EFFECT OF ADHESIVE THICKNESS ON THE INTERFACIAL STRESSES IN STEEL-FRP LAP-JOINTS UNDER FREEZE-THAW CYCLING

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1.0 ABSTRACT

A theoretical model is presented in this paper, which highlights the influence of uncertainties in the thickness profile of the adhesive on the interfacial stresses in steel-FRP lap joints subjected to freeze-thaw cycles and mechanical loading. The model accounts for the effect of moisture swelling, thermal expansion, and change in material properties due to freeze-thaw exposure. The model also accounts for the high order deformability of the adhesive layer in shear and through its thickness and allows for quantitative evaluation of the edge and interfacial shear and peeling stresses. Different potential profiles of the adhesive are examined, and the results are presented in terms of distribution of the internal interfacial stresses in the adhesive layer.

2.0 KEYWORDS

Composite materials, lap shear, adhesive bond, interfacial stresses, freeze-thaw.

3.0 INTRODUCTION

The influence of freeze-thaw cycling on the behavior and bond strength of fiber reinforced plastic (FRP) repaired steel structures is a key parameter in their design in many civil engineering applications. The debonding failure in FRP strengthened members is mainly governed by the weak adhesive layer that can be subjected to both shear and peeling stresses, which becomes more critical under freeze-thaw (F-T) cycling due to two main phenomena. The first is the diffusion of water through the adhesive, which can cause degradation of the steel-FRP interface in a bonded joint, as well as degradation of its mechanical properties, which can lead to premature debonding failures at the interfaces or within the adhesive itself (Kinloch, 1983). The second phenomenon is the expansion of water inside the adhesive after freezing, which generates crevices and may degrade the adhesive bond under repeated F-T cycling. The combination of these two phenomena is critical for the design of the FRP repair system, noting that the service temperatures range between -30°C to +60°C in many civil engineering applications (Zhao and Zhang, 2007).

Experiments conducted by Kim et al. (2012) on steel-FRP joints reveal that there is an increase of about 36% in their bond strength after exposure to 100 F-T cycles. On contrary, Agarwal et al. (2013) measured about 28% reduction in the bond strength of steel-FRP joints after exposure to 40 F-T cycles. Similar inconsistency in the results exists in other types of joints. For example, Tam et al. (2008) reported only a 12% reduction in the bond strength of FRP-FRP bond after exposure to 300 F-T cycles, while Lopez-Amido et al. (2004) observed about 43% reduction in the bond strength upon exposure to only 20 F-T cycles. One of the factors that could have led to this inconsistency is the influence of various and non-uniform adhesive bondline thickness. In most cases, it is very difficult to maintain a constant thickness of the adhesive along the bondline, leading to some level of uncertainty regarding its actual thickness profile, which can initiate unexpected and premature debonding failures of the FRP repair system. Thus, it is important to understand the effect of adhesive bondline thickness combined with F-T cycling.
In general, the influence of F-T cycling on the bond strength of steel-FRP joints requires the use of a stress analysis phase and a failure analysis phase that can be based on limit stress, limit strain, or fracture mechanic approaches. Nevertheless, before the implementation of such failure criteria, a reliable stresses analysis need to be conducted. This paper therefore focuses on the influence of the thickness profile of the adhesive on the interfacial stresses in steel-FRP single lap joints under F-T cycling, which provides a basis for their failure analysis. For this, a theoretical model is developed and presented. In the structural level, the model is based on the high order theory approach, developed in Frostig et al. (1999), while a new modeling approach is proposed for the modeling of the effects of the F-T cycling. In this regard, the effect of moisture swelling, thermal expansion, and change in material properties due to F-T exposure are introduced through the kinematic relations of the materials with varying mechanical properties between the cycles, which enables the estimation of the residual stresses after F-T cycles.

4.0 THEORETICAL MODELING

The structural model developed by Frostig et al. (1999) is used to model the steel-FRP single lap shear specimen. In this model, both the FRP and steel layers are modeled as ordinary Bernouli–Euler beams with axial and bending rigidities, while the adhesive layer is modeled as a 2D elastic continua that can resist shear and normal (through the thickness) stresses. The longitudinal stresses in the adhesive are neglected due to its very low axial rigidity compared to those of the FRP and steel layers. In addition, the stresses and the deformations fields are assumed to be uniform through the width. Figure 1 shows the sign convention used in the model, where $u_{ai}$ and $w_i$ are the horizontal and vertical displacements of the centroidal (reference) axis of the top ($i=t$) and the bottom ($i=b$) adherends, respectively; $u_a$ and $w_a$ are the horizontal and vertical displacements of the adhesive layer; $N^i_{xx}$ ($i=t$ or $b$) stands for the axial force in the top and bottom adherends; $Q^i_{xx}$ and $M^i_{xx}$ are the shear force and the bending moment, respectively, in the top and bottom adherends; $\sigma_{zz}$ and $\tau$ are the vertical normal stress and shear stress in the adhesive; and $c_a$ is the thickness of the adhesive.

