PERFORMANCE OF RC BEAMS RETROFITTED WITH CARDIFRC® AFTER THERMAL CYCLING

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ABSTRACT

A new retrofitting technique using CARDIFRC®, a material compatible with concrete, has recently been developed at Cardiff University. It overcomes some of the problems associated with the current techniques based on externally bonded steel plates and FRP (fibre-reinforced polymer), which are due to the mismatch of their tensile strength and stiffness with that of concrete structure being retrofitted.

This study investigates the effect of thermal cycles on the performance of reinforced concrete control and retrofitted beams. The concrete beams were heated to a maximum temperature of 90˚C from the room temperature of about 25˚ C. The number of thermal cycles varied from 0 to 90 cycles. After the requisite number of thermal cycles, the beams were tested at room temperature in four-point bending.

The tests indicate that the retrofitted beams are stronger, stiffer and more importantly failed in flexure. No visual deterioration or bond degradation was observed after thermal cycling of the retrofitted beams (the bond between the repair material and the concrete substrate remained intact) attesting to the good thermal compatibility between the concrete and CARDIFRC®. Therefore, this type of retrofit material can be successfully used in hot climates.

This paper investigates the feasibility of using CARDIFRC® as a retrofitting material in hot climatic conditions. It also outlines two analytical/computational models for predicting the ultimate moment capacity and the complete load–deflection behaviour of the retrofitted beams. Both models predict very well the ultimate moment capacity of the retrofitted beams.

1 INTRODUCTION

Concrete structures can deteriorate and therefore need repair after long periods in service. To accommodate for a load carrying capacity higher than the original design value, members may need to be strengthened through retrofitting. A common repair and strengthening technique for concrete beams is by bonding a steel plate to the tension side of the beam. However, several problems have been encountered with this technique, including the occurrence of undesirable shear failures, difficulty in handling heavy steel plates, corrosion of steel that can cause deterioration of the bond at a glued steel-concrete interface, and the need of butt joint systems as a result of limited workable lengths [1-2].

Recently, attention has been directed towards the use of fibre-reinforced plastic (FRP) plates, which offer higher strength/weight and improved durability over their steel counterparts [3-5]. Retrofitting using FRP is also vulnerable to undesirable brittle failures due to a large mismatch in the tensile strength and stiffness with that of concrete. Another problem, which has also been observed with this technique, is the effect of long exposure to temperature variations [5-7].

A new retrofitting technique using CARDIFRC®, a material compatible with concrete, has recently been developed at Cardiff University. It overcomes some of the problems associated with the current techniques based on externally bonded steel plates and FRP (fibre-reinforced polymer) which are due to the mismatch of their tensile strength, stiffness and coefficient of linear thermal expansion with that of concrete structure being retrofitted [8].

The results of Karihaloo *et al.* [8] showed that retrofitting of flexural RC members using CARDIFRC® plates on the tension face improves the flexural load carrying capacity and also decreases the crack width and the deflection. Moreover, when the RC beams retrofitted with three strips (one strip on the tension face and two strips on the sides), the damaged beams were strengthened not only in flexure, but also improved in their shear capacity.

To predict the moment resistance and the load-deflection behaviour of the retrofitted beams, two analytical models have been developed by Alaee and Karihaloo, [9-10]. One model is based on the classical strength theory, but takes into account fully the tensile contributions (i.e. pre-peak and post-peak) from concrete and CARDIFRC. The second analytical model is based on the fracture mechanics concepts. This model mimics the initiation and growth of the flexural crack that eventually leads to the failure of the retrofitted beam.

2. CARDIFRC®

The CARDIFRC® is a new class of high performance fibre reinforced cementitious composite (HPFRCC) characterised by high compressive strength (in excess of 200 MPa), tensile/flexural strength (up to 30 MPa) and high energy absorption capacity (up to 20,000 J/m^2). This has been made possible by the use of large amounts (up to 8 % by volume) of brass coated short fibres (6-13 mm long, 0.16 mm diameter) in a cementitious matrix densified by the use of silica fume. The matrix contains only very fine graded quartz sand, instead of ordinary river sand and coarse aggregates. By optimising the grading of fine quartz sands, the water demand was considerably reduced without affecting the workability of the mix. This was achieved using novel mixing procedures. Computer Tomography imaging and sectioning of specimens have confirmed that these procedures ensure remarkably homogeneous mix with a uniform distribution of fibres [11]. The mix proportions of a mix of the CARDIFRC® class is given in Table 1.

Table 1: Mix proportions for CARDIFRC® Mix I[8].

