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Behavior of RC Beams Strengthened by CFRP and Steel Rope under Frequent Impact Load

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A B S T R A C T

The current research aims to study the effect of impact loads on reinforced concrete beams strengthened by carbon fibers and/or steel wire rope. The use of steel wire rope is suggested as a new economic technique to strengthen and rehabilitate reinforced concrete beams, as well as to fix the fibers that are being used in strengthening. Reinforced concrete beams subjected to impact load using both carbon fibers and steel wire rope were tested, and the results were compared with the results obtained from reference beams, from beams strengthened with steel wire rope only, and from beams strengthened with carbon fibers only. The results of concrete beams strengthened using any of the three methods and subjected to impact loading showed a decrease in maximum deflection, residual deflection, damping time, and in the number of strikes to reach each phase of failure. The best results, however, were attained when strengthening using steel rope with and without the addition of carbon fibers, which improved the values of dynamic deflection, residual deflection, damping time, and the number of strikes to reach each phase of failure, when compared to beams strengthened by CFRP strips only.

Introduction

Concrete structures are exposed to damage as a result of 1) natural disasters such as earthquakes or hurricanes, 2) exposure to impact loads such as explosions, 3) change in the function of the original structure, 4) errors that occur during the design process, and 5) setbacks or errors in the construction process such as shortage in rebar or other structural materials. All of the above prevent the structure from functioning in the anticipated manner [1,2]. One of the earliest methods used in repair and rehabilitation consists of steel plates bonded to reinforced concrete using screws [3]. A new major technique was later introduced that allows the use of epoxy as a bonding agent, where reinforced concrete members are strengthened using metal sheets fixed to the member using epoxy, therefore acting as external reinforcement. However, despite all of the advantages and benefits of using steel, it is not without problems [4]. Problems include the heavy weight of steel, difference in thermal expansion coefficient for concrete and steel, and relative ease of separation between both materials. The continuous research was conducted as the need grew to find strengthening materials alternative to reinforcing steel. Researchers found that outer packing using Fiber Reinforced Polymers (FRP) of different fiber types, such as carbon and glass, is the best solution to use in rehabilitation and strengthening of concrete members [5]. It must be noted, however, that FRP materials have several disadvantages; including high cost, low fire resistance, brittleness, low modulus of elasticity, very low resistance to direct impact loads, and medium resistance to indirect impact loads. The brittleness of FRP materials adversely affects the ductility of reinforced concrete members, which results in the failure by sudden rupture. Increasing the number of CFRP layers increases the load-carrying capacity of reinforced concrete sections [6]. However, beams were found to fail by FRP rupture when reinforcing with three to four layers, and by FRP delamination when reinforcing with five to six layers. Moreover, the ductility of strengthened members is reduced. End anchors could be used to prevent the deboning of CFRP sheets and to enhance the flexural ductility. Many researchers studied how to overcome the problem of fiber deboning and concrete cover spelling. Solutions included fixing the FRP sheet edges by screws or by shear stirrup cage fix fibers [7,8]. Others suggested using additives with the adhesive material that binds fibers to concrete to increase its resistance to fire, ultraviolet rays, and acid [9].

Impact loads are imposed on structures due to different reasons [10,11] such as 1) traffic loads of vehicles and trains on bridges, 2) falling bodies from different heights, and 3) loads of operating machinery inside the facility. Impact loads generate stresses and strains, which are large, compared to static loads. The impact load value depends on both mass and velocity of the acting body. To the best of the author's knowledge, there is little research about the behavior of RC beams strengthened with CFRP under impact load, and no study about the behavior of RC beams strengthened by steel rope under static or impact loads.

The present study aims to perform a comparison between three strengthening methods; strengthening using CFRP strips, the proposed new strengthening method using steel rope, and strengthening using both CFRP strips and steel rope. The third method is proposed to fix carbon fibers and prevent separation under the influence of repeated impact loads, as well as to improve the dynamic characteristics and change the shape and phase of failure of the beams under the influence of such loading. The present study additionally aims to investigate the efficiency of the newly proposed techniques in improving the dynamic properties of concrete beams, which are also expected to reduce the extra cost incurred by using FRP materials.

