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Experimental and numerical investigation into strength of bolted, bonded and hybrid single lap joints: Effects of adherend material type and thickness

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ABSTRACT

In line with the developments in advanced engineering applications such as aerospace and automotive industries, the techniques of joining similar and dissimilar materials have become a crucial issue, i.e. the need for a stronger joint has significantly grown. Compared to conventionally used bolted, riveted and pinned joints, adhesively bonded joints have been increasingly used due to its improved fatigue life and damage tolerance and lower structural weight, especially the case when relatively thin adherends are used. Alternatively, hybrid joints, combination of two or more joining techniques, are presently investigated to create a joint with higher strength than those gained from one technique. In this study, we compared mechanical performance of bolted, bonded and hybrid single lap joints subjected to the tensile loading using three different adherend thicknesses and two different adherend materials with different mechanical behaviors, such as yield and tensile strength and ductility. To this end, a combined experimental and numerical study was performed. In finite element simulations, cohesive zone, ductile and shear damage models were used to model the damage initiation and evolution for the adhesive film layer (AF163-2K), aluminium adherend (AL6061 and AL7075) and the steel bolt materials, respectively. Force displacement curves, the amount of energy absorbed and failure history for each configuration tested, were analysed extensively to elucidate the strength of various joints.

1. Introduction

Mechanically fastened systems such as bolted, riveted and pinned joints, are preferred for assembling materials used in aerospace, marine, civil and automotive applications as they are still a well-proven joining methods. On the other hand, adhesively-bonded single lap joints (ADJ) have been increasingly used especially in the aerospace industry as they offer more uniform distribution of stresses in the joining region, improved fatigue life, lower structural weight, prevention or reduction of corrosion between dissimilar materials [1]. Adhesive bonding also offers great advantages to overcome the problems in spot-welding applications in which accessing to both sides of the joint is difficult, also some materials such as aluminium and composites can not be joined effectively [2]. On the other hand, the bonded joints have their inherent disadvantages: they cannot be disassembled without damage, very sensitive to environmental factors like humidity and temperature, uncertainty regarding their long-term structural integrity and tend to fail instantaneously, but not progressively. To overcome the potential drawback of the adhesive bonding, mechanical fastening is added to the bonded joint, called as the hybrid joint (HJ).

The knowledge on HJ configuration in practice requires extensive research to reach the same level of knowledge as compared to bonded or bolted joint (BJ) configurations. Hartman [3] demonstrated that the HJ of similar aluminium adherends showed superior fatigue performance than bolted joints. Even if the adhesive layer failed, the fasteners in HJ could ensure the functioning of the assembly. Later, the study of the Hart-Smith [4] revealed that the HJ with fibrous composite structures did not offer any significant increase in strength compared to bonded joints, which could be explained by the low fraction of load transferred by the fasteners. Studies in [5–11] demonstrated that the strength of HJ was higher than the BJ or the ADJ alone. Kelly [5] investigated the strength and fatigue life of the joints using carbon-fibre reinforced plastic adherends. The HJ proved to have higher joint strength and extended fatigue life compared to the ADJ when a flexible polyurethane adhesive was used. However, the HJ in combination with a stiff epoxy adhesive offered only limited improvements in structural performance. Similar conclusions were obtained for different adherends and HJ configurations in [9–13]. The selection of the adhesive material played a key role in the static and fatigue performance of the HJ. Fu and Mallick [8] found that the performance of HJs was sensitive to the

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washer configuration and for larger washer areas, greater strength and fatigue life were obtained. The propagation rate of fatigue cracks was reduced in HJ when compared to the ADJ. Lee et al. [14] tested various HJ specimens with different width-to-bolt diameter (w/d) ratios and edge-to-bolt diameter (e/d) ratios. It was observed that the failure loads of the HJ with a w/d ratio of 2.8 were higher than those of the adhesive joints with e/d ratios larger than 2 and lower than those of the adhesive joints with e/d ratios lower than 2. In another study, Imanaka et al. [9] observed that the fatigue strength of the joints increased with a decrease in the ratio of its width to hole diameter. Tan [15] investigated the efficiency of the hybrid single lap joint of unidirectional prepregs with two/four bolts and FM400-adhesive and concluded that the number of bolts influenced the load required to debond the adhesive material. Moroni et al. [16] carried out an experimental study to compare simple and HJ also accounting for environmental variables. It was observed that weld–bonded HJs led an increase in strength, stiffness and energy absorption in comparison with simple spot welded, and a strong reduction of dependence from temperature and ageing with respect to bonded joints was reported. Steward [17] tested single lap hybrid joints used for repairs and concluded that the HJ was 50% stronger than the BJ and 16% stronger than the ADJ.

