Performance of RCC Beams Laminated with Kevlar Fabric

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ABSTRACT

The use of kevlar fabric laminates in the structural repair and retrofitting of reinforced concrete members becomes a great deal of research work nowadays. Many research works have been done on the performance of Fibre-Reinforced Polymer (FRP) laminates on reinforced concrete structural members. Some studies have been done on the performance of kevlar fabric laminates on reinforced concrete structural members and only few contributions are available for self-compacting concrete structural members. Hence, in this research work, an attempt is made to study the performance of reinforced concrete and self-compacting beams laminated with various numbers of kevlar fabric layers by an epoxy bonding agent under a two-point concentrated loading system. The experimental data of ultimate load, mid-span deflection and mode of failure was collected and discussed. Theoretical and analytical studies were also conducted and compared with experimental results. When applying the kevlar fabric as an external reinforcement, the flexural strength of two-layer U-shape kevlar fabric-laminated beams has been increased by 88% and 82%, respectively, compared to unlaminated reinforced concrete and self-compacting beams.

KEYWORDS: Kevlar fabric, Laminated beam, External bonding, Load-carrying capacity, Epoxy bonding.

INTRODUCTION

There are numerous construction structures across the world which do not fulfill the present design requirements due to lack of structural design, added loadings on the members, lack of seismic design requirements and deterioration due to corrosion of reinforcement steel by the aggressive environment. The most crucial problems in civil engineering are strengthening, repair and rehabilitation of concrete members. Strengthening of a concrete member plays a vital role to increase strength and serviceability. The plate bonding technique is one of the strengthening techniques used to increase the load-carrying capacity of the existing concrete member, but it has some disadvantages due to heavy weight and nonflexible materials. As a result of drawback of steel, the idea of using kevlar fabric as a strengthening material appeared by using an epoxy bonding agent.

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Strengthening may be required to allow the concrete member to oppose loads that were not expected within the design requirements. Alterations in building structure may cause additional loads, which necessitates a higher load-carrying capacity of structural members. Bearing capacity of structural members can be increased by a method of strengthening. Kevlar fabric materials are non-metallic and most likely used to resist aggressive chemical attacks. In this manner, they are considered as a great alternative for strengthening concrete structures. Mostly, concrete beams fail in two ways: flexural failure and shear failure. Sometimes, shear failure is more severe than flexural failure. Bonding of fabrics with epoxy resin to the tension surface of beams can improve the mechanical performance. This method is effective and has been used in many worldwide projects. The corrosion of steel plates can also easily weaken the structure. So, the intention is to find alternative materials to retrofit structural members without damaging the aesthetic view of the building. Therefore, the usage of synthetic fabric externally applied on the member for improving load-carrying capacity of concrete beams gives an effective solution.

Thakur (2004) found that jute fiber with more cement content strengthens the concrete. An analytical model was developed to study the effect of strengthened beams with glass fiber-reinforced polymer (Subramani et al., 2015). Sayed Behzad (2015) conducted an experimental study and developed the shear-torsion interaction curves for fiber-reinforced polymer-strengthened beams. Dharmesh (2015) studied experimentally the performance of externally bonded strengthened beams with woven and non-woven fabrics. Mohammad Zakaria et al. (2016) found that the ultimate strength of concrete is increased by jute fiber. Raupach (2016) conducted an experimental study on carbon fibre textile-embedded concrete. Gajalakshmi et al. (2016) studied the behaviour of interior beam column joint with FRP wrapping. Davood (2017) proved that load-carrying capacity and mid-span displacement are increased for strengthened reinforced concrete beams which were laminated with longer fiber-reinforced polymer. Revathy et al. (2017) studied the performance of fiber-reinforced concrete sandwiched in double-skinned plated composite beams. Zhang (2018) conducted an experimental study on reinforced concrete T-section beams strengthened with bottom steel plates. Mohammad (2020) and Yasmeen (2018) studied the load-deflection behavior of carbon fiber-reinforced concrete columns and showed a stiffening trend and ductility reduction when eccentricity was increased. Based on the above literature study, it has been found that there is less number of studies related to reinforced concrete and self-compacting concrete beams laminated with kevlar fabric.

In this paper, an effort has been made to study, experimentally and analytically, the behavior of reinforced concrete and self-compacting concrete beams laminated with kevlar fabric.

