

Load-bearing capacity prediction of FRP-metal double-lap bonded joints

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Abstract

Previous work discovered that the critical shear strain energy density of the adhesive layer decreases as the adhesive layer thickness increases. Based on this, the contradiction between theoretical calculations and experimental results regarding the influence of adhesive thickness on load-carrying capacity was preliminarily resolved, and the upper-bound prediction model for load-carrying capacity was revised. Building upon this previous work, this study aims to analyze the evolution mechanism of the critical shear strain energy density of the adhesive layer, refine the failure analysis mechanism of FRP-metal double-lap bonded joints, and extend the load-carrying capacity prediction model from upper-bound prediction to the prediction of capacity for specific lap lengths. First, using the critical shear strain energy density of the adhesive layer as the shear criterion, a formula for predicting load-carrying capacity was derived. An expression for the peel strain distribution coupled with the shear deformation of the adhesive layer was derived; using the maximum peel strain as the peeling criterion, a failure analysis framework coupling shear-peel criteria was constructed. Second, based on previous experimental data of GFRP-steel double-lap bonded joints, the failure modes and the variation patterns of the critical shear strain energy density were systematically analyzed for short-lap (lap length 3mm) and long-lap (lap length 90mm) specimens within an adhesive thickness range of 1mm to 3mm. The evolution mechanism by which the critical shear strain energy density monotonically decreases with increasing adhesive thickness was preliminarily analyzed. Third, based on an equivalent ideal elastic-plastic model and the critical shear strain energy density measured from short-lap specimens, the upper bound of the joint load-carrying capacity and the capacity at a specific lap length (lap length 90mm) were effectively predicted, with the predicted values showing good agreement with the experimental results of long-lap specimens. Finally, the failure mechanism of the joints was analyzed based on the failure analysis framework coupling shear-peel criteria, clarifying that failure is primarily shear-dominated with minimal influence from peeling. Consequently,

a load-carrying capacity prediction model for double-lap bonded joints was established, which possesses a clear failure mechanism, accurately reflects the influence of adhesive thickness, and integrates both upper-bound and specific lap length prediction capabilities. This provides a reliable theoretical basis and engineering analysis tool for the design and strength assessment of such joints.

Full Text

Load-bearing Capacity Prediction and Failure Analysis of FRP-Metal Double-Lap Bonded Joints

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Abstract

Previous research has identified a phenomenon where the critical shear strain energy density of an adhesive layer decreases as the layer thickness increases. This finding has provided a preliminary solution to the theoretical contradiction where calculations regarding the influence of adhesive thickness on load-carrying capacity were inconsistent with experimental results, leading to a revised upper-bound prediction model for load-carrying capacity. Building upon this previous work, the present study aims to analyze the evolution mechanism of the critical shear strain energy density, refine the failure analysis framework for Fiber Reinforced Polymer (FRP)-metal double-lap joints, and extend the load-carrying capacity prediction model from an upper-bound estimation to predictions for specific lap lengths.

First, a load-carrying capacity prediction formula was derived using the critical shear strain energy density of the adhesive layer as the shear criterion. Additionally, an expression for the peel strain distribution, coupled with the shear deformation of the adhesive, was derived. By adopting the maximum peel strain as the peeling criterion, a failure analysis framework coupling both shear and peeling criteria was constructed.

Second, based on experimental data from previous GFRP-steel double-lap bonded joints, the failure modes and the variation patterns of the critical shear strain energy density were systematically analyzed for specimens with short lap lengths (3 mm) and long lap lengths (90 mm) across adhesive thicknesses ranging from 1 mm to 3 mm. This analysis provided a preliminary explanation

for the evolution mechanism behind the monotonic decrease of critical shear strain energy density as the adhesive layer thickens.

Third, utilizing an equivalent ideal elastic-plastic model and the critical shear strain energy density measured from short-lap specimens, the study effectively predicted both the upper bound of the joint's load-carrying capacity and the capacity at a specific lap length (90 mm). The predicted values showed good agreement with the experimental results of the long-lap specimens.

Finally, the failure mechanism of the joints was analyzed using the coupled shear-peeling failure framework. The results clarified that failure is primarily shear-dominated, with peeling effects playing a minor role. Consequently, this study establishes a load-carrying capacity prediction model for double-lap bonded joints that possesses a clear failure mechanism, accurately reflects the influence of adhesive thickness, and is capable of both upper-bound and specific lap-length predictions. This work provides a reliable theoretical basis and engineering analysis tool for the design and strength assessment of such joints.

