Effects of Different Overlap Lengths and Composite Adherend Thicknesses on the Performance of Adhesively-Bonded Joints under Tensile and Bending Loadings

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Abstract: Fiber-reinforced polymer composites are being used in an increasingly wide range of products. They are particularly popular in automotive and aerospace sectors because they offer an attractive combination of stiffness, strength and low mass. Adhesively-bonded joints of such materials are preferred by many designers due to their assembling advantages over other traditional mechanical joining systems, such as bolted and riveted joints. In this study, some experimental works have been carried out on adhesively-bonded adherends manufactured from a woven carbon fiber-reinforced polymer matrix composite (Hexply 8552S/A280-5H, produced by Hexcel), by using a film adhesive (AF163-2K produced by 3M). The bonded specimens were prepared in the SLJ (single lap joint) configuration, and tested in tensile and also in four-point bending loading. In order to assess the joint performance, three different overlap lengths, 15 mm, 25 mm and 40 mm, and two different thicknesses of the composite adherends, 2 mm and 3 mm, were used. The results showed that the parameters are controlled by the loading modes; while the overlap length increases the joint performance significantly in tensile loading, the opposite was the case for those in bending loading, which was affected mainly by the adherend thicknesses. The results were related to the mechanisms of joint failures; while the joints in the tensile failed in the adhesive layer with some exceptions, those in the bending mainly failed in the plies adjacent to the layer. The current study indicates that one of the important factors affecting the joint strength of the adherends manufactured from the laminated composites is the local failure of the plies. It is thought more focused-studies would be needed to lessen such problems, which would be possible via in-depth numerical analysis.

Key words: Adhesive joints, composite adherends, overlap length, adherend thickness.

1. Introduction

In today's modern automotive and aerospace applications, the materials offering an attractive combination of stiffness, strength and low mass are the main point of interest for many engineers and scientists. In general, the materials with high strength-to-weight ratio, design flexibility, high impact and fatigue resistance are demanded by these applications, and these requirements are mostly met by fiber-reinforced polymer matrix composite materials [1, 2]. Assembling such materials is a challenging subject for the designers of the relevant sectors. Some traditional joining methods such as bolted or riveted joints have been used for many years [3, 4], however, it has been revealed that the hole existence in the composite adherends is the cause of the main stress concentrations leading to a poor joint performance. On the other hand, adhesively-bonded joints of such materials are found to have some advantages over the traditional joining methods, as they provide relatively uniform stress distributions and continuity in the bonded region, resulting in relatively higher joint performance [5].

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It is known that there are many parameters such as composite bonding methods, surface preparation, mechanical properties of adherends and adhesives, geometrical parameters (adhesive and adherend thickness, overlap length, stacking sequence, ply angle, fillet etc.) affecting the strength of the bonded joints, which have been reviewed in detail [6]. For example, the effects of the bonding methods between the co-cured joint and the secondary bonded joint method under mode I (opening) and mixed-mode loading were investigated by Mohan et al. [7, 8], and it was found that the co-cured bonded joints showed lower strength than the secondary bonded joints in both loading conditions. Similar results were supported by another work [9]. To protect the bonded region from all contaminants such as lubricants, dusts, and micro-organisms, the surface preparation of the adherends is vital for a good joint performance. There are many works on this subject recommending different surface preparations including chemical and physical treatments for a good surface wettability, surface energy, good activation of material surfaces to be bonded [10, 11]. It is found that peel ply is one of the techniques being able to protect the surface from the contamination and also to maintain the specific surface texture [12, 13]. Related to the effects of the adhesive layer, some experimental works [14, 15] have been conducted on the bonded joints, and the results have shown that the joint strength decreases as the adhesive thickness increases, which is supported by some numerical works as well [16, 17]. In designing bonded joints, a uniform stress distribution is desired, however, this is not the case for many reasons; for example, some stress concentrations occur due to applied load eccentricity, different ratio of adherend/adhesive elastic constants and geometric discontinuity etc. Remedies to these problems have been proposed by some researchers using different techniques [18-21]. It is important to note that a laminate with different angles of fiber orientations has also a significant effect on the joint performance. It was found that a ply with relatively small fiber angles results in relatively higher load bearing capacity [22]. Another important parameter affecting the joint performance is different overlap lengths. Works carried out have shown that increase in overlap length results in increase of joint performance, in general, depending on mechanical behavior of adhesive used and fiber angles of plies [23, 24]. One of the most important enemies of the adhesive joints is the degradation effects of environmental conditions such as moisture, temperature and ultra violet radiation, which have been studied by some researchers [25-28].

