DAMAGE-COUPLED MODELING FOR THE JOINING PROCESSES ANALYSIS OF COMPOSITE-TO-METAL JOINTS

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Abstract

In this study, experimental and FEA techniques are used for investigating the load transfer capacity and associated failure modes in single-lap composite-to-metal joints. Three joining processes are evaluated in terms of their individual effect on the load transfer capacity of test joints; namely, bonding-only, bolting-only, and hybrid bonding-and-bolting. Material combinations include composite, aluminum, and magnesium coupons. Damage-coupled law, and cohesive zone model are respectively used for modeling. Results suggest that the load carrying capacity is largely dependent on overall joint stiffness. The failure mode is fairly consistent for bonded-only and bolted-only joints, but widely varies for hybrid bonded-and-bolted joints. This work provides an insight into the selection process of suitable joint materials and the matching joining process that would optimize the load transfer capacity.

1. Intorduction

Fiber reinforced composite material has been increasingly used in many mechanical and structural applications. Due to their low specific stiffness, the composite materials are often used in conjunction with metals in the form of sandwiched structures. When threaded fasteners are used for joining composite and metallic parts, the bolt hole often results in the cutting of fibers and the introduction of stress concentrations. By contrast, a bonded-only joint is more continuous and has many potential advantages. This includes better strength-to-weight ratio, more even stress distribution, eliminating the corrosion associated with dissimilar metal joining, and increasing the resistance to impact and fatigue loads. However, bonded-only joint may not sufficiently strong in some critical applications where a fail-safe mechanism is necessary. A hybrid bonding-and-bolting joining method provides such fail-safe-option.

Hybrid joining is found to be beneficial for repairing damaged bonded joints and limiting damage propagation. It was previously presented as a relevant concept of fail-safe mechanism for structures. Hart-Smith[1-2] conducted theoretical investigation of hybrid stepped lap joints and found that there was no significant strength benefit over perfectly bonded joints. Also, it is found that under room temperature and ambient humidity condition, 98% of the applied load was predicted to be transferred by the adhesive, bolt do not take an active role in load transfer [3]. However, with the increasing of external loading, bolt becomes increasingly important [4-5]. There is a need for accurate stress analysis of bolted-bonded structure.

Considerable improvement in the design of adequately strong hybrid joints can be achieved with the knowledge of the accurate stress distributions in these joints. In the past several decades a great many of researches have been carried out in the area of analysis and design of composite bonded or bolted joints. The subject of interest ranges from strength prediction of bolted-bonded composite joints using classical analysis approach [1-2, 6-11, etc.] to the finite element analysis [12-15, etc.]. With accurate stress prediction, the failure analysis of hybrid joints could become realistic. In order to determine whether the presence of the bolt affected the initiation of fatigue damage in bolted joints, Kelly [16] studied the static strength, failure mechanisms and fatigue resistance of hybrid joints, Paroissien et al. [17-18] recently developed analytical 1D [17] and 2D [18] models, which allow them to investigate balanced single-lap joints with elastic material systems. Nassar [19-20] introduced damage initiation and propagation laws for the failure analysis of bonded joint, and latter applied to the analysis of hybrid joining of dissimilar materials [4-5].

As a continuation of the previous studies [4-5], the present paper addresses the stiffness, load carrying capacity, static strength, and failure mechanisms of the various joints including bolted joint, bonded joint, and hybrid bonding and bolting of composite-to-metals, such as composite-to-aluminum (Comp-Al) and composite-to-magnesium (Comp-Mg). Test results are compared with FEA simulation performed using ABAQUS, the objective of this study is to help design engineers in the process of selecting best strategy for joining different materials.

