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Ultimate Response of Strengthened RC Beams in the Flexural Using Plain Cementitious Composites Layer

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This paper aims to study the efficiency of applying prefabricated layers made from plain cementitious composite materials for enhancing the flexural behavior of reinforced concrete (RC) continuous beams. The prefabricated layers have 20 mm thickness, 150 mm width, and adequate development length. The prefabricated layers were placed in the tension cover in the positive and negative zones. All specimens have the same concrete dimensions as well as the same positive and negative steel reinforcement ratios. The results showed that the prefabricated layer was deformed with the RC specimen without debonding, which enhanced the cracking patterns and distributed the cracks along the stressed zone. It was found that beam capacity and the yielding load of the strengthened beam were improved by about 7% and 6%, respectively. Besides, the energy absorption capacity of the strengthened beam decreased by 30.67% compared to the control beam, whereas both control and strengthened beams achieved the same ductility indices.

Keywords: Continuous beams, Prefabricated layers, Cementitious composite materials

1 Introduction

Continuous (RC) beams are used as structural members in many RC building sites. Because of the possibility of increasing the stiffness of structures, it is recommended that structural systems that are exposed to seismic hazards, such as bridges, tall buildings, and hospitals [1, 2]. Strengthening RC elements is essential because RC structures become more defective during their service life [3, 4]. Many published articles focused on strengthening the simply supported RC beams rather than the continuous beams [5, 6].

In the past few decades, several techniques have been used to rehabilitate RC members, such as externally bounded (EB) and unbounded FRP or steel sheets, the external prestressed technique, and the near-surface mounted technique (NSM) [7]. These techniques feature many benefits, such as the lightweight and ease of implementation of the EB technique. The NSM enabled the strengthened beam to show higher yielding capacity, and protecting the reinforcement from mechanical harm and environmental impact inside the groove is preferable [6, 8–10]. Although these techniques are quite successful in the flexural strengthening of RC members, numerous shortcomings still exist. In terms of FRP, it is affected by high temperatures, its high cost, and its durability is considered questionable due to environmental attacks as well as the urgent need to use end anchorage systems to avoid premature failure [11, 12]. Regarding the NSM technique, several shortcomings still exist in the concrete cover when using high-tensile stress bars [1, 13].

The continuous development of construction industry as well as the need to build newer and more durable buildings require improvement the quality of materials used in this field. Concrete, as a common construction material has been the subject of research for many years aiming to enhance its the properties [14, 15]. Continuing to overcome the shortcomings in the last conventional strengthening techniques, recently, cement was used as an inorganic binder in cement-based composite materials as an alternative to organic resin. [16–20]. These materials were used as an alternative to traditional strengthening methods and characterized by the tension-softening phenomenon established by fiber reinforcement after the first crack and strain-hardening behavior under uniaxial tension [21–23].

According to [24], strengthening the RC section using cementitious composite materials achieved higher strength than the EB technique. Numerous studies [25–29], applied the different types of cementitious composite materials for strengthening and rehabilitation of RC members and proved a noticeable effect in enhancing flexural behavior. When the fabric is used [30], the end anchorage systems are mandatory for achieving higher capacities and delaying the separation.

The main goal of the present work is to study the use of cementitious composite materials in the form of prefabricated composite layers as a new technique for improving the flexural performance of large-scale RC continuous beams.

2 Experimental work

2.1 Test specimens

The experimental test program consists of two large-scale, statically indeterminate RC beams constructed and tested up to failure. One beam was referred to as a control un-strengthened one and the the other beam was strengthened in the negative and positive zones using plain cementitious composite layers. The tested beams had the same concrete dimensions: 300 mm in total depth, 150mm in width, and 6000mm in full length, comprised of two equal spans of 3000mm, while the center-to-center span was 2850mm. The details of the tested beams are illustrated in Fig. 1.

The strengthening technique was applied with sufficient development length to avoid premature failure. The ACI 440.2R [31] recommended terminating the strengthening length beyond the inflection point (IP) by half the effective depth, or at least 150 mm.

According to the elastic bending moment, the strengthening length in the negative and positive regions has been covered by the IP and terminated after it by 225 mm. On the other hand, the positive strengthening length began without any anchorage from the face of the external support, as shown in Fig. 1.