Experimental Work and *Materials Properties*

Concrete beams: eighteen reinforced concrete beams were designed to avoid shear failure so that beams would fail in flexure. The beams were 1000 mm long and had a cross section of 150 x 150 mm. For all beams, three 6 mm diameter steel bars were provided in the bottom zone to resist tension, and two 6 mm diameter bars were provided in the top zone to resist compression. 6 mm diameter steel stirrups were used to resist shear with a spacing of 75 mm between stirrups. The 28-day cube compressive and flexural tensile strengths of concrete were about 35 and 3.32 MPa, respectively.

Steel reinforcing bars: 6 mm steel bars were used for tension and shear stresses. Ultimate strength, yield strength, and modulus of elasticity were 675 MPa, 580 MPa, and 200 GPa respectively.

Steel rope: 2 mm diameter steel wire rope was used. The rope's ultimate strength, yield strength, and modulus of elasticity were 719 MPa, 613 MPa, and 190 GPa respectively.

Binder material (epoxy)**:** Sika-made product type SikaDur 330 of medium viscosity was used. The product consists of two parts: the glue material (resin), and the solidifying material (hardener). The mixing ratio is one part resin versus four parts hardener. The tensile strength, flexural and tensile elastic moduli were 29, 3780 and 4600 MPa, respectively.

CFRP: Carbon fiber reinforced polymer (CFRP) strips type SikaWrap - 301C with a thickness of 0.17 mm was used for strengthening RC beams. The ultimate strength, ultimate strain, and elastic modulus were 4900 MPa, 2.1%, and 230 GPa, respectively (SikaWrap(R)-301 C).

2.2 Experimental Program

Reinforced Concrete Beam Groups: The beams were categorized into four different groups, as follows:

Group 1: this group included three reference RC beams without any strengthening.

Group 2: this group included nine beams strengthened externally using carbon fiber strips. The strips were all 850 mm long and had widths of 35, 50, and 75 mm. Every three beams shared the same strip width.

Group 3: this group included three beams strengthened using steel rope as shown in Figure 2. A steel plate that is 30 mm wide and 6 mm thick was used to hold the steel rope. The steel plate was installed along the top edge of the beam using three bolts having a 6 mm diameter on each side of the plate.

Group 4: this group included three beams strengthened using both steel rope installed as described in Group 3 and 75-mm wide carbon fiber strips.

Impact Load Test

The test was conducted using the impact load apparatus shown in Figure 3, which was designed and used by Ghanee [1] for small impact loads no more than 4.5 kg, and adapted by the authors for large impact loads up to 20 kg. A sledgehammer, a tube to determine the path of the hammer, and a metal ball, also modified it.

The apparatus consists of a metal frame and a steel hammer that weighs 20 kg and has a length of 520 mm. The hammer is directly bracketed to a tube to control the weight's path and match the position of the beam's mid-span. The hammer falls on a steel ball that has a diameter of 120 mm and weighs 7 kg, which in turn is placed over the middle of the beam span. The steel ball is centered using a metal frame made of square corner rail to prevent movement of the ball during and after the shed of impact. The beam sample is held on supports and is fixed in place using steel angles.

The net height between the top of the ball and the bottom of the hammer is 1200 mm, which simulates high falls. The hammer is lifted and centered by the steel handle until the bottom face of the hammer is 1200 mm higher than the top of the ball, and then it is then allowed to free fall onto the ball. Dynamic Deflection Measuring Device LVDT (linear variable differential transformer) was used to measure the maximum deflection, residual deflection, and damping time of concrete beams. The device is fixed in the bottom middle of the beam as shown in Figure 3. Data Acquisition Device registers the relationship between deflection and time and is responsible for collecting data from LVDT.

Five phases of failure were identified as follows:

-Initial failure: occurs with the appearance of the first visible crack.

-Secondary failure: occurs when the crack progresses from the bottom of the beam to the upper surface of the beam.

-Ultimate failure: occurs when concrete crushes in the compressive zone, or when cracks confluence inside the beam, or when concrete flakes in the tensile zone.

-Semi-penetration failure: occurs when the steel ball reaches the bottom layer of steel reinforcement.

-Splitting failure: occurs when carbon fibers or steel rope split from concrete.

-Each of the above phases is reached after a certain number of strokes. The first three phases listed were adopted by [1]. And the authors suggest the remaining two.