2. Methodology

Two methods were adopted to characterize the load transfer in the hybrid joints; namely, numerical simulation using the finite element (FEA), and experimental methods. In the FEA model, the interfacial behavior is simulated using cohesive zone model. Both adherends (Al 6061-T6 and AZ31B), are modeled, however, using the damage-coupled power law constitutive relation with different parameters (*E*, *K*, *n*) as follows

$$\bar{\varepsilon}_{eq} = \frac{\bar{\sigma}_{eq}}{E} + \left(\frac{\bar{\sigma}_{eq}}{K}\right)^{\frac{1}{n}} \quad (1)$$

where $\bar{\varepsilon}_{eq}$ is the effective Von Mises strain. The effective Von Mises stress $\bar{\sigma}_{eq}$ (for two-dimensional problems) is correlated to Von Mises Cauchy stress σ_{eq} via damage variable *D* as

$$\bar{\sigma}_{eq} = \frac{\sigma_{eq}}{1-D} \quad (2)$$

Obviously, $\sigma_{eq} = \sigma$ for a one-dimensional case (1-D). For three dimensional problems, the equivalent of Eq.(2) would be $\sigma_{eq} = \sqrt{\frac{3}{2}(\sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij})(\sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij})}$, where $\delta_{ij} = 1$ for $i = j$, and $\delta_{ij} = 0$ for $i \neq j$.

A phenomenological model is presented for predicting the onset of damage due to void nucleation, growth, and coalescence of voids as follows

$$w = \int \frac{d\bar{\varepsilon}_p}{\bar{\varepsilon}_D} \geq 1 \tag{3}$$

where $\bar{\varepsilon}_p$ is equivalent plastic strain, $\bar{\varepsilon}_D$ is the equivalent plastic strain at the onset of damage, and w is the damage initiation indicator. After initiation, the evolution of damage is assumed to be related to equivalent plastic displacement as

$$\dot{D} = f\left(\dot{\bar{u}}_p\right) \tag{4}$$

where $\dot{\bar{u}}_p$ is the equivalent plastic displacement rate, which is equal to $L_c\dot{\bar{\varepsilon}}_p$, and L_c is the characteristic length. A simple approximation is $f\left(\dot{\bar{u}}_p\right) = \dot{\bar{u}}_p$. Failure of adhesive material happens when $D \geq D_c$. Both the adhesive and adherends are assumed to follow the above damage model; with applicable material parameters such as $\bar{\varepsilon}_D$ and L_c. All of the above mentioned material parameters are determined by bulk material tests in accordance with ASTM standards.

3. Experimental setup and test procedure

Materials under consideration include composite (Glass Epoxy G10), aluminum (Al 6061-T6), and magnesium (AZ31B): all in 1.524 mm thick sheets. Adherend materials are machined according to ASTM standard (D635-03, E8-04) for experimentally obtaining the bulk material properties; each test is repeated 5 times. The adhesive type used in this study is Loctite® E-20HP™ Hysol® Epoxy Structural Adhesive, which is applied to adherend surfaces after they have been and cleaned with acetone. Interfacial properties calibrated according to ASTM D5868-01 are also repeated for 5 times. Damage related parameters are obtained by fitting to the softening region of true stress-strain curves of each material.

To assess joining processes, samples with 25.4 mm x101.6 x 1.524 mm are used, for bolted joints, additional hole with R=6.35 mm and distance to three near edge of 6.35 mm is drilled. All adherends are machined to the displaced size. Joining processes consist of bolted-only, bonded-only and hybrid bonding-and-bolting with or without bolt preload exerted using torque wrench to target torque of 20 N.m. Material combinations include composite-to-aluminum (Comp-Al) and composite-to-magnesium (Comp-Mg) with overlap length of 25.4 mm. Bonding is prepared according to ASTM D2093-03; tests are performed on servo-hydraulic MTS test machine, and each case is repeated for at least 2 times.

4. Experimental results

In this section, experimental data is presented. Bulk material properties are experimentally determined following ASTM guidelines. Load-deformation curves are generated for bonded-only, bolted-only, and hybrid bonded-and-bolted joints made of various combinations of composite and metal coupons. The effect of bolt preload and the joining method are investigated.

