A Model-Based Simulation of CFRP-Steel Bond Failure Using the Material Point Method

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Abstract: Based on the recent observation of CFRP-steel bond failure in the double lap shear tests, a numerical approach using the Material Point Method (MPM) is proposed in this study to simulate the delamination process of the combined CFRP/epoxy layer from steel plate. In the proposed approach, an elasto-plasticity von Mises model with linear hardening and softening laws is used to model the bonded materials. The MPM, one of the meshfree particle methods, is adopted as a robust spatial discretization method to accommodate the multi-scale discontinuities involved in the CFRP-steel system failure process. To demonstrate the potential of the proposed model-based simulation approach, a parametric study is conducted to investigate the effects of bond length and loading rate on the behaviour of CFRP-steel joint system. The simulation results not only match the available experimental data well but also provide a better understanding on the physics behind the combined CFRP/epoxy layer delamination process.

Key words: CFRP, retrofitting, steel structures, epoxy, delamination, material point method.

1. INTRODUCTION

There exist a large number of aging steel structures that may be found to be structurally unsatisfactory due to a variety of reasons such as a lack of proper maintenance, corrosion, fatigue damage, upgrading of the design standards or increase of the traffic flow. It is believed that carbon fibre reinforced polymers (CFRP) with high or ultra-high modulus are excellent candidates for strengthening and retrofitting these deteriorating steel structures, owing to their excellent mechanical, fatigue and in-service properties. The success of retrofitting steel structures by using the CFRP significantly depends on the performance and integrity of CFRP-steel joint and the effectiveness of the adhesive used. Therefore, many experimental (Fawzia et al. 2006, 2007; Schnerch et al. 2004; Colombi and Poggi 2006; Jiao and Zhao 2004; Xia and Teng 2005) and theoretical studies (Fawzia et al. 2006) have been conducted to investigate the mechanical responses of the CFRP-steel joint systems under various loading conditions. However, many of the past numerical studies (Fawzia et al. 2006; Liu et al. 2008; Teng and Hu 2007) focused on the design and structural performance of the CFRP-steel joint systems and paid limited attention to the mechanical behaviour of the adhesive layer, which results in an un-adequate understanding of how the adhesive layer between the CFRP and steel performs during the loading and failure stages. This situation is partially due to the absence of an effective interfacial debonding model for simulating the failure of CFRP-steel bond. A detailed numerical study focusing on the CFRP-steel double lap joint is thus proposed in this study to gain a better understanding of the CFRP-steel debonding failure mechanism.

Previous simulations of dynamic failure of CFRP-steel joint systems (Fawzia et al. 2006; Liu et al. 2008; Teng and Hu 2007; Wu et al. 1998; Rahimi and Hutchinson 2001; Yin and Wu 2001) were mainly performed using the Finite Element Method (FEM). The

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FEM is a mesh-based method and might have difficulties in modelling the transition from continuous to discontinuous failure modes involved in the process of CFRP delamination from steel plate. Hence, a meshless method that does not employ fixed mesh connectivity might be needed in order to better model the discontinuous failure of CFRP-steel bond under loading.

As one of the innovative spatial discretization methods, the material point method (MPM) is an extension to solid mechanics problems of a hydrodynamics code called FLIP (Brackbill and Ruppel 1986) that, in turn, evolved from the Particle-in-Cell Method dating back to the pioneering work of Harlow (1964). The motivation of the development was to simulate those challenging solid mechanics problems such as impact/contact, penetration, fragmentation and machine processing with history-dependent internal state variables (Chen et al. 2002). The essential idea is to take advantage of both the Eulerian and Lagrangian methods while avoiding the shortcomings of each. Without using the fixed mesh connectivity in the MPM, the complete decohesion or separation of material can be effectively modelled after the material strength is totally lost. Recently, much research has been carried out to improve the spatial discretization methodology proposed in the original MPM such that the MPM could be applied to more general cases, including coupled atomistic and continuum simulation and biological problems (Chen et al. 2005; Guikley and Weiss 2003; Ionescu et al. 2006; Shen 2009; Shen and Chen 2005; Tan 2003; Zhou et al. 1999). In this study, the MPM is adopted to simulate the dynamic failure of the CFRP-steel double lap system under shear loading. The main purpose of the proposed work is to validate the effectiveness of using MPM to model CFRP-steel bond failure with elasto-plasticity laws. More rigorous decohesion model could then be implemented into the MPM to better simulate the delamination of CFRP from steel plate in the future.