EXPERIMENTAL STUDY

The two beam types were cast in this experimental work. In type 1, five beams were cast as conventional concrete out of which one beam was the reference beam. In type 2, with same reinforcement detail and concrete grade, five beams were cast as self-compacting concrete out of which one beam was the reference beam. The cross-sectional dimensions of all beams are 150 mm in width and 200 mm in depth and the total span length is 1000 mm. Two bars of 12 mm diameter have been provided for tension and compression reinforcement and 8 mm bars are used as stirrups with a spacing of 150 mm c-c in order to avoid shear failure and enhance flexural performance. The reinforcement detail of beam specimen in longitudinal section is shown in Fig.1. Plywood was used for casting of beams. The mix design for conventional and self-compacting concrete was done as per design mix procedure IS 10262:2009 (IS-10262, 2009). After specified days, curing was stopped and eight beams were laminated with kevlar fabric having two different layers (1 layer and 2 layers). The surface of concrete is cleaned with a wire brush to remove dust. Then, the fabric is laminated on the cured beam along longitudinal reinforcement of the beam with an epoxy hardening agent mixed in the ratio of 1:1. Uniform pressure is applied on the fabric to make good contact between fabric and concrete and curing is carried out for 7 days at room temperature (20-25°C). The labels for beam specimens are given in Table 1.

Table 1. Labels for beam specimens

Specimen Name	Description
Reference CC	Reference Conventional Concrete Beam
CC B 1	Conventional Concrete Beam Laminated with 1 Bottom Layer of Kevlar Fabric
CC B 2	Conventional Concrete Beam Laminated with 2 Bottom Layers of Kevlar Fabric
CC U 1	Conventional Concrete Beam Laminated with 1 U-Shape Layer of Kevlar Fabric
CC U 2	Conventional Concrete Beam Laminated with 2 U-Shape Layers of Kevlar Fabric
Reference SCC	Reference Self-Compacting Concrete Beam
SCC B 1	Self-Compacting Concrete Beam Laminated with 1 Bottom Layer of Kevlar Fabric
SCC B 2	Self-Compacting Concrete Beam Laminated with 2 Bottom Layer of Kevlar Fabric
SCC U 1	Self-Compacting Concrete Beam Laminated with 1 U-Shape Layer of Kevlar Fabric
SCC U 2	Self-Compacting Concrete Beam Laminated with 2 U-Shape Layers of Kevlar Fabric

