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Reliability analysis of adhesively bonded CFRP-to-steel double lap shear joint with thin outer adherends

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HIGHLIGHTS

- Compiled database of CFRP/steel bonded double lap joints that failed by debonding.
- Quantified model uncertainty for the Hart-Smith model for thin outer adherends.
- Calculated reliability indices, resistance factors for multiple joint configurations.
- Demonstrated the importance of each joint parameter to the debonding variability.

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ABSTRACT

This paper presents the details of a reliability-based analysis of bonded double-lap shear (DLS) joints between steel and carbon fiber reinforced polymer (CFRP) composites. A comprehensive database of experimental results of CFRP-to-steel DLS joints is compiled and a probabilistic analysis of the data is conducted. The compiled experimental results are compared with the bond strengths predicted by the Hart-Smith model for thin adherends and the model uncertainty is characterized, for five popular structural epoxy adhesives and two types of surface preparation techniques. Considering the mechanical and geometrical uncertainties of constituent materials, two reliability-based approaches, First-Order Reliability Method (FORM) and Monte-Carlo Simulation (MCS), are used to calculate the resistance factor at a target reliability index of 3.5. It is found that these two approaches agree well and the resistance factor varies with adhesives, surface preparation techniques, and CFRP types. The importance vector of random variables reveals that the adhesive shear ductility is the most influential material property in determining the reliability index of the bonded joints.

1. Introduction

The use of carbon fiber-reinforced polymers (CFRP) to repair, rehabilitate, and strengthen steel beams has been widely researched in recent years because of its light-weight construction and corrosion resistance [1–9]. Debonding is a key failure mode associated with the CFRP strengthened steel beams, and the debonding failure load is affected by the mechanical properties of the adhesive and bi-material interfaces [2,9–12]. Recent developments in CFRP strengthening technique showed that CFRP materials with small-diameter strands can potentially eliminate debonding failure [13].

It has been demonstrated that surface preparation is important to obtain good bonding between the adherends [14–16]. A clean, rough and chemically reactive surface is preferable for adhesive bonding, especially for CFRP-to-steel bonding, where the steel-adhesive interface is often the weakest link in the joint. A thorough study of the surface preparation for epoxy to steel bonding was carried out by Fernando et al. [17], and it showed that the grit-blasting technique is the most effective way to achieve good bond between epoxy and steel.

Double-lap shear (DLS) joints are commonly used to study the bond behavior between steel and CFRP since the shear and peeling stress distributions within the adhesive layer for long DLS joints are similar to those in CFRP strengthened beams under flexural loading [4,18–22]. Experimental studies showed that debonding

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Abbreviations: CFRP, carbon fiber reinforced polymer; DLS, double lap-shear; FORM, First-Order Reliability Method; FEA, Finite Element Analysis; MCS, Monte-Carlo Simulation; COV, coefficient of variation; LSE, least-square estimation; A, Araldite 420; S, Sikadur 30; TT, Tyfo TC; TS, Tyfo S; MB, Mbrace Saturant; AG, angle-grinding; SB, sand-blasting; WL, wet lay-up; PL, pultruded laminate; SA, steel-adhesive interface debonding failure; C, cohesive failure.

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loads exhibit higher variability compared with those of other failure modes such as steel yielding and CFRP rupture [23,24]. However, the guidelines for structural design using composite material and adhesive for steel strengthening do not have quantitative assessment of the variability of debonding strength, and probability-based resistance factors for such bonded joint are not available [25,26].

Models for lap-shear joint based on first-order shear lag analysis [27,28] provide relatively straightforward closed-form solutions that can be implemented by hand in design code. Although they do not capture the variability of stresses through the thickness of the adhesive layer and violate the zero shear condition at the end of the joint. Higher order model [29] addresses these shortcomings but requires iterative solutions and is not well suited for design. Fracture mechanics based solutions [20,30] can represent the underlying mechanics of the problem more accurately, but they usually require numerical analysis to calculate the stress intensity factors or energy release rate making them difficult to recommend for design applications. Finite element analysis (FEA) models [20,23,30] and bond-slip based model [31,32] are often limited by the joint configuration and are difficult to be applied to more general cases. Moreover, the computational cost of Monte-Carlo simulation (MCS) by adopting models relied on numerical analysis can be formidably high.

The debonding strength of DLS joint is affected by both shear and peeling stresses at the joint ends. DLS joint with thick outer adherends tends to fail prematurely due to the high magnitude of peeling stress, also called adherend-induced failure [27]. The peeling stress can be neglected if the outer adherends are thin enough, as formulated in Hart-Smith model [27]. This provides an opportunity to study the reliability of DLS joint, under limit state governed by shear only and the complexity of considering peeling stress can be eliminated.