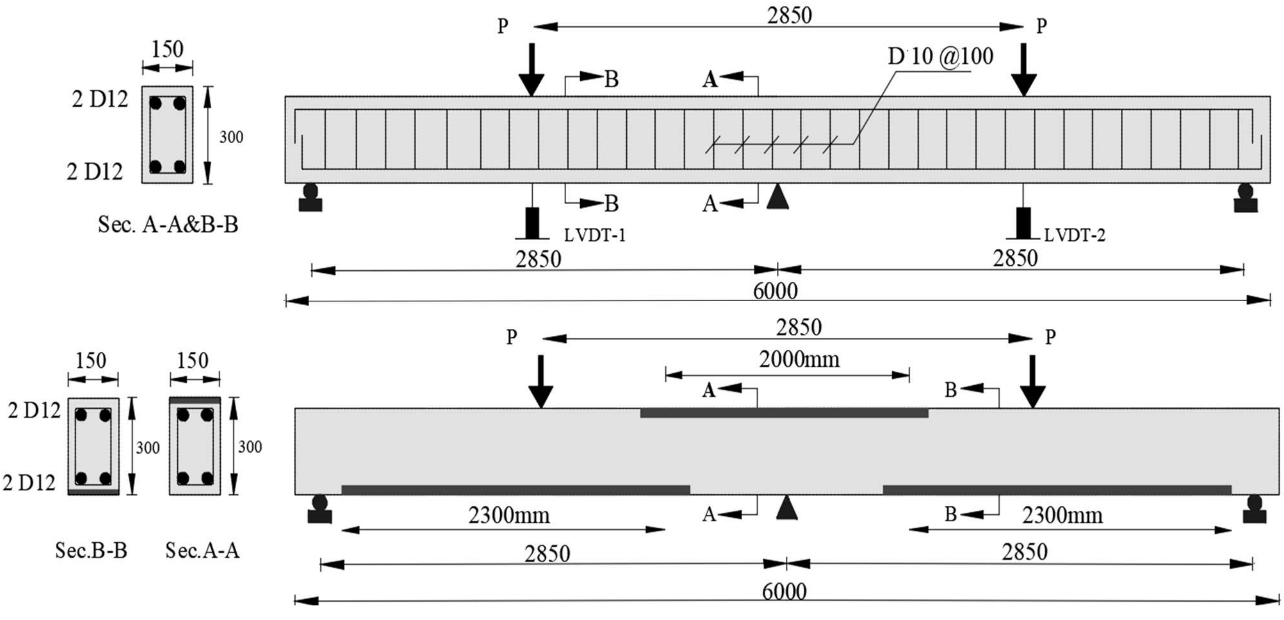


Fig. 1 *Dimensions and detailing of the tested beams*

2.2 Materials

Ready-mix concrete with a target cylinder compressive strength of 35 MPa after 28 days was used for casting both beams. The beams were cured under the same conditions. Table 1 explains the ingredients of the concrete mix for cubic meters as obtained from the supplier of the ready mix. Nine standard 300*50mm cylinders were cast, cured, and kept alongside the beams in the same conditions to ensure the concrete's mechanical properties for all beams. The cylinders were tested on the day the beams were tested by uniaxial compression and splitting tensile tests per ASTM C39/C39M [32].

The slope line in the stress-strain curve from zero to 0.45 compressive stress was defined as the modulus of elasticity (Ec). The concrete strain was obtained using strain gauges attached to the concrete cylinders. Three cylinders were used to determine each test. The average compressive and tensile strengths were about 37 and 3.71 MPa with standard deviations of 1.46 and 0.17, respectively, whereas the modulus of elasticity was 29 MPa with a standard deviation of 0.69.

Both beams were reinforced by four deformed steel bars of 12 mm diameter, with two bars on each side. Closed stirrups with a 10-mm bar diameter were distributed at a spacing of 100 mm to prevent shear failure. To determine the characteristics of the used reinforcement, three specimens with the same dimension for each bar's size were tested in tension to determine the characteristics of steel bars. The average yield and ultimate strengths were about 407 and 625 MPa for the bar of 12 mm in diameter, respectively. The average yield and ultimate strengths were 285 and 425MPa, respectively, for the bar of 10 mm in diameter.

Fig. 2 shows the components of the strengthening layer, which was made from a cementitious composite matrix consisting of binder materials represented by silica fume and ordinary Portland cement. Twenty-five percent of the design cement was replaced by silica fume, and the water-to-binder ratio is 0.2. Fine sand with a diameter of less than 0.5 mm was used. To enhance the crack distribution, 2.0% by volume fraction, polypropylene fibers with 12 mm in length and 0.025 mm in diameter were added. A high-range water-reducing admixture was used to enhance the flowability.

The mechanical properties of the cementitious composite's matrix (compressive and indirect tensile strength) were determined using six cylinders with dimensions of 50 × 100 mm. The average compressive and tensile strengths were about 69.7 and 6.79 Mpa, respectively. The uniaxial tensile strength was determined according to ASTM A770/770 M [33] by testing three standard specimens with cross-sections of 50*900 and 900mm in length. The obtained average tensile strength for tested specimens was about 7.01MPa.

The cementitious composite layer was bonded to the concrete surface using a high-strength epoxy adhesive material. According to the supplier, the compressive and tensile strengths after complete hardening are 82 and 28 MPa and 4.8 MPa for the elastic modulus, respectively.