4.1 Bulk material properties

Monotonic tensile curves are shown in Fig. 1 for Al6061-T6, AZ31B and Glass Epoxy G10, respectively. The curves for metals as shown in Fig. 1 exhibit elastoplastic behavior before damaging which indicate selection of power law model is reasonable. Since the G10 almost linearly correlated between stress and strain, a linear elastic material is thus sufficient.

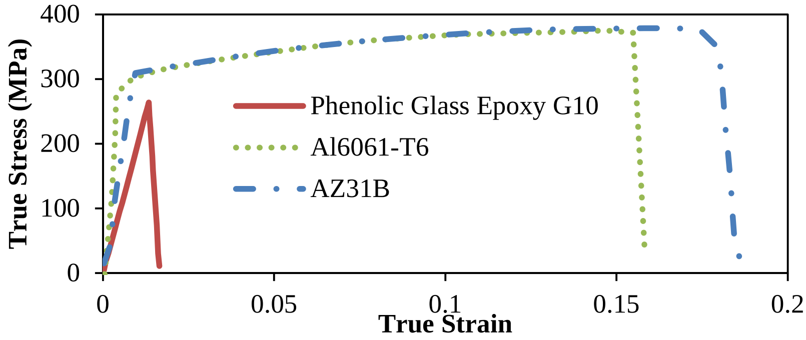

Fig. 1 True stress-strain relationship of each material

	Al 6061-T6	AZ31B	Glass Epoxy G10
E, K, n	68.9 GPa, 386 MPa, 0.07	45 GPa, 448 MPa, 0.08	20GPa,-, -
$\bar{\varepsilon}_D$, L_c, D_c	0.156, 0.35 mm,0.001357	0.17, 0.35 mm, 0.0094	0.01, 0.35 mm, 0.006

Table 1 Material parameters

It is also evident AZ31B is most ductile with failure strain of about 0.18 followed by Al 6061-T6 with failure strain of about 0.16. In contrary to the ductile behavior of the metals, the G10 is very brittle with failure strain of only about 0.016. Although some of material bulk properties are similar for Al6061-T6 and AZ31B (Fig. 1), such as ductility, yield and ultimate tensile strength, there is a significant difference in Yong's modulus (and stiffness). A significant effect of that difference on the performance of various joints will be demonstrated. From the above tests, the model parameters in the model are determined as in Table 1.

4.2 Force-displacement performance of bonded-only joints

The adhesive used in the study is relatively brittle as can be seen from Fig. 2. Typical test results reveal that: a) load transferred in both of the bonded-only joints correlates displacement almost linearly; b) stiffness as well as the maximum transferred load and ductility of the bonded-only Comp-Al joint is higher than that of bonded-only Comp-Mg joint; c) a traction-separation model coupled with damage is well enough for the description of this interfacial behavior.

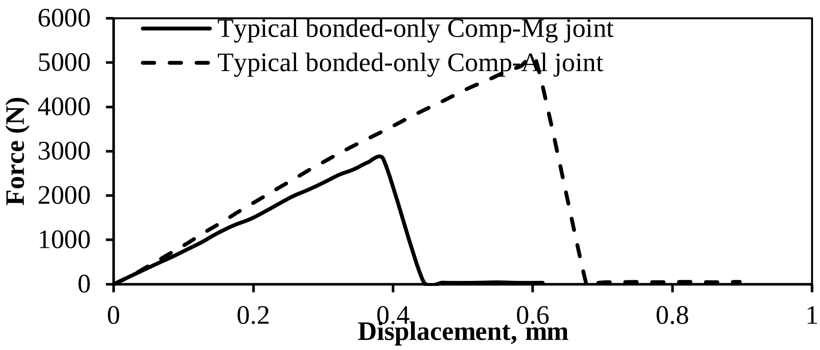

Fig. 2 Typical Force-Displacement relationship for bonded-only joints

Owing to many deleterious conditions, such as surface oxidation, voids, stain and asperities, substantial scatter of test results is normally observed in adhesive-related joint [21]. For the investigated joint combinations, the scatter of shear strength obtained from experiment is displayed in Fig. 3. As shown in Fig. 3, four of the five test in Comp-Al joint have very close results indicating excellent repeatability of bonding Al6061-T6 to G10 composite. As for AZ31B to G10, the result disperses from 3.5 MPa to 4.8 MPa, almost 37% discrepancy. In the numerical simulations, this statistical natural of adhesive-related joint is not considered, and simulation results are compared with median experimental results.

