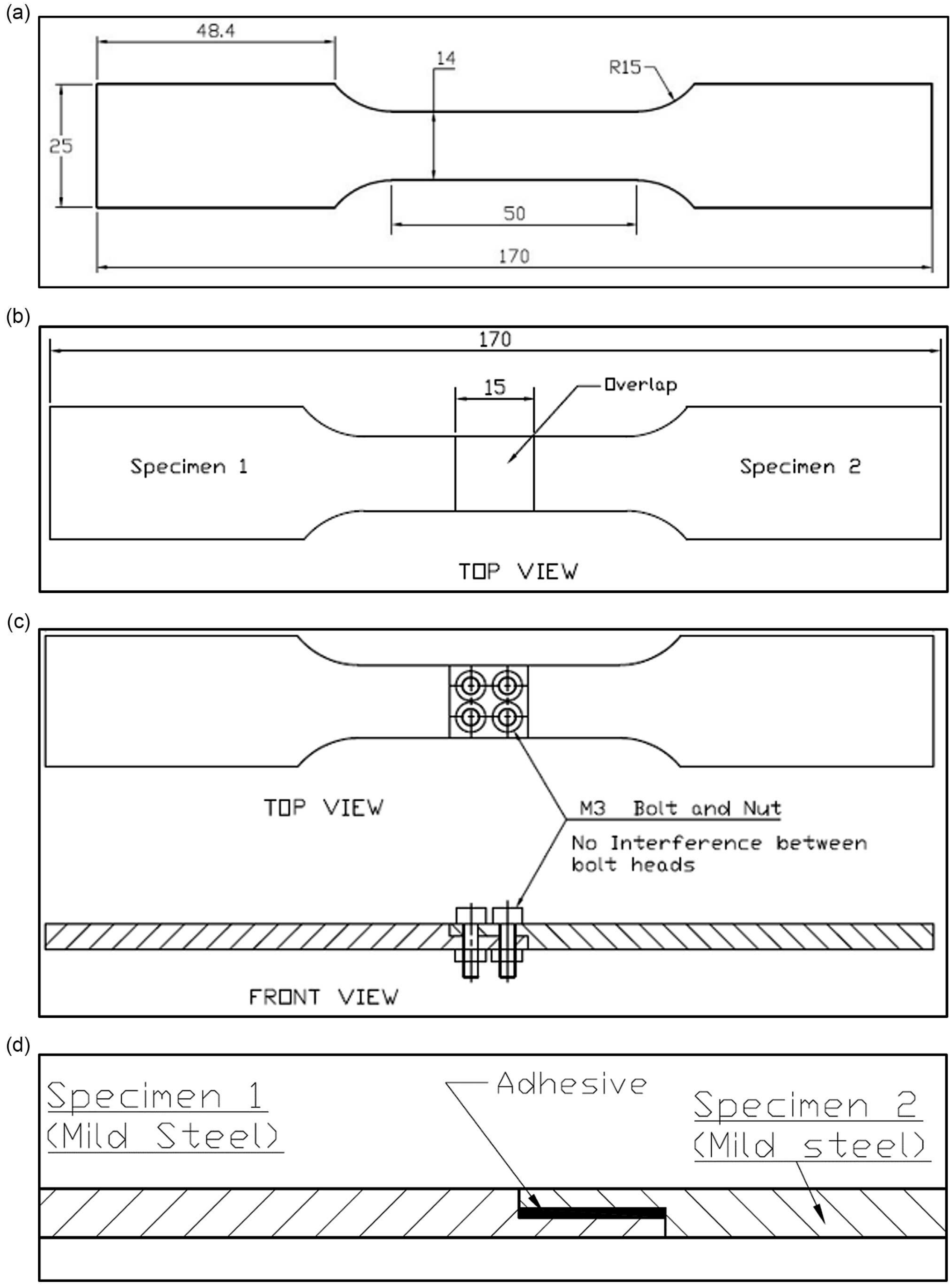


Table 2
Design of experiments with varying joining methods

Experiment number	Joining method	Overlap length (mm)	Number of bolts	Varying parameters
Exp. 1	Bolts	15	1	Number of bolts
Exp. 2	Bolts	15	2	
Exp. 3	Bolts	15	3	
Exp. 4	Bolts	15	4	
Exp. 5	Bolts and adhesive	15	1	
Exp. 6	Bolts and adhesive	15	2	
Exp. 7	Bolts and adhesive	15	3	
Exp. 8	Bolts and adhesive	15	4	
Exp. 9	Adhesive	10	0	Overlap distance
Exp. 10	Adhesive	15	0	
Exp. 11	Adhesive	20	0	
Exp. 12	Adhesive	25	0	
Exp. 13	Bolts	10	2	
Exp. 14	Bolts	15	2	
Exp. 15	Bolts	20	2	
Exp. 16	Bolts	25	2	
Exp. 17	Bolts and adhesive	10	2	
Exp. 18	Bolts and adhesive	15	2	
Exp. 19	Bolts and adhesive	20	2	
Exp. 20	Bolts and adhesive	25	2	

the experiments. Twenty experiments were performed with varying input parameters, as shown in Table 2. In addition to the nature of the joints, two other variables such as (i) overlap length and (ii) number of fasteners were also investigated.

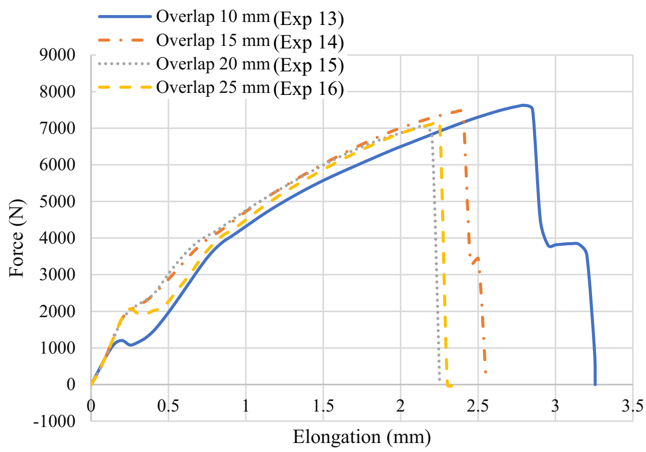
3. Results and Discussion

3.1. Joining of specimens with fasteners

In experiments 13–16, the effect of the overlap distance changes from 10 to 25 mm on tensile strength was investigated, while the number of fasteners was kept constant. The outcome of the experiments is shown in Figure 2 in the form of force-elongation curves.

It seems that the overlap distance of 10 mm has a maximum tensile strength of 7.6 kN with an elongation of 3.3 mm, whereas the overlap distance of 20 mm has a minimum tensile strength of 7.06 kN. As the shear strength of all the fasteners was the same (as the same grade of fasteners was used in all experiments), it can be concluded that the overlap distance doesn't have much of an effect on the tensile strength of assemblies with a single lap joint. The results are within 5% of the range in terms of tensile force; however, the elongation of a 20 mm overlap has increased by 30% over the elongation of a 10 mm overlap. The physical deformation of the joints was investigated after the tensile test as shown in Figure 3. The specimens with an overlap distance of 10 mm have fewer bends in their geometry than the overlap distance of 25 mm. When the joint is intact, at the start of the tensile test, the axial load is uniformly distributed across the cross-section of the joint where the load is carried by bolt, adhesive, and interface friction. As the load increases gradually, only the bolts remain there to carry the load. The bolts undergo shear loads, and these loads are not in line with each other. Therefore, these shear loads induce a bending moment on the bolts.

