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Comparative study of failure mechanisms in steel and concrete members strengthened with CFRP composites

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ABSTRACT: Over the last decade advanced composite materials, like carbon fibre reinforced polymer (CFRP), have increasingly been used in civil engineering infrastructure. The benefits of advanced composites are rapidly becoming evident. This paper focuses on the comparative performance of steel and concrete members retrofitted by carbon fibre reinforced polymers. The objective of this work is a systematic assessment and evaluation of the performance of CFRP for both the concrete and steel members available in the technical literature. Existing empirical and analytical models were studied. Comparison is made with respect to failure mode, bond characteristics, fatigue behaviour, durability, corrosion, load carrying capacity and force transfer. It is concluded that empirical expressions for the concrete-CFRP composite are not readily suited for direct use in the steel-CFRP composite. This paper identifies some of the major issues that need further investigation.

1 INTRODUCTION

Modern advanced composites have been in use since World War II. The ability to design the materials, coupled with high strength-to-weight ratio, allow engineers to maximize material usage for specific applications. While many studies have been conducted on the repair and strengthening of concrete structures using advanced composites [Teng et al 2002, Hollaway & Leeming 1999], only a very limited amount of research has been conducted on the application of these materials to steel structures [Moy 2001, Hollaway & Cadai 2002]. This paper evaluates the performance differences of CFRP for the concrete and steel members which have been reported in the technical literature. Further, the paper discusses the non-applicability of the existing knowledge of the CFRP-concrete systems to the CFRP-steel systems.

2 COMPOSITES IN STEEL AND CONCRETE STRENGTHENING

The common FRP composites, namely GFRP,CFRP and Aramid composites, have been used for strengthening RC structures in both practical application and research. These three FRP materials have comparable stress-strain behaviour: linear elastic up to final brittle rupture when subjected to tension. This is a very important property in terms of structural use of FRP composites. Typical stress strain curves for CFRP, GFRP, concrete and steel show the brittle behaviour of FRP composites and concrete and the ductile behaviour of steel. This has two major structural consequences. First, these materials do not possess the ductility of steel, and second, owing to this lack of ductility, the redistribution of stresses in FRP composite is restricted. Consequently, the methods used to strengthen steel structures with CFRP composite cannot be the same as existing methods for strengthening RC structures.

The upgrading or retrofitting of steel structures is not as widespread as the upgrading or retrofitting of RC structures, as it poses a different and a more complex set of problems [Mertz & Gillespie 1996, Mertz et al. 2001]. First, the likelihood of lateral buckling makes it necessary to fabricate composite steel sections where the compression flange is continuously supported by a reinforced concrete slab. Second, the high strength and stiffness of steel make it a more difficult material to strengthen, especially with high-strength carbon-fiber-reinforced polymers (CFRP). For a given allowable strain, CFRP reinforcement will work at a lower stress than steel, unless the steel is allowed to yield under certain load and geometry conditions. Finally, the CFRP/adhesive bond is generally the weakest link and is likely to control the mode of failure. Epoxy adhesive is much weaker than steel, and nonlinear finite element analyses have indicated [Sen et al. 2001] that the epoxy adhesive may fail at the ends of the CFRP plates, owing to high peeling stresses.

3 DIFFERENCES BETWEEN CONCRETE AND STEEL STRUCTURES STRENGTHENED WITH CFRP

Technically it is possible to compare CFRP strengthened concrete structures with CFRP strengthened steel structures, as some of the aspects are common to both although there are many differences. However, CFRP with steel bonding should not be thought of as simple as CFRP with concrete bonding since the two materials, concrete and steel, are completely different, their strengthening process with CFRP is somewhat different. A brief comparison is made below.

