Research Article

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Experimental investigation of single-lap bolted and bolted/bonded (hybrid) joints of polymeric plates

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Abstract: In this study, the joint strengths of single-lap bolted and bolted/bonded (hybrid) joints formed by using four different engineering plastics were experimentally investigated. High-density polyethylene (HDPE), ultra-high molecular weight polyethylene, Delrin (POM), and Teflon were used as plate materials in single-lap connections. Standard M6 bolts were used in bolt connections. The specimens were prepared as single bolted, double bolted, single bolted/bonded, and double bolted/bonded in 20, 40, and 60 mm single-lap lengths. Weicon company's RK-7100 two-component adhesive was used as the adhesive. Tensile tests were carried out with the displacement control of 2 mm/min. After the tensile tests, load–extension graphs were created for each connection type, and the strengths of the connections were compared with each other. Three parameters were used to evaluate the strength of the additional lap joints. These are effect of the bolt numbers, effect of the adhesive, and effect of single-lap length. Depending on the plate material, double-bolt connections performed 20–56% better than single-bolt connections. The adhesive had no effect on ultimate joint strength. As the overlap length increased, an increase was generally observed in the joint strength of the specimens. Depending on the overlap length increase from 20 to 60 mm, the strength of the single-bolt configurations of HDPE-B specimens was found to be approximately two times that of the best results. When polymeric plates are compared among themselves, double-bolted Delrin (POM) specimens exhibited the highest joint strength in all single-lap lengths.

Keywords: mechanical properties, single-lap joints, bolting, adhesive, polymers

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1 Introduction

Structural applications are usually formed by combining many parts. Loads are transferred to these parts by means of fasteners. Bonding or bolting method is generally used for the connections of these parts [1]. While bolted connections are preferred in aviation due to their advantages such as strength, ease of replacement, and maintenance; adhesive connections are preferred due to their lightness and ease of application. Bolted/bonded (hybrid) joints can be used as an alternative joining method in non-aviation applications [2].

Recent studies have shown that improvement in joint strength is achieved when there is good synergy in the load sharing between bonded and bolted in hybrid joints compared to bonded and bolted separately [3]. There are different studies on the mechanical properties of single-lap joints in the literature and some of these include: Heimbs et al. that experimentally investigated the possible strain rate effects of quasi-static loading [4]. In bolted connections, especially at low loads, a large part of the applied load is covered by friction [5]. Anyfantis and Tsouvalis investigated the single-lap joint strength of different materials according to the variability of lap length and adhesive thickness parameters [6]. Ozenç and Sekercioglu stated that if the bonding process is supported mechanically, the bond strength increases significantly [7]. The joining of polymeric materials is generally done by bonded or bolted joints. The performance of the bonded joints is affected by many parameters such as adhesive thickness of bonded area, joint geometry surface roughness, and material properties [8,9]. Combining these techniques can be effective in long overlap length joints, because the adhesive behaves more rigidly in terms of structural running and is exposed to a large part of the applied load [10]. Recently, the hybrid (bolted/bonded) joint technique has attracted the attention of researchers. For example, Kelly obtained a 21% better strength compared to the bolted joint and 33% better than the bonded joint with the hybrid (bonded/bolted) joint in a study using polyurethane [11]. Bonded/bolted joints can change the load distribution in the stress zone on the side of the hole allowing their plates to bear more load [12]. The strength of adhesive joints decreases with the change of ambient temperature. The strength of some commonly used adhesives decreased by up to 50% between room temperature (24°C) and 70°C [13]. Li et al. investigated the strength of carbon fiber reinforced plastic/aluminum plates' single-lap bolt joints in four interference sizes (0, 0.42, 2.14, and 3.02%) and it reported that the best joint strength was obtained at 2.14% [14]. Luo et al. designed a double-lap bolted joint to connect the composites in three different configurations: glass fiber/epoxy, carbon epoxy, and hybrid. In continuation of the study, three-point bending tests were performed on these designs and the results were compared [15]. Compared to other techniques, the mechanical properties and failure modes of hybrid (bonded/bolted) joints are more difficult to detect. Models need to be developed to understand the structural behavior and failure mechanisms of joined joints [16]. For bolted/bonded joints, mostly existing in numerical models, 3D finite element method is used [17]. Atta et al. investigated the failure modes of bolted connections in double-lap steel plates using artificial neural networks and finite element analysis [18]. El-Sisi et al. evaluated in the axial direction, high vertical parallel force ratio in the bolts of the cross link. It is recommended to consider this force during the design of the laminate [19]. El-Sisi et al. performed experimental tests to determine the initial stiffness of bolted tapped connections. A 3D finite element model was developed to analyze single and double lapped bolted composite plates [20]. Osama et al. investigated the effect of change in weight fraction of glass fiber on the bearing strength of bolted composites of injection molded chopped glass fiber-reinforced thermoplastic composites [21]. A numerical finite element model was developed to determine the remaining fatigue life of the steel component El-Ministerly Bridge combined with rivet connections. And they calculated the remaining service life of the bridge as 11 years [22].