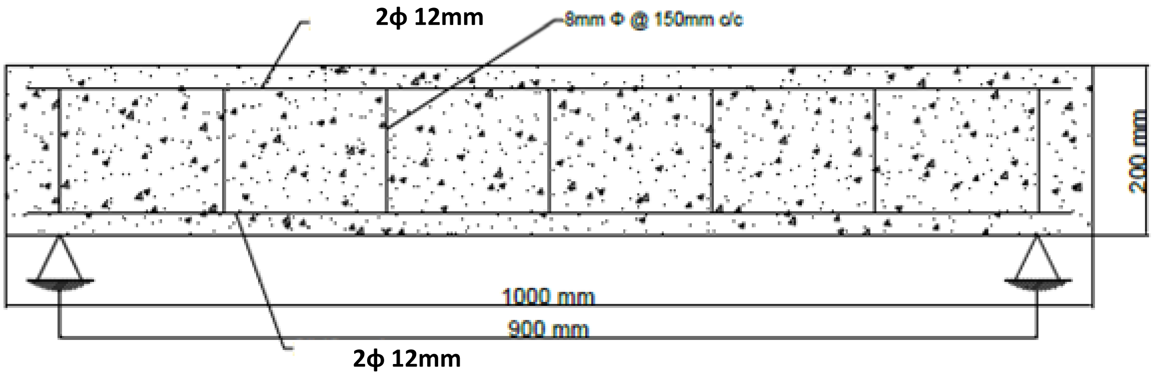


Figure (1) :Longitudinal reinforcement detail of concrete beam

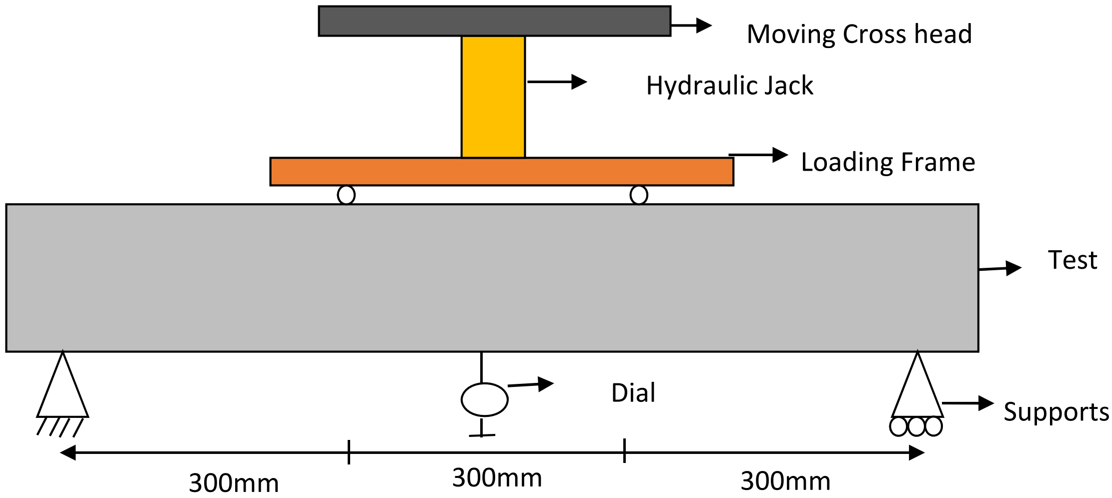


Figure (2): Two-point loading experimental setup

All beams were tested in the loading frame of the Structural Engineering Laboratory at B.S. Abdur Rahman Crescent Institute of Science and Technology. The one end of the beam specimen is placed over a hinged support and the other end is placed over a roller support leaving 50 mm as an edge distance from the ends of the beam. The remaining 900 mm was divided into three parts of 300 mm each. Load is applied by a 50t-capacity hydraulic jack. Dial gauges were fixed at the middle of the beam to detect beam deflection. The two-point loading test setup is shown in Fig. 2.

MATERIALS

Kevlar Fabric

Kevlar is the trademark name of a synthetic material made of para-aramid fibers. Kevlar is a kind of paramid that includes long polymeric chains of a similar direction. It was invented by Stephanie Kwolek (2002) of Du Pont Company in her research. It is heat-resistant and decomposes above 400˚C. Para-aramid does not corrode or rust and its strength is unaffected by immersion in water. The strength of kevlar fabric derives from inter-molecular hydrogen connections and aromatic stacking connections between aromatic groups in neighboring strands. Kevlar fabric contains normally static molecules, which form a planar sheet-like arrangement similar to silk protein. Kevlar materials can be applicable to attach to one another or to other materials to form composite materials. Sometimes, the tensile strength of kevlar fabric may be more than 500 MPa. The physical properties of kevlar fabric are presented in Table 2. The basic properties of kevlar fabric were tested under a Universal Testing Machine as per ASTM D638 (ASTM D638-14, 2014).

Adhesive Bonding Agent

Araldite is an epoxy adhesive that is suitable for bonding a synthetic material to the concrete surface, which is easily applied on the surface of the concrete member. Some of the advantages of epoxy resin hardener are higher shear strength and good resistance to static and dynamic loads. The physical properties of epoxy resin and epoxy hardener are summarized in Table 3.

Table 2. Properties of kevlar fabric

Specification	Category
Material	Kevlar fabric
Arrangement	Biaxial 0 º /90 º
Mass (g/cm^2)	1.44
Nominal width per layer (mm)	0.6
Ultimate tensile strength (N/mm^2)	263
Poisson's ratio	0.36

Table 3. Properties of epoxy resin and hardener

Description	Resin	Hardener
Colour	Creamy / viscous liquid	Amber liquid
Odour	Slight	Ammonia
Specific gravity	1.17	0.92
Solubility in water	Insoluble	Miscible
Physical state	Liquid	Liquid
Density at 25˚ C (g/cm^3)	1.15– 1.2	1

Table 4. Properties of construction materials

Description	Conventional Concrete	Self-compacting concrete
Grade of concrete	M25	M25
Type of cement	OPC-53 grade	OPC-53 grade
Maximum nominal size aggregate	20mm	10mm
Exposure condition	Moderate	Moderate
Specific gravity of cement	3.11	3.11
Specific gravity of fine aggregate	2.59	2.59
Specific gravity of coarse aggregate	2.68	2.68
Fly ash	-	2.56
Superplasticizer	-	Master glenium

Table 5. Design mix proportions for concrete

Material	Type of concrete	
	Conventional concrete	Self-compacting concrete
Cement	439 kg/ m^3	357 kg/m^3
Fine aggregate	666 kg/ m^3	834 kg/ m^3
Coarse aggregate	1104 kg/ m^3	772 kg/ m^3
Fly ash	-	152 kg/m^3
Superplasticizer	-	0.8
Water	197 kg /m^3	178 kg/ m^3

Table 4 shows the properties of materials for conventional concrete and self-compacting concrete and Table 5 shows the design proportioning of conventional and self-compacting concrete.

ANALYTICAL STUDY

Analytical study was carried out by using ANSYS15.0 workbench (ANSYS Meshing User's Guide, 2013) to predict the performance of Reference CC, CC B1, CC B2, CC U1, CC U2, Reference SCC, SCC B1, SCC B2, SCC U1 and SCC U2 beams.