The remaining sections of the paper are arranged as follows. A brief introduction to the MPM is given in Section 2, which is followed by the simulation procedure adopted to model the delamination of CFRP from steel plate in Section 3. In Section 4, the numerical simulation results are first verified by the available experimental data, and then a parametric study on the effects of the bond length and loading rate will be performed to further explore the CFRP-steel joint failure process. The conclusions will be given in the last section.

2. THE MATERIAL POINT METHOD

For the purpose of simplicity, a brief description of the MPM is presented in the section. The reader is referred to (Chen et al. 2002; Sulsky et al. 1994, 1995) for more details. The MPM discretizes a continuum body with the use of a finite set of \( N_p \) material points in the original configuration that are tracked throughout the deformation process. Let \( \mathbf{x}_p^t (p = 1, 2, \ldots, N_p) \) denote the current position of material point \( p \) at time \( t \). Each material point at time \( t \) has an associated mass \( M_p \), density \( \rho_p^t \), displacement \( \mathbf{u}_p^t \), velocity \( \mathbf{v}_p^t \), Cauchy stress tensor \( \mathbf{s}_p^t \), strain \( \mathbf{e}_p^t \), and any other internal state variables necessary for constitutive modeling. Thus, these material points provide a Lagrangian description of the continuum body. Since each material point contains a fixed amount of mass unless the material point is further divided into smaller points for multi-scale modeling, the conservation of mass is automatically satisfied.

In the MPM, a background computational mesh is required to calculate the gradient terms. At each time step, the information from the material points is mapped to a background computational mesh (grid). This mesh covers the computational domain of interest, and is chosen for computational convenience. After the information is mapped from the material points to the mesh nodes, the discrete equations of the conservation of momentum are solved on the mesh nodes. The nodal solutions are then mapped back to update the internal variables associated with the material points, which completes the computational cycle within one time step. The computational mesh used in the current cycle may be discarded, and a new mesh is defined, if desired, for the next time step, in the spirit of the updated Lagrangian frame. The key feature of the MPM is the use of the same set of nodal basis functions for both the mapping from material points to cell nodes, and the mapping from cell nodes to material points. As a result, the use of the single-valued mapping functions yields a natural no-slip contact/impact scheme so that no inter-penetration would occur for penetration problems.

The weak form of the conservation of momentum can be found, based on the standard procedure used in the finite element method, to be

\[
\int_{\Omega} \rho \mathbf{w} : \mathbf{a} \, d\Omega = -\int_{\Omega} \rho \mathbf{S}^S : \nabla \mathbf{w} \, d\Omega + \int_{\Gamma} \rho \mathbf{c}^t : \mathbf{w} \, d\Gamma + \int_{\Omega} \rho \mathbf{w} : \mathbf{b} \, d\Omega
\]

(1)

in which \( \mathbf{w} \) denotes the test function, \( \mathbf{a} \) is acceleration, \( \mathbf{S}^S \) is specific stress (i.e., stress divided by mass density), \( \mathbf{c}^t \) is specific traction vector (i.e., traction divided by mass density), \( \mathbf{b} \) is specific body force, \( \Omega \) is the current configuration of the continuum, and \( \mathbf{S}^t \) is that part of the boundary with a prescribed traction. The test function \( \mathbf{w} \) is assumed to be zero on the boundary with a prescribed displacement. Since the whole
continuum body is described with the use of a finite set of material points (mass elements), the mass density term can be written as

$$\rho(x,t) = \sum_{p=1}^{N_p} M_p \delta(x - x'_p)$$

(2)

where $\delta$ is the Dirac delta function with dimension of the inverse of volume. The substitution of Eqn 2 into Eqn 1 converts the integrals to the sums of quantities evaluated at the material points; namely

$$\sum_{p=1}^{N_p} M_p \left[ w(x'_p,t) \cdot a(x'_p,t) \right] =$$

$$\sum_{p=1}^{N_p} \left[ -s^h(x'_p,t) : \nabla w \right|_{x'_p} + w(x'_p,t) \cdot c^h \right]$$

(3)

with $h$ is the thickness of the boundary layer where external stress will be applied. Usually, $h$ is chosen to be equal to one mesh size. As can be observed from Eqn 3, the interactions among different material points are reflected only through the gradient terms which necessitate the use of a background mesh. Different constitutive models (continuum or discrete) can be applied to the material points (elements) for given total strains. Complete decohesion (separation) would occur if the material strength is totally lost. In other words, a material point would be separated from the original continuum body if there is no internal interaction between the failed and the bulk material points. Because there is no fixed mesh connectivity between the material points and the background mesh in the MPM, localization and the transition from continuous to discontinuous failure modes could be effectively simulated without the difficulties associated with remeshing, which might be necessary in the conventional FEM.