Single-lap joints are one of the most widely used geometries due to the simplicity of fabrication [23,24]. Based on the literature search, it is understood that single-lap joints have been investigated in different materials, but there is a lack of research on the failure modes of single-lap joints bolted and bolted/bonded of polymeric plates. In this study, the effects of lap length on the joint strength of single-lap joint engineering plastics in bolting and bolted/bonded connections were investigated.

2 Materials and methods

2.1 Materials

Polymeric materials find use in many places in daily life. The expected properties of these materials vary according to their intended use [25]. In this study, four different engineering plastics were used as plate. The first is high-density polyethylene (HDPE) used widely as organic polymer, because it is very stable and non-biodegradable. The second polymeric sheet used is ultra-high molecular weight polyethylene (UHMWPE). This material is a subtype of polyethylene and also a geosynthetic. Geosynthetic plates are suitable materials for engineering and structural repairs [26]. Third, polyoxymethylene (POM), trade name Delrin, is an engineering material with a high degree of crystallinity, low friction, and hardness. Because of these properties, it is preferred where high-dimensional stability is required [27]. Fourth, polytetrafluoroethylene (PTFE) is preferred in engineering applications due to its

Table 1: Some properties of polymeric plates [29–33]

Property	HDPE	UHMWPE	Delrin (POM)	Teflon (PTFE)
Melting temperature, T_m (°C)	125–130	130–133	175	327
Glass transition temperature, T_g (°C)	−116.2	−116.1	−35	129.4
Density (g/cm^3)	0.95	0.96	1.41	2.2
Poisson ratio (v)	0.46	0.42	0.44	0.46
Elongation at break (%)	500–700	200–500	15–75	200–400
Chemical formula	$(C_2H_4)_n$	CH_2CH_2	$(CH_2O)_n$	$(C_2F_4)_n$

high temperature resistance, low surface energy, and low friction coefficient [28]. Teflon is the trade name of PTFE polymer. Teflon, which is resistant to heat, chemicals, humidity, and friction, does not stick to any material, and its friction coefficient is smaller than that of all solid objects [28]. Some properties of polymeric plates are presented in Table 1.

Two-component WEICON Easy-Mix RK-7100 adhesive was used for the bonding joints of the polymeric plates in this study. Easy-Mix RK-7100 can be used to bond numerous materials such as plastics, metals, and ceramics among themselves. It is particularly convenient for structural bonding if high-strength connections are required. The adhesive is very viscous and is therefore suitable for applications on vertical surfaces [34].

2.2 Fabrication of specimens

First, hybrid materials in which bonding and bolting are used together were bonded. Tool geometry is a very important consideration when plastic plates are drilled, especially when the quality of the machined hole is critical [35]. In this regard, the holes of the plates were opened with a fixed axis drill using a 6 mm diameter drill bit. Due to the nature of the polymeric materials, low surface roughness and precise dimensional and geometric tolerances were obtained in the holes after drilling (Table 2).

In Figure 2, an example is given over Delrin (POM) for coding the specimens. Here, the commercial name of the sample comes first, then the letter indicating the number of bolts is used as "B" if it is single bolted, and as "BB" if it double bolted. If there is an adhesive in the connection, then letter "A" comes. The last part represents the single-lap lengths in millimeter.

Table 2: Meanings and numerical values of the symbols in Figure 1

Symbol	Meaning	Value (mm)
Lt	Specimen length	220, 200, 180
Lo	Overlay length	20, 40, 60
Ld	Grip length	50
ta	Adhesive thickness	0.4
tp	Plate thickness	5
td	Grip thickness	5
B	Wide	40
Ø	Bolt diameter	6
Cm	Distance between bolt centers	12
Bm	Distance from the edge to bolt center (single bolt)	20
Km	Distance from the edge to bolt center (double bolt)	11
δ	Displacement	—
F	Load	—

2.3 Experimental studies

The single-lap joints of engineering plastics were subjected to uniaxial tension in a 50 kN INSTRON-8801 universal testing machine. The test specimens were loaded with a displacement speed controlled at 2 mm/min. Two single-lap joint specimens, such as bolted and bolted/bonded joints, were subjected to tensile test on a three overlay length. Experiments were carried out at room temperature and ambient humidity conditions.

3 Results and discussion

The mechanical properties of the materials used are already available in the literature. However, there may