Beam Modeling

Concrete was modeled by using SOLID 65 element with eight nodes having three degrees of freedom at each node. SOLID 65 element has the property of formation of cracks under tension and is capable of crushing in compression. Solid 45 element with eight nodes was used to model the steel plates in the supports and the loading points. This element has three degrees of freedom at each node. A link 8 element (3D spar element) with two nodes was used to model steel reinforcement. This element has three degrees of freedom at each node and has the property of bilinear isotropy, which means that it is identical in tension and compression. Kevlar fabric laminates were modeled by the layered solid element Solid 45.

Analytical models of reference beams and laminated beams are shown in Fig.3, Fig.4 and Fig.5. In order to obtain accurate results, the element size of 10mm is considered to mesh the beam. The meshing of the beam is shown in Fig. 6. Concentrated loads were applied on the beam. The support of the beam is modeled as a hinged support at one end and a roller support at the other end, as shown in Fig. 7. Reference beams and strengthened beams are analyzed and load-deflection curves are plotted according to the results.

THEORETICAL STUDY

The load-carrying capacity and maximum deflection of the proposed concrete beam laminated with kevlar fabric was carried out by means of theoretical study. The stress- strain relationship of all beams laminated in the tension face with kevlar fabric is formulated as per Yeole, P.M. (2013). Flexural strength of bottom and U-shape laminated beams was calculated as per Yeole, P.M. (2013).

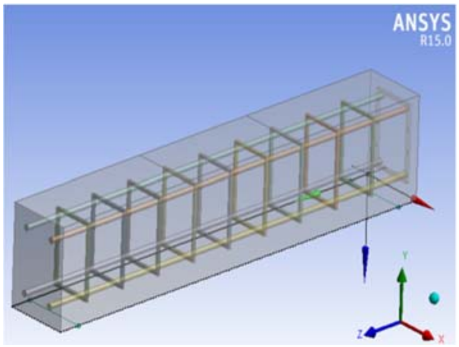


Figure (3): Modeling of Reference CC

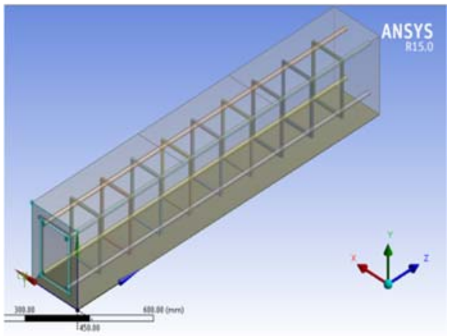


Figure (4): Modeling of CC B 1

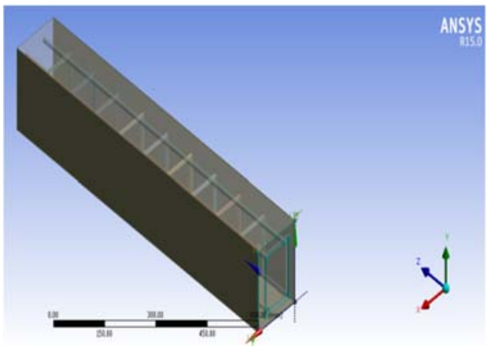


Figure (5): Modeling of CC U 1

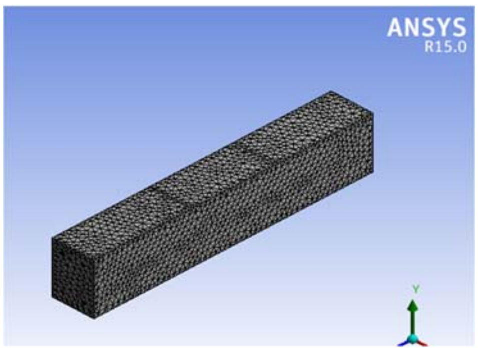


Figure (6): Meshing of reference CC

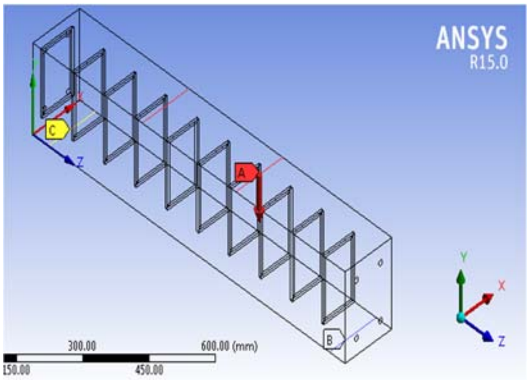


Figure (7): Loading and boundary conditions of reference CC

RESULTS AND DISCUSSION

Compressive Strength Test Results

Compressive strength test was conducted to find the characteristic strength of concrete as per IS 516-1959 (IS 516:1959, 2013). Compressive strength of self-compacting concrete was found higher than that of conventional concrete. From the experimental results, self-compacting concrete attained an increase in compressive strength of 40% higher than conventional concrete at 28 days.