To this end, the uncertainty associated with CFRP-to-steel bond needs to be quantified. This paper presents the findings of a reliability-based study of CFRP-to-steel adhesively bonded DLS joints that failed by debonding limit state. Primary sources of uncertainty, including the type of adhesive used, the surface preparation, the representation of the constitutive relationship of the adhesive in shear, the type of CFRP used and the modeling uncertainty are quantified and discussed. A database of 270 experimental results on CFRP-to-steel bonded DLS joints was compiled to quantify the model uncertainty of the analytical model [27]. The First-Order Reliability Method (FORM) was used and validated using MCS, to study the influence of the uncertainty of different parameters on the predicted bond strength and to calculate the resistance factors for bonded joints. Due to the similarity between debonding of DLS joints and beams, these findings can inform future reliability-based studies to calibrate resistance factors for design specifications.

2. CFRP-to-steel DLS joint details

The CFRP-to-steel DLS joint is made by bonding CFRP laminates (or carbon fiber fabrics) on both sides of two butted steel plates, as shown in Fig. 1. Prior to bonding, the steel surfaces are often treated by sand-blasting or ground by an angle grinder, and cleaned with organic solvents such as Acetone. Different fabrication method is used for pultruded or wet lay-up CFRP laminate: 1) for pultruded laminate, paste adhesive is applied uniformly before applying the CFRP plate, and clamps or weights are used to squeeze out the excessive adhesive to ensure a thin and uniform adhesive layer (adhesive thickness can be controlled by using glass beads as spacer) 2) for wet lay-up laminate, carbon fiber fabrics are bonded to steel with a paste adhesive or saturate resin, and a roller is used to squeeze the excessive adhesive and air bubbles. Detailed fabrication methods can be found for pultruded [33] and wet lay-up laminate [31].

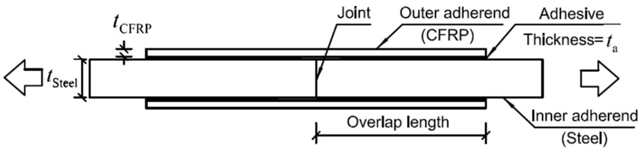

Fig. 1. Schematic of CFRP-to-steel DLS joint (not to scale).

For all of the DLS specimens surveyed in this study, the outer CFRP adherends were thin compared with the inner steel adherends, if the thickness is less than [27]

$$t_{\text{CFRP\_max}} = \frac{E_{\text{CFRP}} t_a}{3(1-\nu^2)} \frac{1}{E'_a} \left(\frac{\sigma_p}{\tau_p}\right)^4 \qquad (1)$$

where E_{CFRP} is the modulus of the CFRP adherend, ν is the Poisson's ratio of the adhesive, t_a is the adhesive layer thickness, E'_a is the elastic modulus of adhesive layer loaded in normal direction, σ_p and τ_p are the peel and shear strength of the adhesive, respectively. The shear stress in the adhesive layer is dominant if the thin adherend criterion is met. By considering these specific joint configurations, the uncertainty associated with the peeling component of the stress, can be excluded in the reliability-based analysis which reflects the range of configurations that were identified in the published literature. Steel plates were used as the inner adherends and the axial rigidity of the inner adherends was higher than that of the outer adherends, so an imbalanced joint configuration was achieved. The joints were all loaded in axial tension, as shown in Fig. 1, inducing a predominantly shear stress in the bonded joint (peeling stresses are negligible according to the Hart-Smith formulation).

3. Limit state function

Several failure modes were identified for CFRP-to-steel bonded joints [34]. Of which debonding failure, i.e. cohesive or adhesive failure modes, are of the primary interest. The cohesive failure, where the debonding occurs within the adhesive layer, is often governed by the strength of the adhesive material. For adhesive failure mode, the debonding occurs at the adhesive/steel or adhesive/CFRP interface and is governed by the strength of the interfaces. The resistance and load models for the debonding limit state are expressed in the following sections.

3.1. Resistance model

The predicted bond strength of a DLS joint with thin outer adherends, P_p, was determined by Hart-Smith [27] to be

$$P_p = b\sqrt{2t_a\tau_p\left(\tfrac{1}{2}\gamma_e+\gamma_p\right)4E_{\text{CFRP}}t_{\text{CFRP}}\left(1+\tfrac{2E_{\text{CFRP}}t_{\text{CFRP}}}{E_{\text{steel}}t_{\text{steel}}}\right)} \quad \text{for } E_{\text{steel}}t_{\text{steel}} \geqslant 2E_{\text{CFRP}}t_{\text{CFRP}} \qquad (2)$$

where b is the width of the joint, t_a is the adhesive layer thickness, τ_p is the shear yield strength of the adhesive if an elastic-perfectly plastic material model is used, γ_e and γ_p are the maximum elastic and plastic shear strains, respectively, E_{CFRP} is the CFRP modulus in the longitudinal direction and E_{steel} is the Young's modulus of steel, t_{CFRP} is the CFRP thickness and t_{steel} is the steel plate thickness, as shown in Fig. 1. The shear toughness of the adhesive, U_{shear} is defined as

$$U_{\text{shear}} = \tau_p\left(\frac{1}{2}\gamma_e+\gamma_p\right) \qquad (3)$$