Results and Discussion

Maximum Deflection Table 1 shows the results obtained from testing concrete beams under the influence of the first strike. The numbers represent the average results for every set of three concrete beams. Figure 4 shows the relationship between impact energy and maximum deflection measured during strike shed. The relationship is described using the Flowing Formula [12] :

$U = n \times m \times g \times h$ .... (1)

Where, U =impact energy (kN.m); n = number of strikes; m = mass of hammer (kg); g = gravity acceleration (m/ s^2); and h = hammer falling height (m).

It can be noted from Figure 4 that strengthening using steel rope decreased the maximum deflection dramatically as compared to control beams. It also gave minor deflection as compared to strengthening by carbon fibers. Strengthening by both steel rope and carbon fibers gave a semi-constant value for maximum deflection, where there was only a slight increase in deflection with the increasing number of strikes (increase in impact energy). This indicates that strengthening by steel rope contributes to the stability of the structure under the influence of frequent impact loads and reduces maximum deflection.

Residual Deflection

Table 1 also shows residual deflection results obtained from testing concrete beams under the influence of the first strike. Figure 5 represents the relationship between impact energy and residual deflection during strike shed on concrete beams. It can be noted from Figure 5 and Table 1 that strengthening by steel rope gave a slightly smaller residual deflection when compared with strengthening by carbon fibers of different widths. On the other hand, strengthening by both steel rope and carbon fibers reduced residual deflection dramatically. Figure 5 shows that the relationship between impact energy and residual deflection is semi-linear. Moreover, the increase in residual deflection with increasing number of strikes is slight. This indicates that the use of steel rope improves the performance of concrete beams under influence of repeated impact loads by reducing residual deflection, and inhibits the increase of residual deflection with growing impact energy.

Table 1: Results of maximum and residual deflection, damping time, and damping ratio of concrete beams under the influence of the first strike.

Symbols	*Group No.*	*Mid Span Max. Deflection (mm)*	*Mid Span Residual Deflection (mm)*	*Damping Time (sec.)*	*Damping ratio (%)*
BD-F0-W0	Group 1	34.72	0.39	2.964	**0.82**
BD-F25-W0	Group 2	32.96	0.26	0.655	**1.43**
BD-F50-W0	Group 2	29.67	0.183	1.072	**1.14**
BD-F75-W0	Group 2	28.01	0.151	1.935	**0.99**
BD-F0-W1	Group 3	20.21	0.24	1.84	**1.34**
BD-F75-W1	Group 4	24.78	0.139	1.688	**1.39**
Note: BD refers to beam. F refers to CFRP and the number next to it is the plate's thickness. W refers to steel rope, where 1 denotes the use of steel rope and 0 denotes its absence.					

Damping Time

Damping time is the time required to reach 10% of the maximum deflection and is measured from the time-deflection curve [12.13,14]. Table 1 shows the measured damping time for concrete beams strengthened by all three methods and for the first strike. Figure 6 demonstrates the relationship between impact energy and measured damping time. It can be noted from Figure 6 that strengthening by carbon fibers reduced damping time dramatically while using steel rope alone didn't reduce damping time upon the first strike. However, for a growing number of strikes, it was observed that strengthening with steel rope alone did reduce damping time, mainly. Strengthening by steel rope and carbon fibers together significantly reduced damping time when samples were subjected to first strikes, and the ratio decreased by increasing the number of strikes. The reason for this is that steel rope works best with the growth in residual deflection.

Damping Ratio

It describes how the response amplitude of a vibrating system decays with time, leading the body to come to rest. It can be calculated using the following formulas [15]:

$$\delta = \frac{1}{n-m} \, ln\left(\frac{v_m}{v_n}\right) \qquad (2)$$

$$\zeta = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}} \qquad (3)$$

Where, ζ= damping ratio; v_m ,v_n = Deflection at peaks and n, m = sequence of the peaks.

The measured damping ratio for the first strike for different strengthening schemes is shown in Table 1. Using steel rope for strengthening increased the damping ratio by 63.41%, whereas using carbon fibers alone increased the rate by 20.7% to 74.39%. The vast range is due to the width of the CFRP plate, where increasing it decreases the damping ratio, owing to the brittle behavior of CFRP. On the other hand, strengthening using carbon fibers along with steel rope increased the damping ratio by 69.51%. This refers to that the using steel rope for strengthening has a positive effect in increasing the damping ratio, whether used alone or with carbon fibers. A comparison between the response of reference beam and that of various strengthened beams using different schemes is further demonstrated in Figure 7 by plotting maximum deflection against time of damping.