Figure 1: a) Single lap shear specimen – sign convention; b) High order theory – internal resultants.

For the modeling of the freeze-thaw cycles, three phenomena need to be highlighted, which include:
1. Change in the elastic modulus of the adhesive after F-T cycles.
2. Swelling strain in the adhesive due to absorption of moisture.
3. Thermal expansion and contraction of the different materials.

The description of these three phenomena in the model is very challenging and it requires sufficient test data for their characterization. In Agarwal et al. (2013b), testing of pure Epoxy specimens in tension was conducted after different number of F-T cycles. This data is used here to evaluate the deterioration of the elastic modulus of the adhesive after F-T cycles using interpolation technique. In such tests, each Epoxy specimen was weighted after different number of F-T cycles, which provide a basis to characterize the moisture content of the adhesive after a given number of F-T cycles. The swelling strain, therefore, is introduced through the kinematic relations of the adhesive using the coefficient of moisture expansion $\beta$ and the change in moisture content, $\Delta C$. The thermal expansion is also introduced through the kinematic relations of the different materials in terms of thermal expansion $\alpha$ and the change in temperature, $\Delta T$. 
The kinematic relations for the adherends and the adhesive are as follows:

\[
\varepsilon_{xx}(x,z) = u_{0i,x}(x) - z_i w_{li,x}(x) - \alpha_i \Delta T - \beta_i \Delta C_i \tag{1}
\]

\[
Y_{xx}(x,z_a) = u_{i,x}(x,z_a) + w_{i,x}(x,z_a) \tag{2}
\]

\[
\varepsilon_{zz}(x,z_a) = w_{a,z}(x,z_a) - \alpha_a \Delta T - \beta_a \Delta C_a \tag{3}
\]

where, \(\varepsilon_{xx}\) is the longitudinal strain; \(\Delta C_i\) and \(\Delta C_a\) are the moisture absorbed in the adherends (steel or FRP) and in the adhesive, respectively; which are taken as average values and assumed to be uniform through the length and height of each component; \(Y_{xx}\) is the engineering shear strain in the adhesive; \(z_i\) is measured downwards from the reference axis (mid-thickness); \(\frac{\partial}{\partial x}\) and \(\frac{\partial}{\partial z}\) denotes a derivative with respect to \(x\) and \(z\), respectively; and \(\varepsilon_{zz}\) is the transverse strain in the adhesive. Also the change of temperature is assumed to be independent of \(x\) and \(z\).

Each F-T cycle consists of three different steps as shown in Figure 2. The first step is the increase in temperature from \(T_1\) (which is the reference room temperature of 23°C) to \(T_2\), which then remains constant for \(t_1\) hours. In this step, the original value (at room temperature) of the elastic modulus of the adhesive, \(E_a\), is taken in the analysis, and the moisture swelling is not considered. The elastic moduli of the steel and the FRP are taken as the characteristic values throughout the cycle due to their minor dependency upon temperature and moisture absorption. The second step includes a temperature change from \(T_2\) to \(T_3\) (below zero temperature), which then remains constant for \((t_2-t_1)\) hours. The elastic modulus of the adhesive during this step is considered to be the average of two values (before and after that particular number of F-T cycle), and the moisture swelling is accounted for. The third step consists of the increase in temperature from \(T_3\) back to \(T_1\) with the final value of elastic modulus (i.e. after that particular number of F-T cycle). It was assumed that no moisture swelling takes place in this step, as all expansion has already took place in the second step.

![Figure 2: Single freeze-thaw cycle and change in elastic modulus](image)

Following the same variational principles presented in Frostig et al. (1999) but with the kinematic relations that appear in Eqs. (1-3), the governing equations can be derived for the case of lap-joint subjected to temperature and moisture changes. For brevity, these equations are not shown here, but they will appear in Agarwal et al. (2013b).

![Figure 3: Variable adhesive thickness (all units are in mm.)](image)
5.0 NUMERICAL STUDY

