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Structural Response of Initially Loaded RC Beam to Different Retrofitting Techniques

Waleed A. Thanoon, M. S. Jaafar, J. Noorzaei, Mohd Razali Abdul Kadir & Thamer A. Mohamed
Civil Engineering Department, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

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ABSTRACT

Penambahan bilangan struktur konkrit yang rosak telah menggariskan peri pentingnya memajukan teknik baik pulih yang boleh diterima. Kertas ini membentangkan kajian ke atas kelakuan struktur rasuk konkrit tetulang yang dibaik pulih dengan dua kaedah yang berbeza. Teknik pertama menggunakan CFRP sebagai pengukuh, sementara sistem prategasan luaran digunakan sebagai teknik kedua. Spesimen dikenakan beban awal sehingga dua pertiga daripada beban muktamad yang dijangka. Beban kemudian dilepaskan dan rasuk-rasuk tersebut dibaik pulih dengan CFRP atau prategasan luaran. Spesimen dikenakan dengan beban sehingga ke tahap gagal. Respons struktur telah ditinjau berkenaan kelakuan retakan, hubungan beban-pesongan, kemuluran, agihan terikan, beban muktamad dan ragam kegagalan. Keputusan menunjukkan respons yang serupa pada kedua-dua teknik tersebut. Oleh itu, konsep reka bentuk kenyal yang digunakan untuk konkrit prategasan boleh digunakan untuk reka bentuk konkrit dengan CFRP.

ABSTRACT

The increase in the large number of distressed reinforced concrete structure underscores the importance of developing acceptable retrofitting techniques. This study investigates the structural behaviour of full scale reinforced concrete beams strengthened by two different techniques. The first technique used is the strengthening of the beam by CFRP, while the second technique used is the external pre-stressing. The specimens were initially loaded to two-thirds of their predicted ultimate flexural capacity. They were then unloaded and strengthened with either CFRP or external prestressing. The beams were subsequently subjected to incremental loads until failure. The structural response of the tested specimens had been found in terms of their cracking behaviour, load-deflection relationship, ductility, strain, distribution, ultimate load and failure mechanism. The results indicate similar structural response in both retrofitting techniques at the ultimate range. Hence the concept of elastic design used in prestressed concrete members may be used for reinforced concrete members strengthened with CFRP.

Keywords: Loaded RC beam, retrofitting techniques, CFRP, structural response

INTRODUCTION

The repair of structurally deteriorated reinforced concrete structures becomes necessary as the structural element ceases to provide satisfactory strength and serviceability. Many different types of distress in the reinforced concrete structures have been observed recently. Cracking and spalling are the common distresses in reinforced concrete slabs and beams. To restore the structural capacity of the damaged element in order to resist the stresses developed due to the applied load, repair and/or strengthening techniques are needed. There are different techniques available for repair and strengthening of different reinforced concrete structural elements. With the rapid development in material and polymer technology, more effective and practically convenient material has been introduced in this field.

Carbon Fibre Reinforced Polymer has a high strength to weight ratio, favourable fatigue behaviour and excellent resistance to electrochemical corrosion to make it practically suited for structural application. Clark and Waldron (1996) presented the application of the advance fibre materials in construction. The carbon CFRP bonded externally appears to be the favourite solution for strengthening reinforced and/or pre-stressed concrete structures. Thin FRP laminates, less than 1 mm thick, are currently used in Switzerland, U.K and Japan in bridge strengthening.

Tan and Wong (1997) investigated the behaviour of 3 simply supported prototype beams externally bonded with CFRP plates. The internal longitudinal steel ratios used are 0.57%, 0.86% and 1.29%. Different amounts of CFRP plates had been added to achieve similar replacement ratio of 0.5 in all the beams. It has been found that for the beam reinforced with a steel ratio less than 0.86%, collapse was due to full bond failure of the CFRP plate. However, for the beam with higher steel ratio of 1.29%, the final collapse was due to flexural compression, i.e. crushing of concrete of the top of the beam.

Alfarabi *et al.* (1998) studied the effect of different strengthening configurations of 10 reinforced concrete beams using CFRP plates. The behaviour of the repaired beams is represented by their load-deflection curves and their different modes of failures. The results generally indicate that the flexural strength of the repaired beams is increased. Failure of different strengthened specimens was initiated at the plate curtailment zone at the beam ends.