As mentioned above, many efforts have made to investigate shear performance of adhesives in the SLJ (single lap joint) configuration in tensile loading. However, it is believed that the adhesive joints are subjected to tensile as well as bending loading during their service life, and so it is worth investigating these two loading modes simultaneously. The aim of this works is to investigate the performance of adhesively-bonded joints using the adherends manufactured from a woven carbon fiber-reinforced polymer matrix prepreg, and an adhesive film. The joints in single lap configuration were subjected to tensile loading for their shear performance, and to four-point bending loading for their pure bending performance. While the thickness of the adhesive layer was kept constant, 0.2 mm, two different thicknesses of adherends, 2 mm and 3 mm, and three different overlap lengths, 15 mm, 25 mm and 40 mm, were used as parameters to assess their effects on the joint performance. For the current experimental work, a special consideration was also given to failure modes and also failure mechanisms to gain an in-depth insight into the joint behavior, which will help to model the joint configuration by conducting a numerical analysis, to be conducted later on.

2. Experimental Works

The materials used in this study are an adhesive film, AF163-2K (TM) produced by 3M, and

adherends manufactured from a prepreg of woven carbon fiber-reinforced epoxy matrix composite, Hexply 8552S/A280-5H, produced by Hexcel. While the adhesive used was cured at 125 °C for 60 min under a pressure of 2 bars, the cure procedure for the prepreg of the composite adherends was 120 °C for 120 min, after an initial heating-up procedure of 80 °C for 90 min under a pressure of 5 bars. The adherends were manufactured from the plates of the cured prepregs, and machined to the required dimensions. The joints were bonded in a specially designed mould in which the specimens were allowed to be manufactured with different adherend thicknesses and different overlap lengths. For the study, while the thickness of the adhesive layer was kept constant, 0.2 mm, two different thicknesses of adherends were used, 2 mm and 3 mm, to be able to assess the effects of different adherend thicknesses on the joint performance in tensile and bending loadings. Three different overlap lengths, 15 mm, 25 mm and 40 mm, were also tested for the same purpose. Geometrical details of the SLJ specimens tested are shown in Fig. 1, prepared according to the ASTM1002 standard specifications. Surface preparation of the adherends to be bonded was made using peel-ply removal as the sole surface preparation technique, and all the specimens were tested at 23 °C room temperature and 50% relative humidity, to avoid effects of different environmental conditions. Four different samples of joints were tested for each type to see if the results are repeatable.

Some of the mechanical properties of the adherend and the adhesive film are shown in Table 1, where σ and E and v are the tensile stress, Young's modulus and Piossion's ratio of the materials used, and where subscripts 11 and 22 are related to the coordinate system in x and y directions, respectively.

