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Technologies**JASET**¹Aziz Ibrahim Abdulla, ²Khalid NajiMahasneh, ³Mohammad W. Shaheen, ⁴AmmarSaleem Khazaal and ⁵Muataz Ibrahim Ali¹Engineering/Tikrit University,²College of Eng., Jerash University,³Civil Engineering/ The University of Jordan, ⁴Civil Eng. Dept. /College of Engineering/ Tikrit University,⁵Civil Eng. Dept. /University of Samarra**Keywords**

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<http://creativecommons.org/licenses/by/4.0/>**Open Access****Behavior of Reinforced Concrete Beams Strengthened by CFRP and Wire Rope****A B S T R A C T**

The current research aims to study the effect of static loads on concrete beams strengthened by wire rope. Each beam was subjected to a central concentrated load with an average loading speed of 1 kN/min. The use of steel wire rope has been suggested as a new economical technique to strengthen and rehabilitate reinforced concrete beams, as well as to support the CFRP used in strengthening. The best results were obtained when using either CFRP and wire rope together, or wire rope on its own. It was found that strengthening by CFRP and wire rope increased the flexural strength, hardness, and toughness, and decreased the maximum deflection. Furthermore, the use of wire ropes with CFRP increased the splitting strength and prevented the concrete cover separation between CFRP and concrete. The use of wire rope is a new technique that significantly enhances the performance of concrete in flexure. Using a combination of wire ropes and CFRP, and wire rope on its own showed an increase in stiffness up to about 135.24% and 72.13%, and a reduction in ultimate deflection up to about 70.31% and 49.1%, respectively as compared with control beams. Wire ropes can be used in various forms to resist flexure, shear, and torsion stresses due to ease of formation per required shape. Moreover, increasing the rope's diameter or reducing the spacing between the wrapped rope's segments can enhance its efficiency. This renders strengthening by wire rope a new, efficient, and economic technology.

Introduction

Structures that are weak, damaged, or require a new extension might need strengthening and rehabilitation to ensure the safety of occupants and the capability of structures to withstand new loads. Steel sections and plates were firstly used for the purpose of strengthening and rehabilitation before new techniques emerged [1]. A different method consists of bonding external metal sheets with reinforced concrete members using epoxy. This allows the metal sheet to act as external reinforcement [2]. Despite the many benefits of using steel, it has several disadvantages such as deboning and low fire resistance [3]. Many Studies showed that Fiber Reinforced Polymers (FRPs) of all types such as carbon, glass, and aramid are the best solution for use in the field of rehabilitation and strengthening of concrete members [4]. These fibers, however, have several disadvantages; including high cost, low fire resistance, very low strength to direct impact loads, and medium strength to indirect impact loads [5]. Due to their brittle behavior, FRPs change the structural behavior of reinforced concrete beams from ductile to brittle, leading them to fail by sudden rupture. Although increasing the width of FRPs may incur a brittle behavior, such increase is necessary to avoid the separation of these fibers out of concrete unexpectedly. Carbon Fiber Reinforced Polymer (CFRP) is tested according to ASTM in two ways: the dry test and the saturated test where CFRP is cured in resin. As per ASTM D3039/D3039M (2008) and ASTM D7565/D7565M (2010), the dry

CFRP sheets should be cured in resin with an amount of 0.75 kg/m² for each layer. Steel tabs, 1.5 mm in thickness and 56 mm in length, should be placed at the specimen edges and bonded using resin to distribute the load successfully through the specimen and to prevent premature failure at grips due to discontinuity. During testing, the strain in material is recorded using a strain gage located in the center of the specimen. [6]. A third method used in both new and existing structures is external processing, which involves connecting tendons or strands to the outer sections of structural members through deviators and end-anchorage. Several researchers studied the effectiveness of using pre-stressed FRP in strengthening and rehabilitation of beams, slabs, and columns subjected to the influence of static and impact loads. The disadvantages of this method include high cost, quality control concerns, anchorage problems, and frequent required maintenance [7], [8], and [9]. External pre-stressing using FRP materials constitute a good alternative to steel cables. The method of externally bonding pre-stressed FRP laminates to structures has proven to be highly efficient, offering light weight, good durability, good resistance to corrosion and excellent behavior in creep and relaxation. Moreover, its high tensile capacity contributes to the load bearing capacity of the entire system under both ultimate and service conditions. However, anchorage of the bonded laminates is weak in handling high stresses, undermining the efficiency of the proposed solution. This issue is being addressed in research projects around the world [10] and [11]. Other issues being addressed by research