Constituents (Kg)	**Mix I**
Cement	855
Quartz sand:	
9-300μm	470
250-600μm	470
Microsilica	214
Water	188
Superplasticizer	28
Fibres: -6 mm	390
-13 mm	78
Water/cement ratio	0.22
Water/binder ratio	0.18

Table 2: Typical material properties of CARDIFRC®

Material properties	**Mix I**
Indirect tensile strength (GPa)	24
Fracture energy (J/m^2)	17000
Compressive strength (MPa)	207
Modulus of elasticity (GPa)	46

3. TEST BEAMS

Twenty four under-reinforced RC beams were prepared. Of these, 16 were retrofitted with CARDIFRC® and 8 left as control. The beams were fabricated in 6 batches, with each batch consisting of 4 beams. Along with each batch of beams, three cylinders (100 mm in diameter x 200 mm high) and three cubes (100 mm) were also cast. The beams were allowed to cure in a water bath for 28 days. The cement : fine aggregate : coarse proportions in the concrete mix were 1:1.8:2.8 by weight and the water/cement ratio was 0.50. Ordinary Portland cement was used and the maximum size of aggregate was 10 mm.

The beams were reinforced with a single 12 mm rebar 1200 mm long, 100 mm wide and 150 mm deep. Shear reinforcement consisted of 6 mm deformed bars placed at 65 mm spacing. According to the British Standard BS 8110 the beams were over-designed for shear to prevent brittle failure due to the increased shear load on the strengthened beam so the flexural behaviour could be observed throughout the loading up to failure. Two different configurations of retrofitting were investigated; one strip bonded on the tension face and three strips (one bonded on the tension face and the others on the vertical sides. Of the twenty-four beams used in this programme, eight were tested to failure as control beams to compare with the performance of those retrofitted with CARDIFRC® strips. The remaining sixteen were pre-loaded to approximately 75 % of this failure load to induce flexural cracking. The beams were tested under four-point bending over a span of 1100 mm. The spacing between the applied loads was 400 mm.

4. RETROFITTING PROCEDURE

The retrofit material, CARDIFRC® was cast as flat strips in 1030 mm long and 100 mm wide steel moulds with a well oiled base and raised border whose height is 16 mm. The strips were left to cure in the moulds for 24 hours at 20 C before de-moulding. The retrofit strips were then hot-cured at 90° C for further 7 days. The CARDIFRC® retrofit strip was then bonded to the prepared surfaces of the damaged concrete beam using epoxy based adhesive (Sikadur® 31). In order to improve the bond between the repair material and the original concrete, the contact surfaces of concrete were cleaned and roughened using an angle grinder. The repair strip was placed on the adhesive and evenly pressed. The adhesive was then cured for 24 hours. The beams were exposed to 30 or 90 thermal cycles and then tested at room temperature in four-point bending.

Table 3: Compression and splitting strength results for ordinary concrete

Thermal cycles	Average (MPa)	COV (%)	Average (MPa)	COV (%)
0	56.10	1.8	4.46	2.3
30	66.73	1.7	5.10	7.0
90	60.67	2.5	4.84	2.7

5. TEST RESULTS

The test results show that the response of the control beams has very little scatter, especially before the attainment of the maximum load. It appears that thermal cycling has very little effect on the load carrying capacity of control beams reinforced in flexure and shear. After 90 thermal cycles the shear reinforcement seems to counteract the reduction expected due to the reduction in compressive strength (Table 3).

As expected, all beams retrofitted with one strip failed in pure flexure. The flexural failures observed were generally characterized by a single flexural crack occurring in the middle third of the beam extending upwards to the concrete top fibre between the load points and downwards through the retrofit material. All beams failed at loads higher than the average failure load of control beams. Moreover, both the deflection behaviour and failure modes were similar for all exposure conditions.

Of the eight beams retrofitted with three continuous and four short strips only one beam failed in shear. This failure occurred through the joint connecting the long and short strip. Due to the bridging action of the tension strip, the crack was arrested in the CARDIFRC® tension strip. This type of failure can be classified as a ductile shear failure. All the remaining beams failed in pure flexure. The first crack appeared in the middle third of the tension strip As the load was increased, this crack propagated vertically in the side strips and the mouth of the initial crack in the tension strip opened gradually. As the load was increased further the propagation of the cracks on both sides of the beam towards the compression top fibre became visible. After the peak load, the load-deflection curves descended gently. Finally, the beam exhibited plastic behaviour with the yielding of steel.

6 ANALYTICAL MODEL

To model the response of a structure based on fracture mechanics, it is necessary to have a good knowledge of the details of the formation and growth of cracks in the structure.

When the retrofitted beam is under bending, the resistance to crack opening consists of three different components. The first component is due to the bridging force across the crack faces from the reinforcing steel, the second is from the post-peak tension softening response of concrete, and the third is from the bridging stresses in the retrofit strips. The closure pressure thus exerted counteracts the opening action of the applied moment *M.* As the stress at the crack tip is finite, the net stress intensity factor at the crack tip must vanish. In fact, this requires that the crack faces close smoothly near the tip. The net K_I at the crack tip is obtained by superimposing the stress intensity factors produced at the crack tip by the applied moment (K_{IM}), and the closure forces exerted by steel (K_{IS}), concrete (K_{Iconc}), tension retrofit strips ($K_{I(t\text{-}strip)}$), and side retrofit strips ($K_{I(s\text{-}strip)}$) (if they are used). The condition of finite stress at crack tip, i.e. $K_I = 0$ is therefore