3. Results and Discussions

Figs. 2a and 2b show the typical curves of load against crosshead displacement of the joints with the 2 mm and 3 mm adherend thicknesses, respectively, for different overlap lengths under the tensile loading. The curves show that increasing the overlap lengths results in an increase in the displacements, which is an indication of the high energy stored within the samples. The failure load against the overlap length is shown in Fig. 3a for the both adherend thicknesses. The figure shows that there is generally a linear relationship between the failure load and the overlap length, and that the effect of the different adherend thicknesses on the failure load is not important. However, samples with 40 mm of 3 mm adherend thickness gave less failure load compared to those with the 2 mm thickness. While the minimum failure load is about 10 kN for the joints with 15 mm overlap
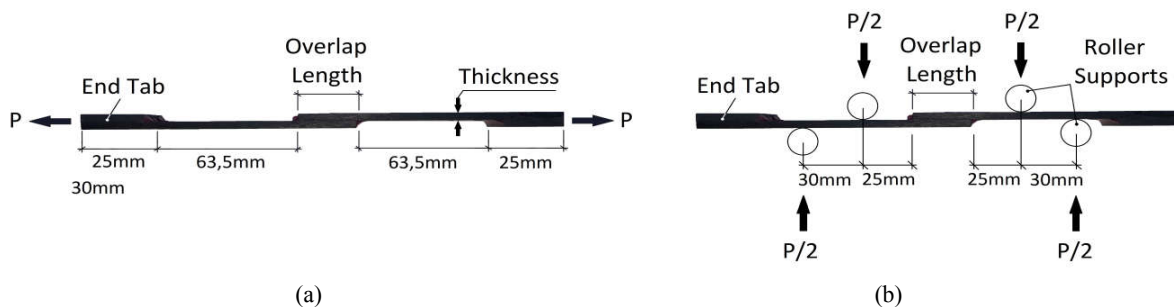

(a)   (b)

Fig. 1   Dimensions of the SLJ configuration in (a) tensile and (b) bending loading.

Table 1   Mechanical properties of the materials used for the adhesively-bonded joints.

Adherend	σ_{11} (MPa)	σ_{22} (MPa)	E_{11} (MPa)	E_{22} (MPa)
	850	850	65,000	65,000

Adhesive	σ (MPa)	E (MPa)	v	
	48	1,800	0.3	

(a)   (b)
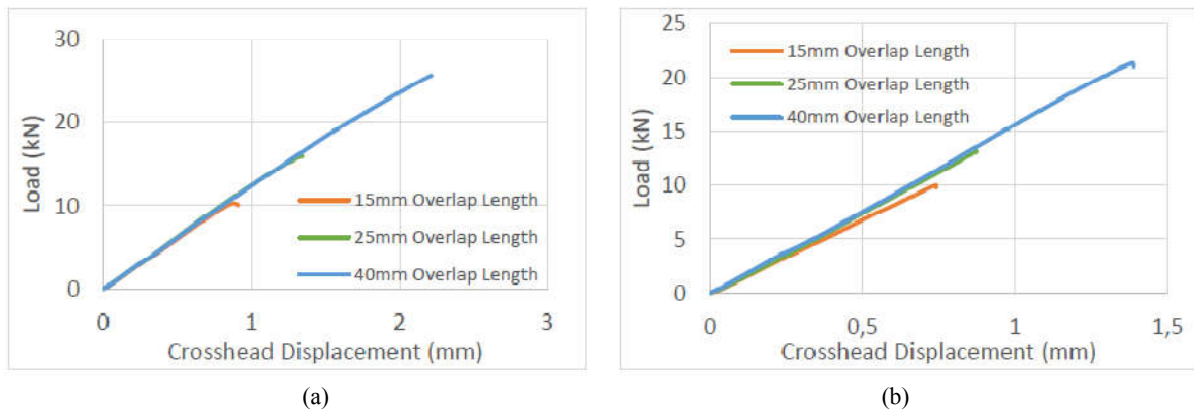
Fig. 2   Plots of load against crosshead displacement for the SLJ specimens in tensile loading, for the adherends with (a) 2 mm and (b) 3 mm thicknesses.
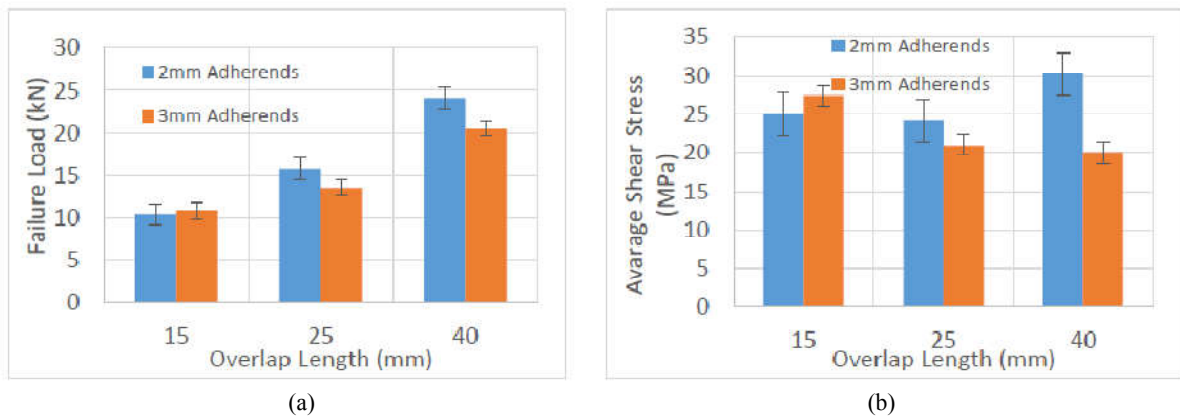