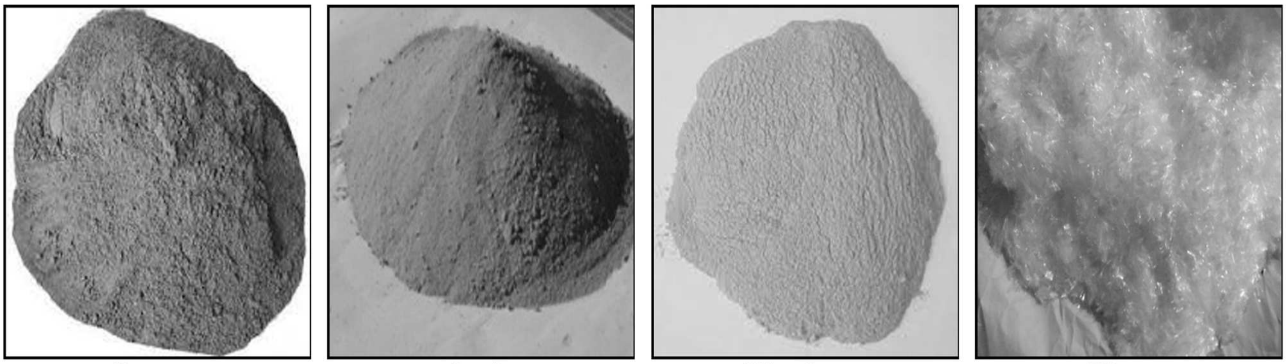


Fig. 2 *Components of the strengthening layer*

Tab. 1 *Mix ingredients for one cubic meter*

Concrete mix	W/B*	Cement	Sand	Coarse limestone	Water	Silica fume	Super-plasticizer	Fiber (Volumetric ratio %)
RC	0.45	400	530	1280	180	-----	-----	-----
Prefabricated Layer	0.16	1365.32	171.12	----	260	342.1	35.1	16.4

** W/B is the water/ binder ratio, B = cement + silica fume*

2.3 Strengthening methodology

The strengthening layers have a width of 150 mm and 20 mm in thickness. The strengthening length was designed to cover the point of zero moments to be 2300 mm at the positive and 2000 mm in the negative bending moment zone.

In separated horizontal wooden formworks, the strengthening layer was cast and de-molded after 24 hours to cure in a wet condition for 14 days and then allowed to air dry. Fig. 3 shows the fabrication steps for the cementitious composite layer. After the complete hardening of the RC beams and cementitious composite layers, the concrete surface was prepared for the application of the layers. First, grooves in the concrete cover in the positive and negative regions are allocated by the complete beam width and 21 mm depth. Second, distribute the epoxy adhesive on the cementitious composite layer and the concrete surface. Third, ensure the full bond between the layers and the substrate beam. To reduce the air voids under the strengthening plate, steel clamps were used and pressed firmly, refer to Fig. 4.

Casting of the prefabricated layer Surface finishing Prefabricated layer after hardening

Fig. 3 *Fabrication steps for cementitious composites layer*

Removing of concrete cover Cleaning groove Application of the epoxy adhesive

Fig. 4 *Steps of application of the cementitious composites layer*

2.4 Five-point bending test

Fig. 5 shows the test setup. It consists of a knife-edge steel support at both ends resting a top jack load distributed in two points and three at the center, representing a five-point bending load scheme. Under the loading points, two LVDTs with a gauge length of 100 mm were fixed to measure the deformed shape in each span.

Electrical strain gauges with a 5 mm gauge length were bonded to the internal steel bars at the midspan and central support before concrete casting. The tested beams were loaded incrementally at the middle of each span until total the occurrence of complete failure. A load cell with a capacity of 1200 kN was positioned under the loading jack to measure the overall beam load. The steel bars' normal strains and the midspan vertical deflections were recorded and saved using an automatic data logger unit (TDS-150).