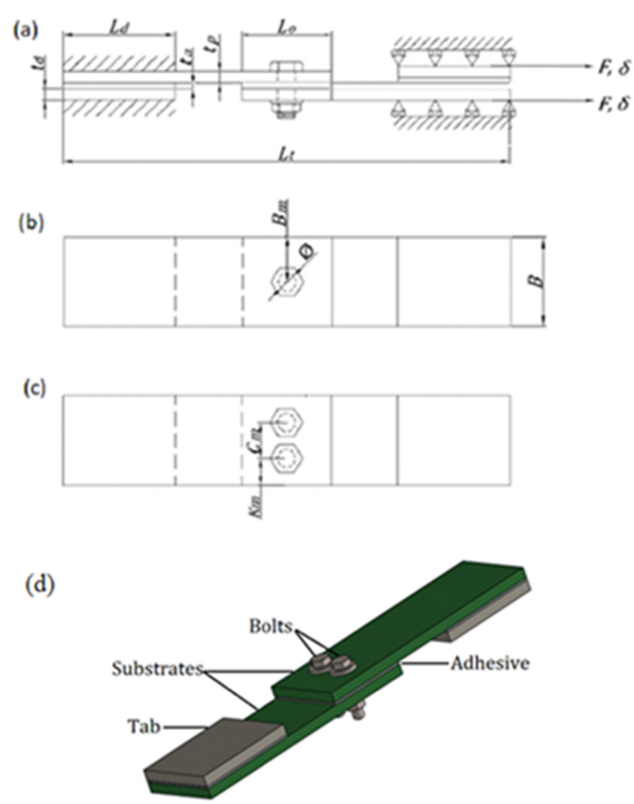


Figure 1: Configuration and dimensions of specimens: (a) dimensions and loads, (b) dimensions of single-bolt joint, (c) dimensions of double-bolt joint, and (d) three-dimensional view.

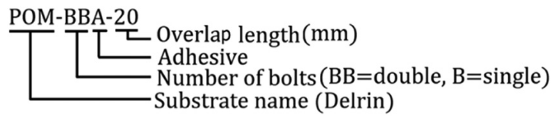


Figure 2: Coding of joint configurations.

be slight differences due to the production process of the companies. Therefore, tensile strengths and elastic modulus of the materials used in the study were determined from the tensile specimens by performing tensile tests. Stress–strain curves and modulus of elasticity values given in Figure 3 are the average values obtained as a result of 60 mm × 40 mm × 5 mm sized specimens.

Adhesive bonding is the process of bonding two components using a suitable binder (i.e., an adhesive). In bonded/bolted joints load applied to the specimens is primarily covered by the adhesive. Adhesive thickness has a significant effect on the strength of the joint. Experiences show that the thinner the bond line, the higher the lap joint strength [36,37]. The decrease in bond strength versus adhesive thickness is attributed to the thicker bond lines containing more defects such as voids and microcracks [36]. In this context, the adhesive thickness was adjusted to be 0.5 mm. Also, surface treatment is another parameter that can significantly affect the joint strength. In order to obtain a quality bonding, the polymeric plates were roughened with a sandpaper.

If good plate stiffness is provided, the out of plane stresses in the adhesive bonds of lap joints are reduced and the stress distribution in the bonds becomes very close to the pure shear load. On the other hand, lower plate hardness causes the out of plane tension of the adhesive to be higher, which leads to early damage of the joint [6].

It also affects the strength of the joints and the strength of the bonded materials. Therefore, due to the mechanical properties of the adhesive and the material, different types of damages may occur in the joints joined with the adhesive [6].

Adhesive damage occurs when the adhesive is separated from the material (Figure 4(a)). Cohesive damage is a progressive damage caused by plastic deformation of the adhesive along the bonded border (Figure 4(b)). In practice, damage types often occur together. In plate-tear damage, the separation occurs from the surface of the material due to the high bonding strength of the adhesive (Figure 4(c)).

Common types of damages seen in mechanically fixed plate joints may occur in the form of shearing, bearing, and tensile depending on the plates' material and joint types [4,38,39]. In Figure 5, possible damage types in single-lap bolted joints are shown schematically. Bolt shear damage, which is one of the damages, is generally encountered in connections where high-strength

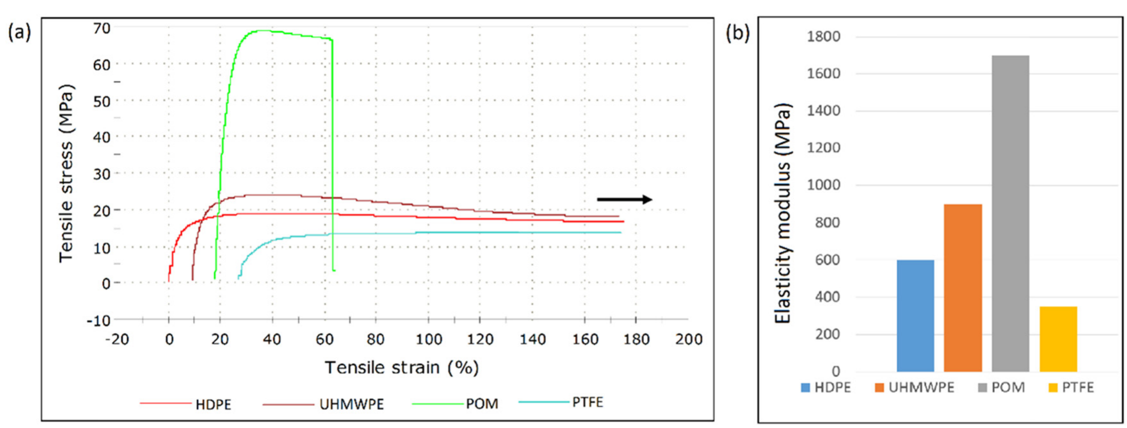


Figure 3: (a) Stress–strain curves and (b) elastic modulus of the materials.