Phases of Failure

Concrete beams were subjected to continuous strikes until ultimate failure was reached. The results are shown in Table 2.

Table 2: Number of strikes to achieve phases of failure of concrete beams under influence of impact load.

Symbol	*Group No.*	*Number of blows*				
		Initial failure	*Secondary failure*	*final failure*	*Semi-Penetration failure*	*Splitting failure*
BD-F0-W0	Group 1	1	2	4	151	**0**
BD-F25-W0	Group 2	1	2	7	177	**6**
BD-F50-W0	Group 2	1	2	9	203	**25**
BD-F75-W0	Group 2	1	2	12	223	**69**
BD-F0-W1	Group 3	1	3	14	190	**58**
BD-F75-W1	Group 4	4	11	20	278	**112**

In case of reference beams, bending cracks appeared at mid-span as well as 50 mm away from it. Cracking started from the bottom and propagated towards the top upon continuous striking. After the ball reached the beam's top reinforcement or shear reinforcement, shear cracks appeared and spread from the point of load application towards the bottom of the beam. For concrete beams strengthened using carbon fibers, cracks propagated from the bottom similar to the behavior of reference beams. However, the cracks tacked and veered in a route parallel to the carbon fibers. It was also noted that for the 75 mm wide CFRP strips, shear cracks appeared before the ball reached the top layer of steel reinforcement or shear reinforcement. This is attributed to the high tensile strength of carbon fibers, which increases the flexural strength of concrete beams, leading them to fail by shear instead of flexure. With repeated strikes, carbon fibers began to split at mid-span and towards the supports until total splitting occurred at one of the edges, as opposed to failure by static loading which starts at the edges and propagates towards the middle. The difference in the behavior between static and impact loads is attributed to the nature of the latter, the influence of which is in the form of rebound waves that initiate at the center and spread from the top towards the bottom in an inclined path until they reach the supports.

Failure in concrete beams strengthened by steel rope was also similar to failure in reference beams. The difference was in the number of ball strikes required to reach the top layer of steel reinforcement or shear reinforcement. Repeated loading caused splitting in the plate that connects steel rope. This was followed by complete splitting of the rope due to the ripping of bolts out of their positions near the supports. When using both CFRP strips and steel rope, failure occurred by spalling of the concrete beam's top surface at the point of load application. Moreover, the plate, which connects the fibers, split off due to continuous striking. Table 2 shows that strengthening by steel rope with or without the addition of CFRP contributes to significant improvement in the behavior of concrete beams, as elaborated below:

A. Initial failure: there was no significant increase in the number of strikes to reach initial failure for concrete beams belonging to groups 2 and 3 as compared to reference beams. On the other hand, the number of strikes increased by 300% for concrete beams strengthened by steel rope and CFRP together.
B. Secondary failure: the number of strikes to reach this phase of failure increased by 50% for Group 3 beams, and 450% for Group 4 beams as compared to reference beams. Group 2 beams did not exhibit a change in the number of strikes in comparison to reference beams, regardless the width of CFRP strips.
C. Final failure: the number of strikes to reach final failure increased by 75% to 200% for concrete beam belonging to Group 2 of various CFRP strip widths, 250% for strengthening with Group 3 beams, and 400% for Group 4 beams.
D. Splitting failure: increasing fiber width from 25 mm to 75 mm increased the number of strikes to reach splitting failure from 6 to 69. The number of strikes was 58 for Group 3 beams strengthened by steel rope only, and 112 strikes for Group 4 beams strengthened by steel rope and CFRP together.
E. Semi-penetration failure: the number of strikes to reach semi-penetration failure increased between 17% to 48% for concrete beams

belonging to Group 2 of various CFRP widths, 26% for Group 3 beams, and 84% for Group 4.

Conclusions

The performance of reinforced concrete beams strengthened using steel rope with and without the addition of CFRP sheets was investigated, and the behavior was compared to that of reference RC beams, as well as concrete beams strengthened with CFRP sheets only. The following conclusions can be drawn:

Strengthening with steel rope decreases the maximum impact deflection dramatically, and gives smaller deflection values when compared to strengthening by CFRP.