The geometry and material properties of the lap joint used for the numerical simulation is taken from Agarwal et. al. (2013a) and is shown in Figure 3. The thickness of the FRP and steel plates is 1.4 mm and 3 mm, respectively. The width of the joint is 25 mm, and the bonded length is 25 mm. The elastic modulus of the FRP and the steel is 165 GPa and 207 GPa, respectively. The coefficient of thermal expansion of FRP, steel, and adhesive are $9 \times 10^{-5} / ^\circ C$, $1.05 \times 10^{-5} / ^\circ C$, and $4.5 \times 10^{-5} / ^\circ C$, respectively. The coefficient of moisture expansion of FRP, steel, and adhesive are $0.32 \times 10^{-4}$, 0, and $4.5 \times 10^{-3}$ per one percent of absorbed moisture, respectively. The results are presented for a mechanical load of 1000 N that is applied after 40 F-T cycles as described in section 4.2, with $T_1 = 23 ^\circ C$, $T_2 = 38 ^\circ C$, $T_3 = -18 ^\circ C$, $t_1 = 8$ hours, and $t_2 = 24$ hours. The results are presented for three cases that include a constant adhesive thickness (case I), as well as two variable adhesive thickness profiles as shown in Figure 3 (cases II and III). For comparison, the results for a case with mechanical loading only, constant adhesive layer, and no F-T cycles (control) are also presented.

Figure 4 shows the shear stress profile in the adhesive for the cases mentioned above. The maximum shear stress is 4.7 MPa (left end) in the case of constant adhesive thickness and no F-T cycles (control). After F-T cycles, the maximum shear stress is significantly increased to 8.7 MPa (left end) in case I, and to 14.7 MPa (right end) and 18.4 MPa (left end) in cases II and III, respectively. Thus, it can be seen that the application of F-T cycles increases the shear stress in the adhesive layer, and that the location and magnitude of the maximum shear stress significantly depends upon the thickness profile of the adhesive layer, which along with the vertical normal stresses, may affect the mode of failure in steel-FRP joint.

![Figure 4: Shear stress profile in the adhesive layer with different thickness profiles](image)

The vertical normal stress profile in the adhesive layer is shown in Figure 5 for the same cases described above. The maximum stress in the control case (constant thickness and no F-T cycles) generated at the right end of the adhesive layer is 23.4 MPa (tension) at the upper interface and 5.8 MPa (tension) at the lower interface. These stresses
significantly increase to 42.5 MPa and 10.7 MPa, respectively, for case I. For case II, the maximum stresses at the upper and lower interfaces are 55.1 MPa and 6.0MPa, respectively; and for case III, these values are 30.4 MPa and 13.6 MPa, respectively. Thus, the freeze-thaw cycles, along with the adhesive thickness profile, dramatically influence the magnitude of the maximum vertical normal stresses, which can have significant effect on the bond strength and failure mode of steel-FRP joint.

Eight different adhesive thicknesses varying from 0.25mm to 2.0mm with a size step of 0.25mm were analyzed to obtain maximum shear stress and maximum vertical normal stresses before the application of 40 freeze-thaw cycles and a mechanical load of 1000 N. The maximum shear stress is normalized with respect to the maximum stress predicted for an adhesive thickness of 0.5 mm (case I), and is shown in Figure 6(a). It can be seen that the shear stress almost exponentially decreases with the increase in the adhesive thickness. Similarly, the maximum vertical normal stresses are also normalized with respect to those predicted with a 0.5 mm thickness. The normalized stresses versus adhesive thickness are shown in Figures 6b and 6c. It can be seen that the peeling stress also decreases exponentially with increasing the adhesive thickness, and becomes almost constant after the thickness of 1.5 mm.

**Figure 5: Peel stress profile in the adhesive layer with different thickness profiles.**

### 6.0 CONCLUSIONS

The influence of the adhesive thickness on the interfacial stresses in the steel-FRP lap joints has been numerically investigated using a high order theory, including the effects of freeze-thaw cycles. The influence of the freeze-thaw cycles has been introduced in terms of reduced elastic modulus of the adhesive, swelling strain in the adhesive layer due to moisture absorption, and thermal expansion/contraction of the different materials. It has been shown that the potential variation in the adhesive profile and thickness significantly affect the interfacial stresses in such type of joints, which may control the bond strength of steel-FRP lap joints that are exposed to freeze-thaw cycles. As a result, it can be concluded that the thickness of the adhesive plays a major role in the detailing of the strengthening system and in the expected failure mode of the strengthened steel structures. These observations imply that in cases of
uncertainty regarding the actual thickness of the adhesive layer (which is generally the case), the design must account for a response envelope obtained using different adhesive thicknesses and profiles rather than be limited to a single characteristic case.

Figure 6: a) Normalized maximum shear stress vs. adhesive thickness; b) Normalized maximum peeling stress at top vs adhesive thickness; c) Normalized maximum peeling stress at bottom vs adhesive thickness.

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8.0 REFERENCES

Agarwal, A., Foster, S., Hamed, E., and Ng, T. "Influence of Freeze-Thaw Cycling on the Bond Strength of Steel-FRP Lap Joints". 2013a (Submitted).


Tam, S. and Sheikh, S. "Behaviour of fiber reinforced polymer (FRP) and FRP bond under freeze-thaw cycles and sustained load". Fourth International Conference on FRP Composites in Civil Engineering, 2008.