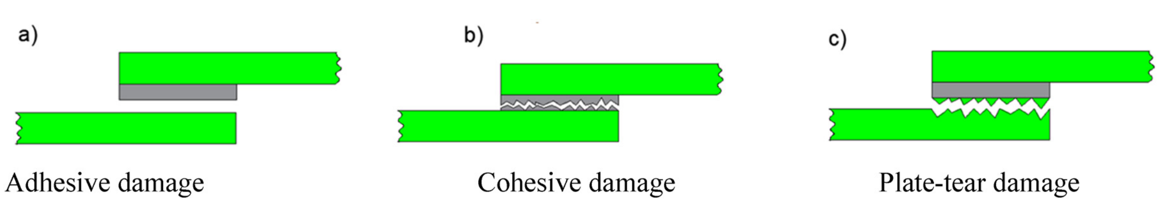
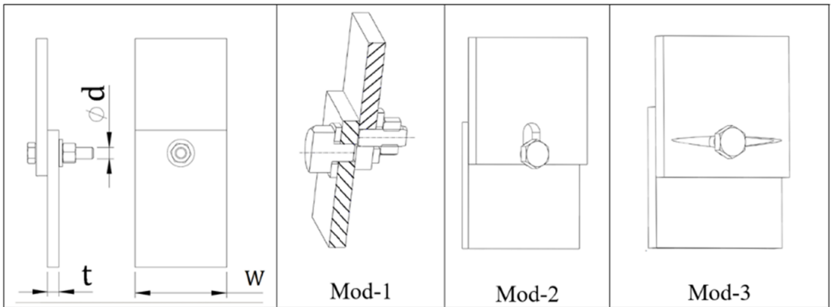


Figure 4: Damage types in single-lap joints: (a) adhesive damage, (b) cohesive damage, and (c) plate-tear damage.



	Mod-1	Mod-2	Mod-3
d: Bolt diameter **t:** Plate thickness **W:** Plate width	**Shear Stress**	**Compressive (Bearing) Stress**	**Tensile Stress (Net tension)**
A: Area under failure	$A_s = \frac{\pi . d^2}{4}$	$A_c = d.t$	$A_t = (W.t) - (d.t)$

Figure 5: Bolt joint failure modes.

plate materials are joined. This type of damage was not found in the engineering plastics tested in this study. In Mod-2, damage occurs due to the bearing stress caused by the compressive force exerted by the bolt on the plate. This type of damage is generally seen in soft materials with short single-lap lengths. It occurred in HDPE, UHMWPE, and PTFE plate specimens in this study. Finally, in Mod-3, tensile damage is seen due to the tensile load. This type of damage is observed in the double-bolted joints in POM plates.

3.1 Bolted/bonded (hybrid)

As an example, tensile tests and load–extension curves of specimens with POM-BA-60, UHMWPE-BBA-40, and HDPE-BA-60 configurations are given in Figure 6(a–c), respectively. All the bolted/bonded joints first suffered adhesive damage as shown in Figure 6(a). Large displacement curves were obtained as a result of the applied tensile loads. In bolted/bonded joints, the curves show linear behavior until the adhesive is damaged. Up to this point, it is thought that bonding forces dominate. After the adhesive is damaged, the plates begin to slide on each other, and in this region, friction forces come to the fore. Adhesion damage values on the bolted/bonded joints are given in Figure 6(a) for bolted/bonded (BA) and in Figure 6(b) for double-bolted/bonded (BBA) configuration.

Figure 7 shows the values where the adhesive is damaged in bolted/bonded joints. Adhesive damage of the double-bolted/bonded specimens occurred at relatively higher loading values when compared to the bolted/bonded specimens. When compared on a material basis, the bonding of Delrin (POM) materials showed the highest strength in the corresponding single-lap length, indicating that it bonded the best with the adhesive.

3.2 Bolt joints

3.2.1 Load transfer in bolted joint

In Figure 8, the forces acting on the plate are shown in the free body diagram created friction model. The applied force is first (initial stage) met by the friction force, and if the friction force is defeated, the plates begin to slide over each other, at this point the laminate friction changes from static to kinetic, and the friction magnitude begins to decrease. Also, during the slide, the frictional forces under the washer reach the maximum just before the bolt contacts the plate. The increase in frictional force between the washer and the plate is most likely due to the bolt being bent toward the hole and the washer widening the hole [40]. After the bolt is tipped over, the frictional force generated by the bolt in the axial direction has a very small component.

In the first stage of loading, the washers prevented the bolt rotation in the axial direction [14]. If the substrate materials are not rigid enough, in the late stage, as shown in Figure 9, the washers can widen the hole and cause the bolt to come out of the hole.

