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Experimental study and probabilistic bond strengths of adhesively-bonded steel butt joints under mixed-mode loadings

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ABSTRACT

To study the bond behavior of adhesive-steel bonded interfaces under mixed-mode loading, a tension-torsion testing arrangement was adopted to subject adhesively bonded steel butt joints to various combinations of shear and tensile stresses. It was observed that failure mode transitions from shear cohesive with subsequent adhesive-steel interface debonding to pure tensile cohesive failure as the ratio of tensile to shear stresses increases. The interfacial tensile strength exhibits greater variability than the shear strength. For combined loading scenarios the variability of the strength increases as the normal stress to shear stress ratio increases. Statistical tests demonstrate that the shear and tensile bond strengths can each be represented using a two-parameter Weibull distribution. A superelliptical interaction relationship is presented to predict the capacity of joints that are subjected to combined shear and tensile stresses. Finally, the difference between normal and Weibull distributions in determining the characteristic and guaranteed strengths are highlighted. These comparisons indicate that normal distributions can yield non-conservative bond strengths. The research findings can provide guidance in the design of bonded joints in metallic components.

1. Introduction

Structural bonding has been widely used in aerospace, automobile, and other manufacturing industries, due to its unique way of joining two materials (similar or dissimilar) without compromising their individual mechanical properties. In recent years, considerable research has been conducted on strengthening civil steel structures with adhesively bonded fiber reinforced polymer (FRP) composite materials as highlighted in several recent review papers [1–5].

Miller et al. [6] conducted laboratory and full-scale tests of carbon fiber reinforced polymer (CFRP) strengthened steel bridge girders. The debonding failure mode was observed in the laboratory scale tests. Tavakkolizadeh and Saadatmanesh [7] conducted an experimental study of steel-concrete composite girders with multiple layers of CFRP, and demonstrated that insufficient curing of adhesive can lead to premature debonding failure. Schnerch et al. [8] tested double lap-shear joints using different adhesives to demonstrate the importance of the adhesive in achieving high debonding failure loads. They also demonstrated the importance of detailing of CFRP plate ends to reduce the stress intensity factor and delay debonding. Deng and Lee [9] tested CFRP strengthened steel beams and found that debonding is the predominant failure mode with failures predominantly occurring at the adhesive-steel interface. Rizkalla et al. [10] summarized the use of high modulus CFRP materials for strengthening steel structures, and demonstrated that debonding is one of the dominant failure modes. Sahin and Dawood [11] conducted flexural tests of CFRP strengthened steel beams under room and moderately elevated temperatures. The testing showed that premature debonding occurred at room temperature but that adhesive ductility postponed debonding at moderately elevated temperatures. Experimental studies widely showed that the bond of CFRP strengthened steel beams often fails at the adhesive-steel interface, even when robust surface preparation techniques such as grit blasting are used [11–14].

Analytical models suggest that the debonding failure is an outcome of the combination of high shear and peeling stresses close to the joint end [15–17]. The existence of such a stress state requires the use of a failure criterion that incorporates the interaction between shear and normal stresses to predict the debonding failure. While there is a movement towards fracture mechanics based failure criteria [12,18–23], most design guidelines still use stress-based formulations [24–26]. Therefore, stress-based failure criteria are still important before a widely accepted fracture-based test procedure and failure criterion are established. A stress-based failure criterion can be used for any joint configuration for which the shear and tensile bond stresses can be determined, whereas the classical approach of testing representative lap-shear samples implicitly assumes that the ratio of peeling to shear

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stresses in the representative sample and in the actual joint are the same (or at least similar).

Experimental and reliability studies show that debonding strength of bonded joints exhibits significant scatter [27–31], with associated coefficients of variation as high as 30% in some cases [27], which is much higher than for other failure modes, such as FRP rupture, which is typically in the range of 5–15% [33]. To develop guidelines for strengthening steel structures with FRP in load and resistance factor design (LRFD) format, the statistical characteristics of the FRP-to-steel bond need to be elucidated. However, studies carried out on failure criteria of structural bond either focus on adherends other than steel or consider deterministic rather than probabilistic approaches [34–40], only relatively few studies have investigated the statistical characteristics of adhesively bonded joints [34,35,41–43]. The uncertainty affecting the strength of bonded joints with steel adherends under mixed-mode loading has not yet been well characterized. Lack of the statistical characterization of the strength of the adhesive-to-steel interface makes it difficult to design a reliable CFRP-to-steel bond [32]. It is recommended that the statistical characterization of FRP materials be performed to quantify their variability and comply with LFRD requirements [33]. For structural adhesive and bond, a similar framework should also be developed to ensure the structural integrity, in light of the complexity and importance of the structural bond. Therefore, this study aims to investigate the bond strengths of adhesively-bonded steel butt joints under mixed-mode loading condition, by conducting tension, torsion, and combined loading tests of adhesively bonded steel tube joints. In addition, the statistical characteristics of the bond strengths will be studied to facilitate reliability-based design of FRP-strengthened steel structures.