Split Tensile Test Results

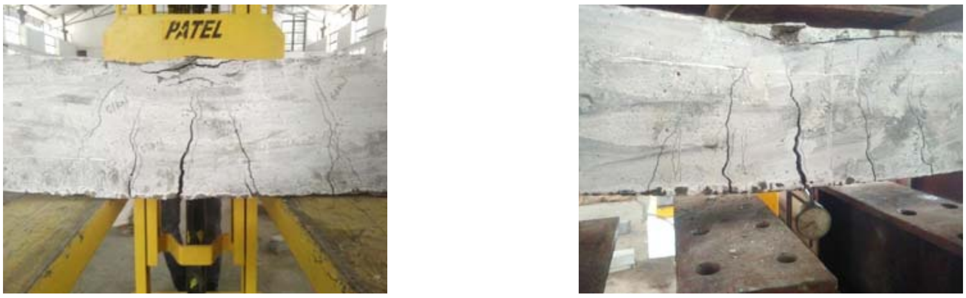
Split tensile test was carried out as per IS 5816 -1999 (IS:5816: 1999, 2004) to determine the tensile strength of concrete. It was found that the tensile strength of self-compacting concrete beam increased by 7% more than that of conventional concrete at 28 days.

Table 6. Experimental test results of CC and SCC beams and mode of failure

Specimen	Load at initial crack (kN)	Ultimate load (kN)	Average crack width (mm)	No. of cracks	Failure mode
Reference CC	30	70.5	0.3	6	Flexural failure
CC B1	34	84.06	0.25	3	Flexural failure + rupture of fabric
CC B2	36	97.07	0.15	2	Flexural failure + rupture of fabric
CC U1	Crack not visible	119.26	Rupture of fabric	Rupture of fabric	Flexural failure + rupture of fabric
CC U2	Crack not visible	132.86	Rupture of fabric	Rupture of fabric	Flexural failure + rupture of fabric
Reference SCC	37	74.9	0.25	4	Flexural failure
SCC B1	39	91.26	0.2	3	Flexural failure + rupture of fabric
SCC B2	40	101.2	0.10	2	Flexural failure + rupture of fabric
SCC U1	Crack not visible	123.30	Rupture of fabric	Rupture of fabric	Flexural failure + rupture of fabric
SCC U2	Crack not visible	136.93	Rupture of fabric	Rupture of fabric	Flexural failure + rupture of fabric

Failure Modes of Beams

When compressive strain in the concrete reaches its maximum serviceable strain of 0.0035, crushing of concrete occurs. If the strain in the fabric reaches its maximum strain before concrete reaches its maximum strain, rupture of fabric occurs. Figures 8 through 12 show the crack pattern and number of cracks that occurred in reference and kevlar fabric-laminated conventional and self-compacting concrete beams.



(a)Reference CC **(b) Reference SCC**

Figure (8): Flexural failure of reference CC and SCC beams

(c) CC B1 **(d) SCC B1**

Figure (9): Flexural failure of CC B1 and SCC B1 beams

(e) CCB2 **(f)SCCB2**

Figure (10): Flexural failure of CC B2 and SCC B2 beams

(g) CC U1 **(h)SCC U1**

Figure (11): Flexural failure of CC U1 and SCC U1 beams

(i) CC U2 **(j) SCC U2**

Figure (12) :Flexural failure of CC U2 and SCC U2 beams

Cracking Behaviour

The cracking behavior of reinforced concrete and self-compacting concrete beams is modified due to the external lamination of kevlar fabric which transfers the additional stresses to the concrete in tension. There is a significant reduction in average crack width at both service and ultimate limits due to kevlar fabric strengthening and shear failure was not observed in any of the beams. In the reference CC beam, the load at the first crack was 30 kN in the flexure region. By increasing the load, additional cracks were generated with an average spacing of 15mm from the initial crack and cracks were extended toward the shear span region. The beam finally failed at a load of 70.5 kN under flexure. For the reference SCC beam, the first crack was initiated at 37 kN in the flexure region and the average spacing of additional cracks from the initial crack was 20 mm. In the beams CC B1 and CC B2, the first flexural cracks formed at loads of 34 kN and 36 kN. The crack width decreased and the number of cracks also decreased due to the addition of one-and two-layer kevlar fabric lamination at bottom region. The beams finally failed at loads of 84 kN and 97 kN under flexure and rupure of kevlar fabric lamination. In the beams CC U1 and CC U2, cracks were not visible and failure mode was induced by rupture of the kevlar fabric. The beams finally failed at load of 75 kN under flexure. In the beams SCC B1 and SCC B2, the first flexural cracks formed at loads of 39 kN and 40 kN. The crack width decreased and the number of cracks also decreased due to the addition of one-and two-layer kevlar fabric lamination at the bottom region. The beams finally failed at loads of 101 kN and 123 kN under flexure and rupture of kevlar fabric lamination. In the beams SCC U1 and SCC U2, cracks were not visible and failure mode was induced by rupture of the kevlar fabric. Failure mode for the U-shaped laminated reinforced concrete and self-compacting concrete beams was due to rupture of kevlar fabric lamination. Table 6 shows the experimental results of load at initial crack, ultimate load, maximum deflection, failure modes, average crack width and number of cracks of all beams.