$$K_{IM} - K_{IS} - K_{Iconc} - K_{I(t-strip)} - K_{I(s-strip)} = 0 \qquad (1)$$

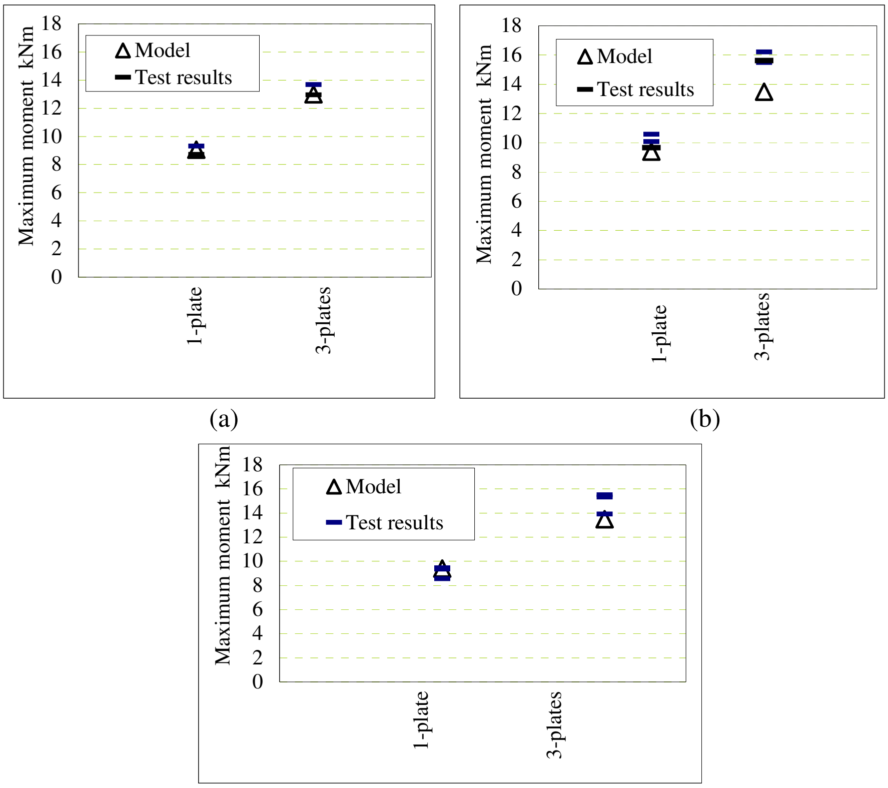
In addition to the condition of smooth closure of crack faces at its tip, we must consider the compatibility of crack opening displacement of a retrofitted beam [12]. The crack opening displacement can again be written as the vectorial sum of the contribution from the applied bending moment and the closure forces exerted by steel, concrete and retrofit strips. The compatibility condition of the crack opening need be satisfied only at the level of the steel reinforcement, because of the assumed known (i.e. linear) variation along the length of the crack:

$$(w_S)_M - (w_S)_S - (w_S)_{conc} - (w_S)_{t-strip} - (w_S)_{s-strip} = w_S \qquad (2)$$

where $(w_S)_i$ are the crack opening displacement at the level of the steel bar produced by the applied bending moment and the closure forces exerted by steel, concrete, tension strip, and side strips, respectively. Note that the crack opening w_s at the level of the reinforcement is not known, but is to be determined. Each term in the left hand side of (2) can be expressed in terms of the corresponding compliance coefficients. For instance, the crack opening at the level of the steel bar produced by the applied moment is

$$(w_S)_M = \lambda_{SM} M \tag{3}$$

where λ_{SM} (compliance coefficient) is the crack opening at the level of steel when a unit bending moment is applied to the crack. The compliance coefficients can be computed from energy principles and Clapeyron's theorem [13]. These are listed in Alaee and Karihaloo [4]. To determine the three known parameters *a*, *w* and *M*, equations 1 and 2 should be simultaneously satisfied for a flexural crack.



(a) (b)

(c)

Figure: 1 Comparison of the moment resistance of beams with the prediction of the model after; (a) 0, (b) 30, and (c) 90 thermal cycles, respectively.

Figure 1 compares the moment resistance of the beams predicted by the model with the test results. It can be seen that the trend of the model results is in agreement with test results. Most of the predicted results are quite close to the experimental data.

7 CONCUSIONS

Retrofitting with CARDIFRC® strips bonded to the tension face improves the load carrying capacity and the serviceability of the beam. To prevent shear failure, CARDIFRC® strips should be bonded to the sides of the beams. This configuration of retrofitting can increase the failure load by up to 86 percent. With thermal cycling, the failure load increased by up to 90 and 87 percent after 30 and 90 thermal cycles, respectively. The room temperature figure provides a safe value for design at elevated temperatures.

No visual deterioration or bond degradation was observed after thermal cycling of the retrofitted beams (the bond between the repair material and the concrete substrate remained intact) attesting to the good thermal compatibility between the concrete and CARDIFRC®. Therefore, this type of retrofit material can be successfully used in hot climates.

The moment resistance of the retrofitted beams is very well predicted by the fracture model.

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