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Recent Developments in FRP Strengthening of Metallic Structures

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ABSTRACT: This paper presents a summary of the recent developments in FRP (Fibre Reinforced Polymer) strengthening of metallic structures. It includes bond behavior, strengthening of flexural members (steel, composite steel-concrete, hybrid sections), compression members (circular or square hollow sections, open sections, concrete-filled tubular sections, hybrid sections), web buckling (rectangular hollow sections, lightsteel beams, open section beams), fatigue resistance and connections.

1 INTRODUCTION

FRP (Fibre Reinforced Polymer) has a potential in strengthening structures such as bridges, offshore platforms, large mining equipment and buildings. It has been widely used to strengthen concrete structures (Teng et al. 2002, Oehlers and Seracino 2004). The use of such advanced material to strengthen metallic structures has become an attractive option (Hollaway and Cadei 2002, Shaat et al. 2004, Zhao and Zhang 2007). Examples include the I-704 Bridge in Newark, Delaware, USA (Miller et al. 2001), the Boots building in Nottingham, the Tickford bridge in Newport Pagnell, and the King Street railway bridge in Mold, UK (Hollaway and Cadei 2002), aluminum overhead sign structures (Pantelides et al. 2003, Fam et al. 2006).

This paper presents a summary of the recent developments in FRP strengthening of metallic structures. It includes bond behavior, strengthening of flexural members and compression members (steel, composite steel-concrete, hybrid sections), web buckling (rectangular hollow sections, lightsteel beams, open section beams), fatigue resistance and connections. The existing research and main findings are presented. Future research is pointed out.

2 BOND BEHAVIOR

2.1 Existing research and main findings

Bond behavior between normal modulus CFRP (carbon fibre reinforced polymer) laminate and steel was studied by Xia and Teng (2005), whereas bond between CFRP sheet (both normal modulus and high modulus) and steel was studied by Fawzia et al. (2006, 2010). Five failure modes were classified in Zhao and Zhang (2007). The failure mode in CFRP laminate specimens depended on the adhesive thickness and material properties. The failure mode in CFRP sheet specimens depended mainly on the modulus of CFRP sheet, e.g. CFRP rupture for high modulus CFRP sheet. Bond-slip model was established by Xia and Teng (2005) and Fawzia et al. (2010).

The influence of temperature (ranging from -40°C to 60°C) on bond behavior was studied by Al-Shawaf et al. (2006, 2009). It was found that the bond strength does not change under sub-zero temperatures. However the bond strength reduced significantly when the temperature approached the glass transition temperature. The effect of fatigue loading on bond strength was investigated by Liu et al. (2010). The influence is insignificant for high modulus CFRP sheet, whereas a reduction of 20 to 30% was found in bond strength for normal modulus CFRP sheet.

2.2 Future work

Research is needed to verify the bond between ultra high modulus (UHM) laminates and steel plate (Wu et al. 2010). The influence of large deformation cyclic loading, impact loading and surface conditions on bond behavior requires further investigation. Research is being conducted by Nguyen et al. (2010) to predict bond strength and effective bond length at elevated temperatures using a mechanism-based model which considers the kinetic modeling of glass transition of adhesives. More research is needed to study the durability of bond between CFRP and steel.

3 STRENGTHENING OF FLEXURAL MEMBERS

3.1 Existing research and main findings

Photiou et al. (2006) performed tests on artificially degraded rectangular hollow section beams repaired by CFRP and GFRP (glass fibre reinforced polymer). All the upgraded beams reached the plastic collapse load of the original undamaged RHS beams. CFRP strengthening of circular hollow section (CHS) was conducted by Haedir et al. (2009). It was found that the longitudinal CFRP layers contributed more to the increase in moment capacity, whereas the hoop layers played a more important role in restraining or delaying the local buckling. Similar work was done by Seica and Packer (2007), where curing of the specimens was performed both in air and in seawater, the latter simulating the conditions for underwater application to offshore structures. A slightly lower increase in the ultimate moment capacity was observed for specimens cured in seawater.

Lanier et al. (2009) conducted tests on steel monopoles strengthened with high modulus CFRP sheet. The ultimate load capacity increased by 20% and the stiffness within the elastic region increased from 13 to 64%. Teng et al. (2007) established a new double skin hybrid section which contains a CFRP outer tube and a steel inner tube surrounded by concrete. Li et al. (2007) developed a new composite beam which consists of a perforated steel tube confined by a layer of FRP. Concrete is poured into such beams. Test results showed that the grid tube encased specimens led to higher specific strength and ductility than the solid steel tube encased counterparts.

CFRP strengthening of steel I-beams was performed by Miller et al. (2001), Lenwari et al. (2005, 2006), Colombi and Poggi (2006a), Linghoff et al. (2010). The increase in elastic stiffness ranged approximately from 10 to 35% and the strength from 15 to 25%. Schnerch and Rizkalla (2008) indicated that further increase may be achieved through prestressed CFRP. Lenwari et al. (2005, 2006) demonstrated that the length of CFRP plates affected the failure mode. Debonding at the steel-adhesive interface was observed for short CFRP plates, whereas CFRP rupture occurred for long CFRP plates.