Include static flexural and fatigue performance of reinforced concrete beams strengthened by external pre-stressed FRP laminates, and their behavior under freeze-

thaw cycles[12]. Strengthening by wire rope is an emerging technique that is being investigated. Wire rope is a type of cable which consists of several strands of metal wire twisted into a helical pattern, with a steel or fiber composed core. The main material used in the fabrication of wire rope is steel. The cables are used mechanically for lifting and mobilizing objects and transmission of mechanical power, and statically for supporting structures. They provide good strength, flexibility and resistance to deterioration.

Steel wire rope can be tested according to ASTM A931-08(2013) and ASTM A1023/A1023M [14] [15], where metallic coated or uncoated stranded steel and cord products are covered. The following characteristics and properties should be considered for the purpose of testing: 1) dimensional characteristics such as rope diameter and length, 2) mechanical property requirements including tensile strength, torsion and rope breaking force. The use of wire rope in strengthening concrete structures is not adequately investigated. Ali et al. studied the performance of RC beams strengthened by steel wire rope subjected to impact loads, as compared to carbon fiber reinforced beams and reference beams. The newly proposed method performed favorably in terms of maximum and residual deflection, stability and damping ratios. A significant improvement in different failure phases was also noticed. Moreover, steel wire rope showed a positive effect when used in combination with CFRP sheets [13]. The present study aims to conduct a

comparison between strengthening by CFRP and strengthening by wire rope to explore the efficiency of the newly proposed technique. Properties including ultimate strength, yield strength, ductility, and toughness of RC beams are investigated. The new method can also be used jointly with CFRP to prevent separation of CFRP sheets from concrete members.

Experimental Approach

1. Material properties:

Concrete beams: the 28-day cube compressive, flexural and splitting tensile strengths of concrete used were about 35, 4.2, and 3.1 MPa, respectively. Reinforced concrete beams with a cross section of 150 x 150 mm and a length of 1000 mm were casted and tested. All beams were cured in water under a laboratory temperature of 27 ± 3 °C. The specimens were later taken out and prepared for strengthening, followed by a flexural load test.

Reinforcing steel: 6 mm diameter steel bars were used for all beams. The ultimate stress and yield stress of the steel bars were 675 MPa, and 580 MPa, respectively.

Steel wire rope: steel wire rope of the type employed in internet and radio broadcasting and receiving towers was used in this study. The steel rope had a 2 mm diameter. Its yield and ultimate strengths were 613 MPa and 719 MPa, respectively. A cross section of the rope is shown in Figure 1.

Binder material (epoxy): the binder material SikaDur 330 of medium viscosity was used. It consists of adhesive (Resin A) and solidifying material (Hardener B). The mixing ratio of resin to hardener is 1:4. The

tensile strength, flexural and tensile elastic moduli were 29, 3800 and 4500 MPa, respectively.

Carbon fiber reinforced polymer (CFRP):

Experimental Program: Thirteen reinforced concrete beams were prepared for testing. All beams had the same dimensions as mentioned above and they were all reinforced using 6 mm diameter steel bars. Three bars were placed in the tension zone at the bottom of the beams, while two bars were placed in the compression zone at the top. 6 mm diameter steel stirrups spaced at 75 mm were used for shear resistance.

The concrete beams were tested under the influence of central static load. They were classified in four groups as follows:

- Group 1: beams strengthened by CFRP sheets
Six beams belong to this group. The length of the CFRP sheets used in strengthening was 850 mm. The following three different sheet widths were adopted: 25, 50, and 75 mm, where every two beams shared the same width.
- Group 2: beams strengthened by wire ropes
Two beams were strengthened by wire rope of 2 mm diameter. The wire rope was coated with a thin layer of epoxy to increase their efficiency and prevent total disconnection upon failure. In addition, a 30-mm-wide and 6-mm-thick steel plate was employed in each beam to connect the steel rope. The plates were attached and installed along the top edge of the beam by using three 6-mm bolts. A schematic of the A unidirectional carbon fiber sheet type Sika Wrap- 301 C with a thickness of 0.17 mm was used. The ultimate strength,

ultimate strain, and elastic modulus were 4900 MPa, 2.1%, and 230 GPa, respectively. The described setup is shown in Figure 2.