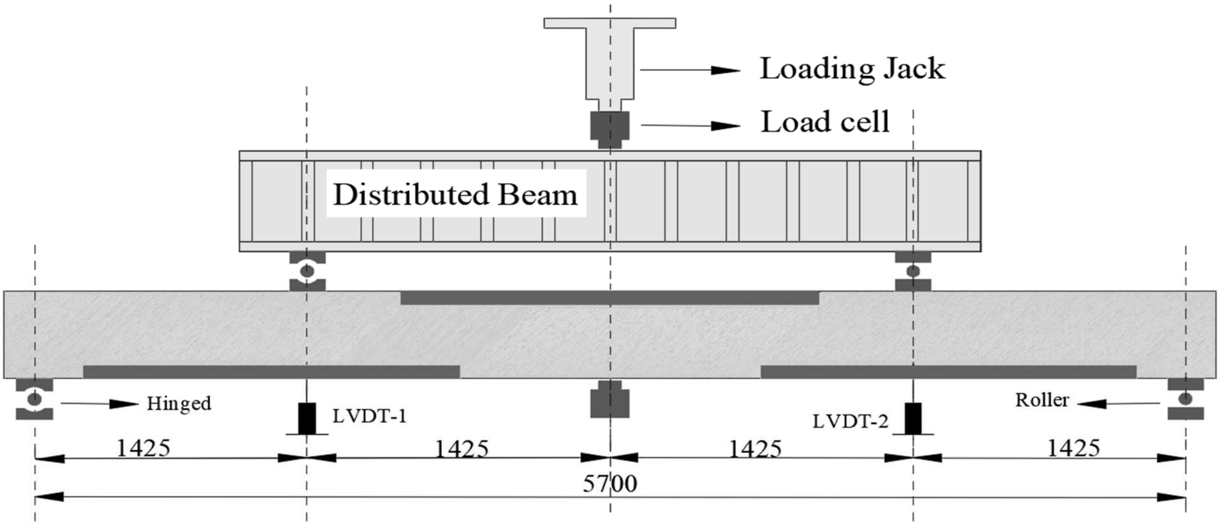


Fig. 5 *Test setup and loading configuration*

3 Results and discussions

3.1 Failure mode and overall capacity

The reference beam followed a conventional ductile flexural failure of reinforced concrete continuous beams. In this mode of failure, the plastic hinge was formed at intermediate support and mid-span sections, followed by concrete crushing in the compression at loading zones as shown in Fig. 6. According to the results of the developed strains on the steel reinforcing bars, the yield loads for positive and negative steel bars are 92 and 95 kN, respectively. The ultimate load is 150 kN (Pu = 150 kN), after which the load decreases until the maximum deflection (δu = 40.2 mm), refer to Fig. 6.