Keywords: FRP-Metal Double-Lap Adhesive Joints; Adhesive Thickness; Critical Shear Strain Energy Density; Peeling Strain; Load-Bearing Capacity; Failure Mechanism

1 Introduction

The adhesive bonding of Fiber Reinforced Polymer (FRP) and metal is widely utilized in lightweight structures. However, the joint remains a weak link that directly affects the overall strength and reliability of the structure. Compared to single-lap joints, double-lap joints are better suited for load-bearing applications. Accurately predicting the load-carrying capacity of FRP-metal double-lap adhesive joints and clearly analyzing their failure mechanisms are essential prerequisites for their application in structural connections.

Research on the load-carrying capacity and failure mechanisms of adhesive joints began with the shear-lag model proposed by Volkersen based on a one-dimensional rod theory. Building upon this, Goland and Reissner introduced a one-dimensional beam model that accounts for the influence of end bending moments [?, ?]. Hart-Smith further extended this model [?] by treating the adhesive layer as an ideal elastic-plastic material [?]. This approach employs an equivalent ideal elastic-plastic stress-strain curve to replace the actual complex curve [?] and utilizes the critical shearing deformation energy density (CSDED) of the adhesive layer as the failure criterion [?, ?]. This method effectively predicts the mechanical behavior of ductile adhesive layers [?] and analyzes shear deformation under specific loads, making it a simple yet accurate model [?].

However, two significant issues persist. First, existing models fail to resolve the contradiction between theoretical calculations and experimental results regarding the effect of adhesive layer thickness on load-carrying capacity. Currently, no theoretical model can accurately calculate the influence of adhesive thick-

ness on capacity [?, ?]. Second, the prediction of load-carrying capacity and the analysis of failure are dominated by adhesive shear, while the consideration of adhesive peeling is limited. Consequently, a failure analysis framework that fully couples shear and peel criteria has not been established.

In our previous work [?], we focused on the experimental phenomenon where the CSDED decreases as the adhesive layer thickens. The load-carrying capacity and its variation trends predicted based on experimentally determined CSDED were found to be fundamentally consistent with experimental values. However, that work did not address the evolution mechanism of CSDED, nor did it construct a failure analysis framework coupling shear and peel criteria. Additionally, the modified model could only predict the upper limit of the load-carrying capacity. Building upon previous research, this paper establishes a closed-loop research logic of “theoretical derivation - experimental data - comparative verification.”

2 Load-bearing Capacity Prediction Based on Shear Criterion

The double-lap bonded joint is shown in [Figure 1: see original paper], where the coordinate origin o is located at the midpoint of the overlap length l , and the load-bearing capacity is denoted by P . When the shear deformation of the adhesive layer remains elastic after loading, the shear stress τ is given by [?, ?]:

$$\tau = \frac{\tau_{av}\lambda \cosh(\lambda x)}{\sinh\left(\frac{\lambda l}{2}\right) \left[1 + \frac{E_i t_i}{2E_o t_o}\right]} + \frac{(\alpha_i - \alpha_o)(\Delta T)\lambda E_i t_i \sinh(\lambda x)}{\cosh\left(\frac{\lambda l}{2}\right) \left[1 + \frac{E_i t_i}{2E_o t_o}\right]}$$

In the above expression, E_i and E_o represent the elastic moduli of the inner and outer lap plates, respectively; t_i and t_o denote the thicknesses of the inner and outer lap plates; α_i and α_o are the coefficients of thermal expansion; ΔT is the temperature difference; l is the overlap length; and τ_{av} is the average shear stress of the adhesive layer ($\tau_{av} = \frac{P}{2Wl}$, where W is the width).

The parameter λ is defined as $\lambda = \sqrt{\frac{G}{\eta} \left(\frac{1}{E_i t_i} + \frac{1}{2E_o t_o} \right)}$, where η is the thickness of the adhesive layer and G is the shear modulus. When $\tau\left(\frac{l}{2}\right) - \tau\left(-\frac{l}{2}\right) > 0$, the plastic shear stress τ_p first appears at the right end of the adhesive layer ($x = \frac{l}{2}$). As loading continues and the joint enters the elasto-plastic stage, failure initiates at $x = \frac{l}{2}$.