3.1 Material properties

The Young's modulus of CFRP is about 6 times that of concrete whereas the Young's modulus of CFRP is up to 2 or 3 times that of steel. Ohelers (2000) compared the material properties of steel with FRPs. It is evident that the peeling mechanism of RC structures strengthened by FRP plates and by steel plates is the same but the load at which peeling occurs differs due to the difference in the material properties. For the same reason the composite action between CFRP and steel would be different compared to that of CFRP and concrete structures. In concrete structures the CFRP can be kept thin because of the very favorable stiffness of CFRP compared to concrete and also because the bond strength between CFRP and concrete is limited by the concrete rather than the adhesive. In steel structures the CFRP strips have to be thicker because the stiffness of CFRP will be high and the stiffness has to be transmitted across the adhesive. Another concern is in regard to Poisson’s ratio. Poisson’s ratio for the CFRP and the steel structures are different which can cause edge failures [Mertz & Gillespie 1996].

3.2 Surface Preparation

Previous studies have shown that for an effective adhesive bonding process either with a concrete or steel surface, a fresh, chemically active surface is essential [Laura et al 2001, Hollaway & Cadei 2002]. Surface preparation may be achieved chemically by etching or by abrasion. There are three types of abrasion, namely hand abrasion, grinding with stone and mechanical abrading. Hand abrasion is less efficient than other abrasion. In the case of concrete structures usually abrasion pad is used which can trap contaminants and moisture. However, in case of steel tubes mechanical abrasion is used and found to be more effective [Fawzia et al.2004] because of the non-contact process.

Surface preparation of the steel substrate is very important if a good bond is to be achieved between the steel and the CFRP. The choice of bonding method is also important. The obvious approach is to use a suitable adhesive applied to the bonding surfaces. The choice of glue is more critical for steel structures than for the concrete structures.

3.3 Force transfer

It is evident from the literature that how the force transfer takes place between adhesive and adherends is a very wide subject. It is important because the rate of force transfer and the corresponding development length affect the length and position of the CFRP. Many investigations have been carried out to evaluate the bond force transfer in the case of the concrete structure strengthened with CFRP [Chajes et al. 1996]. The test results concluded that strain distribution in the composite plate along the bonded length decreases at a fairly linear rate, which means that the force transfer is largely uniform. This leads to a constant value of bond resistance. In the case of bond force transfer in steel members, Miller (2000) have discussed experimental and analytical studies to quantify force transfer. The test result concluded that 98% or more of the force transfer between the steel and CFRP plates occurs within 100mm. They also showed that the force transfer across bonded plate-to-plate interface may reduce the required force transfer distance. An analytical model of the bonded joint was also used to investigate the adhesive shear stress and CFRP strain distribution. This research only focused on the sustained loads. More research is needed under varying environmental conditions subjected to static and cyclic loads.

3.4 Environmental effects

The effect of environmental conditions on debonding failure is different for CFRP-steel system [Stehn & Hedman 2001] compared to that for CFRP-concrete system [Malvar et al. 2003, Karbhari 2002]. Concrete tends to creep and shrink, while steel doesnot. CFRP is the largest class of materials with mechanical properties that have characteristics of both elastic solids and viscous fluids, and hence they are classified as viscoelastic materials. For this reason creep becomes a significant consideration in assessing their long-term carrying capacity. Thus, when CFRP is used to strengthen a concrete structure, it is easier to design the bonding process because creep is the common characteristic of both of these materials.

The incompatibility of thermal coefficients for CFRP and concrete may cause significant stresses to develop at the bond line during large swings in temperature [Hamilton & Dolan 2000]. The thermal coefficient for concrete is $1.0x10^{-5}$ ^{0}C while that of CFRP is near zero. The difference in thermal coefficients is even larger between steel and CFRP.

There is a potential galvanic corrosion problem associated with the strengthening of steel members using CFRP [Karbhari & Shulley 1995, Tavakkolizadeh & Saadatmanesh 2001, Torres-Acosta 2002]. Corrosion is more likely to happen in steel structures than in concrete structures. However, in the case of direct contact between carbon fibers and steel in the presence of an electrolyte, the wet corrosion cell could accelerate the corrosion of steel and create possible blistering and subsequent delamination or debonding. In order to prevent the formation of such an electric circuit, it is necessary to insulate the two materials from one another. In theory, the adhesive alone should be sufficient to isolate the two constituents. However, material discontinuities or installation defects could result in local galvanic couples. In order to safeguard against this possibility, a fibreglass scrim may be used in the bond line [West 2001]. It was demonstrated that the current flow through the composite was eliminated through the presence of the fibreglass scrim and that the corrosion resistance was significantly improved.

