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BOND AND SPLICE BEHAVIOR OF HIGH MODULUS CFRP MATERIALS BONDED TO STEEL STRUCTURES

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ABSTRACT
Research on the use of CFRP materials for retrofit and strengthening of steel bridges and structures has increased in recent years. In order to implement these types of strengthening systems to longer span members, it is important to establish an effective method to splice adjacent lengths of CFRP laminates. This paper describes an experimental program to investigate the bond behavior of carbon fiber reinforced polymer (CFRP) laminates with the objective of developing an effective bonded splice joint. The experimental program was conducted in two phases. In the first phase, the effectiveness of three different CFRP splice joint configurations was evaluated using double lap shear coupon tests. In the second phase, steel beams were strengthened with CFRP laminates which incorporated a bonded splice joint located at the midspan of each of the beams. The test results demonstrate that debonding of the CFRP splice plate was the primary mode of failure for the tested joints. The research also indicated that the use of a reverse tapered joint configuration can significantly increase the splice joint capacity. The findings indicate that careful detailing can significantly increase the capacity of bonded CFRP splice joints.

KEYWORDS
CFRP, steel bridges, splice joints, bond behavior, reverse taper

1. INTRODUCTION

Recently, considerable research has been conducted on the use of carbon fiber reinforced polymer (CFRP) materials for rehabilitation and strengthening of steel bridges and structures (Al-Saidy et al., 2005, Mertz & Gillespie, 1996, Sen et al., 2001, Tavakkolizadeh and Saadatmanesh, 2003). The previous research indicates that externally bonded CFRP laminates can be used to increase the ultimate strength of steel girders and to restore the lost capacity and stiffness of damaged or deteriorated girders. However, due to the relatively low modulus of elasticity of conventional CFRP materials as compared to steel, large amounts of strengthening materials are required to achieve a significant increase of the elastic stiffness. The use of high modulus CFRP (HM CFRP) materials has been demonstrated to be a more effective technique to increase the stiffness of steel beams (Rizkalla and Dawood, 2006).

Similarly to reinforced concrete beams, for steel beams reinforced with externally bonded CFRP materials, the bond stresses at the interface between the beam and the strengthening materials, including both shear and peeling components, must be carefully considered to prevent premature debonding failures (Buyukozturk et al., 2003). Bond stresses are particularly critical at lap-spliced connections between CFRP laminates. The behavior of these splices is dramatically affected by the bond behavior and the bond stress distribution between CFRP laminates. There have only been a limited number of studies which investigate the behavior of spliced connections of CFRP laminates under flexural loading. Stallings and Porter tested eight reinforced concrete beams strengthened with various configurations of externally bonded CFRP splice joints (2003). They recommend that in order to prevent debonding of the CFRP splice plate, the maximum strain in the main CFRP plate immediately prior to the splice should not exceed a limiting value. To the authors knowledge there have not been any studies investigating the splice behavior of steel beams reinforced with CFRP laminates.

2. EXPERIMENTAL PROGRAM

An experimental program was conducted in two phases to investigate the bond and splice behavior of CFRP laminates. In the first phase three different configurations of double-lap shear coupons, shown schematically in Figure 1(a) – (c), were tested. The objective of the first phase was to determine the effectiveness of implementing a reverse taper detail at various critical locations throughout the spliced joint. The splice coupons were 35 mm wide and were fabricated from 4 mm thick CFRP laminates with a modulus of elasticity of 460 GPa and an ultimate strain of 0.00334 as reported by the manufacturer. For all three joint configurations, strains were measured at various locations along the splice joint using electrical resistance strain gauges.