Load-Deflection Behaviour

The load-deflection behavior of all beams was recorded. When the beams are externally bonded with kevlar fabric, mid-span deflection becomes much lower than in the control beam. It was well-known that shear strength and flexural strength enhanced when bonded with kevlar fabric. The use of kevlar fabric resulted in delaying crack growth. The graphs shown in Fig. 13 exhibit a comparison of mid-span deflection of laminated beams with the corresponding reference beams. It was found that the load-carrying capacity of reference SCC beam is 23% that of reference CC beam. The deflection of reference SCC beam is greatly reduced as compared to reference CC beam. The load-deflection behavior from the analytical study showed good agreement with the experimental results as shown in Fig. 13.

SCC B2 beam showed a higher loading capacity of 101 kN, whereas SCC B1 beam attained 91 kN. It was found that the load-carrying capacity of SCC B2 beam is relatively more than those of other bottom laminated beams as shown in Fig.14. The deflection of the SCC B2-layer beam is greatly reduced as compared to other beams laminated by a single layer and two layers of fabric. However, when applying the kevlar fabric as external reinforcement, load-carrying capacity of bottom laminated beams, such as CC B1, CC B2, SCC B1 and SCC B2, has been increased upto 19%, 37%, 21% and 35%, respectively, when compared to reference beams.