- Group 3: beams strengthened by both CFRP sheets and wire rope

Two beams were strengthened by CFRP sheets having a width of 75 mm. 2-mm diameter wire rope was convoluted around the beams overlaying the CFRP sheets for purposes of fixing and strengthening, as shown in Figure 2.

- Group 4: beams without strengthening

The remaining three beams were used as reference beams and left without any strengthening.

Static loading was applied to all beams by Universal Testing Machine. The central concentrated load had a 1 kN/min average speed. A digital data logger was used to read the applied load values, while central deflections were recorded using a dial gauge. The gauge was fixed to the frame using a magnetic base, as illustrated in Figure 3. In this study, the effect of the different suggested strengthening methods on the behavior of beams was analyzed and recorded in terms of failure load, deflection, stiffness, toughness, toughness index, and ductility.

Results and Discussion

The results obtained from testing the beams belonging to the four groups classified above are discussed and compared below. It should be noted that whenever Group 1 beams are mentioned, the width of the CFRP sheets used is 75 mm, unless stated otherwise. The following symbols are used within the text, where BS refers to beam, F refers to CFRP and the number next to it is the plate's thickness,

and W refers to steel rope, next to it is either 1 or 0 denoting the use of steel rope or the absence of which, respectively.

Load at failure:

It was found that strengthening using the above described methods increases the ultimate load varyingly. It can be seen in Table 1 that as compared to reference beams, the ultimate load increased by 45.8%, 22.73%, and 68.89% for group 1, group 2 and group 3 beams, respectively. This indicates that the method which uses both steel ropes and CFRP in strengthening yields the most significant increase in the ultimate capacity of concrete beams. This enables the beams to sustain extra applied loads.

The use of steel ropes positively improves the static properties of concrete beams for the following reasons:

1. The possibility and ease of shaping wire ropes in any way required, unlike steel plates and CFRP.
2. The capability of steel ropes to resist shear, flexural, and torsional forces at the same time. This provides an integrated resistance all over the structure under the influence of applied loads.
3. The flexibility of handling and anchoring steel ropes as compared to steel plates and CFRP, and their ability to sustain a wide range of applied loads.

The efficiency of steel wire ropes in handling over reinforcement, and high shear problems.

The top steel plate used to connect steel ropes acts as double reinforcement, thus solving the former issue, while the latter is addressed by minimizing the distance between the ropes at high shear force locations and preserving their inclination.

By contrast, the previous two problems are highlighted when using steel plates or CFRP in strengthening. Here, the issues could be overcome by strengthening the supports and any location that shows high shear force. Despite its efficiency, this method is expensive and requires highly skilled labor.

The results of testing Group 3 beams showed that failure occurs by the disconnection of ropes followed by the splitting of CFRP, as illustrated in Figure 4. Since the forces are transferred to steel ropes first, failure could be prevented either by increasing the rope's diameter or decreasing the spacing between the loops. In addition to increasing the resistance of structural members, the above two solutions help prevent the splitting of CFRP, which is the most crucial problem facing structural designers.

Mid-span deflection

Table 1 shows that using wire ropes with CFRP gives the greatest reduction in deflection by 70.31%. On the other hand, 49.1% reduction was reached when strengthening by wire ropes, while the reduction rate was 66.54% for concrete beams strengthened by CFRP only. These reduction rates demonstrate that all three methods are successful at reducing the maximum deflection, and that using steel ropes is relatively effective to the use of CFRP.

Stiffness

The stiffness of concrete beams was found by entering the load-deflection curve at 45% of the maximum load and dividing the obtained load by its corresponding deflection value [17]. It can be concluded from Figure 5 that the use of steel ropes increases the stiffness by 72.13%, which

adds to its other positive characteristics, such as ease of use and affordability. Moreover, adding steel ropes to CFRP increases the stiffness by a good percentage of 135.24%, as compared to a 117.21% increase when using CFRP on their own. Stiffness results are summarized in Table 1.

Ductility

The ductility was determined by dividing the maximum deflection by the yield point deflection for steel reinforcement bars, as shown in formula 1 [17];

$$\text{Ductility} = \Delta_u / \Delta_y \dots\dots\dots (1)$$

Where Δ_u represents defection value at ultimate load And Δ_y represents defection value at yield load.