(a)   (b)

Fig. 3   (a) Failure load against overlap length and; (b) average shear stress against overlap length for the SLJ in tensile loading.

length, the maximum value is about 24 kN for those with the 40 mm, and the failure load for the 25 mm overlap length is about 15 kN. The plot of average shear stress against the overlap length is presented in Fig. 3b. The joints with adherend thickness of 2 mm and 3 mm showed a stress value of 20 MPa and 30 MPa respectively. It is seen that the joints with 2 mm adherend thickness shows generally higher shear stress values compared to those with the 3 mm, which is thought to be because of the load eccentricity being large for the thicker adherends. For the tensile shear test, all the specimens with 15 mm and 25 mm overlap lengths showed a cohesive surface failure (the failure within the adhesive layer (see Fig. 4a), whereas those with 40 mm overlap lengths, under high failure loads, experienced a mixed failure, failure of plies adjacent to the adhesive layer as well as failure of adhesive

layer itself (see Fig. 4b). In this situation, more damage of the plies was the case for the joints with the 3 mm, compared to those with the 2 mm. It was clear that the joints with the higher adherend thickness experienced more peel effects at the ends of the overlap length, due to applied load eccentricity, which could be the cause of the more plies damage. The stress concentrations (peel effects) at the end of the overlap have been studied in a previous numerical work [22], which shows the stress distribution in adhesive layer in SLJ configuration is not uniform.

For all the joints with 15 mm and 25 mm overlap lengths, the surface showed nearly the same failure as presented in Fig. 4a. In this case, no initial failure of the adherends was observed and the failure mechanism was reasonably symmetric. Stress concentrations due to the peel effects were clear at the

ends of the overlap, which was before a catastrophic failure, coincided in the middle of the joint. For the joints with 40 mm overlap length, the joint failure was not only controlled by the adhesive but also accompanied by the failure of plies adjacent to the layer (see Fig. 4b).

Some representative curves of bending load against crosshead displacement for the joints with 2 mm and 3 mm adherend thicknesses are shown in Figs. 5a and 5b, respectively. From the curves, it is seen that increasing overlap length does not results in a significance increase in the failure load and crosshead displacement; while all the joints with 2 mm adherend thicknesses fail about 1,000 N, those with the 3 mm fail around 2,000 N, implying an increase of 100% for the thicker adherends. This is considered to be due to the relatively small deflection of the thick adherends experiencing under the bending, compared to the thin ones, which is believed to have important effects on the stress concentrations at the edges of the overlap length, the main cause of failure initiation. Figs. 6a and 6b show the plot of the bending failure load and the bending moment against the overlap length, respectively, which indicate the values from the thick adherends double compared to the thin ones, which is again related to the adherend deflections under the bending.