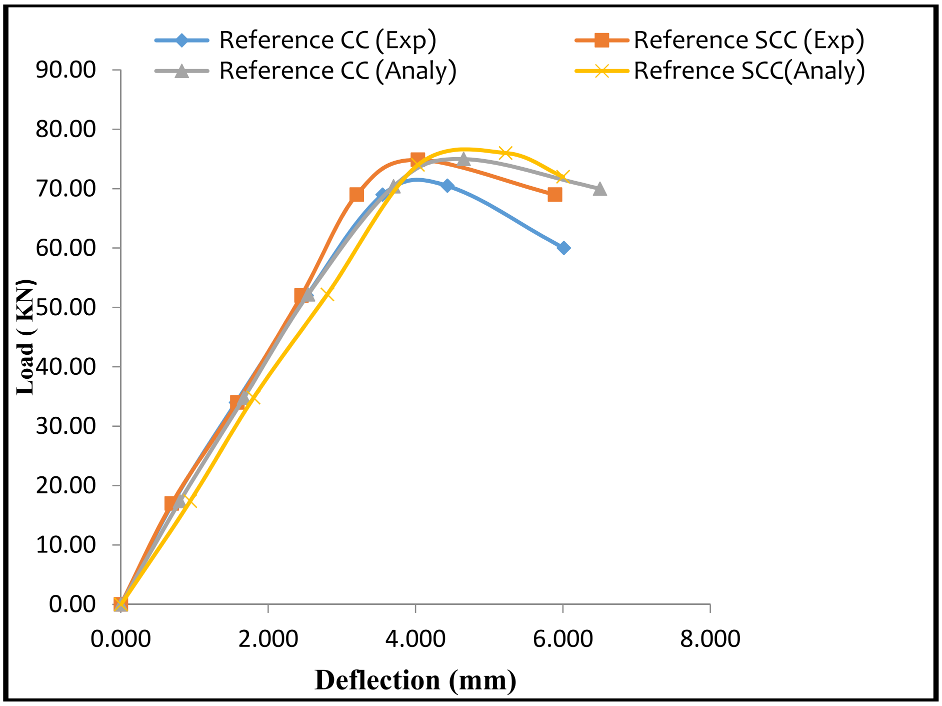


Figure (13): Load *vs.* deflection response for reference RCC beams

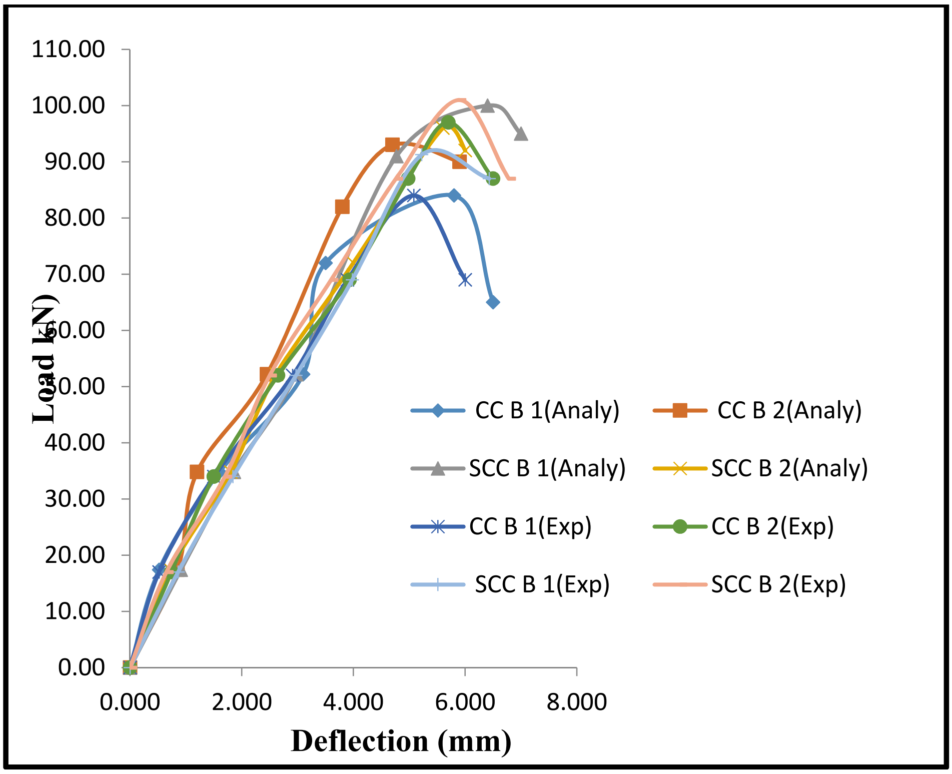


Figure (14): Load *vs.* deflection response for bottom laminated beams

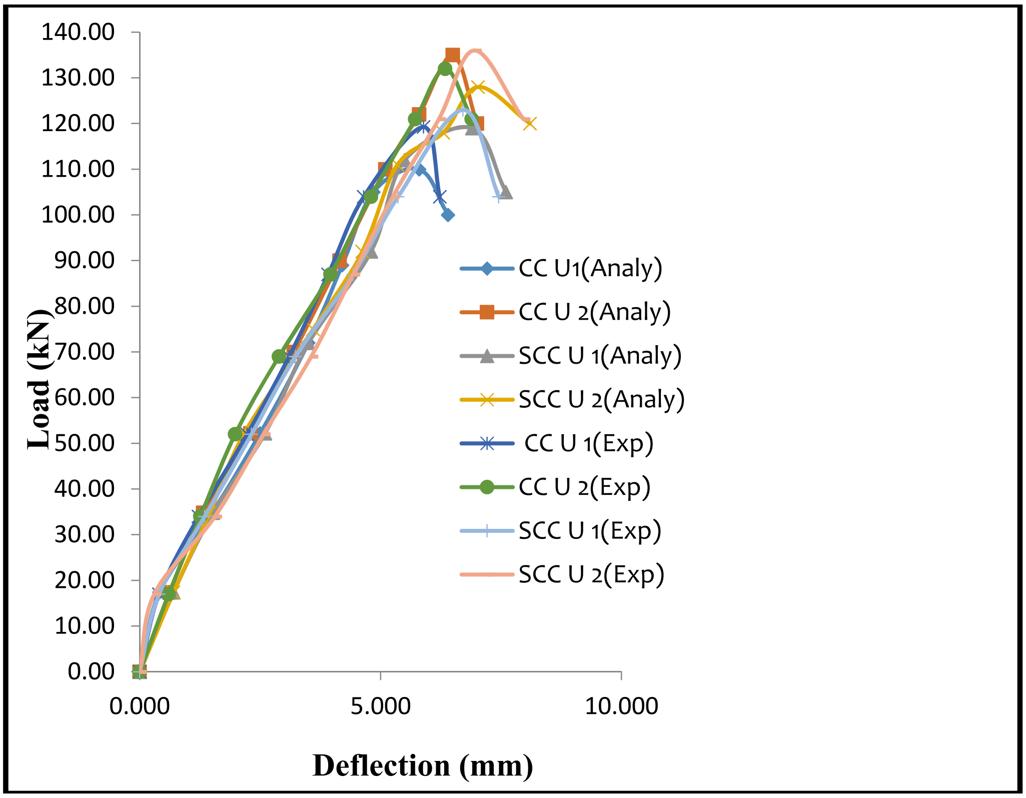


Figure (15): Load *vs.* deflection response for U-shape laminated beams

Ultimate load-carrying capacity and maximum deflection of all U-shape laminated beams are shown in Fig.15. The strengthened beams were loaded upto maximum load and subjected to failure. The SCC U2 beam showed a higher loading capacity of 136 kN, where CC U2 beam achieved 132 kN, SCC U1 beam attained 123 kN and CC U1 beam attained 119 kN. SCCB1 beam showed 29% and 22% and SCCB2 beam showed 53% and 44% compared to reference CC and SCC beams, respectively. U-shape laminated beams such as CC U1, CC U2, SCC U1 and SCC U2 exhibited increased load-carrying capacity values upto 69%, 88%, 64% and 82% when compared to reference CC and SCC beams, respectively.

The analytical model developed using ANSYS software was found to closely simulate the behavior and failure modes of all beams and agreed well with the experimental loads with a margin of 1.50%, as shown in Figures 13,14 and 15. Since the load-carrying capacity predicted by the ANSYS model closely simulate the experimental values, the analytical model truly represents the actual behaviour of kevlar fabric-laminated reinforced and self-compacted concrete beams.

Theoretical Results

Flexural strength values of U-shape laminated beams are calculated as per Yeole, P.M. (2013). The calculated values of flexural strength are compared with the experimental values and are tabulated in Table 7. U-shape laminated beams, such as CC U1, CC U2, SCC U1 and SCC U2, had increased flexural strength values upto 69%, 88%, 64% and 82% when compared to reference CC and SCC beams, respectively. Flexural strength values of bottom laminated beams such as CC B1, CC B2, SCC B1 and SCC B2 increased up to 19%, 37%, 21% and 35% when compared to reference beams. Of all beams compared, SCC U2 beam showed 94% and 82% increase in flexural strength compared to reference CC and SCC beams, respectively.

Table 7. Comparison of experimental results with theoretical results

Beam designation	Theoretical results	Experimental results
	Mu (kNm)	Mu (kNm)
Reference CC	13.63	10.58
Reference SCC	12.54	11.23
CC B1	14.63	12.61
SCC B1	15.36	13.69
CC B2	16.47	14.22
SCC B2	17.58	16.18
CC U1	18.75	17.89
SCC U1	20.50	18.46