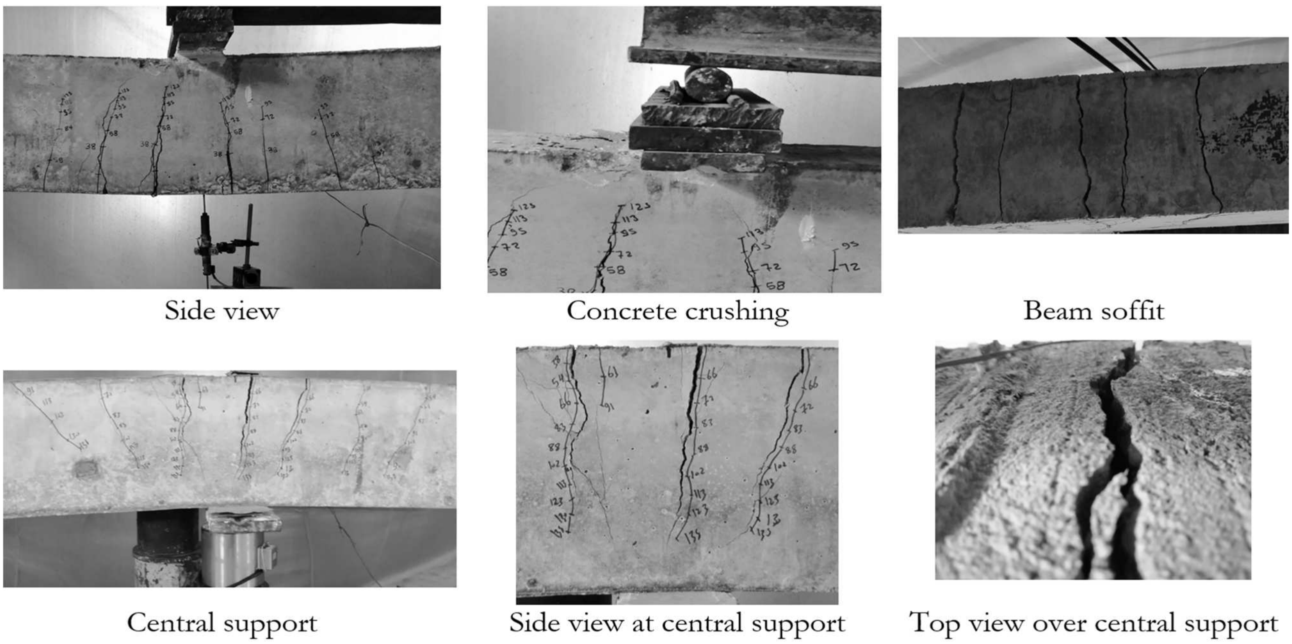
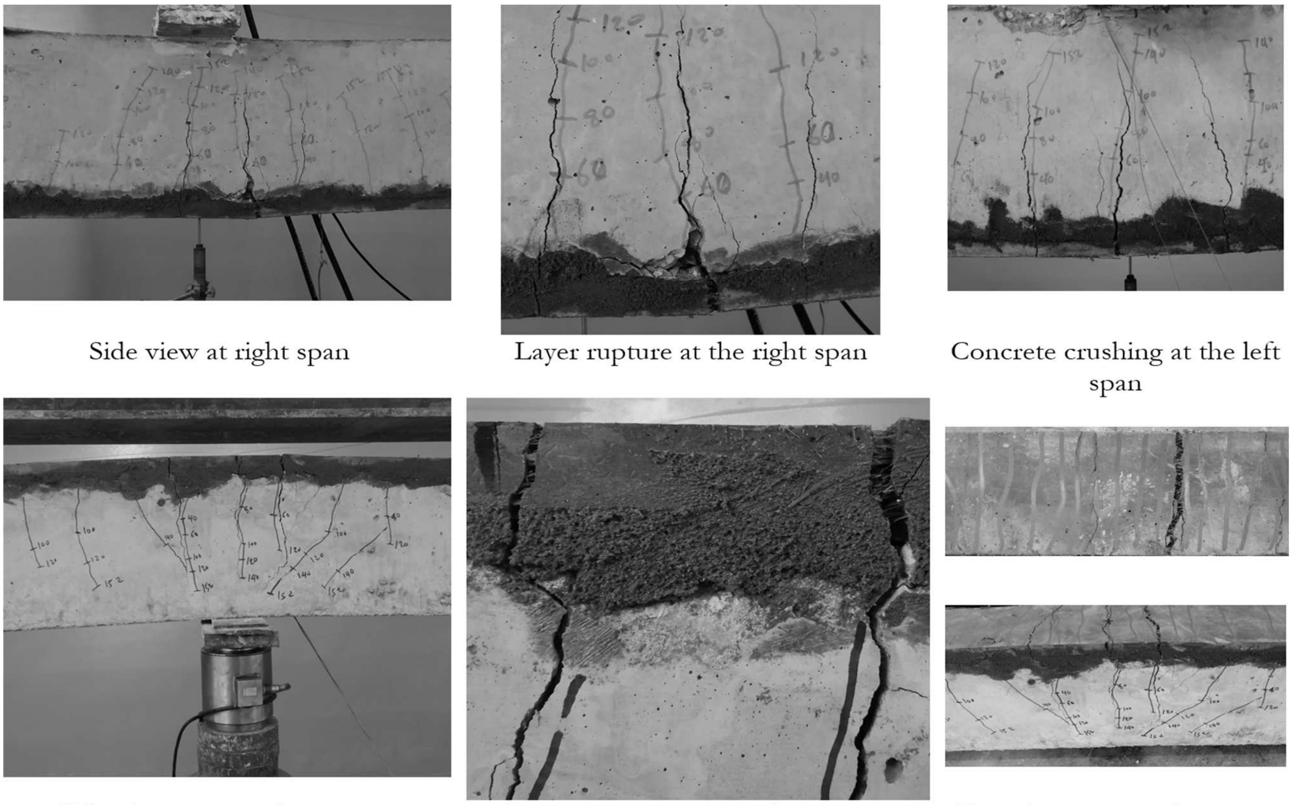


Fig. 6 *Reference control beam*

As for the strengthened beam, there is no debonding between the strengthening layer and the resin-filling substance. It was noticed that the prefabricated layers deformed and deflected with the tested substrate beam, which demonstrates the high toughness of the cementitious composite's matrix. The failure was developed when approaching the prefabricated layer's maximum tension resistance. After tensile steel yielded at the middle support at a yielding load, Py, equals 98.65 kN corresponding to 62.7% of the ultimate load, followed by right and left span steel yielding 104.48 kN corresponding to 65.65% of the ultimate load, the beam resistance to the external load tacked to increase up to the ultimate load (Pu = 159.16 kN), then, the load decreased until the maximum vertical deflection at mid-span (δu =39.1mm), refer to Fig. 7.



Side view at right span | Layer rupture at the right span | Concrete crushing at the left span

Side view at central support | Layer rupture at central support | Top view at central support

Fig. 7 *Strengthened Beam*

3.2 Load-deflection relationship

The relationship between midspans deflection (δ) and jack loads (Pt) is shown in Fig. 8. These results were derived from the tested beams' LVDT data. The four independent stages of the load-deflection curves, A: concrete cracking, B: steel yielding, C: ultimate load, and D: failure load are spaced three points apart. The prefabricated layer's negligible impact at this point is shown in the virtually equal breaking loads for the enhanced and reference beams. The yield load and ultimate load of the strengthened beam were 7% and 6% higher, respectively, than those of the reference beam. Before yielding the positive steel, the stiffness of the strengthened beam had somewhat risen. This was explained by the prefabricated layer's constraining action, which served as extra reinforcement. The strengthened beam has a higher modulus of elasticity than the reference beam. At the yielding and failure sites, the deflection of both beams was equal. The strengthened beam's ultimate load occurred at 26.6mm, or 66.4% of its maximum deflection, whereas the reference beam's ultimate load happened at its maximum deflection. These outcomes demonstrate the prefabricated layer's strain-hardening tendency after yielding the tensile strength