Assuming $\tanh(\zeta l) \rightarrow 1$, the predicted load-carrying capacity P is given by:

$$P = \left[2\eta\tau_p(\gamma_e + \gamma_p) 2E_i t_i \left(1 + \frac{E_i t_i}{2E_o t_o} \right) + (\alpha_o - \alpha_i)(\Delta T)E_i t_i \right] W$$

In this expression, γ_p represents the plastic shear strain of the adhesive layer. The term $\eta\tau_p(\gamma_e + \gamma_p)$ is defined as the Critical Shearing Deformation Energy Density (CSDED).

3 Peeling Criterion Coupled with Shear Deformation

To analyze the effects of peeling, we introduce the adhesive peel strain $\epsilon = y/\eta$, where y represents the peel deformation of the adhesive layer. Consider a micro-element of unit width from the outer lap plate [Figure 2: see original paper]. The mechanical equilibrium relationship is:

$$\frac{dV_o}{dx} = -\sigma$$

$$V_o = \frac{dM_o}{dx} + \tau \left(\frac{1}{2}t_o \right)$$

The analysis is divided into cases based on the shear state of the adhesive. For an outer lap plate where $t_o/l < 1/5$ and the adhesive layer is in shear plasticity ($\tau = \tau_p$), the displacement y is solved as:

$$y = \cosh(b_0x) \sin(b_0x)A + \sinh(b_0x) \cos(b_0x)B + \cosh(b_0x) \cos(b_0x)C + \sinh(b_0x) \sin(b_0x)F - \frac{t_o\tau_p}{2\eta E}$$

The variation of $\epsilon = y/\eta$ is coupled with shear deformation. Its maximum value, ϵ_{max} , serves as the peeling criterion.

4 Experimental Data and Analysis

The specimens consist of Q235 steel outer adherends and GFRP inner adherends. Material parameters are provided in and .

Failure primarily manifested as interfacial failure between the outer cover plate and the adhesive layer [Figure 3: see original paper]. The $\tau - \gamma$ curves for each group were fitted to obtain a global curve [FIGURE:4, FIGURE:5]. From the equivalent ideal elasto-plastic model, the corresponding τ_p , γ_e , γ_p , and CSDED for each thickness η were determined .

4.1 CSDED Evolution Mechanism

The variation trends of CSDED with respect to η are shown in [Figure 6: see original paper]. CSDED exhibits a monotonic decrease as η increases. This is attributed to a competitive mechanism between defect probability and slumping effects. At small thicknesses, defect probability dominates; as thickness increases, the slumping effect becomes more pronounced, particularly in specimens with smaller bonding areas.

5 Load-bearing Capacity Prediction Results

Using the derived formulas, the upper limit of load-bearing capacity P_{upper} and the capacity for a specific lap length ($l = 90$ mm) were calculated. The

convergence of the iterative calculation for $l = 90$ mm is shown in [Figure 8: see original paper].

A comparison between predicted and experimental values [Figure 9: see original paper] shows that the upper bound prediction essentially envelopes the experimental data. The predicted curve for $l = 90$ mm passes through the dense region of the experimental data points, indicating high accuracy.

6 Failure Analysis

The peeling strain ϵ was calculated for different cases. For $l = 3$ mm (Experiment I), the distribution of ϵ is shown in [Figure 10: see original paper]. For $l = 90$ mm (Experiment II), the distribution is shown in [Figure 11: see original paper].

Comparison reveals that when $l = 90$ mm, the maximum peeling strain ϵ_{max} is significantly smaller than that at $l = 3$ mm. Since the load P calculated using the shear criterion (CSDED) aligns well with experimental results, it is concluded that failure is dominated by shear, and peeling effects are negligible for these double-lap joints.

7 Conclusion

This study analyzed the CSDED evolution mechanism and extended the load-carrying capacity prediction model for FRP-metal double-lap joints. 1. CSDED decreases monotonically with adhesive thickness due to defect probability and slumping effects. 2. The refined model accurately predicts both the upper limit and specific lap-length capacity, resolving previous theoretical contradictions. 3. Failure analysis using a coupled shear-peeling framework confirms that these joints are primarily shear-governed.

This work provides a reliable theoretical basis for the design and strength assessment of adhesive joints in engineering applications.

Note: Figure translations are in progress. See original paper for figures.

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