Research was performed on damaged steel-concrete beams strengthened by CFRP (Sen et al. 2001, Tavakkolizadeh and Saadatmanesh, 2003a, Al-Saidy et al. 2004, Fam et al. 2009). Sen et al. (2001) introduced the damage by preloading the beams beyond the yield strength of the tension flange. Damage was simulated by removing part of (25% to 100%) the tension flange from the steel beam in other testing programs. Strength of damaged (up to 75%) beams was fully restored to its original undamaged state. About 80% of strength was restored for 100% damage case (Fam et al. 2009).

3.2 Future work

There is a need to develop consistent closed-form solutions for flexural members strengthened by CFRP. Numerical simulation may be utilized to identify key parameters for design formulae.

4 STRENGTHENING OF COMPRESSION MEMBERS

4.1 Existing research and main findings

Teng and Hu (2007) investigated the enhancement in ductility of compression members for seismic resistance. Tests were conducted on CHS (circular hollow section) tubes reinforced with varying layers of GFRP sheet. The ultimate load increased only 5 to 10%. Cylindrical shell structures, such as tanks or silos, can be subjected to axial compression coupled with high internal pressure. Batikha et al. (2009) performed experimental testing and FE analysis on such type of cylindrical shell strengthened with CFRP and GFRP. It was found that the length of the buckle decreased as the elastic modulus of the FRP increased. They also showed that increases in strength can be achieved by placing only a small amount of FRP at a critical location on the structures. This strengthening is dependent on the thickness and the height of the composite material.

Shaat and Fam (2006) studied short and long SHS (square hollow section) columns strengthened with CFRP. The parameters tested included the number of layers, the type of CFRP and the fibre orientation. Failure of retrofitted SHS columns was via overall buckling followed by secondary local buckling associated with delamination and crushing of the CFRP. The increase in strength was found to be about 13 to 23%. More gains were obtained for specimens with higher slenderness ratio. Shaat and Fam (2007) performed FE analysis to study the effect of imperfection. The higher the imperfection was, the higher the lateral displacement was. However, the percentage gain in axial strength was mostly independent of the imperfection level. The slenderness ratio also determines how much strength is gained. Bambach and Elchalakani (2007) carried out quasi-static tests on CFRP reinforced SHS under large deformation axial compression. Different combinations of longitudinal and transverse fibers are adopted. Multiple folding mechanisms were observed with an increased ultimate strength and energy absorption. Plastic mechanism analysis was used to predict the unloading curves. This work was extended to impact loading by Bambach et al. (2009a, 2009b).

Xiao et al. (2005) studied FRP confined CFT (concrete-filled tubes). Shan et al. (2007) performed an investigation on confined CFT under high speed impact. The maximum axial and circumferential strains developed in confined CFT specimens were 27 to 40% that of standard CFT cylinders. Research has recently been undertaken to determine the effectiveness of using FRP composites to repair damaged CFT, particularly for damage due to fire exposure. The reinforcing of fire-exposed CFT has been studied in stub-columns, beams and beam-columns (Tao et al. 2008). These results indicated that CFRP is best suited only for specimens with low exposure to fire. Teng et al. (2007) developed a hybrid FRP–concrete–steel double-skin tubular column. The test results confirmed that the concrete in the new column is very effectively confined by the two tubes and the local buckling of the inner steel tube is either delayed or suppressed by the surrounding concrete, leading to a very ductile response.

Silvestre et al. (2008) performed experimental and numerical investigations on the local, distortional and global buckling behaviour of CFRP-strengthened cold-formed steel lipped channel columns. It was found that failure was mainly via local or distortional buckling, followed by debonding of the CFRP. The strength increase was up to 15% for short columns and 20% for long columns. Harries et al. (2009) determined whether the application of FRP could improve local and global buckling of welded T-sections. It was concluded that whilst a minimal improvement is seen for global elastic buckling in longer sections, local inelastic behaviour is enhanced with FRP.

4.2 Future work

There is a need to conduct more tests to cover wider ranges of parameters, such as steel tubular section sizes, CFRP modulus, adhesive types and thickness, strain rate. Theoretical models are needed to predict CFRP strengthened steel or CFT or double skin tubular columns under various loading conditions.

5 STRENGTHENING OF WEB BUCKLING

5.1 Existing research and main findings

The web crippling failure becomes critical at the loading points or supports of beams where concentrated bearing forces are applied. Research has been conducted on FRP strengthening of thin-walled sections subject to end bearing forces, e.g. RHS (rectangular hollow sections) by Zhao et al. (2006), LSB (LightSteel Beam) by Zhao and Al-Mahaidi (2009), I-sections and channel sections by Zhao (2009), and aluminum RHS by Islam and Young (2010), Zhao and Phiphat (2010). In the testing programs a wide range of web depth-to-thickness ratios were included. Various strengthening schemes were adopted, such as applying CFRP outside or/and inside the steel sections. Significant increase (1.5 to 5 times) in load carrying capacity was achieved especially for those with large web depth-to-thickness ratio. The main reasons for the improved behaviour are the increased restrains again web rotation and the change of failure mode from web bucking to web yielding. Design formulae were proposed to predict the improved web buckling capacity, which is similar to those for un-strengthened webs with different effective length factor.