CC U2	21.22	19.93
SCC U2	23.17	20.54

CONCLUSIONS

Experimental and analytical investigations have been carried out on the performance of reinforced concrete and self-compacting beams laminated with externally bonded kevlar fabric and the results were compared with unlaminated beams.

The following conclusions are drawn from the theoretical, analytical and experimental test results.

1. Load-carrying capacity can be enhanced by laminating kevlar fabrics on the tension side of the beams.
2. When applying the kevlar fabric as external reinforcement, flexural strength of single- and two-layered bottom laminated reinforced concrete and self-compacting concrete beams increased by 19%, 37%, 21% and 35% compared to reference beams.
3. Single- and two-layered U-shape laminated reinforced concrete and self-compacting concrete increased the flexural strength upto 69%, 88%, 64%

and 82% compared to reference beams.

4. Due to increase in flexural stiffness by adding of fabric layers, bottom and U-shape laminated beams showed less deflection at the failure load of reference beams.
5. Initial flexural cracks are attained at higher loads when the beams are strengthened as bottom and U-shape laminates.
6. Greater flexural strength can be obtained and crack growth can be controlled by the addition of various numbers of layers.
7. The failure of laminated beams was caused by the rupture of kevlar fabric and the failure mode was a flexural failure mode.
8. Shear failure is not encountered in any of the studied beams.
9. The ultimate load-carrying capacity of all laminated beams increased due to flexural strengthening and cracks were not visible. The failure of the beams was not sudden, which was due to use the of U-lamination of kevlar fabric which reduced the risk of collapse of the members. It ensures the life safety for the occupants, removing any fear in their minds.
10. Load-carrying capacity of weak structures will be improved by flexural strengthening of beams with kevlar fabric which will enhance the performance of weak structures under flexural loading.
11. Kevlar fabric-laminated beams yield lower crack width and average crack spacing.
12. Kevlar fabric-lamination will also act as an additional concrete cover to prevent corrosion of the reinforcement of reinforced concrete beams.
13. In this study, an attempt is made to find an effective solution to strengthen existing old and weak buildings by kevlar fabric laminates.

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