3.2.2 Failure modes

Fractured specimens were visually examined to determine the failure mode. Figure 10 shows the joint damage of the single-lap bolted specimens. Any shear load acting

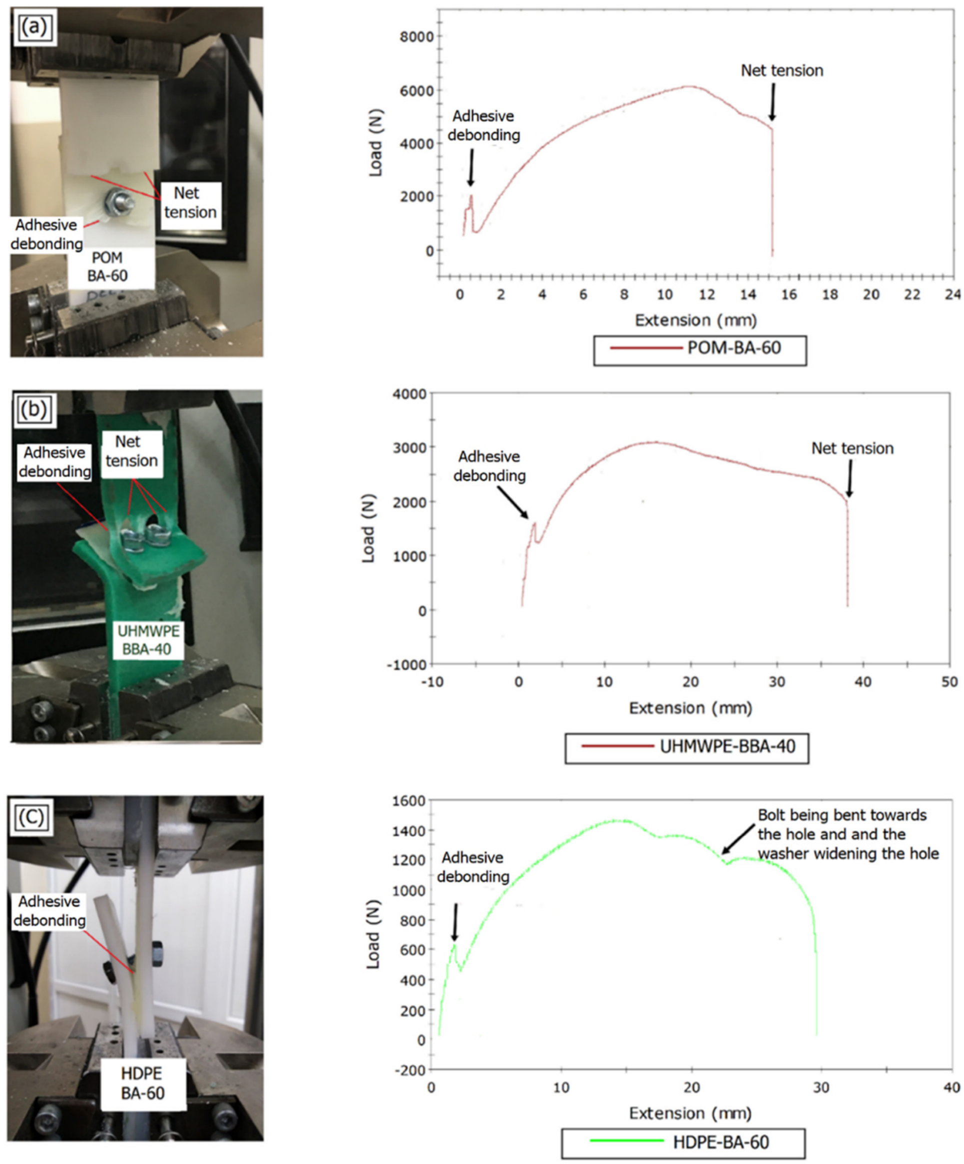


Figure 6: Tensile tests of specimens with bolted/bonded: (a) POM-BA-60, (b) UHMWPE-BBA-40, and (c) HDPE-BA-60.

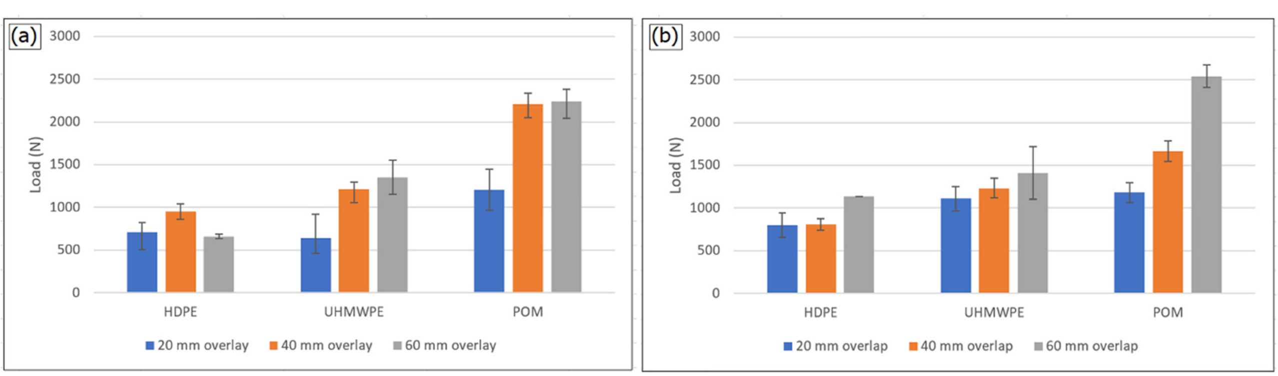


Figure 7: Adhesive damage loads of single-lap joints: (a) bolted/bonded (BA) and (b) double-bolted/bonded (BBA).