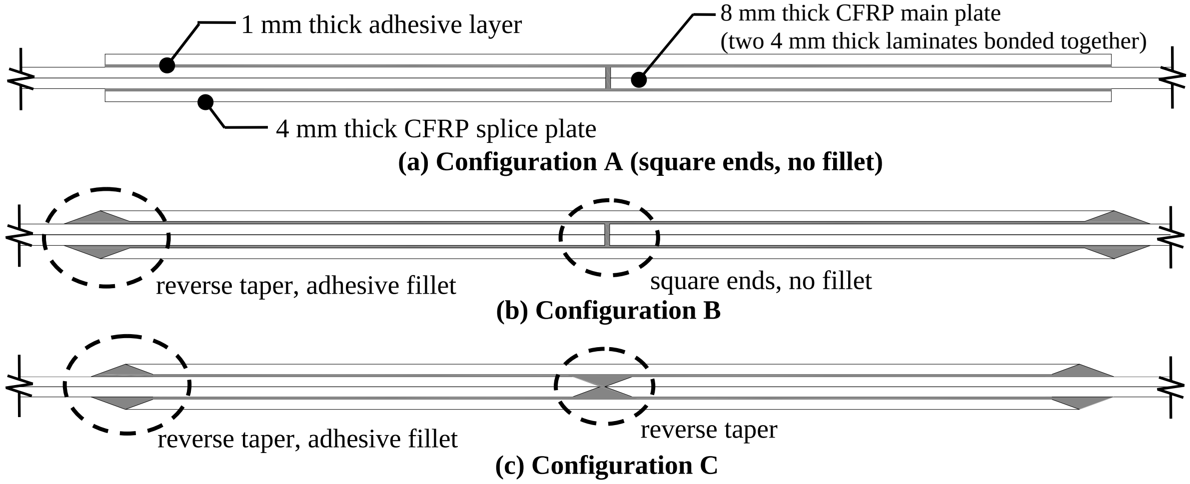

Figure 1: Double-lap shear coupon joint configurations and instrumentation

In the second phase of the experimental program, two steel beam tests were conducted to investigate the behavior of spliced joints under flexural loading conditions. The typical test beam is shown schematically in Figure 2. The beams each consisted of a standard wide-flange steel beam. A steel channel was welded to the top flange of the steel beam to simulate the presence of a reinforced concrete deck. The test beam was strengthened by bonding a 100 mm wide by 4 mm thick HM CFRP laminate to the tension flange. The laminate was left discontinuous at the midspan of the beam as shown in Detail A of Figure 2. Continuity of the strengthening system was provided by bonding an 800 mm long CFRP splice plate at the joint location which overlapped 400 mm on either side of the CFRP main plate. All of the plate ends were left square without incorporating a reverse taper to serve as a reference for future tests which will incorporate different joint details. Due to the high level of uncertainty associated with the bond behavior, two such beams were tested to provide repeated test data for a given splice configuration. The strengthened beams were loaded monotonically to failure in four point bending using a hydraulic actuator. The longitudinal strain in the CFRP splice plate and the main plates was measured at several locations using electrical resistance strain gauges.