Khaled *et al.* (1999) tested six reinforced concrete beams; five of the beams were strengthened with one CFRP strip of SikaCarboDurS1012, which was epoxied to the tension side of the beam. The sixth beam had no CFRP strip and was used as a control beam. The study focused on the effect of strengthening beams by CFRP strips externally to the tension face of the beam with varying un-bonded regions. Beams strengthened with CFRP strips had larger flexural capacity over the control beam. The beams with partially bonded CFRP strips exhibited higher ultimate capacity than the beam with fully bonded CFRP strips. Moreover, it was found that the CFRP strips slipped relative to concrete near the ends of the beam during the loading period. The flexural resistance of the strengthened beams increased by about 20% for yield strength and 34% for ultimate strength when compared to the un-strengthened beams.

Toong and Li (2000) investigated the effect of using CFRP plates to strengthen one-way spanning slab to increase the flexural capacity with particular emphasis on the cracking behaviour at working load. All the CFRP strengthened specimens exhibited large increase in load-carrying capacity ranging from 60% to 140 %.

In the externally post tensioning pre-stressing strengthening technique, a pre-stressing strand or bar is used to apply a predetermined compressive force. To get effective results, the developed cracks are initially treated before applying the pre-stressing force so that there will be minimum loss in energy required to close the cracks (Raina 1994).

Emmons (1994) describes the use of external post-tensioned prestressing methods for increasing the flexural capacity of reinforced concrete members. External post-tensioning prestressing provides for immediate and active participation in both dead and live load distributions

Tan and Ng (1997) investigate the structural response of 6 reinforced concrete T beams strengthened using external prestressing tendons. The study focuses on the effect of tendon configuration and the number and location of the deviators into the structural response. Test results indicate that the provision of a deviator at the section of maximum deflection led to satisfactory service load behaviour and a higher load carrying capacity compared to the case where no deviators were provided. Moreover, the configuration of the tendon has a significant effect on the structural response of the strengthened beams.

According to ACI Committee-224 (1993), the external post-tensioning is a desirable solution when a major portion of a member must be strengthened or when the cracks that have formed must be closed. Adequate anchorage must be provided for the pre-stressing steel, and care is needed so that the problem will not merely migrate to another part of the structure. The effects of the tensioning force (including those of eccentricity) on the stress within the structure should be carefully analysed.

To date, the effect of many parameters on the structural behaviour of the strengthened structural elements using CFRP strips and external pre-stressing is still not clear especially in the absence of codal requirements and clearly defined design specifications. The main goal of this paper is to investigate experimentally the effectiveness of using CFRP strips in strengthening reinforced concrete beams compared to external pre-stressing concrete beams. The study provides insight on the overall structural behaviour and ductility.

EXPERIMENTAL PROGRAM AND STRENGTHENING TECHNIQUE

Three full scale reinforced concrete beams have been cast, cured and tested. The beams have a span of 3.2m with rectangular cross section having dimension of 130mm by 250mm (width *x* depth). The steel reinforcement in the beam consists of 2Y10 (steel ratio= 0.48%). The steel has characteristic strength of 460 N/mm^2. The 28-day cube compressive strength, f_{cu} of the concrete used is 30 N/mm^2.

All the specimens are tested under two-point load. Initially, two beam specimens are loaded to two-thirds of their predicted ultimate load capacity. Subsequently, the load was released and the specimens were removed from the testing frame for strengthening. The other specimens (control specimen) are loaded until failure. The specimens are re-tested after allowing a suitable curing period till failure.

The structural response of each specimen in terms of deflection, stiffness, cracking load, ultimate load, and failure patterns are analysed. A 50 mm wide and 12 mm thick carbon fibre strip (CFRP) have been externally bonded to the soffit of the specimen at the tension face of the reinforced concrete beam using Sikadur30 epoxy adhesive (bonding agent). The carbon fibre strip has been placed at the central part of the beam specimens. The tensile strength of the carbon fibre strip is 2800 N/mm^2. Its modulus of elasticity = 165000 N/mm^2 and the density is 1.5 g/cm^3. The main characteristic of the Sikadur30 epoxy is presented in Table 1.

The third beam was strengthened externally by using 7 mm pre-stressing wires at both sides of the beam. To maintain the cable profile during the application of load, two deviators have been fixed at a distance equal to L/3 from each end of the beam using steel angle section fixed using two steel bolts. In addition, two 10 mm steel plates are fixed at the ends of the beam to anchor the pre-stressing wires. Both wires were pre-stressed until 75% of their ultimate strength (f_{pu}=1570 N/mm^2). After initial loading, the developed cracks are treated before applying the pre-stressing force using epoxy to minimize the loss in the pre-stressing force required to close the cracks.