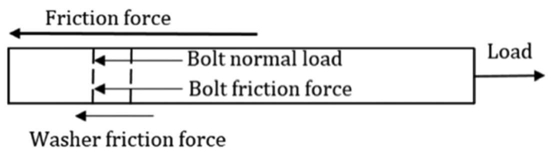


Figure 8: Force components on the specimen (initial stage).

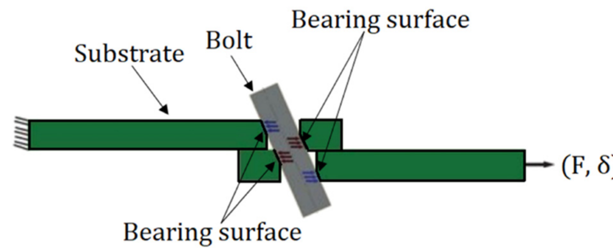


Figure 9: Force distribution of bearing surfaces during late stage.

on the bolts can cause axial loads on the bolt by moving the plates [41]. As a result of these loadings, bearing stress occurs between the bolt and the plates, and the material changes its shape, after this deformation the bolt head comes out of the plastic plate and the joint is separated. This type of joint damage is been observed in HDPE, UHMWPE, and PTFE specimens in single-bolt joints with the lap lengths of 40 and 60 mm. All the configurations of these specimens with a single bolt of 20 mm

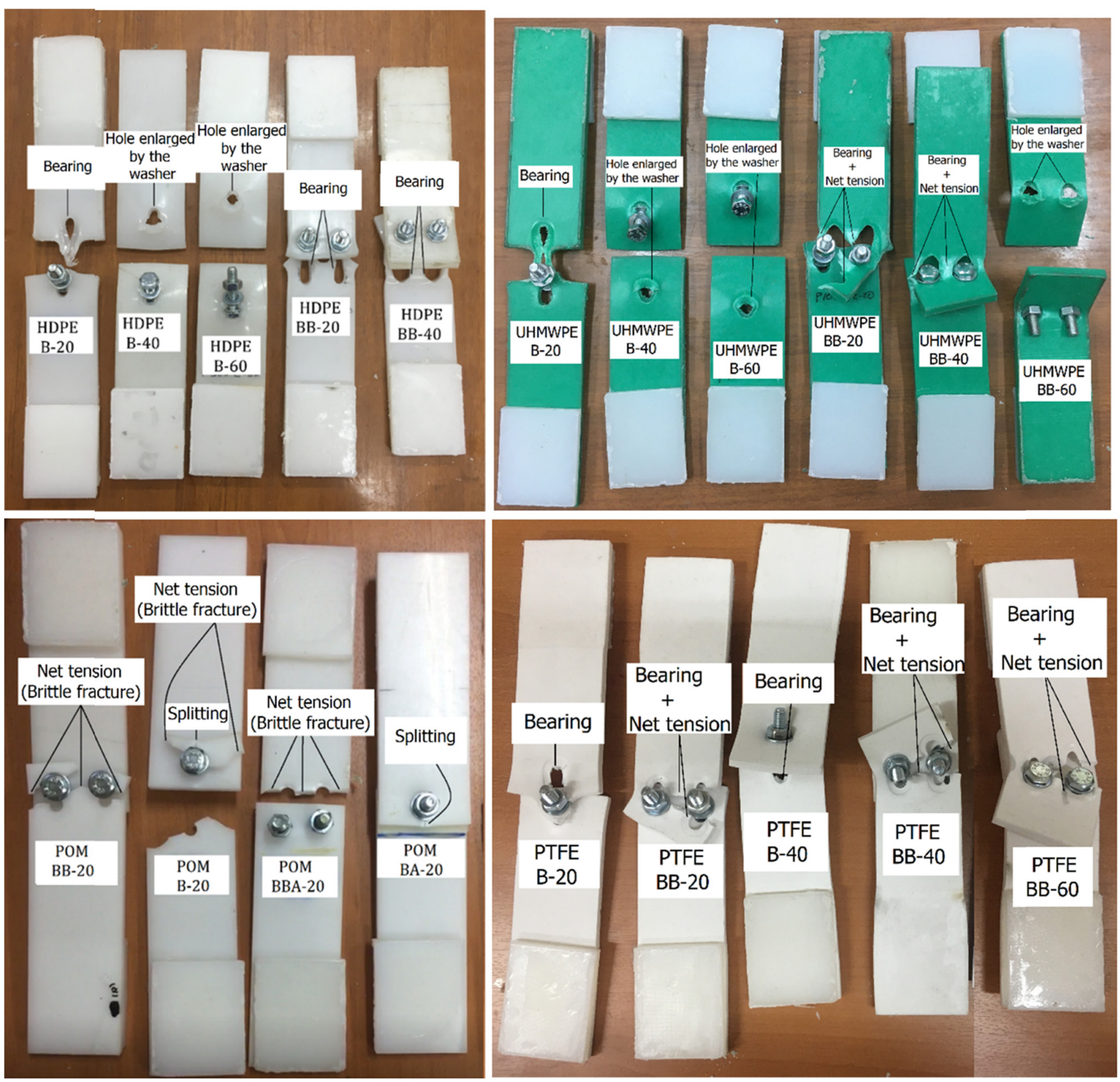


Figure 10: Experimental damage patterns of plates in the joints.