Thermal exposure may be an advantage up to a certain temperature, as it can result in a post-cure for the CFRP composite and adhesive. However, at an elevated temperature, adhesive can soften and cause an increase in viscoelastic response, a reduction in mechanical performance and an increase in the susceptibility to moisture absorption. The effect of elevated temperatures on bond strength is different for the CFRP-concrete system and for the CFRP-steel system. Concrete and steel behave differently at elevated temperatures because they have very different thermal conductivity and thermal expansion properties. Tests indicated that at 350^{o}C CFRP retains 35% of its normal temperature breaking load and 40% of its normal temperature tensile elastic modulus [Alsayed et al. 2000]. Research work on CFRP strengthened concrete beams at elevated temperatures [Sakashita et al. 1997] found that the capacity and ductility of such beams depend on the types of CFRP used.

Recent fire resistance tests at EMPA – Swiss Federal Laboratories for Materials Testing and Research [Busel & Barno 1996] conducted on reinforced concrete beams show that CFRP has demonstrated excellent fire resistance when a protective coating is applied to the composite layer. Vermitex, a Vermiculite-Cement blend plus trace chemical additives and lightweight polymer beads, is now available to provide passive fire protection to CFRP strips used to reinforce concrete beams, slabs and columns [LAF group 2003]. The impact of Vermitex on the debonding failure of CFRP strengthened steel members is unknown.

Concrete itself is more susceptible to the effects of moisture than steel [Hollaway & Leeming 1999]. Of greater significance at this stage is that the properties of the matrix resin in CFRP materials, together with the properties of adhesives, are susceptible to the effects of heat and moisture. The result of moisture absorption, which is reversible, is to lower the glass transition temperature of these materials, leading to a change in their mechanical properties. If water is trapped behind the CFRP bonding, the insulating properties of the composite materials reduce the risk of disruption of the concrete due to freeze /thaw [Hamilton & Dolan 2000]. However, this problem would be more difficult to detect with steel structures.

The effect of cyclic loading on bond strength is different for the CFRP-concrete system and for the CFRP-steel system. There are two types of cyclic loads namely low-amplitude cyclic load related to fatigue and high-amplitude cyclic load related to earthquakes. Research has been conducted on CFRP strengthened RC bridges [Barnes & Mays 1999, Shahawy & Beitelman 1999, Masoud et al 2001, El-Tawil et al 2001] and steel bridges [Miller 2000, Tavakkolizadeh & Saadatmanesh 2003a, Bassetti et al 2000, Sean & Scott 2003] under low-amplitude fatigue load. For CFRP-strengthened RC beams, fatigue fracture of the internal reinforcement steel bar was found to be the dominant failure mode, whereas for CFRP-strengthened steel girders, fatigue crack initiates in the steel followed by debonding failure. The CFRP reduces the crack growth rate in the steel. On the other hand, the performance of the CFRP strengthened concrete or a steel system under high-amplitude cyclic load is almost unknown as pointed out in the latest review article on this topic [Buyukozturk et al 2004]. The Precast Seismic Structural Systems (PRESS) program has taken the lead on research and design recommendations for precast concrete structures in areas of high seismicity [Priestly 1996]. One of the vulnerable structural elements observed in an earthquake [Earthquake 1995] is the connection between precast concrete shear wall panels. The lack of available repair techniques for these welded connections led to the investigation by Volnyy & Pantelides (1999). It is well known that steel and concrete behave very differently under high-amplitude cyclic loads. A completely new debonding model is expected for CFRP-steel system under such loading.

4 BOND CHARACTERISTICS AND FAILURE MODES OF CFRP LAMINATES

The bond of the CFRP reinforcement to the concrete and steel is of critical importance since it is the means for the transfer of stresses between the CFRP composite and the substrates. Many studies were carried out to investigate CFRP bonding. The findings of these studies are presented in the following sections.