Increasing the number of blows leads to increasing the maximum impact deflection. Strengthening with steel rope and CFRP together gives lesser values of maximum deflection, which also has a semi-constant relationship with the number of strikes.

Strengthening by steel rope contributes to the stability of the structure under the influence of repeated impact loads; the beams had very small increases in maximum deflection with large increases in impact energy.

Strengthening by steel rope also reduces the value of residual deflection, which increases with increasing impact energy.

No significant decrease in damping time at low impact energy is noticed when strengthening with steel rope. However, this changes by increasing the impact energy, where we find a large reduction in damping time.

Damping time decreases from the first impact strike when strengthening by steel rope and CFRP together, and the value continues to decrease by increasing the impact energy. The phenomenon is explained by the fact that the rope acts optimally with increasing residual deflection.

Strengthening by steel rope with or without carbon fibers leads to greater damping ratios. Damping ratios of beams strengthened with CFRP alone depends on the width of the strip, where the former decreases by increasing the latter.

Strengthening by steel rope with or without CFRP contributes to significant improvement in phases of failure under the influence of impact load.

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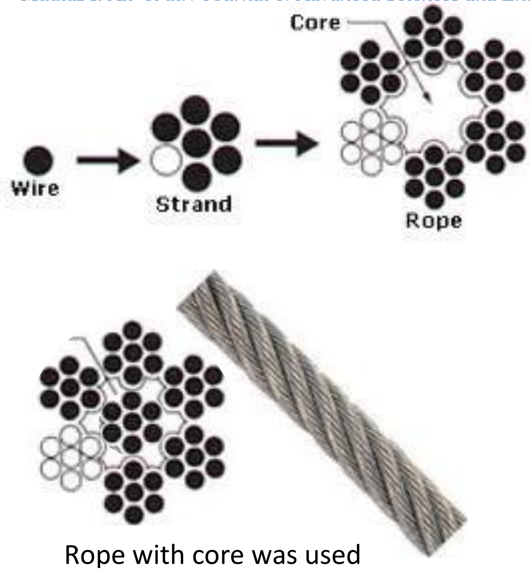


Figure 1: Steel rope.

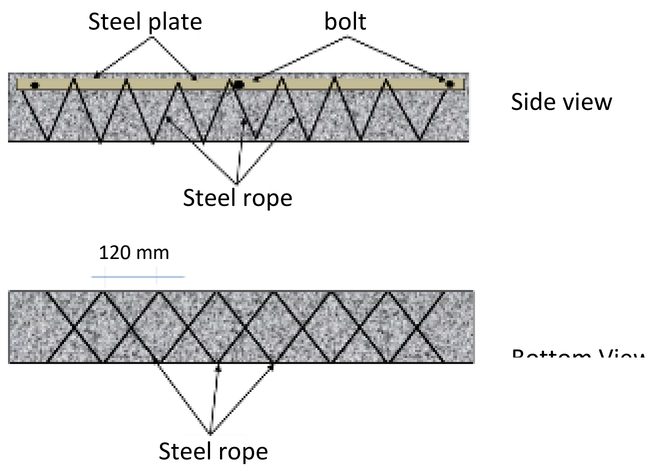
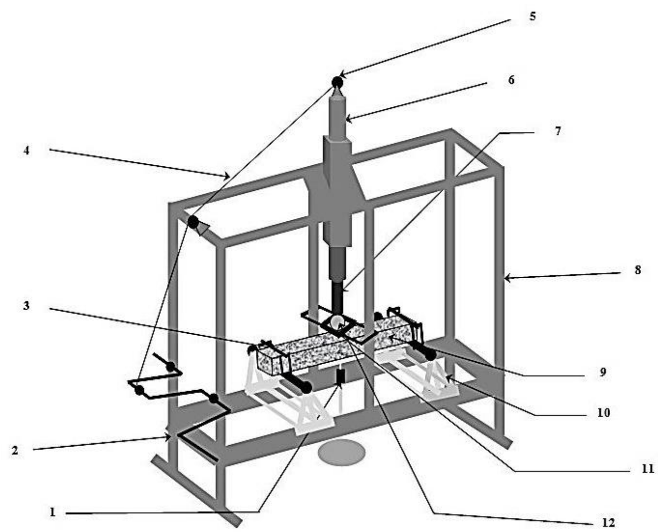


Figure 2: Beam strengthening by steel rope.