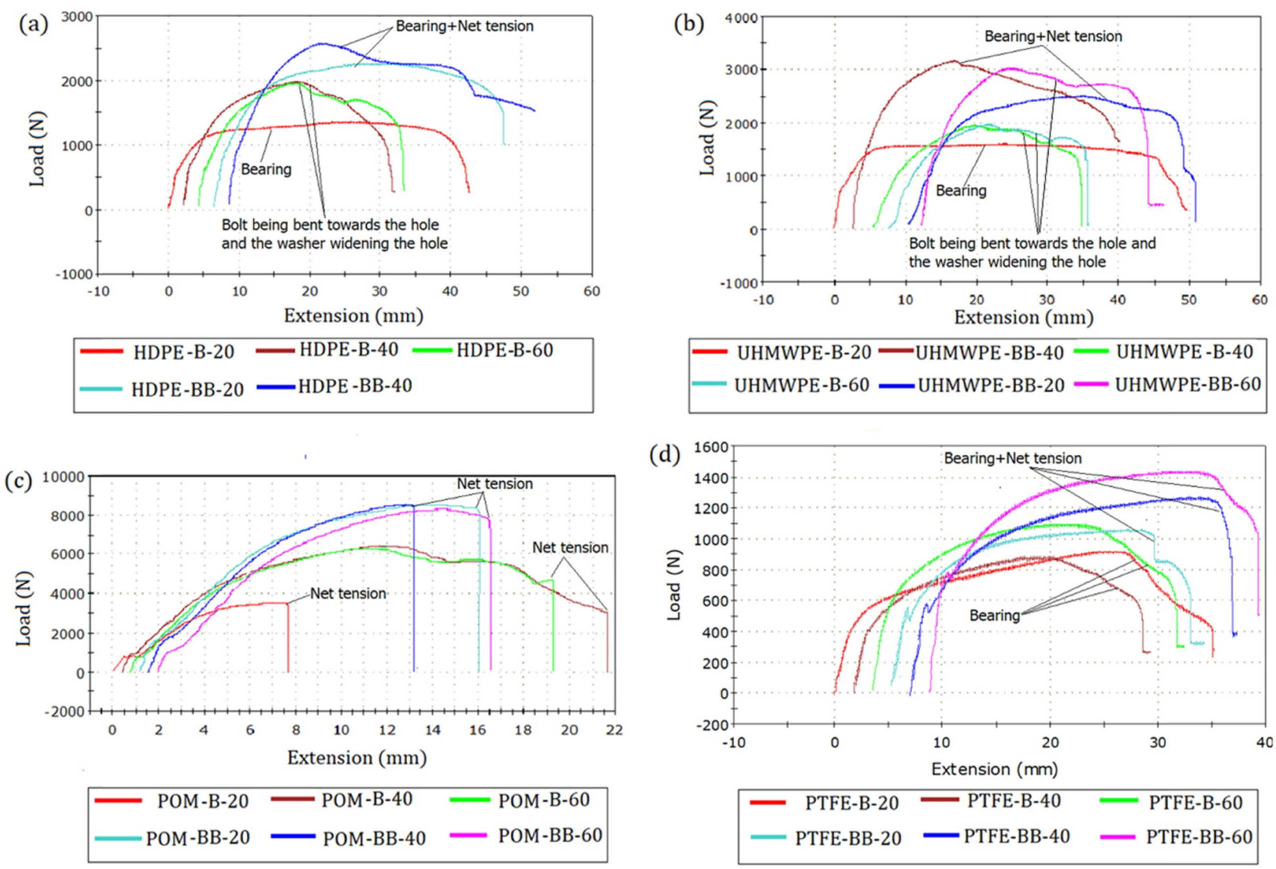


Figure 11: Load–extension curves: (a) HDPE, (b) UHMWPE, (c) POM, and (d) PTFE specimens.