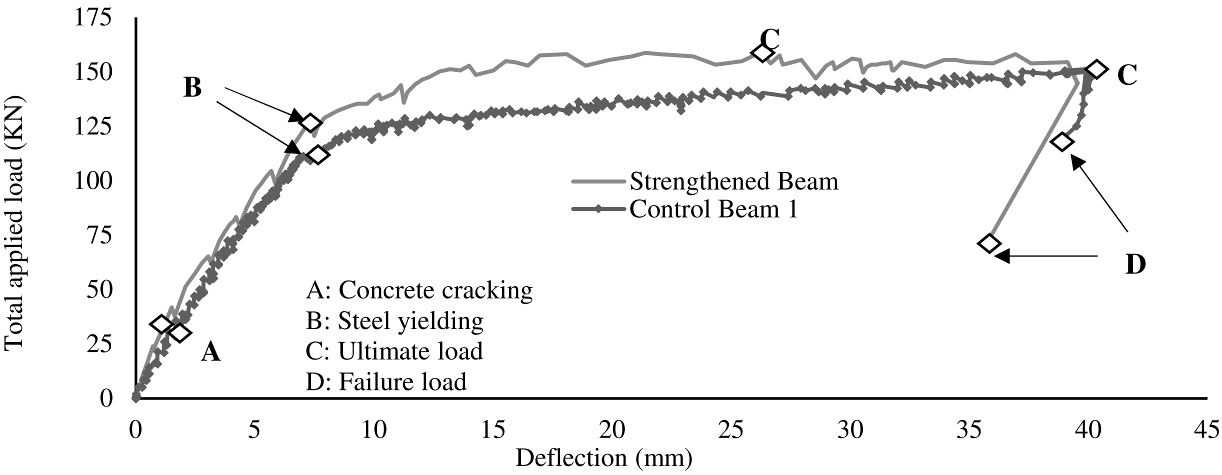


Fig. 8 *Load-deflection relationship for tested beams*

3.3 Cracking patterns and cracking behavior

At a total load of about 33 kN, the upper side of the middle support and lower side of the mid-span zones of the reference beam showed nearly simultaneous formation of the first crack. As shown in Fig. 8, the cracks developed and widened due to the increased loading. Additionally, they grew in the direction of the loading points and central supports. Both beams failed in a tension-controlled manner due to the tension steel yielding and the concrete crushing in the compression zones. As shown in Figs. 8 and 9, the plastic hinges first developed in the hogging zone at a total load of 120 kN and then developed in the sagging region at 125 kN.

Regarding the strengthened beam, the initial crack's onset was delayed due to the strengthening mechanism. The first crack appeared in the hogging region at a total load of about 40 kN, while the first crack appeared in the sagging region at about 55 kN. There were more cracks dispersed over a larger area in the reinforced beam. When the strengthened beam was arrested at a service load equal to 0.6 of the ultimate load, its crack width was smaller than the reference beam's. The outcomes demonstrate how ductile the cementitious composite's matrix.