3. SIMULATION PROCEDURE

In this study, the effectiveness of the MPM for investigating the failure mechanism of the CFRP-steel system is verifed by comparing the MPM simulation results with the previous experimental data of double lapped CFRP-steel system under shear loading (Fawzia et al. 2006; Fawzia 2007).

In the experiments (Fawzia 2007), three dry CFRP fabric sheets were bonded together using two 0.2-mm thick epoxy layers. The resulting combined CFRP/epoxy layers are 50 mm wide with lengths of 40, 50, 70 or 80 mm. One CFRP/epoxy combined layer was then attached to each side of two 5 mm thick, 50 mm wide steel plates using 0.2 mm thick epoxy layer, as demonstrated in Figure 1. All specimens were tested up to failure under tensile loading at the rate of 2 mm/min.

Since the total thickness of specimen (7 mm) is much smaller than its width (50 mm), it is reasonable to assume that no significant stress or strain changes will occur in the width direction under uniformly distributed load at the ends of the steel plates. Therefore, the MPM simulation could be simplified into a two-dimensional plane strain problem. Due to the symmetrical conditions in the X and Y directions, only a quarter of the CFRP-steel system is modelled in the MPM.

The MPM simulation configuration is divided into three different materials layers, namely, 2.5 mm thick steel layer, 0.2 mm thick epoxy layer, and 0.98 mm thick combined CFRP/epoxy layer, as shown in Figure 2. To make sure that there are, at least, two material point layers in each part along the thickness direction, a mesh size of 0.1 mm high and 1 mm long is chosen to descritize the CFRP-steel joint system. A constant velocity of 2 mm/min is applied to the right edge of steel plate to simulate the displacement controlled loading in the experiment.

Since the combined CFRP/epoxy layer consists of 3 CFRP sheets and 2 epoxy layers, the mechanical properties of the combined CFRP/epoxy layer are dependent on its components and their corresponding thickness. Following the work of (Fawzia et al. 2006), the equivalent mechanical properties such as strength, elastic modulus and Poison’s ratio are used in this study. For example, the equivalent modulus of the combined CFRP/epoxy layer is calculated by

$$E_{CFRP} = \frac{E_e t_e + E_f t_f}{t_e + t_f}$$

(4)

where $E_e$ and $E_f$ are the elastic moduli of the epoxy and CFRP sheet, respectively, $t_e$ the thicknesses of the epoxy, and $t_f$ the thickness of the CFRP sheet. For the purpose of simplicity, a linear elasto-plasticity von Mises model is adopted to describe steel, CFRP and epoxy. The proposed elasto-plasticity model with linear hardening and softening laws for epoxy is presented in Figure 3 and the models for the steel and combined CFRP/epoxy layer are shown in Figure 4. Since the main deformation of CFRP occurs in the fibre direction, for the purpose of simplicity, the anisotropic effect in the thickness direction is ignored and an isotropic model is adopted. The key mechanical properties of materials used in this study are given in Table 1.
4. SIMULATION RESULTS

4.1. Bond Length Effect

The MPM simulation is evaluated by comparing the simulation results with available experimental data. The load-deflection curves for 40 mm, 50 mm, 70 mm and 80 mm bond lengths obtained from the experiments (Fawzia 2007) are compared with the corresponding MPM simulations in Figures 5, 6, 7 and 8, respectively. As can be seen from the figures, for the CFRP-steel joint under loading rate of 2 mm/min, the MPM simulation results match the experimental data well. Furthermore, the MPM simulation is able to provide the unloading section of the load-deflection curve with the use of the constitutive models containing softening regime. The comparison of the ultimate loads of the steel-CFRP joints predicted by the MPM and measured in the experiment is given in Table 2. With a difference ranging from $-1.3\%$ to $7.0\%$, the simulated load carrying capacity is in close agreement with experimental measurement.