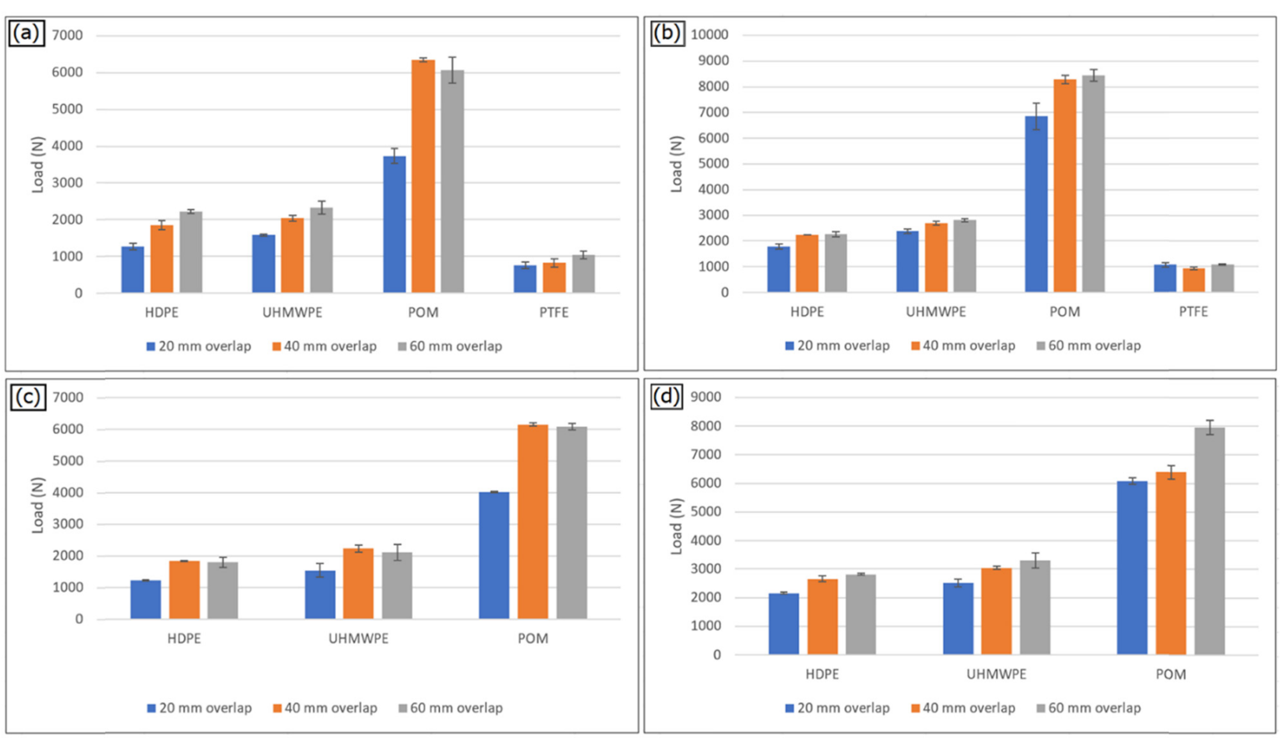


Figure 12: Ultimate load of single-lap joints: (a) single bolted (B), (b) double bolted (BB), (c) single bolted/bonded (BA), and (d) double bolted/bonded (BBA).

single-lap length (B-20 and BA-20) were damaged due to the bearing stress. On the other hand, in double-bolted configurations (BB and BBA) both bearing and tensile damages were seen together. Unlike these three plastics, the damage of POM specimens was in the form of brittle fracture as a result of sudden fragmentation. In the POM B-20 and POM-BA-20 configurations, a capillary crack occurred in the direction of the tensile axis before disintegration.

3.2.3 Load–extension curves and connection strengths

The load–extension curves of the connections consisting of HDPE, UHMWPE, POM, and PTFE specimens are given in Figure 11. It was seen from the load–extension curves of HDPE in Figure 11(a) that there was an increase in load values with a small elongation and after reaching the maximum strength value, the material began to flow and damage. In the last stage of the tensile curve, the material was damaged and becomes unable to bear the load. In Figure 11(b), load–extension curves of UHMWPE, which is another type of the same material, behaved similarly. However, UHMWPE specimens showed higher strength values than HDPE specimens. In Figure 11(c), the slope of the load–extension curves of the joints made of Delrin (POM) material obtained was lower than those of other materials until the load values in the curves reached maximum, and the specimens were damaged by breaking apart after the maximum load values. After the damage, the load curves suddenly continued straight down. In Figure 11(d), the load value increased rapidly in the first stage of the connections with Teflon (PTFE) material. In the next stage, the flow of the material accelerated and the rate of increase in the load value slowed down. In the last stage, damage occurred and the load carried by the material decreased to zero.

The ultimate load values of the connections are given in Figure 12(a–d). As can be seen from the figure, the strength values are, respectively, from the low through the high for PTFE, HDPE, UHMWPE, and POM specimens. It can be said that the increase in single-lap length provides a proportional increase in the strength of the double-bolted (BB) joints, excluding PTFE. The ultimate strengths of bonded and unbonded specimens are similar in both single-bolt joints and double-bolt joints.

4 Conclusions

In this study, joint failure mechanisms of single-lap bolted and bolted/bonded engineering plastics were investigated. Key observations from the research presented in this paper are as follows:

- When polymeric plates are compared among themselves, double-bolted Delrin (POM) specimens exhibited the highest joint strength in all single-lap lengths.
- Since Teflon (PTFE) plates are not suitable materials for bonding, only mechanical joints have been made. As a result of the experiments, these plates exhibited the lowest joint strength.
- As the overlap length increased, an increase was observed in the joint strength of the specimens in general. As the overlap length increased from 20 to 60 mm, the best results were observed in single-bolt configurations of HDPE specimens, with an approximate two-fold increase in joint strengths.
- In all the specimens, the adhered areas were separated as a result of adhesive damage.
- In both adhesive and bolt joint strengths, it is seen that the materials are in correlation with their tensile strength.
- In double-bolted Teflon (PTFE) connections, lap length variations did not have a significant effect on joint strength.

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Ethical approval: Ethical approval is not required, as the study was not performed *in vivo*.

Data availability statement: The processed data necessary to reproduce these findings are available upon request with permission.

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