Despite having higher strengths, concrete beams of low ductility fail suddenly. Strengthening by CFRP reduced ductility of concrete beams due to its brittle behavior. The use of wire rope on its own didn't reduce the ductility significantly when compared to CFRP, since the former is more ductile than the latter. Ductility decreased by 62.27%, 21.21%, and 44.39% for Group 1, Group 2, and Group 3 beams, respectively. The use of wire rope with CFRP is converting the structural behavior of strengthened concrete beam from brittle (sudden failure) to ductile (gradual failure).

Toughness

An increase in toughness was noticed in strengthened concrete beams, which results in higher energy absorption and higher energy dissipation. The absorbed energy can be determined by calculating the area under the load-deflection curve of concrete beams [17]. Table (2) summarizes toughness and toughness index values for

all different setups. The toughness of beams strengthened by wire rope is comparable to those strengthened by CFRP. It is clear from the table that the first crack toughness, yield toughness, and ultimate toughness for concrete beams strengthened by wire rope are slightly higher than those obtained by strengthening with 25 mm CFRP strips. Moreover, even though 50 and 75 mm CFRP strips provide RC beams with higher toughness than wire rope does, the difference is slight and does not exceed 11% for first crack and ultimate toughness. The difference is higher for yield toughness due to partial failure in wire rope at yield stress, thus reducing yield toughness without reducing ultimate toughness. In summary, Group 1, Group 2, and Group 3 RC beams have a respective increase in toughness values amounting to 24.36%, 39.10%, and 52.79% for first crack toughness, 6.43%, 47.05%, and 57.77% for yield toughness, and 21.44%, 23.80%, and 72.83% for maximum toughness, as compared to Group 4 reference beams.

Toughness Index

Toughness index is an indication of the efficiency of strengthening and its compatibility with concrete sections after occurrence of first crack. It is calculated by finding the area under the load-deflection curve up to a certain deflection point and dividing it by the area up to the first crack deflection. It is classified into three categories as explained below:

1. Toughness index (I₅): the deflection value corresponding to 3.0 times the first crack deflection is first determined. The area under the curve corresponding to this point is found and divided by the area up to first crack.

2. Toughness index (I10): the deflection value corresponding to 5.5 times the first crack deflection is first determined. The area under the curve corresponding to this point is found and divided by the area up to first crack. .
3. Toughness index (I20): the deflection value corresponding to 10.5 times the first crack deflection is first determined. The area under the curve corresponding to this point is found and divided by the area up to first crack.

As noted in Table 2, the highest toughness indices values were obtained when strengthening with CFRP. there was no significant increase in toughness indices when increasing the CFRP strip width from 50 to 75 mm. This serves as an indication that, in addition to its high cost, increasing the width of fiber strips to more than 75 mm (half the width of concrete beam) will not be useful in increasing the toughness and compatibility. On the other hand, significant increase in toughness indices was noticed when using wire rope with CFRP, which can reach up to a 95% increase as compared to reference concrete beams.

Conclusions

Including wire rope in strengthening, either by itself or in combination with CFRP enhances the static properties of reinforced concrete members dramatically, as described below:

- RC beams strengthened by wire rope exhibited a significant increase in failure load. Moreover, failure load of RC beams strengthened by wire rope combined with CFRP increased up to 68.89%, as compared with references beam. It also gives a higher value than beams strengthened with CFRP

strips.

- Failure occurred in steel rope before CFRP strips. such failure can be controlled by increasing the diameter of steel rope or decreasing the inter-rope spacing.
- Using steel wire rope significantly decreased maximum deflection.
- Steel wire rope enhances the brittle behavior of concrete beams strengthened by CFRP by ensuring a ductile failure mode.
- Strengthening by steel wire rope increased toughness of first crack, yield toughness, and total toughness as compared to reference beams. On the other hand, it gave slightly lower values as compared to using CFRP of different widths.
- Using a combination of wire ropes and CFRP increased toughness indices by values reaching 95%, as compared to reference beams.
- Wire rope, when used with CFRP, prevented splitting of CFRP fibers from concrete.
- Using a suitable steel rope diameter and inter-rope spacing gives a good flexural resistance, and increases ductility, stiffness, and hardness, while maintaining affordability.
- Steel rope can be used in strengthening and rehabilitating of reinforced concrete beams efficiently, where it can be formed according to required shapes to resist flexure, shear, and torsional stresses.
- Steel rope provides strength of concrete structures by promoting a full composite section behavior. It also balances tensile and compressive forces under the influence of flexural load.