Figure 2
Effect of overlap on force-elongation curves during tensile loading



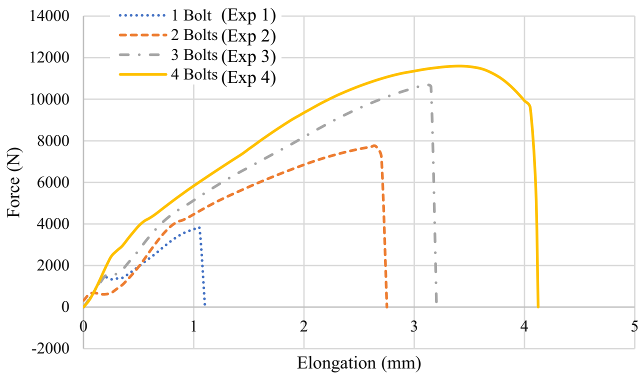
This causes the bending of the joint end toward the final stage. The fasteners tend to break at 45°.

In experiment numbers 1–4, the number of fasteners increased from 1 to 4, respectively, with an overlap distance of 15 mm and torque of 3 Nm on each fastener. The response of tensile loading on such joints is shown in Figure 4, in terms of a force-elongation curve. The tensile strength of assembled specimens with single fasteners has only a tensile force of 4 kN, whereas the specimen with four fasteners has a tensile force of 11.5 kN. Thus, there is a significant increase in tensile force as well as in elongation.

The physical deformation of the joints was investigated after the tensile test, as shown in Figure 5. Fasteners fail before the mate-

Figure 3
Physical deformation of the joints subjected to tensile test with different overlap areas

Figure 4
Effect of number of fasteners on force-elongation curves during tensile loading



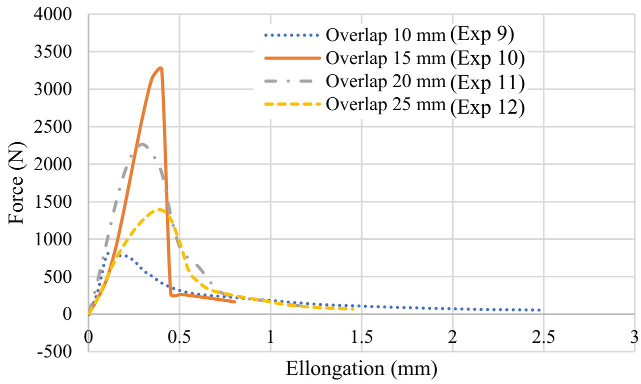
rial when a number of fasteners used are less than 4. This shows that the shear strengths of the bolts are greater than the tensile strength of the cross-sectional area of the specimen. After this point, the increase in the number of fasteners in the assembly does not contribute to the tensile strength of the assembly, which was maximum at 11.8 kN. In addition, it was observed that the values obtained from the experiment numbers 2 and 14, which have the same variable parameters, vary by 4% and thus confirm the reputability of the experiments. In all cases, there was a noticeable bend in the specimens except for experiment number 1, where only one fastener was used, as shown in Figure 5.

3.2. Joining of specimens with adhesive

Figure 6 shows the effect of overlap distance on force-elongation curves of adhesively jointed specimens. From Figure 6, it has been observed that the specimen with an overlap distance of 15 mm has the maximum tensile strength (3.2 kN) of the assembly, whereas the overlap distance of 10 mm has the minimum tensile strength of 0.75 kN. The tensile strength of the assembly decreases with the increase of overlap length beyond 15 mm overlap. Thus, the use of adhesive does not increase the ultimate tensile strength significantly. This type of bond or assembly can be used in structure where very less movement is required.