4.1 Concrete structures

Chajes et al (1996) conducted tests investigating bond strength and force transfer. Their results show that the use of ductile adhesives (i.e. those having a low stiffness and a large strain to failure) leads to a less effective bond. Concrete itself does not have ductile behaviour like steel. Two types of failure mechanisms were observed: direct concrete shearing beneath the bond surface and cohesive type failure. The results presented are based on single lap shear tests. The effect of double lap shear test as well as the plate width is unknown.

Brosens & Van Gemert (1997) showed that an increase in bonded length increases the failure load. This is contrary to the findings of other researchers. However, they found that the influence of bonded length decreased beyond a certain threshold.

In another study by Lee and Al-Mahaidi (2003), advanced photogrammetry measurement technique was used to study the deformation mechanism of shear deficient reinforced concrete T-beams post strengthened with web bonded L-shaped CFRP laminate strips. A maximum increase in the shear capacity of 81% was achieved in one of the T-beams strengthened with the external CFRP reinforcement.

The study conducted by Horiguchi and Saeki (1997) showed that there is high correlation between the bond strength and the compressive strength. The bond strength decreases with the decrease of the compressive strength. The combined effect of varying compressive strength, adhesive ductility and composite-material properties is still unknown. Four types of failure mechanism were observed in this study. They are concrete fracture, delamination of CFRP, CFRP rupture, and concrete Aggregate/matrix interfacial fracture.

An analytical model based on shear lag theory has been developed by Bizindavyi & Neale (1999). This theory is valid only in the elastic range. There is a significant difference between the analytical model for determining shear stress distribution of the CFRP bonded concrete member and the CFRP bonded steel member [Miller 2000]. The observed modes of failure were shearing of the concrete beneath the glue line and rupture of the composite coupon. With regard to transfer lengths, empirical expressions by Bizindavyi & Neale (1999) are not readily suited for direct use for composite-to-steel joints, unless appropriate correction factors based on experimental investigations are applied.

Karbhari and Engineer (1996) developed a peel test for bond and also developed a methodology for understanding the different mechanisms and modes of interfacial fracture.

The investigation by Pham and Al-Mahaidi (2004) attempted to assess all available theoretical models. Their assessment is based on failure mechanisms and verification against a database comprised of 154 simply supported retrofitted RC beams. They found that for simple and conservative design, midspan debond can be avoided by limiting FRP stress level . End debond (or anchorage failure) can be avoided by limiting the interfacial bond stress between FRP and concrete to a concrete shear stress of $0.4f_{ct}$.

It has been shown in the literature [Hassan and Rizkala 2003, Pham and Al-Mahaidi 2002] that the debonding failure in CFRP-concrete system depends on many factors such as concrete properties (strength, modulus and thermal conductivity), quality of surface preparation, creep and shrinkage of concrete, CFRP modulus and types of resins or adhesives, stiffness, bonded length, number of plies, CFRP width.

4.2 Steel structures

Unlike RC structures, the bond characteristics of steel structures strengthened by CFRP has not been widely reported in the literature. The principles of CFRP bonding to steel structures are not similar to those used for CFRP reinforced concrete structures because of the more complex nature of the steel with CFRP strengthening, particularly with aging steel structures [Miller 2000]. Some of the problems have already been discussed in this paper. In addition, researchers have verified the durability of the CFRP-steel bond under few environmental conditions. However, there is a need to understand bond characteristics and durability of the bond between steel CFRP bonded structure under varying environmental conditions subjected to static, cyclic and sustained loads.

From the study by Miller (2000), it is evident that effective parameters for CFRP bonded steel member are the geometric and material properties of the steel substrate, CFRP reinforcement, and adhesive. More experimental and analytical research is needed for steel CFRP bonded structure to find an effective parameter for the debonding failure.