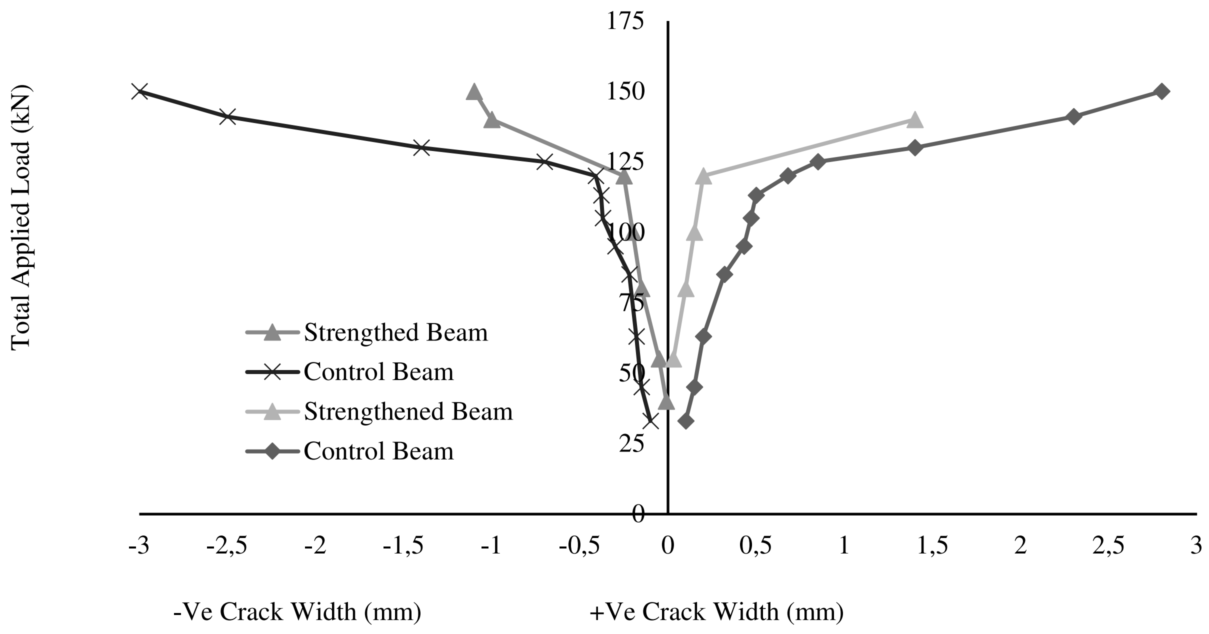


Fig. 9 *Total load vs. positive and negative crack width*

3.4 Energy absorption capacity

Energy absorption capacity was calculated using the area under the load-deflection curves up to the ultimate load. The strengthened beam's energy absorption capacity is lower than the reference beam's, at 30.67% (3900 kN.mm) as opposed to 5100 kN.mm. Enhancing the energy absorption capacity did not involve applying a basic cementitious composite layer. That is because the prefabricated layer served as extra reinforcement on the tension sides. Additionally, because the prefabricated layer's tensile resistance was lower than that of the steel reinforcement, the likelihood of a prefabricated layer rupture decreased as the resistance of the beam decreased.

3.5 Displacement ductility

The ductility of RC members was considered an essential criterion for RC continuous beams. The displacement-based ductility index is calculated according to Equation (1).

$$DI = \frac{\Delta_u}{\Delta_y} \tag{1}$$

Where:

(Δ_u) and (Δ_y)…The mid-span deflection at yield and ultimate load.

The results showed that the reference and strengthened beams achieved the same result, due to the small tension resistance of the prefabricated layer.

3.6 Strain measurements

Three steel strain gauges are distributed at the maximum positive and negative bending moments. The load-strain curves for the tested beams are distinguished by three main stages separated by the cracking point and yield point.

As shown in Fig. 10, the control and strengthened beams achieved a similar steel strain before the concrete cracked. This is due to the slight effect of the prefabricated layer at these stages.