Furthermore, the numerically simulated and experimental measured distributions of the normal strain $\varepsilon_{xx}$ along the top surface of the combined CFRP/epoxy for the bond lengths of 70 mm and 80 mm at time $t = t_{\text{failure}}$ are compared in Figures 9 and 10, respectively. It is evident that the simulated strain distributions agree with those measured experimentally.

To study the bonding length effect on ultimate strength, specimens with 90 mm and 100 mm bonding...
Table 2. Comparisons of experimental data and MPM results

<table>
<thead>
<tr>
<th>Bond length L₁ (mm)</th>
<th>Test 2 mm/min</th>
<th>MPM 2 mm/min</th>
<th>MPM 20 mm/min</th>
<th>MPM 200 mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>49.90</td>
<td>51.99</td>
<td>69</td>
<td>72</td>
</tr>
<tr>
<td>50</td>
<td>69.80</td>
<td>68.9</td>
<td>78.6</td>
<td>82.4</td>
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<td>70</td>
<td>80.80</td>
<td>86.91</td>
<td>90.55</td>
<td>93.11</td>
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<tr>
<td>80</td>
<td>81.3</td>
<td>81.39</td>
<td>90.8</td>
<td>94.5</td>
</tr>
<tr>
<td>90</td>
<td>NA</td>
<td>74.14</td>
<td>87.7</td>
<td>90.3</td>
</tr>
<tr>
<td>100</td>
<td>NA</td>
<td>79.3</td>
<td>85.9</td>
<td>90.6</td>
</tr>
</tbody>
</table>

Figure 5. Comparison of load displacement behaviour of bond length 40 mm

Figure 7. Comparison of load displacement behaviour of bond length 70 mm

Figure 6. Comparison of load displacement behaviour of bond length 50 mm

Figure 8. Comparison of load displacement behaviour of bond length 80 mm

Figure 9. Normal strain distribution in the combined CFRP/epoxy layer with bond length of 70 mm

Figure 10. Normal strain distribution in the combined CFRP/epoxy layer with bond length of 80 mm
length are modelled and the failure strengths are still around the ultimate strength, as reported in Table 2 and Figures 23–24. The results from Table 2 and Figures 5–8, 23 and 24 are consistent with the Hart-Smith (1973) concept of the bond length effect on the ultimate strength, namely, as the bond length increases, the ultimate strength increases until it reaches the maximum value. After that the strength is not greatly affected by the bond length. However, the deflection at the ultimate strength will continue to increase slightly, as can be seen from Figures 22–24.

The failure pattern is very important for understanding the performance of the steel-CFRP joint system because it provides a detailed view on the evolution of the system failure. In the experiments (Fawzia 2007), there existed two main failure mechanisms, i.e., steel-adhesive interface debonding and CFRP delamination. These two types of failure are effectively simulated by the MPM, as shown in Figures 11–14 for bond lengths of 40 mm, 50 mm, 70 mm and 80 mm, respectively. Due to the extreme aspect ratio of the real specimen, the dimension in the y-direction has been enlarged by 10 times in these figures. Figures 11(a), 12(a), 13(a) and 14(a) show that the samples start to develop a distortion at the upper part of the composite layer when time \( t \) is at 90% of the complete failure time. This distortion is observed in all simulated specimens with different degree of clarity when the bond length varies.

In the 40 mm bond length case, the distortion evolves to become a full and clear delamination within the composite CFRP layer below which the distortion starts as reported in Figure 11(b). In the 50 mm and 70 mm bond length samples, the distortion evolves to become a combination of delamination within the CFRP combined layer and a rupture of combined CFRP/epoxy layer reaching the steel as presented in Figures 12(b) and 13(b). The MPM simulated failure shapes for 50 and 70 mm bond lengths match the experimentally observed failure patterns (Fawzia 2007), as shown in Figures 12(c) and 13(c), respectively. When the bond length increases to 80 mm, which is the optimum bond length according to Fawzia et al. (2006), the failure becomes a delamination pattern similar to but not as clear as that of 40 mm bond length as demonstrated in Figure 14(b).