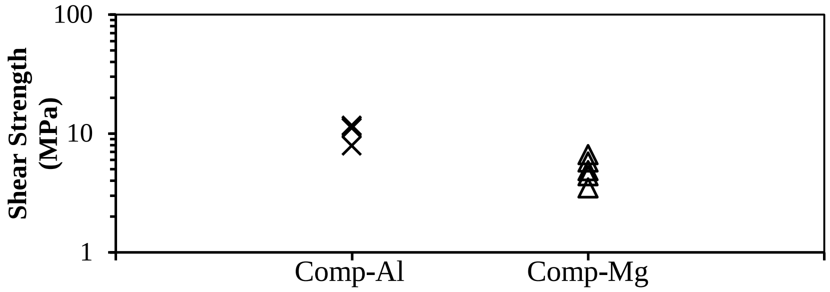

Fig. 3 Shear strength test data for bonded-only Comp-Al and Comp-Mg joints.

Repeatability of test data (for sample size= 4) is illustrated Figs. 4 and 5 for hybrid bonded-and-bolted joints. For the Comp-Al joints with zero bolt preload, Fig. 4a shows that the test data is fairly repeatable in terms of the load transfer capacity and the force-displacement relationship (until the failure initiation). However, Fig. 4b shows a lower rate of repeatability for the Comp-Mg joints. A similar repeatability pattern is shown for hybrid bonded-and-bolted joints (Comp-Al and Comp-Mg) with bolt preload.

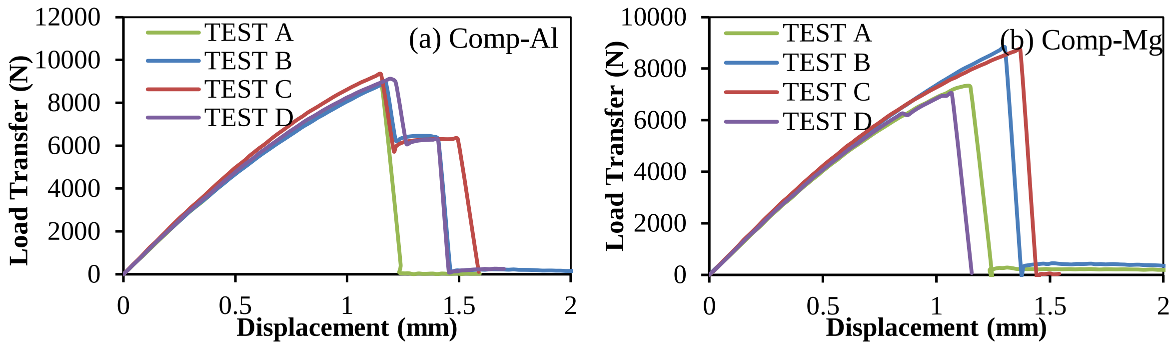

Fig. 4 Repeatability of bolted-bonded joints without preload (a) Comp-Al, (b) Comp-Mg