1	LVDT	7	Weight drop (hammer)
2	Handle to pull hammer	8	Steel structure
3	Steel angle to support sample	9	The sample

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Figure 3: Sketch and photo of impact load machine.

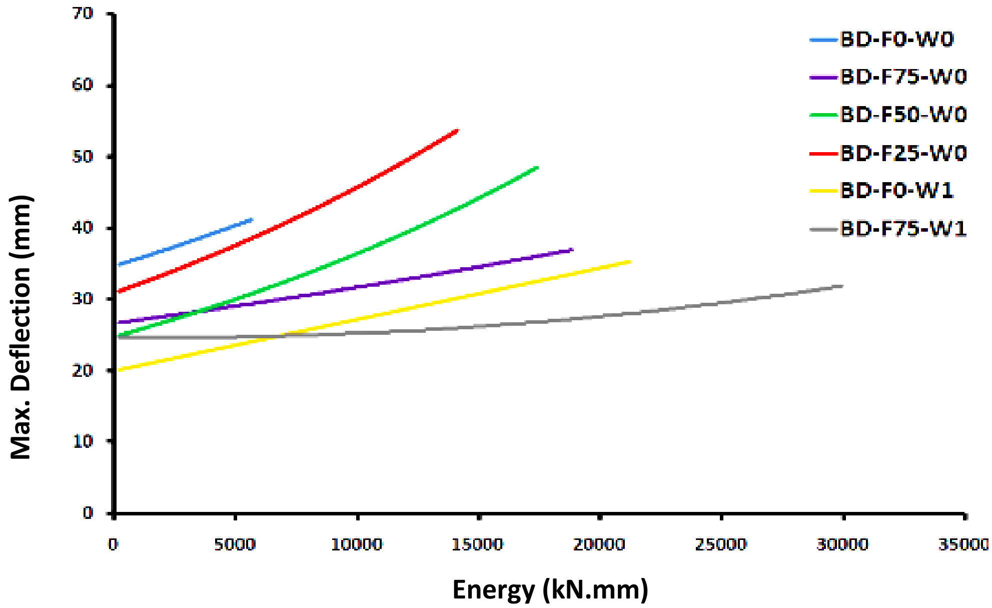


Figure 4: Relation between impact energy and maximum deflection.

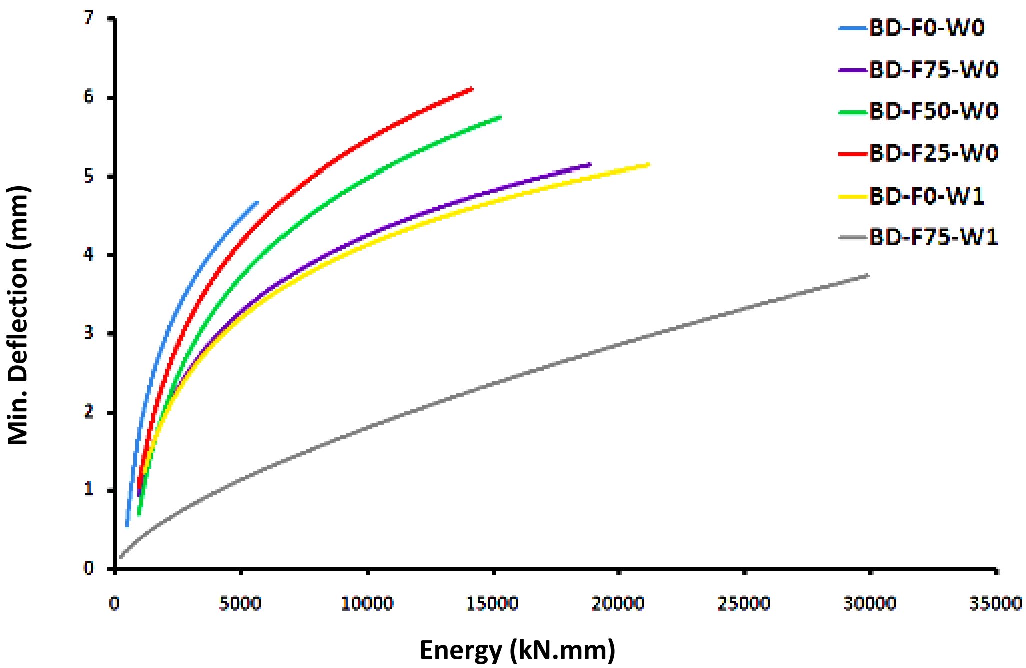


Figure 5: Relationship between impact energy and residual deflection.