TABLE 1
Characteristic of the sikadur30 epoxy

Characteristics	Guide Values
Sag flow	3 – 5mm at 35°C
Compressive strength	75 – 100 N/mm^2
Tensile strength	20 – 30 N/mm^2
Shear strength	15 – 20 N/mm^2
E-modulus (Static)	8000 – 16000 N/mm^2
Shrinkage	0.04 – 0.08%
Glass transition point	50°C – 70°C

STRUCTURAL RESPONSE

Cracking Load & Patterns

The initial cracking loads for the control specimen and strengthened beam specimens are shown in *Fig. 1*. The strengthening of the beam by bonding Carbon Fibre Strip (CFRP) at its bottom will not alter the cracking load. The number of cracks observed in the strengthened specimen with CFRP is approximately equal to the number of cracks in the control specimen at service load. However, with the increase of the applied load, the number of cracks increased in the strengthened specimens.

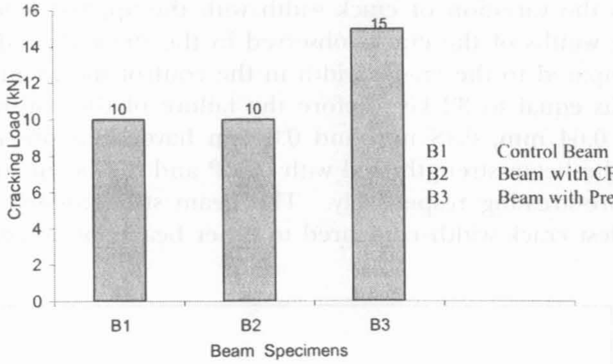


Fig. 1: Cracking load for the tested specimens

Beam specimens strengthened with external pre-stressing wires show the highest cracking load due to the development of compressive stress in concrete because of the external pre-stressing (50% increase in the cracking load has been observed). In the range of service load, the width of the cracks observed in beam B3 are smaller than those observed in B1 and B2. However with further increase in the applied loads, the crack width increases and becomes wider as compared to B1 and B2. The crack patterns for the three beam specimens are shown in *Fig. 2.*

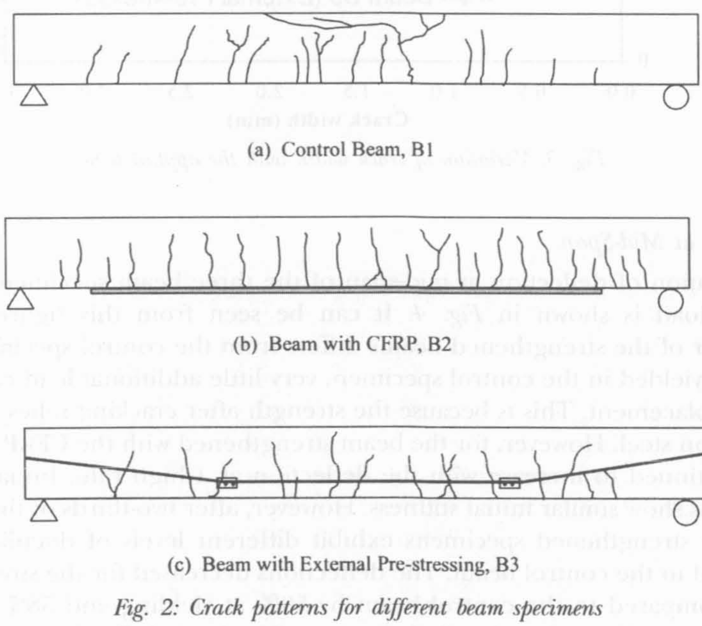


Fig. 2: Crack patterns for different beam specimens

Fig. 3 shows the variation of crack width with the applied load for beam specimens. The widths of the cracks observed in the strengthened specimens are smaller compared to the cracks width in the control specimen. When the applied load was equal to 32 kN (before the failure of the control beam) a crack width of 0.64 mm, 0.18 mm and 0.8 mm have been observed in the control beam, the beam strengthened with CFRP and the beam strengthened with external pre-stressing respectively. The beam strengthened with CFRP shows the smallest crack width compared to other beam specimens.