Figure 5
Physical deformation of the joints subjected to tensile test with different number of fasteners

Figure 6
Effect of overlap on force-elongation curves during tensile loading on adhesiveonly joints



3.3. Joining of specimens with fasteners and adhesive

In the previous sections, adhesive and fasteners were used separately. In this section, the experiments were performed on the specimens, which were assembled with the help of both adhesive and fasteners. The Araldite was applied to the mating surface, and then the fasteners were applied to the assembly with 3 Nm torque. After applying the torque, all the extra glue came out of the assembly, leaving behind a fine layer of adhesive on the mating surface. Figure 7 shows the effect of tensile loading on the force-elongation curves of the specimens. A maximum tensile strength of 7.5 kN has been observed for the overlap of 15 mm, whereas the minimum tensile strength was 7.1 kN in the case of 20 mm overlap. An elongation of 3.2 mm has been noticed in the overlap distance of 20 mm because of the ductility in fasteners. The elastic region for the assembly has been increased when adhesive has been used in assembly with fasteners if compared to the assembly done only with fasteners.

Figure 8 illustrates the effect of fasteners on the force-elongation curves of hybrid joints. The overlap distance of 15 mm and torque of 3 Nm have been applied to all fasteners used in assembly. The assembly used with four bolts has the maximum tensile strength of 11.78 kN, and the assembly with a single bolt has the minimum tensile strength of 4.5 kN. The elastic region has been increased for the assemblies when adhesive has been used with the fasteners compared to the assemblies used the fasteners only in same conditions. The fasteners fail when the number of fasteners used is

Figure 7
Effect of overlap on force-elongation curves during tensile loading on hybrid joints

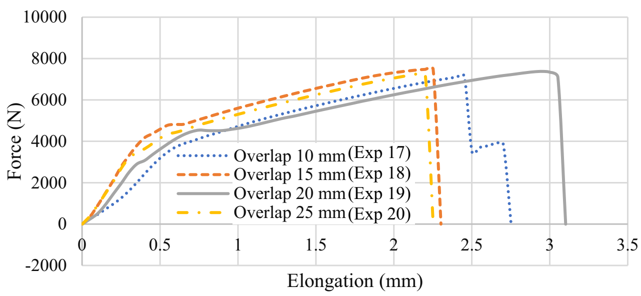
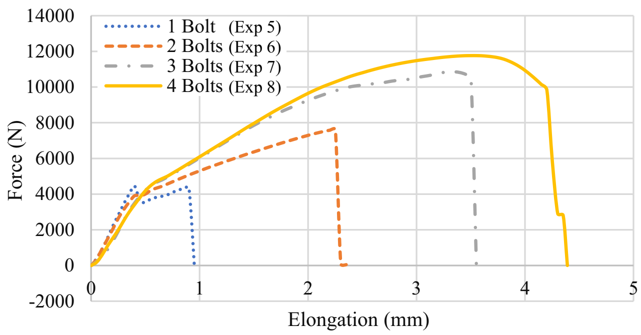


Figure 8
Effect of number of fasteners on force-elongation curves during tensile loading



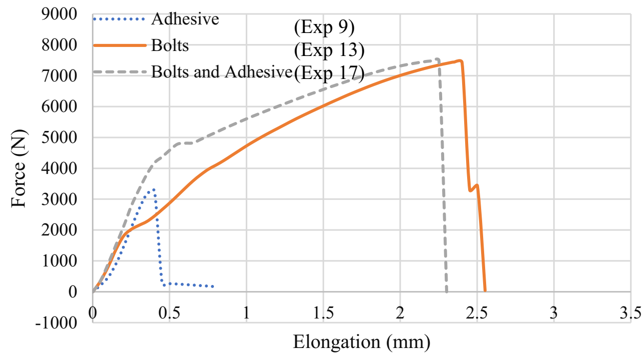
3 or less, and the specimen material fails when the number of fasteners has been increased to 4, which gives the idea that the shear strength of four fasteners is more than the tensile strength of the specimen material. One more important observation has been made that the fasteners have stayed with the assembly even after the fasteners have failed. This was due to the presence of adhesive in the clearance between the bolt and the specimen. The adhesive used in the assembly makes the bond stronger, increases the elastic region, and reduces the initial displacement because of clearance in the hole and fasteners.