Jiao and Zhao (2004) investigated the behaviour of CFRP strengthened butt-welded very high strength circular steel tubes. A significant strength increase was achieved using the CFRP-epoxy strengthening technique. Failure modes observed were the adhesive failure mode, fiber-tear failure mode and mixed failure mode (combination of fiber tear and adhesive failure). This research was restricted to very high strength steel tube, so that behaviour of normal strength steel tube bonded with CFRP needs to be investigated.

Sen et al (2001) conducted experiments on damaged specimens repaired by using CFRP laminates bonded to the tension flange and tested to failure. Test results showed significant increases in ultimate capacity of steel composite bridge members strengthened by CFRP laminates. The failure mode of the strengthened sections was generally ductile and accompanied by considerable deformation.

Tavakkolizadeh and Saadatmanesh (2003b) found that the stress in the CFRP laminate for the one-layer system was 75% of its ultimate strength while in the five-layer system, it dropped to 42%. This indicates that a balanced design should be considered to effectively utilize the strength of CFRP laminates. Several distinct failure modes observed in this test, namely: concrete crushing; CFRP debonding; CFRP rupture; web crippling; and shear stud failure.

Brent et al. (2003) tested two existing, structurally deficient steel girder bridges strengthened utilizing CFRP composite materials. They concluded that there is a significant increase of live load carrying capacity of these bridges.

Nikouka et al (2002) establish the effects on bond strength of the adhesive during the curing period when it is subjected to cyclic loading similar to that experienced in real bridges not closed to rail traffic during the strengthening process. It has concluded that adhesive cure under cyclic loading can affect the bending stiffness and failure load of the reinforced beam.

5. CONCLUSIONS

The existing knowledge of CFRP-concrete debonding may not be applicable to CFRP-steel system because of the reasons stated in section 3. There is a distinct difference between the debonding mechanism of the CFRP-steel system and the CFRP-concrete system even under normal conditions, i.e. without the effect of environment, elevated temperature and cyclic loading. It is well known that concrete tends to fracture under tension or shear force while steel tends to yield under tension and buckle under shear force. The debonding in CFRP-concrete is mainly caused by concrete fracture whereas the debonding in CFRP-steel tends to be an interface one.

Empirical expressions for the concrete-CFRP composite are not readily suited for direct use for the steel-CFRP composite. Less research work has been conducted on the steel CFRP composite structures. Although they provide good results, some test methods seem to be completely dedicated to one type of material or to one bonded surface per specimen. CFRP steel composite members require many more tests in order to obtain more definite information regarding the behaviour at the interface.

REFERENCES

Alsayed, S.H., Al-Salloum, Y.A. and Almusallam, T.H. 2000. Fibre-reinforced polymer repair materials - some facts. *Proceedings of the Institution of Civil Engineers.*, Civil Engineering, 138(3): 131-134.

Barnes, R.A. & Mays, G.C. 1999. Fatigue performance of concrete beams strengthened with CFRP plates. *Journal of Composites for Construction.* ASCE. 3(2): 63-72.

Bassetti, A., Nussbaumer, A. & Hirt, M.A. 2000. Crack repair and fatigue extension of riveted bridge members using composite materials, *Bridge Engineering Conference*, ESE-IABSE-FIB, 26-30 March, Sharm El Sheikh: Egypt. 227-238.

Bizindavyi, L. & Neale, K.W.1999. Transfer lengths and bond strengths for composites bonded to concrete, *Journal of Composites for Construction.* ASCE. 3(4):153-160.

Brent, M.P., Terry, J.W., Wayne. F.K., Hawash, A.A.and Lee, Y.S.2003. Strengthening of steel girder bridges using FRP. *Proceedings of the 2003 Mid-Continent Transportation Research Symposium.* Iowa State University. August.

Brosens, K. & Van Gemert, D.1997. Anchoring stresses between concrete and carbon fiber reinforced laminates. *Non-Mettallic (FRP) Reinforcement for Concrete Structures*, Japan Concrete Institute, Japan, 1:271-278.

Busel, J.P. & Barno, D. 1996. Composite extend the life of concrete structures, *Composites Design & Application.* Winter. 12-14.