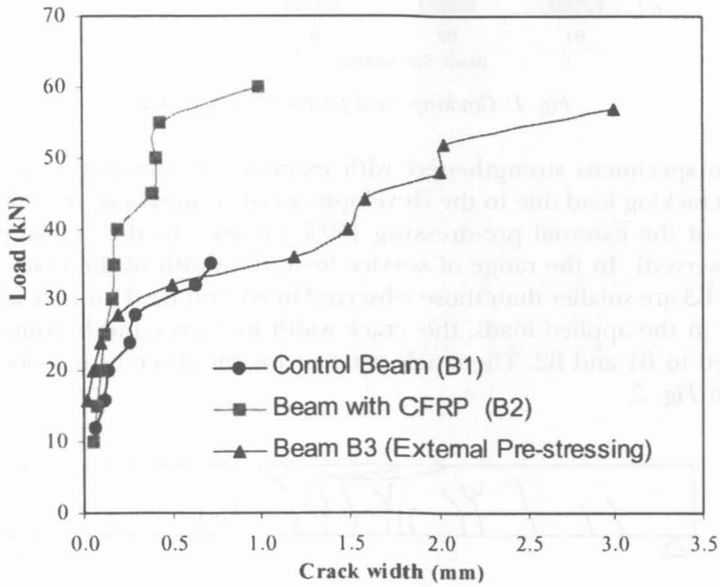


Fig. 3: Variation of crack width with the applied load

Deflection at Mid-Span

The variation of deflection at mid-span of the three beam specimens with the applied load is shown in *Fig. 4*. It can be seen from this figure that the behaviour of the strengthened beams differs from the control specimen. Once the steel yielded in the control specimen, very little additional load caused very large displacement. This is because the strength after cracking relies mainly on the tension steel. However, for the beam strengthened with the CFRP strips, the load continued to increase with the deflection at a high rate. Initially all the specimens show similar initial stiffness. However, after two-thirds of the ultimate load, the strengthened specimens exhibit different levels of ductility pattern compared to the control beam. The deflections decreased for the strengthened beams compared to the control beam by 50% at yielding and 58% at failure load, which indicates less ductile behaviour. The load–deflection curves of the strengthened beams are quite similar.

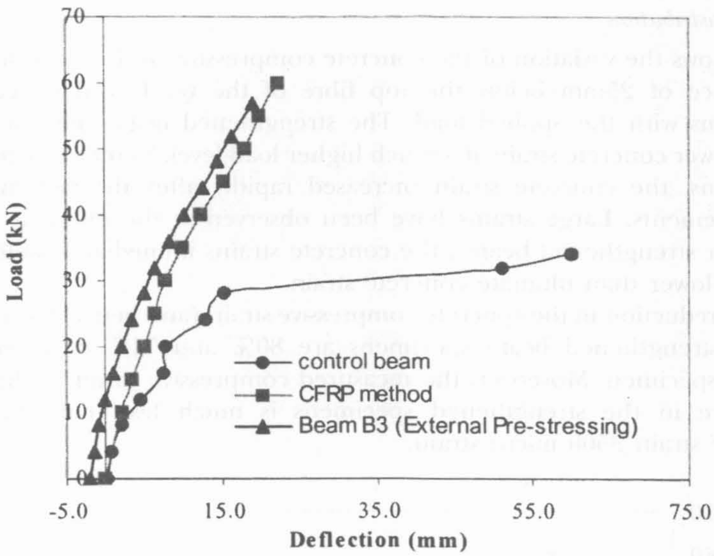


Fig. 4: Load-deformation characteristic for beam specimens

Ultimate Load

The strengthened beam specimens exhibited a significant increase in the flexural capacity over the control specimens. *Fig. 5* shows the ultimate failure loads for all the tested specimens. The increase in strength found in B2 and B3 are 71.5% and 62.8% respectively. This indicates that both beam specimens show similar increase in strength when strengthened by CFRP strips and external pre-stressing wires.