3.4. Comparative analysis on the role of adhesive and/or fasteners

In this section, a comparison has been made for all three different joining methods under similar conditions like 3 Nm torque and 15 mm overlap with two fasteners. This comparison will represent a better understanding of the role of adhesive and/or fastener on the joints, as shown in Figure 9. The joints with or without the adhesive exhibit similar tensile strength, namely, 7.43 kN. However, the presence of adhesive increased the proof stress from 2 to 4 kN. Thus, there is about a 100% increase in yield strength with hybrid joints compared to joints using fasteners only. However, the ultimate tensile strength of the assembly stays approximately the same for both cases. The tensile strength of 3.1 kN has been attained when only an adhesive has been used, and it has been observed that there is only an elastic region in that case during elongation. In other words, the assembly fails instantly after crossing the plastic region.

It was observed that the assembly with fasteners and adhesive has less initial shear movement because of the adhesive bond, whereas the assembly with fasteners has initial shear movement when subjected to tensile force because of clearance in the hole and

Figure 9
Effect of joining method on force-elongation



fasteners. The only thing that restricts the initial shear movement is the torque on the fasteners, but every fastener has its own recommended torque; exceeding the recommended torque may result in the stresses on fasteners and workpieces. Therefore, the use of adhesive can give extra yield strength to the assembly without placing any additional stresses.

It has been analyzed from the results that the increase in the number of fasteners in the assembly increases the tensile strength of the assembly until a point. This point is the value when the shear strength of all the fasteners is less than the tensile strength of the specimen. In other words, if the fasteners fail in the assembly when subjected to tensile force on the assembly, then the increase in the fasteners can give strength to the joined parts. However, if the material failed before the fasteners, then an increase in the number of bolts would not affect the tensile strength of the assembly. In the latter case, the increase in cross-sectional area would give extra strength to assembly, if needed. This finding could be used in engineering applications to prevent the use of excess fasteners, thus reducing the weight of the assembly and making it economically viable.

The effect of torque was not investigated in the present work, which may play a role in the overall strength of the joints. Thus, the role of the M6 bolt with 20.3 Nm torque will be worth investigating, which was outside of the scope of the present work. This will provide more flexibility in selecting the tightening torque on the fasteners. In addition to that, adhesive with a bond strength of 1 kN may provide more insight into that.

4. Conclusions

The role of different joining methods together with joining parameters on the overall tensile strength of the joints was investigated in the present work. Based on the experimental results and associated analysis, the following conclusion could be drawn:

1) Change in overlap length of the assembly with fasteners does not affect much the tensile strength of the assembly. This was because the assembly got the two fasteners in each case, and the tensile strength of the assembly depends upon the shear strength of the fasteners, which stays the same for all cases (i.e., overlap lengths).
2) An increase in the number of bolts in the assembly increases the tensile strength of the assembly until the tensile strength of the material is equal to the shear strength of all fasteners. After this point, a further increase in the number of bolts in the assembly does not have any influence on the assembly.

3) The use of adhesive in assembly with fasteners increases the yield strength of the assembly. It did not affect the tensile strength of assembly as the cohesive strength of adhesive was normally less than the shear strength of fasteners.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Alokesh Pramanik: Conceptualization, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision. **Dinesh Garg:** Methodology, Software, Formal analysis, Resources, Writing – original draft, Visualization. **Animesh Kumar Basak:** Conceptualization, Formal analysis, Resources, Data curation, Writing – original draft, Visualization, Supervision. **Chander Prakash:** Methodology, Validation, Investigation, Resources, Data curation, Writing – review & editing, Project administration. **Subramaniam Shankar:** Methodology, Validation, Investigation, Resources, Data curation, Writing – review & editing, Project administration. **Somnath Chattopadhyaya:** Methodology, Validation, Investigation, Resources, Data curation, Writing – review & editing, Project administration.

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