Buyukozturk, O., Gunes, O. & Karaca E. 2004. Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites, *Construction and Building Materials.* 18: 9-19.

Chajes, M.J., Finch, W.W.Jr., Januszha, T.F. & Thomson, T.A.1996 Bond and force transfer of composite material plates bonded to concrete. *ACI Structural Journal*, 93(2).295-303.

Earthquake Engineering Research Institute.1995. Guam earthquake reconnaissance report. *Earthquake Spectra*, Supplement to volume 11, 95(2): 63-137.

El-Tawil., Ognuc, S., Okeil, C. A., & Shahawy, M 2001. Static and Fatigue analysis of RC beams strengthened with CFRP laminates, *J.of Comp. for Construction.*, ASCE. 5(4): 258-267.

Fawzia, S., Zhao, X.L., Al-Mahaidi, R. & Rizkalla, S. 2004. Investigation into the bond between CFRP and steel tubes, *The*

Second International Conference on FRP Composites in Civil Engineering, December, Adelaide, submitted.

Hamilton, H.R & Dolan, C.W. 2000. Durability of FRP reinforcements for concrete. *Prog. Struct Eng Mat*., 2 .139-145.

Hassan, T. & Rizkalla, S. 2003. Investigation of bond in concrete structures strengthened with near surface mounted carbon fiber reinforced polymer strips. *J.of Comp. for Construction*. August 1.7(3): 248-257.

Hollaway, L.C & Caidei, J 2002. Progress in the technique of upgrading metallic structures with advanced polymer composites. *Progress in structural engineering*.131-148.

Hollaway, L.C. & Leeming, M.B.1999. Strengthening of reinforced concrete structures. *Woodhead publishing limited*. Cambridge, England.

Horiguchi, T. & Saeki, N. 1997. Effect of test methods and quality of concrete on bond strength of CFRP sheet. *Non-Mettallic (FRP) Reinforcement for Concrete Structures. Japan Concrete Institute*, Japan, 1: 265-270.

Jiao, H. & Zhao, X.L. 2004. CFRP strengthened butt-welded very high strength(VHS) circular steel tubes. *Thin Walled Structures*. accepted 19 March 2004.

Karbhari, V.M.2002. Response of fiber reinforced polymer confined concrete exposed to freeze and freeze-thaw regimes. *J. of Composites for Construction* . ASCE. 6(1). 35-40.

Karbhari, V.M. & Engineer,M. 1996 Investigation of bond between concrete and composites: Use of a Peel Test. *Journal of Reinforced Plastics and Composites*, 15. 208-227.

Karbhari, V.M. & Shulley, S.B., 1995. Use of composites for rehabilitation of steel structures- Determination of bond durability. *J. of Mater in Civil Eng.* ASCE, Nov, 7(4): 239-245.

LAF Group. 2003. Protection of carbon fibre reinforced polymer (CFRP), *http://www.lafgroup.com/4-Protection-of-Carbon-Fiber-Reinforced-Polymer.htm*.

Laura, De Lorenzis., Brian, Miller., Antonio, nanni. 2001.Bond of FRP laminates to concrete. *ACI Materials Journal*, 98(3), May-June, 256-264.

Lee, K and Al-Mahaidi, R. 2003. Shear strength and behaviour of RC T-beam retrofitted with CFRP L-strips. *6th international symposium on fibre-reinforced polymer (FRP) reinforcement for concrete structures (FRPRCS-6)*, July 2003, Singapore.

Malvar, L.J., Joshi, N.R., Beran, J.A., & Novinson, T. 2003, Environmental effects on the short-term bond of carbon fiber-reinforced polymer (CFRP) composites, *Journal of Composites for Construction, ASCE*, 7(1): 58-63.

Masoud, S., Soudki, K. & Topper, T. 2001. CFRP-Strengthened and corroded RC beams under monotonic and fatigue loads, *J. of Comp. for Constr. ASCE*, 5(4): 228-236.

Mertz, D.R. & Gillespie, J.W. 1996. Rehabilitation of steel bridge members through the application of advanced composites. *Final report, NCHRP-93-ID001*.