This paper first introduces the specimen design, instrumentation, setup of the experiments and theoretical basis for the analysis. Test results are then presented to illustrate the failure modes, tensile-shear interaction failure envelope, and variability of the results under different combinations of shear and tensile loading. The failure envelope defined in this study is compared to shear and tension bond stresses in CFRP-plated steel beams that failed by debonding to demonstrate the agreement of the results. A statistical analysis is performed to determine the statistical characteristics of the bond strength under mixed-mode loading. Finally, average, characteristic, and guaranteed strengths are compared based on the findings of experimental results and the statistical analysis.

2. Materials and methods

The experimental program of this study is conducted by devising a setup to apply tension, torsion, and combined loadings on adhesively bonded butt joints between two steel tubes as shown in Fig. 1.

2.1. Materials

2.1.1. Steel

The steel tubes were cut from an ASTM A106 mild steel pipe [44], with outer diameter of 88.9 mm and an average wall thickness of 10.6 mm. The bonding surface was milled by a CNC machine to achieve a flat surface and to minimize the variation of the thickness of the adhesive layer. A small fillet was created at the edges of the steel tube to mitigate the stress concentration [45] at the edges of the bi-material interface.

2.1.2. Adhesive

A structural adhesive, Spabond 345, was selected to bond the steel tubes [46]. This adhesive is a toughened epoxy which has been used in bonding CFRP to steel for which detailed mechanical properties were reported in the literature [11]. The Young's modulus of the adhesive is reported as 2260 MPa, and tensile strength is reported as 25.1 MPa.

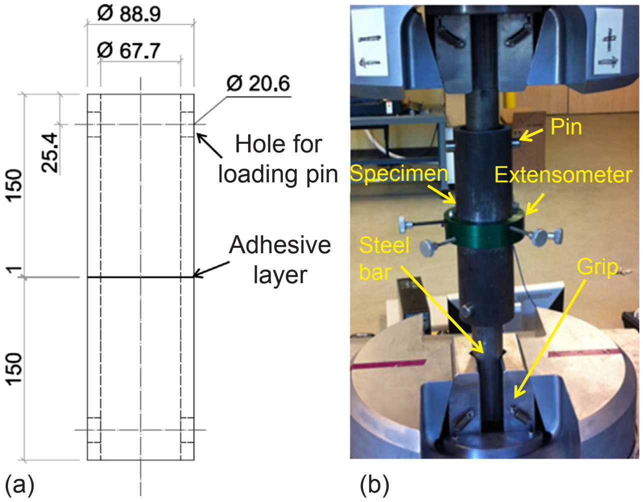

Fig. 1. (a) Specimen geometry and (b) test setup shows the specimen is loaded through a pair of steel solid bars with drilled holes for pin connection.

2.1.3. Blasting sand

Medium-grit blasting sand (#4) was used to blast the steel surface to create a roughened, chemically active surface. The fineness modulus of the sand was reported by the supplier as 4.5 [47].

2.2. Specimen preparation and test setup

2.2.1. Specimen preparation

Prior to bonding, the surfaces were sand-blasted by medium grit sand with pressure no less than 550 kPa. The blasted surfaces were then carefully cleaned with acetone using a lint-free cloth to remove the dust and contaminants. A small amount of adhesive was applied to one of two surfaces using a dispenser with a baffled static mixing nozzle. A spade was used to spread the paste adhesive into a thin layer to cover the entire bonding surface. Glass beads with 1 mm nominal diameter were placed at four locations along the annulus as spacers to control the adhesive thickness. Adhesive was similarly applied on the steel surface of the second tube. The two tubes were then aligned in a steel fixture and pressed against each other. Excessive adhesive was expelled while a desired thickness of the adhesive layer (~ 1 mm) was achieved due to the presence of glass spacer beads. The specimens were left curing at room temperature for at least one week before testing. The surface of the steel tubes was then cleaned and sanded carefully with fine emery papers to remove the extra adhesive. The specimen geometry is shown in Fig. 1(a).

2.2.2. Test setup

The test setup is shown in Fig. 1(b). The fabricated specimens were tested in a servo-hydraulic axial/torsion testing frame (Shore Western 306 Series 4-column testing frame), under monotonic tension, torsion, and mixed-mode loadings. Two solid circular steel bars were gripped in the upper and lower grips of the hydraulic test frame. The diameter of the bars was smaller than the inner diameter of the test specimens. The bars were inserted into the ends of the test specimens. Holes were drilled in the steel bars and in the upper and lower steel tubes of the test specimens perpendicular to their longitudinal axes. The test specimens were connected to the steel bars using steel pins which transmitted forces from the steel rods to the test specimens through double-shear. A specially-designed axial-torsional extensometer that was developed by Epsilon Technology Corporation was used to measure the axial and rotational deformation across the adhesive layer. The extensometer consisted of two rings with inner diameters slightly larger than the outer-diameter of the test specimens. Each ring was fitted to the specimens, one directly above and one directly below the adhesive layer