In all cases, the adherends used in bending loading experienced plies failures adjacent to the adhesive layer, and no failure was witnessed in the adhesive
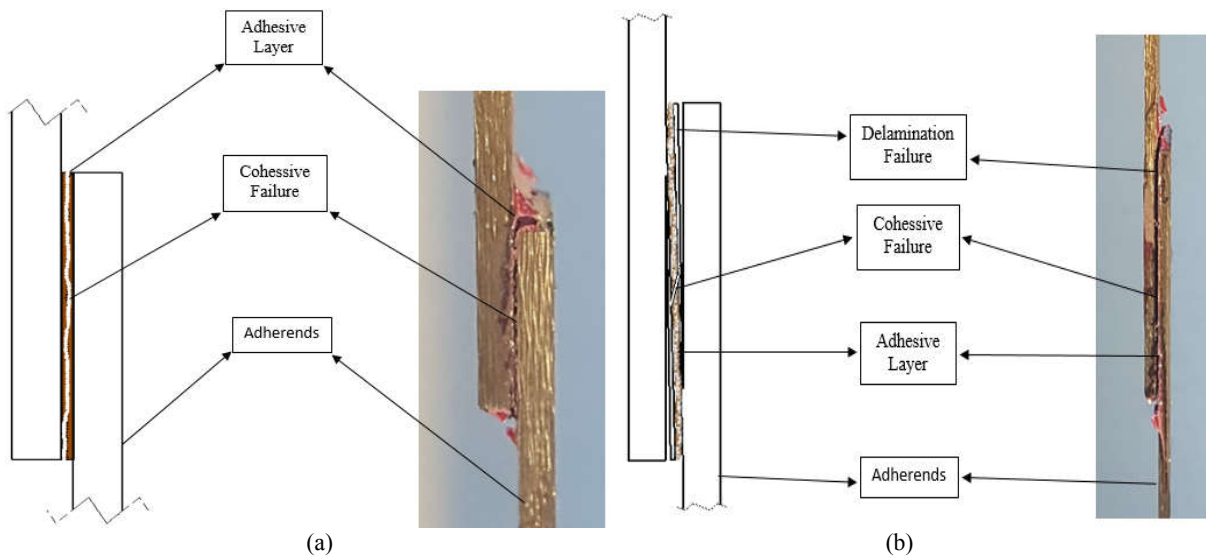

(a)   (b)

Fig. 4   Failure mechanisms for the SLJ in tensile loading, (a) cohesive failure and (b) mix failure.

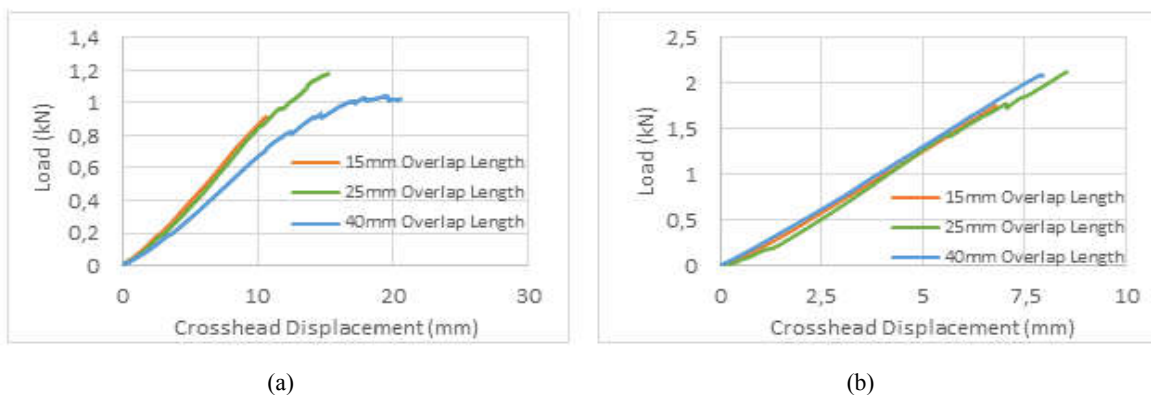(a)   (b)