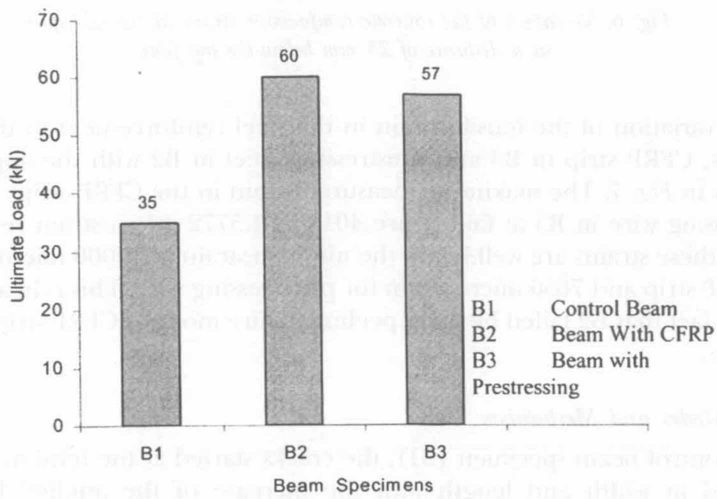


Fig. 5: Ultimate load for the tested specimens

Strain Distribution

Fig. 6 shows the variation of the concrete compressive strain at the mid-span at a distance of 25mm below the top fibre of the reinforced concrete beam specimens with the applied load. The strengthened beam specimens exhibit much lower concrete strain at a much higher load level. In the un- strengthened specimens, the concrete strain increased rapidly after the yielding of steel reinforcements. Large strains have been observed at the moment of failure, while for strengthened beams, the concrete strains immediately before failure are still lower than ultimate concrete strain.

The reduction in the concrete compressive strain (and hence stress) observed in the strengthened beam specimens are 80% and 71% compared to the control specimen. Moreover, the measured compressive strain in the concrete at failure in the strengthened specimens is much less than the ultimate concrete strain 3500 micro strain.

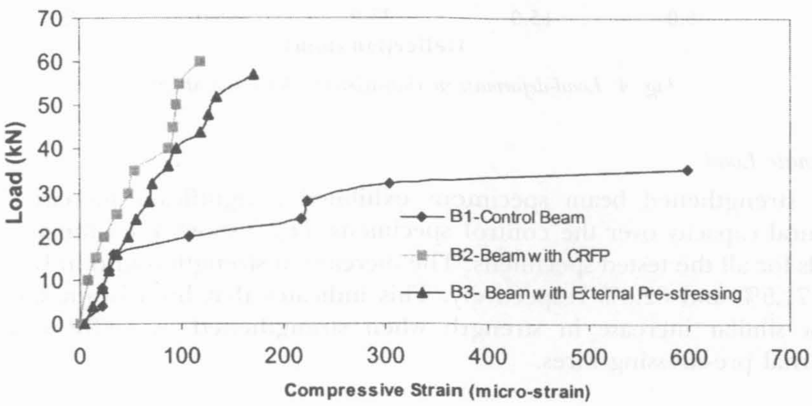


Fig. 6: Variation of the concrete compressive strain at the mid-span at a distance of 25 mm below the top fibre

The variation of the tensile strain in the steel reinforcement in the control beam-B1, CFRP strip in B3 and prestressing steel in B2 with the applied load is shown in *Fig. 7*. The maximum measured strain in the CFRP strips in B2 and pre-stressing wire in B3 at failure are 4011 and 5772 micro strain respectively. Both of these strains are well below the ultimate strain of 17000 micro-strain for the CFRP strip and 7650 micro strain for pre-stressing wire. This is in agreement with the fact that B2 failed by shear peeling failure mode at CFRP strip-concrete interface.

Failure Modes and Mechanism

In the control beam specimen (B1), the cracks started at the tension sides and increased in width and length with the increase of the applied load. The neutral axis location is shifted upwards until the concrete strain reaches its

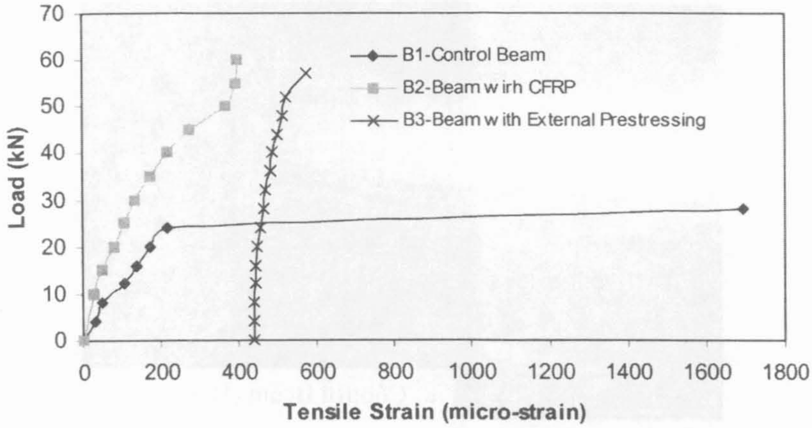


Fig. 7: Variation of the tensile strain at the mid-span in the steel reinforcement, prestressing steel and CRFP strip