Recommendations

1. A study should be conducted to investigate the shear and bending behavior of concrete beams reinforced by steel wire rope.

2. Strengthening of concrete beams by steel wire rope and using NSM technique should be researched and studied under the influence of static loads.
3. The effects of wire rope diameter and inter-rope spacing on behavior of concrete beams should be further investigated.
4. The behavior of the proposed strengthening method should be looked into using more details and the experimental program should be further expanded.
5. The responses obtained due to the applied loading should be verified.

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Table 1: Data of failure load, deflection, stiffness, and ductility for concrete beams.

Beams	Average Failure Load(kN)	Deflection at Failure load(mm)	Stiffness (kN/mm)	Ductility $\Delta u/\Delta y$
BS-F0-W0 (Reference)	28.6	10.61	12.2	11.69
BS-F25-W0	34.6	4.20	16.3	4.93
BS-F50-W0	37.5	3.72	19.1	4.45
BS-F75-W0	41.7	3.55	26.5	4.41
BS-F0-W1	35.1	5.40	21	9.21
BS-F75-W1	48.3	3.15	28.7	6.50
Note: BS refers to beam, F refers to CFRP and the number next to it is the plate's thickness, and W refers to steel rope, next to it is either 1 or 0 denoting the use of steel rope or the absence of which, respectively.				

Table 2: Data of toughness and toughness indices of concrete beams.

Beam (Average)	methods	Toughness (kN.mm)			Index Toughness		
		First Crack	Fy	Fu	I ₅	I ₁₀	I ₂₀
BS (reference)		1.97	9.33	78.89	5.9	16.3	35.4
BS-F25-W0	A	2.41	9.92	92.45	7.9	18.2	44.7
BS-F50-W0		2.53	10.1	96.56	10.4	23	61.8
BS-F75-W0		2.74	13.72	97.66	10.5	23.7	64.8
BS-F0-W1	B	2.45	9.93	95.81	6.4	18.2	39.1
BS-F75-W1	C	3.01	14.72	136.35	11.7	25.4	69.3

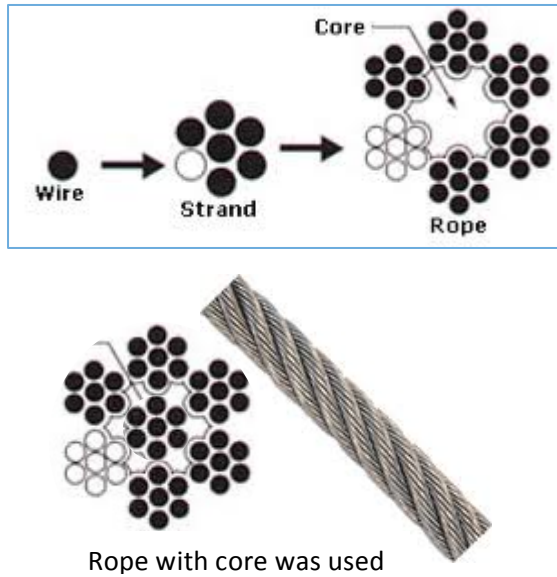


Figure 1: Steel wire rope

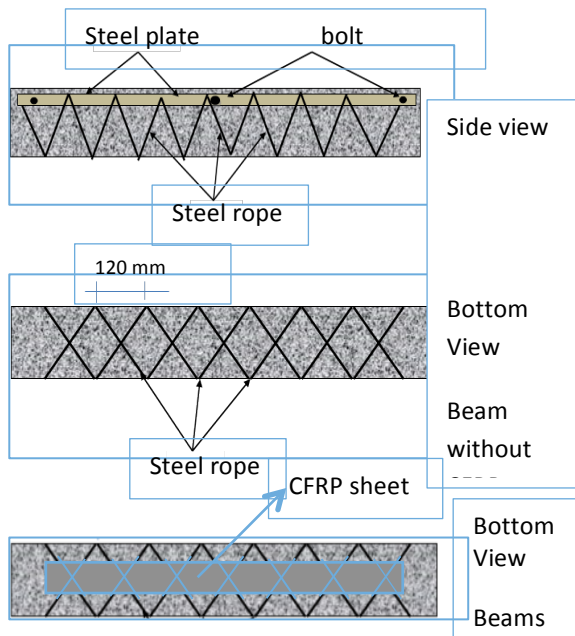


Figure 2: Details of strengthening by steel ropes with or without CFRP sheets.