Fig. 5   Plots of load against crosshead displacement for the SLJ specimens in bending loading, for the adherends with (a) 2 mm and (b) 3 mm thicknesses.
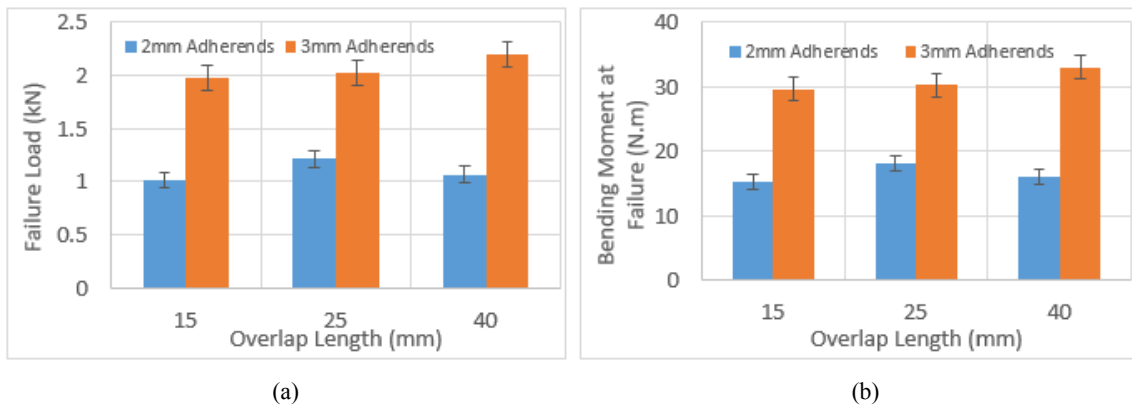
(a)   (b)

Fig. 6   **(a) Failure load against overlap length and; (b) Bending moment against overlap length for the SLJ in bending loading.**
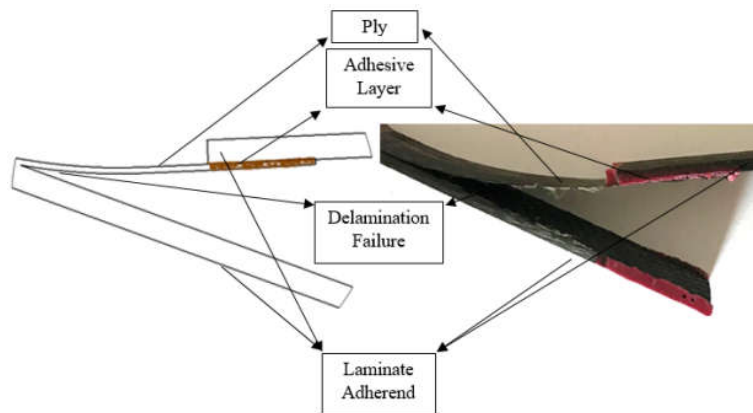

Fig. 7   **Failure mechanisms for the SLJ in bending loading.**

layer during the test. As can be seen from Fig. 1b, one end of the overlap region is in tension (right side) while the other end is in compression (left side), which are the possible points where the failure may initiate. As far as the critical points at the overlap edges are concerned, the failure should be expected at the side in tension since polymers are always stronger in compression rather than in tension [5], which was exactly the case for all the joints in bending loading; it was clear that initial failure started at the edge in tension and then propagated towards the edge in compression, resulting in a delamination failure of plies of the composite laminates (adherends) (see Fig. 7). It should be noted that the peel stress in the laminated composite is mainly controlled by the matrix (polymer) part of the material, rather than the fibers.

4. Conclusions

It has been shown that the joints with three different overlap lengths, and two different thicknesses of adherends manufactured from a woven carbon fiber-reinforced polymer matrix composite had different mechanical performance depending on the loading modes, tensile and bending; for the tensile loading case, increase in the overlap length resulted in increase in the joint performance almost linearly, except those with 40 mm overlap length of 3 mm adherend thickness, which had low strength. The decisive parameter was the change in the overlap lengths, in general, other than adherend thickness for this loading mode. However, for the joints under four-point bending, the decisive parameter was the adherend thickness rather than the overlap length, and

the thick adherends contributed to the performance around 100% increase, compared to the thin ones. There are mainly two different failure mechanisms for the tensile loading case; a failure in the adhesive layer resulting in cohesive failure, and a mix failure, partly the adhesive layer and also the plies for those with 40 mm overlap length. For the bending loading case, all the failures occurred in the piles adjacent to the adhesive layer. A detailed numerical analysis would help explain this phenomenon.

Acknowledgments

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