ANALYTICAL AND EXPERIMENTAL STUDY ON REPAIR EFFECTIVENESS OF CFRP SHEETS FOR RC BEAMS

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Most research on using FRP plate bonding for flexural strengthening was carried out in the last decade (Ritchie et al. 1991; Saadatmanesh, Ehsani 1991; Triantafillou, Plevris 1992). There has been an explosive growth in the recent years, which resulted from the increasing global need for structural performance updating and retrofitting works. The strengthening and repair of RC structures has become increasingly important, especially in the last decade. Strengthening is usually needed to improve the performance of existing RC structures. A change in the capacity of a structure in service could be due to an increase or change in applied loads, for example, increase in traffic above bridges, addition of extra floors on an existing structure, or installation of new equipment. Many RC structures are damaged mostly due to various forms of deterioration, like cracks or large deflections. These are affected by different factors, such as earthquakes, vibrations, corrosion of reinforced bars and environmental changes.

Externally, Carbon Fibre Reinforced Polymer (CFRP) is one of the new materials used to strengthen or repair RC structures. It is particularly suitable for insitu rehabilitation, and has become an increasingly applied and important technology because of CFRP advantages, such as, availability in any length, corrosion-resistance, high tensile strength, low weight, low installation cost and flexibility of storage, transportation and use. Many experimental and analytical studies have been carried out on strengthening or repairing RC beams using various types of FRP, including those related to design criteria and failure modes.

Reporting tests and investigations have been reviewed by Almakt et al. (1998) to develop a thorough understanding of the behaviour of beams strengthened by CFRP plates. CFRP plates were found to increase the flexural capacity within certain limits (Almakt et al. 1998). Externally bonded CFRP plates were found to perform well under the effect of the impact loading (Erki, Meier 1999). Adding an anchoring system at the end of the plates can improve the impact performance of the strengthened beam (Erki, Meier 1999). Repair of a real bridge with externally bonded FRP plates was found to decrease the flexural stresses in the steel reinforcements and the mid-span deflection (Stallings et al. 2000). Strengthening of concrete beams with externally bonded FRP plates was found to increase the ultimate capacity by 70% and reduce the size and the density of the cracks along the beam length (Fanning, Kelly 2001). A significant increase in the ultimate capacity was observed after adding the externally bonded CFRP sheets (Nguyen et al. 2001). Ultimate capacity of strengthened beams increased by up to 230%, and even for the preloaded beam before strengthening, the ultimate capacity significantly increased, which indicates good performance for repair situations (Rahimi, Hutchinson 2001).

Based on early studies of the last decade on the use of the bonded FRP plates to beam soffit as flexural system, a number of failure modes have been observed. These modes can be generally classified as: (1) flexural failure by FRP rapture; (2) flexural failure by crushing of concrete at compression; (3) shear failure; (4) concrete cover separation; (5) plate end interfacial debonding; (6) intermediate flexural crack induced interfacial debonding; and (7) intermediate flexural shear crack induced interfacial debonding (Ritchie et al. 1991; Saadatmanesh, Ehsani 1991; Triantafillou, Plevris 1992; Chajes et al. 1994;

Sharif et al. 1994; Heffernan, Erki 1996; Arduini, Nanni 1997; Ross et al. 1999; Bonacci, Maalej 2000).

Strengthening of corroded RC beams with externally bonded CFRP plates was found to increase the ultimate capacity by 37‑87% (Masoud et al. 2001). Strengthening of the RC beam with one layer of the CFRP plate was found to increase the ultimate capacity by 200% and strengthening with two layers increased it by 250% (Capozucca, Cerri 2002). Use of CFRP plates for repair of damaged prestress bridge beams restored a portion of the lost flexural stiffness and reduced the mid-span deflection (Klaiber et al. 2003). Repairing of corroded concrete beams with externally bonded CFRP sheets was found to increase the load capacity up to 30% (Kutarba 2004). Kachlakev et al. (2001) investigated the Finite Element (FE) modelling of RC structures strengthened using FRP laminates. They showed a good agreement between the FE modelling and the full-scale test in terms of load against mid-span defection. The FE model shows higher stiffness than the experiential approach, which can be due to the effect of the bond slip between the concrete and steel reinforcement, and the micro-cracks occurring in the actual beams, which were excluded in the FE model. Issues related to ductility of FRP strengthening of RC flexural members, that is, the ability of materials to sustain plastic deformation before fracture, were studied by Delpak (2002). The results showed that the load capacity of the strengthened section increased up to 125% based on the FE method, and the deflection at the ultimate increased up to 24%.

Modelling of RC beams strengthening with externally bonded FRP plates using nonlinear FE analysis was done by Supaviriyakit et al. (2004). They modelled the FRP plate as 8-nodeisoperimetric2D elastic element and the adhesive as perfect compatibility by directly connecting nodes of FRP with those of concrete. The study found that FE modelling can predict the load against deflection relation, ultimate load and failure modes correctly. Repairs of damaged RC beams with externally bonded CFRP sheets were carried out by Benjeddou et al. (2007). The study validates the effectiveness of the CFRP sheet as repairing technique for all the damage degrees. The peeling off failure mode was controlling the failure mechanism. The load capacity had increased by 87% for the strengthening beam when no pre-crack load was applied, and it was 44% for the highest damage degree. Choo et al. (2007) investigated the retrofitting of an actual bridge damaged under extreme loading using externally bonded CFRP sheets. The FE modelling was used to estimate the force emanated due to the extreme loads, and it also showed that repairing with CFRP sheets made a significant difference for the ultimate limit, while a small increase in the strength was observed for the service limit load.