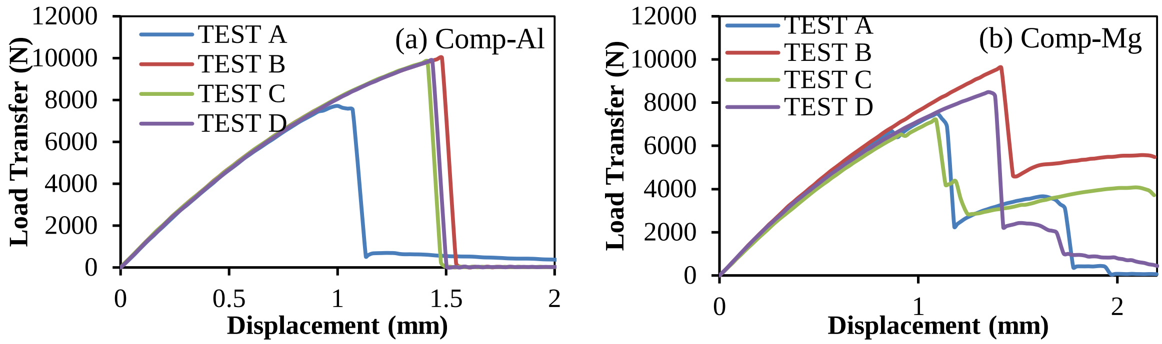

Fig. 5 Repeatability of bolted-bonded joints with preload (a) Comp-Al, (b) Comp-Mg

4.3 Effect of bolt preload

Bolt preload on bolting-related joint system has significant effect on its performance. In both investigated joints (Fig. 6), the bolt preload dramatically affects the ductility (not in every case, however) and load transfer capacity of joint. In addition, the load transferred in bolted-boned Comp-Al joint (Fig. 6a) goes to the maximum with slight nonlinearity as the displacement is increased, while it's very different for bolted-only joint: On one hand, there is large portion that bears no load in bolted-only joint without preload due to the clearance between bolt and hole of adherends; on the other hand, two distinct loading regions are identified for bolted joint with preload: one is related to friction force between G10 and Al 6061-T6, the other is related to bolt. After reaching maximum load, sudden rupture of G10 occurs. Depending on whether or not the simultaneous adhesive failure happens, load drops about 30% as adhesive bonding becomes the solely load transfer media, or 100%. The Comp-Mg joint has very similar behavior to Comp-Al joint as shown in Fig. 6b.

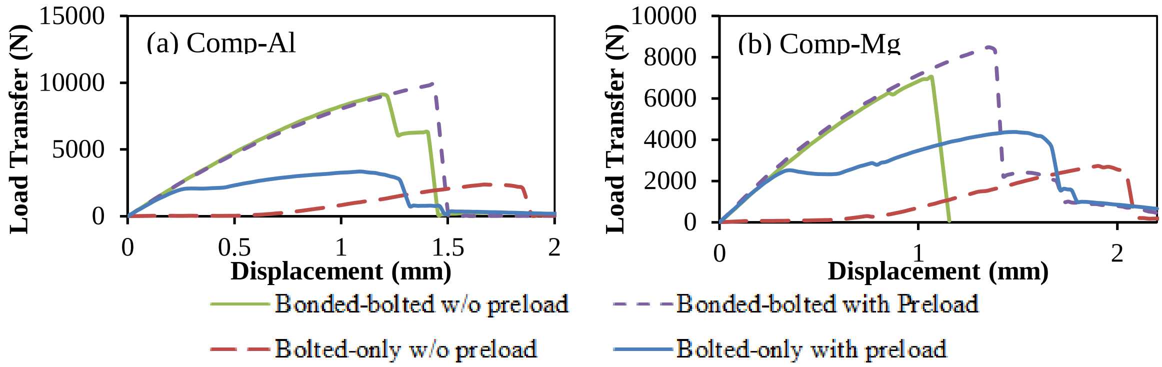

Fig. 6 Effect of bolt preload on joint load transfer capacity: (a) Comp-Al, (b) Comp-Mg

4.4 Comparison of various joining methods

All the joining methods are compared for both material combinations. Their load transfer trends are very similar as illustrated in Fig. 7. In the bolted-only Comp-Al joint (Fig. 7a), the one with bolt preload has slightly higher load transfer capacity than that of no bolt preload; it is the same for the bolted-bonded Comp-Al joint, but the one with bolt preload has simultaneous G10 failure and adhesive failure (or even earlier) while the one without bolt preload has G10 failure first followed by adhesive failure. It appears from Fig. 7b, adhesive failure occurs before G10 failure for bolted-bonded Comp-Mg joint with bolt preload.