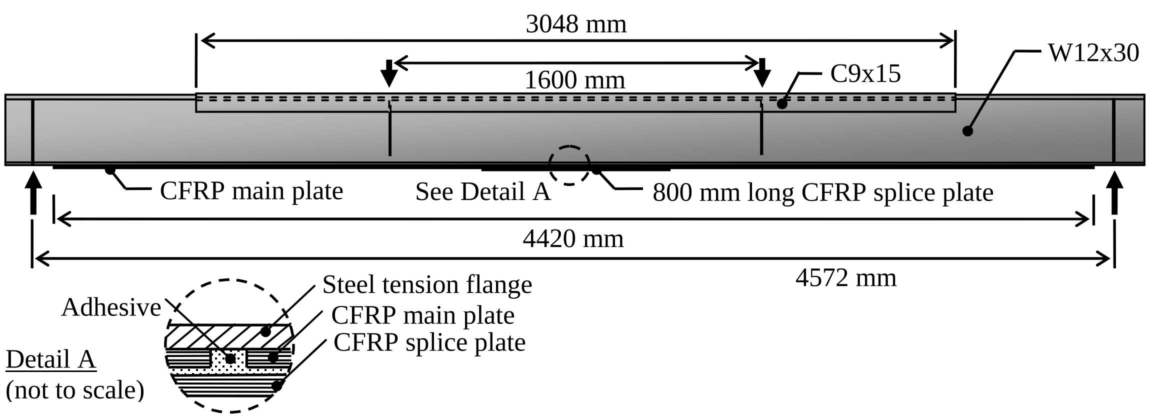

Figure 2: Typical steel test beam configuration

3. EXPERIMENTAL RESULTS

The measured load-strain behavior at the surface of the splice plate at the center of the joint is shown for the three double lap-shear joint configurations in Figure 3. The initial stiffness of all three joint configurations was similar up to a load level of 40 kN. At the 40 kN load level a sudden increase of the measured strain was observed for joint configurations A and B which was likely due to cracking of the adhesive due to a stress concentration near the square plate end within the center of the joint. Cracking of the adhesive resulted in a corresponding loss of stiffness of the joint as shown in Figure 3(a). Joint C did not exhibit a similar increase of strain which suggests that cracking did not occur and that the reverse taper was effective in reducing the stress concentration near the plate end. Joint A failed suddenly due to debonding of the CFRP splice plates at a load level of 90 kN. Failure occurred primarily by separation of the adhesive from the CFRP laminates as shown in Figure 3(b). Joint B exhibited additional cracking at a load level of 144 kN and ultimately failed by debonding of the splice plates at a load level of 160 kN. Joint C failed at a load level of 190 kN suddenly due to debonding of the splice plates and did not exhibit any cracking throughout the entire loading range. The experimental results demonstrate that the presence of the reverse taper and the adhesive fillet details can approximately double the capacity of a bonded splice joint.

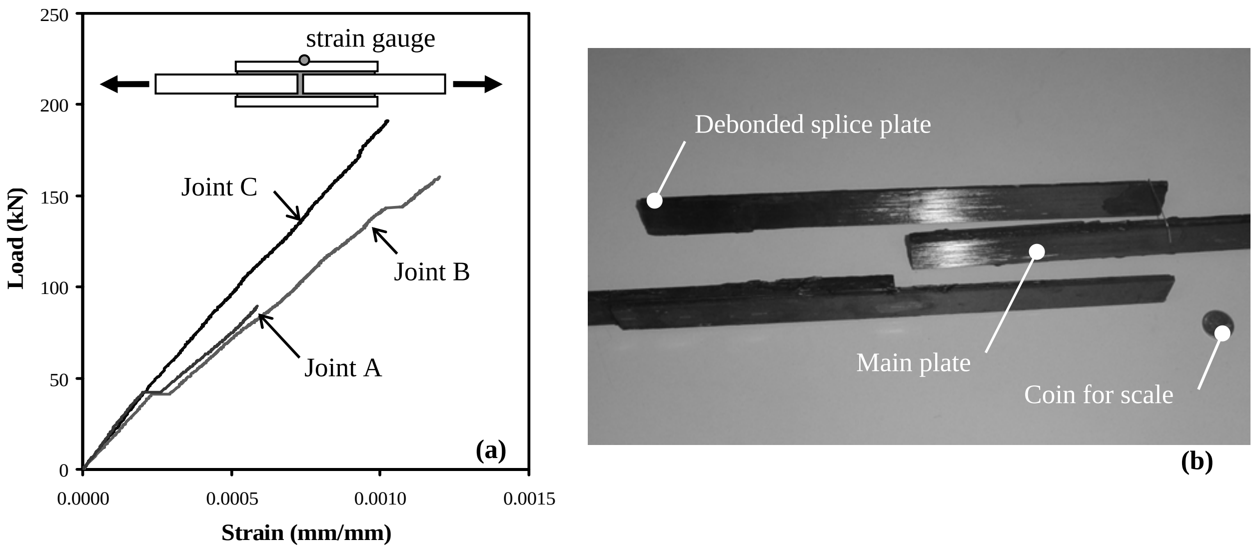

Figure 3: (a) Measured load-strain behavior for double-lap shear coupon tests (b) Debonding failure

Failure of the two tested beams occurred due to debonding of the splice plates prior to yielding of the tension flanges of the steel beams. The total measured load immediately prior to debonding was 177 kN and 205 kN for each of the beams respectively which corresponds to approximately 37 percent and 43 percent of the estimated yield load of the strengthened beams, respectively. The yield load was determined based on a non-linear moment curvature analysis. The longitudinal strain distribution along the length of the splice plate, which was measured during the second beam test, is shown in Figure 4(a) for various load levels. The measured strain profile from the first test closely matched that shown in Figure 4 and therefore is not presented in this paper.