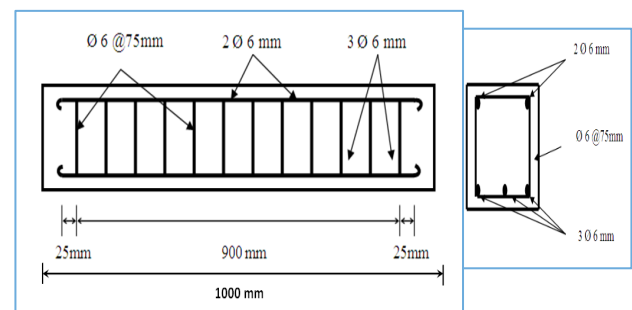
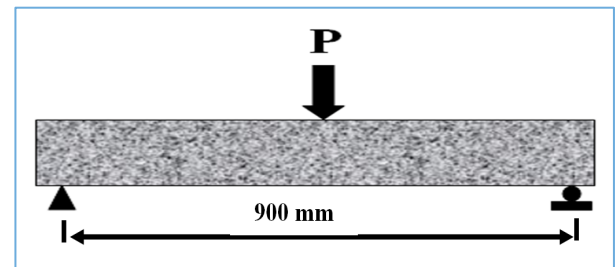
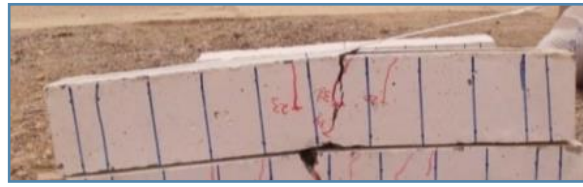


Figure 3: Static load type and reinforcement details.



BS-F0-W0



BS-F25-W0



BS-F50-W0



BS-F75-W0



BS-F75-W0



Side view



Bottom view

BS-F75-W1

Figure 4: Beams failure

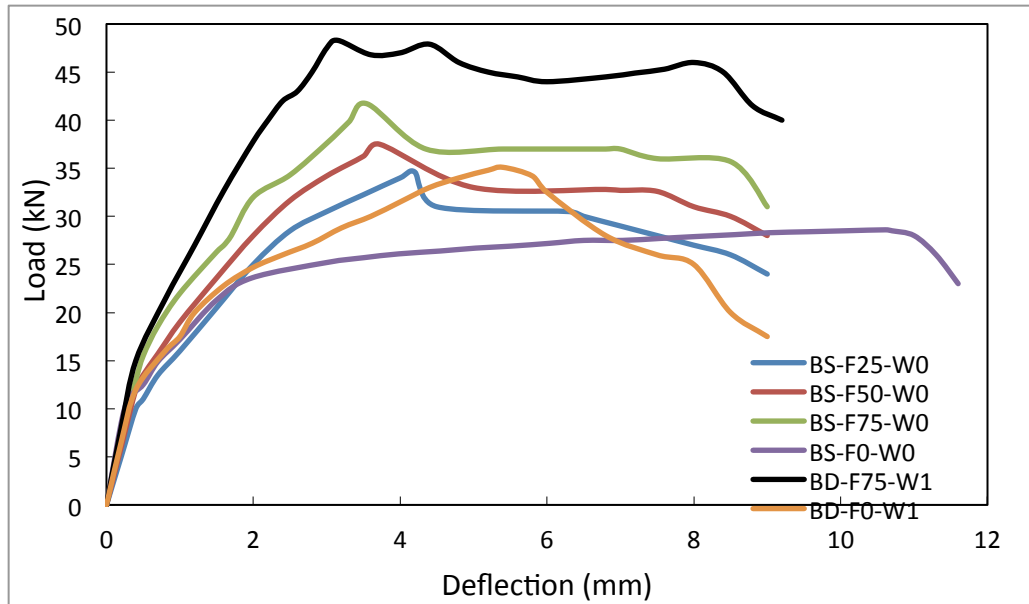


Figure 5: Load-deflection curve for strenthened beams