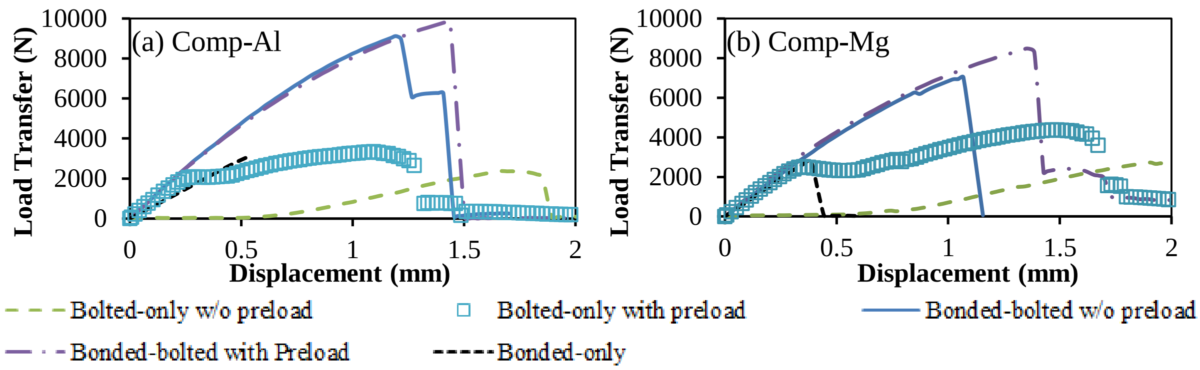

Fig. 7 Load transfer capacity of various joining methods (a) Comp-Al, (b) Comp-Mg

4.5 Model predictability

Model predictions on load transfer capacity of bolted-bonded joint combinations have been shown in Fig. 8 as a function of experimentally determined ones. Also shown in the figure is the ± 2 interval bonded by dotted lines. The model predictions could well fitted into the interval for both joint combinations.

5. Conclusions

Various joining methods are investigated for their effect on the static load capacity and the failure mode of composite-to-metal single-lap joints. Investigate joining methods include Bonding-only, bolting-only, and hybrid bonding and bolting. Numerical and experimental methods are used in this investigation. The results of this study support the following conclusions:

- Bonded-only Composite to Aluminum joints have higher load transfer capacity (with less scatter) than that of composite-to-magnesium joints.
- For some material combinations such as composite-aluminum, bonded-only joints may have a higher load transfer capacity than bolted-only joints, with or without bolt preload.
- For bolted-only joints, with or without bolt preload, hole clearance would significantly affect the force-displacement behavior of the joint; bolt preload increases the joint load transfer capacity.
- Hybrid bonded-and-bolted joints with bolt preload have higher load transfer capacity than that without bolt preload.
- The nonlinear constitutive relationship for metals considered in the study could be well approached by an elastoplastic material model coupled with damage. An almost linear correlation between stress and strain in adhesive/interface indicating a traction-separation rule with damage coupling is a good model for simulating interfacial behavior.

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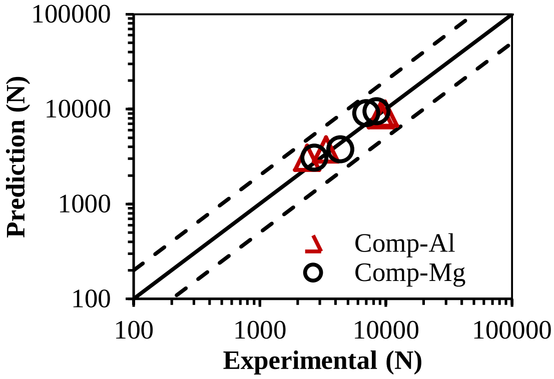

Fig. 8 Predicted and experimental load transfer capacity of joints

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