Experimental investigation for the behaviour of RC structures strengthened with externally bonded CFRP sheets has been done by Ceroni (2010). Added CFRP sheets have increased the load capacity by 26% up to 50% in cases of the minimum steel reinforcement and 15% up to 33% for the case of maximum steel reinforcement. Ombres (2010) investigated intermediate crack debonding in reinforced concrete structures strengthened with externally bonded FRP sheets. The author derived and adopted a nonlinear local deformation model from cracking analysis based on the slip and bond stresses to predict the stress and strain distribution at failure. The FE modelling of the interface between the CFRP sheets and the concrete surface has been carried out by Obaidat et al. (2010). The study validated the modelling based on experimental work on RC beams in the laboratory. The CFRP sheets were modelled adopting two models: one with orthotropic material and another with elastic isotropic material. The study found that the perfect bond model was unable to model the softening behaviour of the beam. Use of CFRP sheets with U-shape anchorage can increase the capacity of the strengthened RC beam up to 10–24% depending on the number of U-shape anchorages along the beam length (El-Ghandour 2011). Repair of damaged steel beams with CFRP sheets increased the ultimate capacity up to 22.5% and the pre-repair levels did not affect the strain development in the CFRP sheets, while it did affect the debonding progression of the sheet (Kim, Brunell 2011). CFRP plates were found to be unaffected by the change in the environmental conditions due to superior quality control during the manufacture, while hand laid-up CFRP fabric was affected by the elevated temperature (Cromwell et al. 2011).

The present study aims to investigate the effect of different pre-repair damage levels on the repairing effectiveness using externally bonded CFRP sheets. It will highlight the effect of fixing CFRP sheets to damaged beams on the load capacity, mid-span deflection, the steel strain, the CFRP strain and failure modes. The study will suggest a method to model the adhesive interface between the RC beam and the CFRP sheets based on the ultimate adhesive strain values carried out experimentally. The developed FE model of repaired RC beam using externally bonded CFRP sheets based on the ultimate adhesive strain will be compared with the results of the experimental approach in terms of load against defection, load against the steel strain, load against CFRP strain and failure modes.

Experimental work

In order to investigate and validate the effect of the prerepair damage level on the effectiveness of CFRP sheets as a repairing system, four RC beams were prepared for the tests, where for each beam the clear span length is 2.2 m and beam cross section is 150 mm wide and 250 mm deep (dimensions were scaled down to actual beam due to laboratory facilities and equipment limitations). Beams were designed according to ACI 318 (2008) Code requirements, where beams were reinforced with two 12 mm diameter deformed steel bars. Figure 1 and 2 show details of the beams and the test setup. Table 1 shows details of the RC beams. The RC beams were tested under point load located at mid-span. Load was applied gradually with a loading rate of 4 kN/min. One of the beams was used as the datum and was tested under cyclic loading of 10 kN for each cycle up to failure. The repaired beams were initially damaged under design limit load, steel yield limit load and ultimate load. For repairing, beams were turned over and roughness equipment was used on the tension face to get a suitable face and have as much as possible fraction with the CFRP sheet. Figure 3 shows the beam surface after roughness equipment was used and the CFRP sheets were fixed. The surface was cleaned by using air pressure to avoid any dust on the surface, as the substrates must be sound, dry, clean and free from laitance, ice, standing water, grease, oils, old surface treatments or coatings and all loosely adhering particles. The concrete was cleaned and prepared to achieve a laitance and contaminant free, open textured surface. When the concrete surface was prepared, the CFRP sheet was fixed by using adhesive material and then was left for one month for hardening. Repairing with CFRP sheet was designed according to ACI 440.2R (2002) Code requirements with a 100 mm width and 1.2 mm thickness and the length was the clear span of the beam. The CFRP properties are shown in Table 2. Static load was gradually applied again on the repaired beams with an increase rate of 4 KN/min up to failure. During the test, load against deflection data, the steel strain and CFRP strain was carried out. Failure modes were highlighted.

Finite element modelling

This part presents the simulating of the experimental work setup and samples. The undertaken cases were as unrepaired beam and three repaired beams. The repair of the beam was designed according to ACI 420.2R (2002) Code, where a CFRP sheet with 100 mm width and 1.2 mm thickness was fixed on the tension face of the RC beam and along the clear span of the beam. The modelling of the RC beam was done using the 20-node brick elements to represent the concrete. In addition, a 2-node embedded bar inside a 3-D brick element was used to represent the reinforcement bars and 4-node two-dimensional curved shell elements were used to represent CFRP sheets as composite material. The adhesive interface was modelled by using the 4-nodes two-dimensional curved shell elements as composite material. Figure 4 shows the FE modelling for the RC beam. Concrete was modelled using smeared crack model. For concrete, the linear behaviour was modelled as isotropic material with certain compressive strength value, modulus of elasticity, Poisson's ratio and mass density. For nonlinear behaviour, it was modelled using linear stress cut-off, linear tension softening, ultimate strain based and constant shear retention models. The concrete properties were as shown in Table 1. Reinforcement steel bars were represented as bonded reinforcement and for steel nonlinearity, the Von-Mises plasticity criteria was used with work hardening rule to present the actual steel stress-strain curves. The tensile test was carried out on steel bar samples and the stress-strain curves were as shown in Figure 5. Reinforcement steel bars were given properties as shown in Table 1 above. CFRP sheet was represented as a composite material with Hill-Orthotropic plastic model using yield. The CFRP was given by the material producer as shown in Table 2. The adhesive interface was modelled as composite material using Hill-Orthotropic plastic model and using yield Stress-Princip anisot and was given the actual debonding strain, which was found while carrying a static load test and as shown in Table 3. Both CFRP sheets and the adhesive layer were modelled as orthotropic material, which has higher strength in the longitudinal direction and no strength in the transfer directions.

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