It can be seen from Figures 19–24 that the deflection corresponding to the ultimate load increases with the bond length. In other words, the failure is brittle, but the ductility of the system slightly increases as the bond length increases. As the epoxy layer length increases, the effectiveness of transferring the stress from steel plate to the CFRP layer increases due to a high ductility of the epoxy layer compared with CFRP layer. The change of the failure mode from delamination to rupture failure is due to the different stress distribution along the bond length direction. Figures 15–18 demonstrate the ratio of shear stress \( \tau_{xy} \) to the maximum stress that the epoxy can reach along the bond length direction at time \( t = 0.9t_{\text{failure}} \) and \( t = t_{\text{failure}} \) for bond lengths of 40 mm, 50 mm, 70 mm and 80 mm respectively. The straight part of the 0.9t failure curve indicates that the stresses have been fully transferred from steel plate to CFRP layer. The shear stress is more evenly distributed in the short bond specimen than that in long bond specimen. Therefore, the shear stress will be evenly distributed along the bond length, which allows the material points in the epoxy layer to reach the failure stress almost simultaneously, as shown in Figure 15, and leads to a clear delamination as can be observed in Figure 11.

For the specimen with longer bond, the maximum shear stress is reached before the shear stress is evenly distributed along the bond length, as presented in Figures 16–17, which will lead to a rupture failure at the stress concentration point. This point (around 25 mm from the steel edge for the 50 mm bond length specimen and 30 mm for the 70 mm bond length
specimen) acts as a separation point that stops the stress redistribution, which leads to the build up of stress before it and the disappearance of stress after it. Therefore, failure occurs due to stress concentration on the bonding length before this point. This point is clearly verified when the stress distribution line changed from straight to a curved line in Figures 15–18. For the even longer bond length (80 mm), the shear stress will first concentrate at approximately 30 mm from steel edge, and then cause a local rupture failure.
4.2. Loading Rate Effect

The mechanical behaviour of CFRP is known to be loading rate sensitive (Jiang et al. 2006). Hence, it is important to understand the effect of loading rate on the failure mechanism of CFRP-steel joint system. In this study, the MPM is used to study loading rate effect on the ultimate load and failure mode of CFRP-steel systems with 40, 50, 70, 80, 90 and 100 mm bond lengths. The simulated loading rates are 2, 20 and 200 mm/min.

Figures 19–24 show the load-deflection curves of the CFRP-steel system under different loading rates for 40, 50, 70, 80, 90 and 100 mm bond length, respectively. For 40 mm bond length, when the loading rate increases from 2 mm/min to 20 mm/min, the ultimate load increases by more than 35%, when the loading rate increases further to 200 mm/min, however, no significant increase of the ultimate load is at that point. However, the un-delaminated part of the bond will be long enough to allow for stress redistribution and to cause delamination, as can be seen in Figure 18.

Figure 18. Shear stress distribution along 80 mm bond length samples at the failure layer
results indicate that the Hart-Smith (1973) concept about the existence of the optimum bonding length holds regardless of the loading rate. Figure 25 shows that for all the simulated bond lengths there is a loading rate which corresponds to a maximum strength. Beyond this rate, the maximum strength will not be greatly affected by the loading rate. This loading rate is around the 20 mm/min for the modelled specimens.

observed. This pattern will repeat for longer bonding lengths as reported in Table 2. The ultimate strength increases by 8-18% as the loading rate increases from 2 to 20 mm/min. It will slightly increase as the loading rate increases from 20 to 200 mm/min. As the bonding length increases, the effect of loading rate increase decreases until it reaches a stable range as the bond length reaches the effective bonding length. These
5. CONCLUSIONS

A double lap CFRP-steel system under shear loading is simulated using elasto-plasticity material models within the framework of the MPM. In this study, the effects of bond length and loading rate on the load carrying capacity and failure mode of the CFRP-steel joint system is investigated. The simulated load-deflection curves and normal strain distributions in the combined CFRP/epoxy layer well match the available experimental data.

It is observed from the simulation results if the bonding length is short enough, the development of the failure mode of the CFRP-steel joint system will be a “clear” delamination without any rupture within the layer. As the bond length increases, the failure mode starts to become a mixed delamination and rupture within the combined CFRP/epoxy layer. For a given CFRP-steel system there is an optimum loading rate.

The parametric study on the effects of bond length and loading rate demonstrates that the proposed model-based simulation procedure with the framework of the MPM is able to capture the essential failure mechanism of the CFRP-steel joint system under shear loading. To better study the delamination process of CFRP from the steel plate, a bifurcation-based decohesion model is currently being developed and will be implemented into the MPM in the future.

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