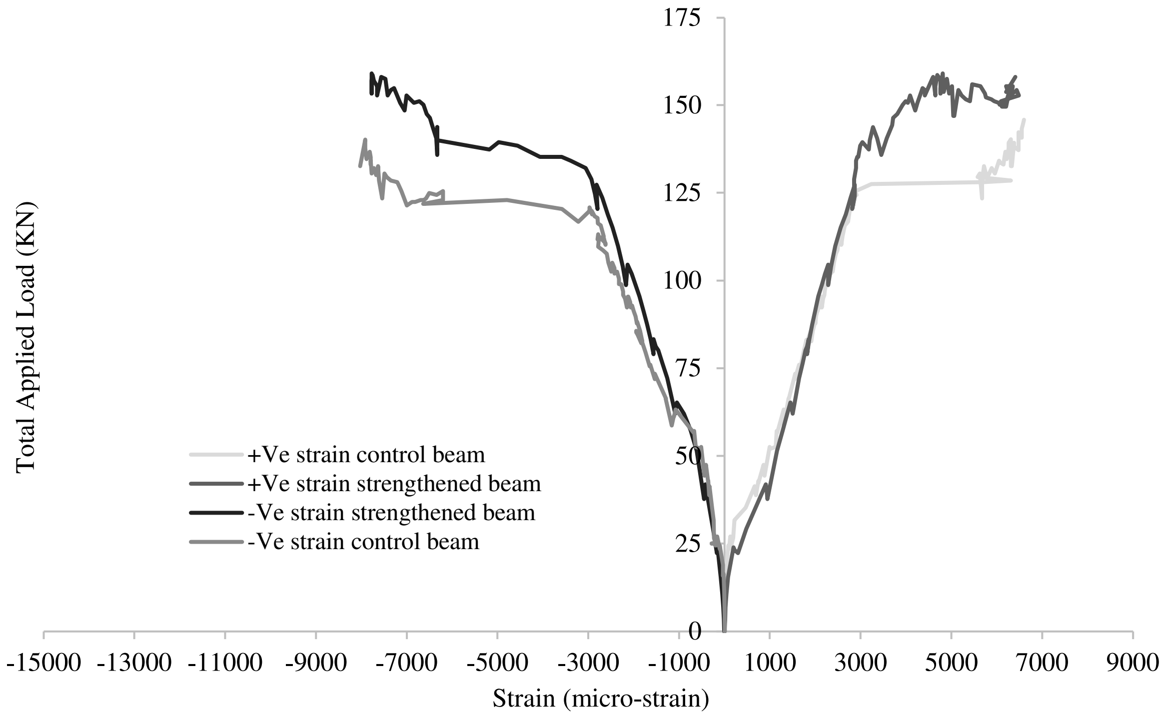


Fig. 10 *Load vs. main steel strain at the negative and positive regions*

After initiation cracking and before negative steel yielding, a visible effect of the prefabricated layer was observed, with a small decrease in the negative steel strain compared with their reference beam until steel yielded at 2960 and 3175 με for control and strengthened beams, respectively. These results reflect the participation of the prefabricated layer as additional reinforcement. The steel strain in the negative zone has a multi-load drop point. That is caused by the fiber resistance after the occurrence of cracks in the prefabricated layer. In contrast, in the positive steel strain, both control and strengthened beams exhibited the same steel strain until steel yielded at 2716 and 3090με for control and strengthened beams, respectively. That is because of the contribution of the prefabricated layer to resist the applied load in the negative zone of the strengthened beam, which decreases the positive strain until it yields the negative steel.

4 Indications for industrial practice

Using a cementitious composite layer to strengthen the flexural behavior of RC beams is a very effective method to enhance the performance of reinforced concrete beams. Some indications for the industrial practice of using a cementitious composite layer for strengthening the flexural behavior of RC beams include:

- 1) Increased load-carrying capacity: If there is a need to increase the load-carrying capacity of the RC beam without significantly altering its dimensions, adding a cementitious composite layer can help achieve this goal.
- 2) Structural deficiencies: If the RC beam shows signs of structural deficiencies such as cracking, deflection, or inadequate load-carrying capacity, a cementitious composite layer can be applied to improve its flexural behavior.
- 3) Retrofitting requirements: In cases where existing RC beams need to be retrofitted to meet updated design standards or address changes in loading conditions, a cementitious composite layer can be a proper solution.
- 4) Durability enhancement: The application of a cementitious composite layer can also improve the durability of RC beams by providing additional protection against environmental factors such as corrosion and weathering.

To effectively use a cementitious composite layer for strengthening the flexural behavior of RC beams, it is important to carefully assess the specific requirements of the structure, determine the appropriate thickness and composition of the layer, and ensure proper installation techniques are followed. Additionally, quality control measures should be implemented to verify the effectiveness of the strengthening process.

5 Conclusion

Based on the results of the experimental program, the following conclusions can be drawn: Utilizing the prefabricated layer for strengthening the RC continuous beam in both positive and negative regions reduced the developed tensile strains in the adjacent reinforcing steel bars for the same applied load compared to those of the reference beam. It is worth mentioning that no debonding or peeling-off in the concrete covers happened between the strengthening layer and the concrete cover along the entire loading history.

The reference and strengthened beams achieved the same ductility index; however, the energy absorption capacity corresponding to the ultimate load decreased by about 30.67% for the strengthened beam compared to the control un-strengthened beam. The prefabricated layer on the tension side in this experimental program works as additional reinforcement. Despite this layer having low tension resistance compared to the steel reinforcement, these strengthening systems enhanced the cracking patterns and mode of failure and improved the yielding and ultimate capacity by about 7 and 6.1%, respectively.

When considering the novelty of using a plain cementitious composite layer to strengthen RC beams in flexure, it is important to highlight the unique aspects and advancements that this approach brings to the field of Structural Engineering. One aspect of novelty in this method is using a simple and cost-effective material such as plain cementitious composites to enhance the flexural behavior of RC beams. This can be quantified by comparing the material and labor costs of applying a cementitious composite layer to the traditional methods of beam strengthening, such as steel plate bonding or carbon fiber-reinforced polymer sheets.

Another quantification of the novelty of this approach can be shown in the improvements achieved in the load-carrying capacity, stiffness, and ductility of the strengthened RC beams. By comparing the results before and after the application of the cementitious composite layer, the effectiveness of this strengthening method can be quantitatively assessed.

One limitation of the proposed strengthening technique is the potential for bond strength issues between the existing concrete substrate and the cementitious composite layer. Thus, proper surface preparation and application techniques are essential to ensure a bond between the layers. Additionally, the long-term durability of the cementitious composite layer and its compatibility with the existing concrete structure should be carefully considered. Factors such as age, cracking, and environmental exposure can impact the performance of the strengthened RC beams over time.

In conclusion, using plain cementitious composite layers for strengthening RC beams in flexure represents a novel and cost-effective approach to enhance the structural performance of existing concrete beams. The advancements in understanding the behavior and performance of strengthened RC beams through this method contribute to the progress in knowledge and innovation in Structural Engineering.

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