The average shear stress along a given interval of the adhesive layer can be determined from the measured strains by considering equilibrium of forces and is proportional to the slope of the strain profile. The calculated bond shear stress distribution along the length of the splice plate is shown in Figure 4(b). Significant shear stress concentrations were calculated at localized regions near the end of the CFRP splice plate and near the center of the splice joint which can be observed in Figure 4(b). The maximum calculated shear stress in the adhesive at a load level of 205 kN was 20 MPa near the end of the CFRP splice plate and 7.3 MPa near the center of the splice. At the same load level, the calculated shear stress at a distance of 200 mm to 300 mm away from the splice plate end was only 0.9 MPa. This significant concentration of stresses near the plate ends is likely the cause of the premature debonding failure which was observed during both flexural tests. This highlights the need to investigate various details to help reduce the stress concentration near the plate ends.

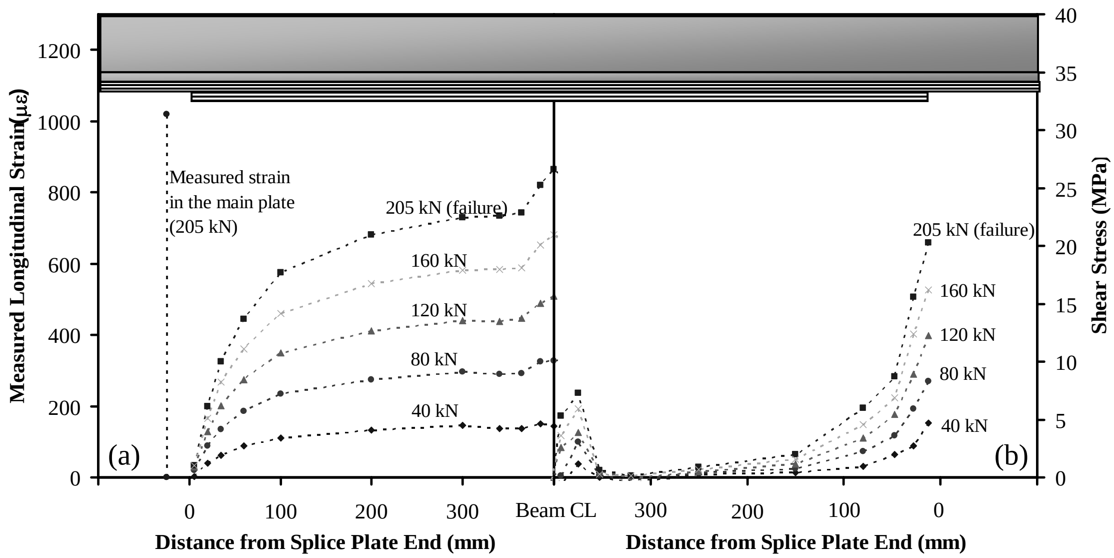

Figure 4: (a) Measured splice plate longitudinal strain (b) Calculated adhesive shear stress

4. CONCLUSIONS

This paper describes an experimental program which was conducted to investigate the bond and splice behavior of CFRP laminates. Initial lap-shear coupon test results indicate that a reverse tapered detail near plate ends can significantly reduce the bond stress concentrations at these locations and consequently increase the ultimate capacity of the spliced joints. The results of the beam tests indicated the presence of significant stress concentrations near the plate ends which resulted in premature debonding failure of the CFRP splice plates.

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