Overall, it has been found that the strength of the HJ is higher than the BJ or the ADJ alone. For the optimized joining techniques enabling the highly integrated structures, the influencing parameters for their performance need to be determined. However, in none of the above studies, the effect of different adherend thicknesses and the adherend materials as potential affecting parameters on the static strength of the HJ, w.r.t. the BJ and the ADJ, was investigated at the same time both experimentally and numerically. To this end, a series of experiments as a combination of three different thickness (2 mm, 4 mm and 6 mm) of two different adherends (Al7075 and Al6061), assembled through BJ, ADJ and HJ subjected to the tensile loading was performed. To obtain an in-depth understanding of the joint behaviour including failure modes, also, numerical analyses were carried out using ABAQUS/Explicit finite element program. Since aluminium adherends have different mechanical behaviours with different yield strengths, maximum tensile strengths and ductility values, their different responses under loading give us the opportunity to explore the deformation mechanism with underlying physics of different joints.

This work is laid out as follows: Description of the materials used in the experiments is given in Section 2. Relevant experimental studies are presented in Section 3. Section 4 describes first the details of developed finite-element model, then the theoretical description of the cohesive zone model, ductile and shear damage models was given. In Section 5 we present validation of numerical model developed against experimental data with the discussion of critical results. The paper ends with some concluding remarks in Section 6.

2. Materials

Tensile tests were carried out with a Besmak BMT-S 100kN universal test machine to characterize the elastic, plastic and failure response of the adherend materials, AL6061 and AL7075, and the adhesive film (AF163-2K), a knit film made of thermosetting modified epoxy produced by 3 M Scotch-Weld™, used in this study. Tensile test specimens with the geometrical details presented in Fig. 1 were elongated with a cross-head speed of 2.0 mm/min. The bulk adhesive formed by putting twenty adhesive film layers on top of each other was cured for 60 minutes at a temperature of 125 °C with a pressure of around 2 bar as the supplier recommended. Then, the bulk adhesive was cut into the tensile test samples. 4 specimens of each material were tested. The axial extensometer mounted on the test section of the specimen was used to make accurate measurements of the strain in the specimen. Their representative engineering stress-strain curves are shown in Figs. 2 and 3. The obtained elastic properties with their standard deviations are shown in Table 1. Yield strength and ultimate tensile strength of the steel bolt (M6 × 30 grade 8.8) are 640 MPa and 800 MPa, respectively.

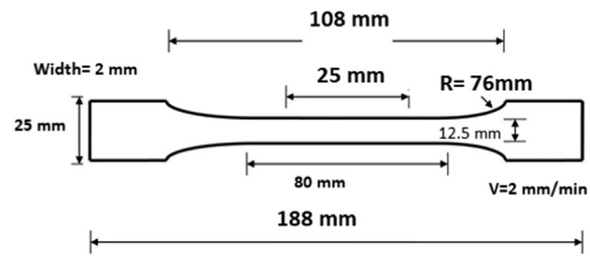

Fig. 1. Geometrical details of tensile test specimens for the aluminium adherends and the adhesive material.

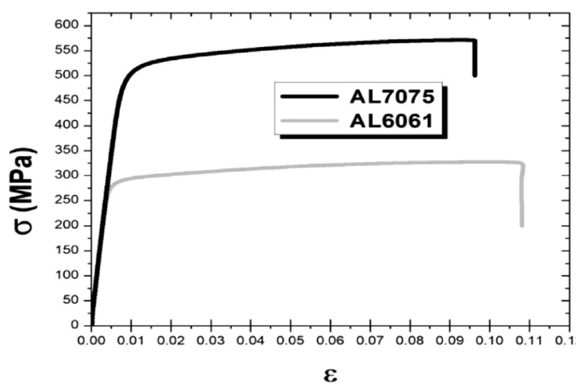

Fig. 2. Engineering stress-strain curves for the AL6061 and AL7075 adherends.

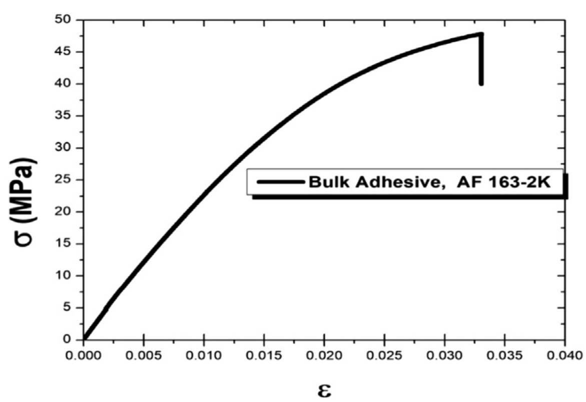

Fig. 3. Engineering tensile stress-strain curve for the adhesive film (AF163-2K).

Table 1
Elastic properties of materials.

	E (GPa)	*υ*
AL6061	68.9 ± 1.15	0.33
AL7075	71.7 ± 0.96	0.33
Steel bolt	210 [1]	0.3 [1]
	E (GPa)	***G*** (GPa)
AF163-2K	1.911 ± 0.131	0.505 ± 0.0083

3. Experimental work

In the experiments, three different thickness of the adherends, 2 mm, 4 mm and 6 mm, were used. The thickness of the adhesive layer was adjusted to being constant with a value of 0.2 mm using teflon shims in the free length of the joint. The joints were produced using the same adhesive film and adherends, with the same procedure explained