5.2 Future work

Most of the work completed so far was on steel sections subject to end bearing forces. There is a need to investigate the interior bearing case, where the distance between the point of loading and the edge of the section is greater than 1.5 times the overall depth. There is a lack of detailed FE simulation of web buckling with FRP strengthening. The proposed design formulae are rather simplistic. More sophisticated theoretical models are needed to predict more accurately the web buckling capacity.

6 STRENGTHENING OF FATIGUE RESISTANCE

6.1 Existing research and main findings

Studies on fatigue crack propagation in steel members strengthened by CFRP plates were carried out by Jones and Civjan (2003), Colombi et al. (2003), Tavakkolizadeh and Saadatmanesh (2003b) and Suzuki (2004). Slightly different strengthening layout was adopted by different researchers. The elastic modulus of CFRP in the studies ranged from 144 GPa and 174 GPa. Significant increase in fatigue life or decrease in crack propagation rate was observed. It was also found that pretension of CFRP gave even better results (Jones and Civjan 2003, Colombi et al. 2003).

CFRP sheets were utilized for fatigue strengthening by Liu et al. (2009a). Both normal modulus (240 GPa) and high modulus (640 GPa) CFRP sheets were used. Beach mark technique was adopted to study fatigue crack propagation. Two-sided repair increased the fatigue life up to about 2.7 times when normal modulus CFRP sheets were applied and up to about 8 times when high modulus CFRP sheets were used. Fracture mechanics approach was applied by Liu et al. (2009b) to two-side repaired steel plates. Liu et al. (2009c) conducted BEM analysis of cracked steel plates repaired with CFRP using BEASY software. Both fracture mechanics and BEM analysis agreed reasonably well with the experimental results.

Dawood et al. (2007) conducted fatigue tests on steel-concrete composite beams strengthened with CFRP. The load level is between 30% and 60% of the yield strength of the unstrengthened beam. All beams, including both strengthened and unstrengthened sections, showed a 5% loss of stiffness when subjected to the fatigue cycles. However, whilst the strengthened beams had only a 10% increase in deflections, the unstrengthened beam had a 30% increase in deflection.

6.2 Future work

Ultra high modulus (UHM, 460 GPa) CFRP plates have recently become available (Wu et al. 2010). Research is needed to study the effect of fatigue loading on bond strength between steel and UHM CFRP plate, and the increase in fatigue life if such UHM CFRP plates are used.

Most of the studies described in Section 6.1 were based on idealized cracks in steel members. Studies are needed to investigate the behaviour of crack propagation in welded specimens where residual stresses and boundary conditions may play an important role. Typical welded connection types may include those identified in plate girder and box girder bridges, steel orthotropic bridge, structural systems in undercarriages of motor vehicles and trailers and truss bridges with cast steel joints. Some preliminary results can be found in Chen et al. (2010) and Xiao et al. (2010).

7 STRENGTHENING OF CONNECTIONS

7.1 Existing research and main findings

Jiao and Zhao (2004) investigated the behaviour of CFRP strengthened butt-welded very high strength (VHS) circular steel tubes. There is a significant (up to 50%) strength reduction in the HAZ (heat affected zone) of VHS tubes after welding. Significant strength increase was obtained for CFRP strengthened butt-welded VHS tubes. The full yield capacity of VHS steel tubes was recovered when the bond length reaches about 50 mm.

GFRP was used to repair cracked aluminum welded K-joints by Pantelides et al. (2003). For field samples the cracks in the welds ranged from 24 to 66% of the total welded length whereas for the fabricated specimens the chord were entirely separated to simulate a crack extending the total length of the weld. The GFRP composite retrofitted field connections reached capacities about 20% higher than that of the welded aluminum connection with no visible cracks. The fabricated specimens with GFRP retrofitting reached capacity of 95 to 99% of the welded aluminum connection with no visible cracks. A similar study was carried out by Fam et al. (2006) on using CFRP and GFRP to repair cracked aluminum welded K-joints. The cracking was simulated by grinding the welded perimeter at the intersection between diagonals and main chord to simulate a 90% loss of weld. It was found that the use of CFRP restored the full strength of the welded joints whereas the GFRP restored about 80% of the capacity. Nadauld and Pantelides (2007) focused on the fatigue performance of GFRP-strengthened aluminium connections. The repaired connections exceeded the fatigue limit of the aluminium welded connections with no known cracks.

Colombi and Poggi (2006b) obtained preliminary results on the behaviour of strengthened connections by investigating the static behaviour of reinforced bolted joints. It was concluded that an increase in the failure load can be induced by CFRP reinforcing.

7.2 Future work

Further study is needed for strengthening bolted connections. There is a need to develop strengthening techniques for welded steel tubular connections subjected to various loading conditions. Theoretical modeling and numerical simulation are also necessary.

8 CONCLUSIONS

This paper presented a summary of the recent developments in FRP strengthening of metallic structures. It covered the following areas: bond behavior, strengthening of flexural and compression members, improved web buckling capacity and fatigue resistance, and connections.

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