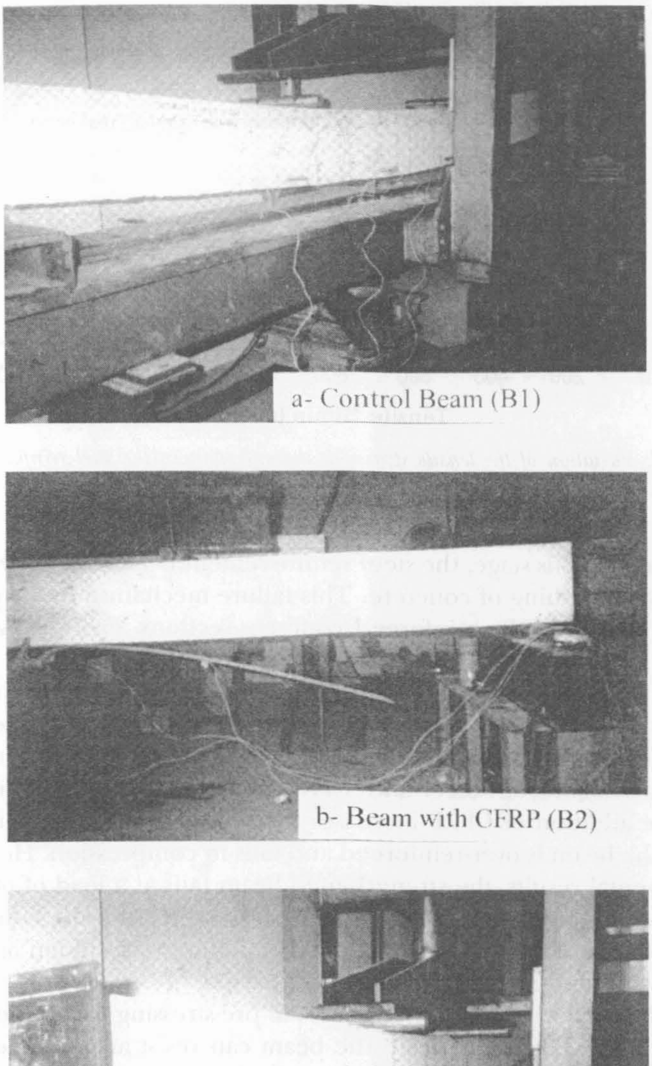
ultimate value. At this stage, the steel reinforcement is yielded which quickly led to compressive crushing of concrete. This failure mechanism is a typical ductile failure observed in under-reinforced concrete sections. *Fig. 8* shows the crack pattern of the beam specimens at failure.

For the beam specimen with CRPF, the theoretical analysis using strain compatibility method according to the BS8110 indicates that the beam can resist a total load of 87.2kN before the concrete crushed in the strengthened beam. At this load, both steel and CFRP layers have reached their yielding stresses. The addition of CFRP increases the tensile area of the reinforcement and hence the beam is over-reinforced and fails in compression. However, from the experimental results, the strengthened beam fails at a load of 60 kN due to the separation of both the Sika paste and CFRP strip from the concrete at the strip ends after showing large deflection. The failure was sudden and occurred immediately after the peeling of the CFRP strips.

For the beam strengthened with external pre-stressing wires, the theoretical calculations using BS8110 indicate the beam can resist an ultimate load of 54 kN which is very close to the experimental value.

CONCLUSIONS

The structural behaviour of reinforced concrete beam strengthened by CFRP strip and external pre-stressing wires have been investigated. Within the serviceability range of load, strengthening the beam with external pre-stressing wires will delay the occurrence of cracking because of the development of compressive stresses due to pre-stressing. However, as the applied load increases, the crack width increases and the strengthened beam with CFRP exhibit much lower crack width compared to those observed in the beam strengthened by external pre-stressing wires. Bonding CFRP with the concrete will control and reduce the crack width.



a- Control Beam (B1)

b- Beam with CFRP (B2)

c- Beam with External Pre-Stressing-B3

Fig. 8: Failure mode of tested specimens

Both strengthening techniques show similar structural response within the ultimate range of loading. The ultimate failure load found was approximately double the failure load of the un-strengthened beam. However, both techniques lead to brittle failure under much higher applied load and lower deflection compared to the un-strengthened beam specimen. The concept of prestressing might be used for the design of reinforced concrete beams strengthened with CFRP.

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