Mertz, D.R., Gillespie, J.W., Chajes, M.J. & Sabol, S.A. 2001.The rehabilitation of steel bridge girders using advanced composite materials. *Final Report NCHRP-98-ID051*.

Miller, T.C. 2000. The rehabilitation of steel bridge girders using advanced composite materials. *University of Delaware, Master's thesis*, Civil Engineering Department.

Moy, S. 2001. ICE design guides-FRP composites life extension and strengthening of metallic structures. *Thomas Telford Publishing*, London, UK.

Nikouka, F., Lee, M. & Moy, S.S.J. 2002. Strengthening of mettalic structures using carbon fibre composites. *IABSE Symposium Melbourne*.

Oehlers, D.J. 2000. The choice of plating techniques for retrofitted of reinforced concrete bridge beams and slabs. *AUSTROADS 4th Bridge Engineering Conference*. 29 Nov-1 Dec Adelaide, Australia.

Pham, H.B and Al-Mahaidi,R. 2004. Assessment of available prediction models for the strength of FRP retrofitted RC beams. *Journal of Composite Structures (in press).*

Pham, H.B. and Al-Mahaidi, R. 2002. Anchorage zones of FRP laminates bonded to concrete beams State-of –the-Art review. *Proc ACUNN-4. Composite systems-Macrocomposites, Microcomposites, Nanocomposites*. UNSW, Sydney, Australia, 21-25 July 2002.

Priestley,M.J.N.1996. “The PRESS program-current status and proposal plans for phaseIII.” *PCI Journal*. 41(2):22-40.

Sakashita, M., Masuda, Y., Nakamura, K., Tanano, H. & Nishida, I. 1997. Deflection of continuous fibre reinforced concrete beams subjected to loaded heating, *Proceedings of the 3rd Inter. Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Sapporo, Japan, 2. 51-58.

Sean, C. J. & Scott, A. C. 2003.Application of fiber reinforced polymer overlays to extend steel fatigue life”. *Journal of composites for construction. ASCE*. 7(4). Nov.331-338.

Sen, R.,Liby, L & Mullins, G. 2001. Strengthening steel Bridge sections using CFRP laminates. *Composites*.B32:309-322.

Shahawy, M. & Beitelman, T. 1999. Static and Fatigue performance of RC beams strengthened with CFRP laminates, *Journal of Structural Engineering, ASCE*, 125(6): 613-621.

Stehn, L & Hedman, E. P. 2001. Resistance and thermal insulation of a composite FRP-steel beam. *Thin walled structures*. 39: 375-394.

Tavakkolizadeh, M. & Saadatmanesh, H. 2001. Galvanic corrosion of carbon and steel in aggressive environments, *Journal of Composites for Construction, ASCE*, 5(3): 200-210.

Tavakkolizadeh, M. & Saadatmanesh, H. 2003a. Fatigue strength of steel girders strengthened with carbon fiber reinforced polymer patch, *Journal of Structural Engineering, ASCE*, 129(2): 186-196

Tavakkolizadeh, M. & Saadatmanesh, H.2003b. Strengthening of steel-concrete composite girders using carbon fiber reinforced polymers sheets, *Journal of Structural Engineering*, January 1. 129(1):30-40.

Teng, J.G, Chen, J.F, Smith, S.T & Lam, L. 2002. FRP Strengthened RC Structures. *John Willey & Sons, Ltd*, West Sussex, UK.

Torres-Acosta, A.A. 2002. Galvanic corrosion of steel in contact with carbon-polymer composites. II: experiments in concrete, *J. of comp. for construction, ASCE*. 6(2):116-122.

West, T.D. 2001. Enhancements to the bond between advanced composite materials and steel for bridge rehabilitation. *Master of civil Engineering thesis*. University of Delaware.U.S.A

Volnyy, V.A., & Pantelides,C.P. 1999. Bond length of CFRP composites attached to precast concrete walls, *Journal of Composites for Construction, ASCE*, 3(4).168-176.