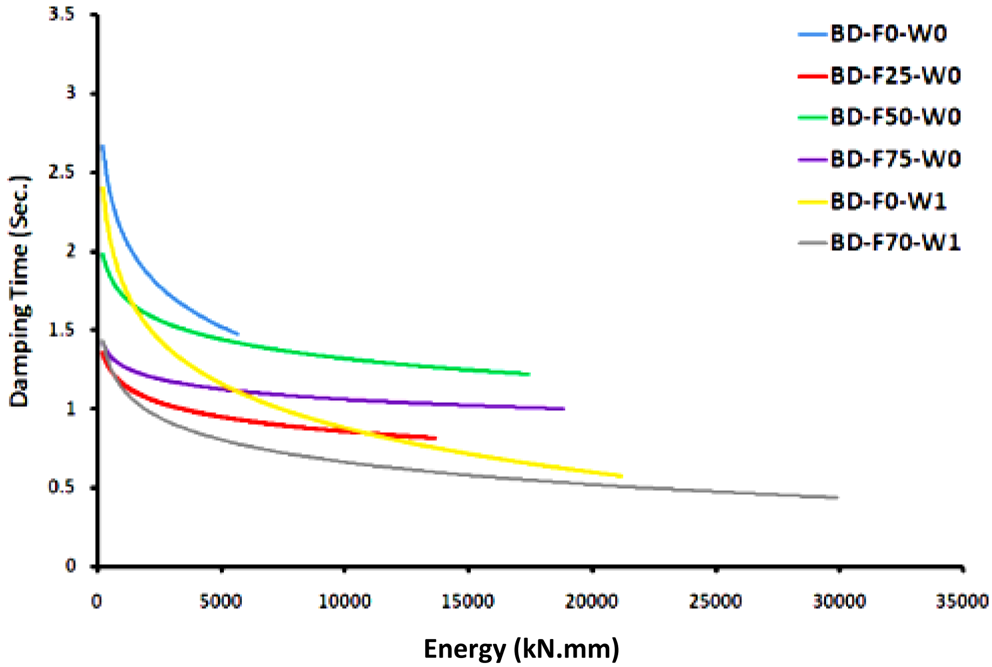
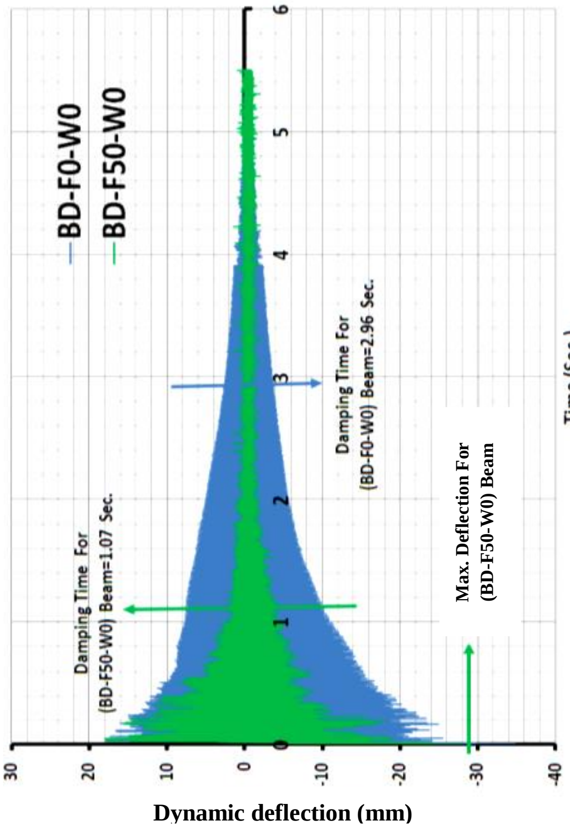
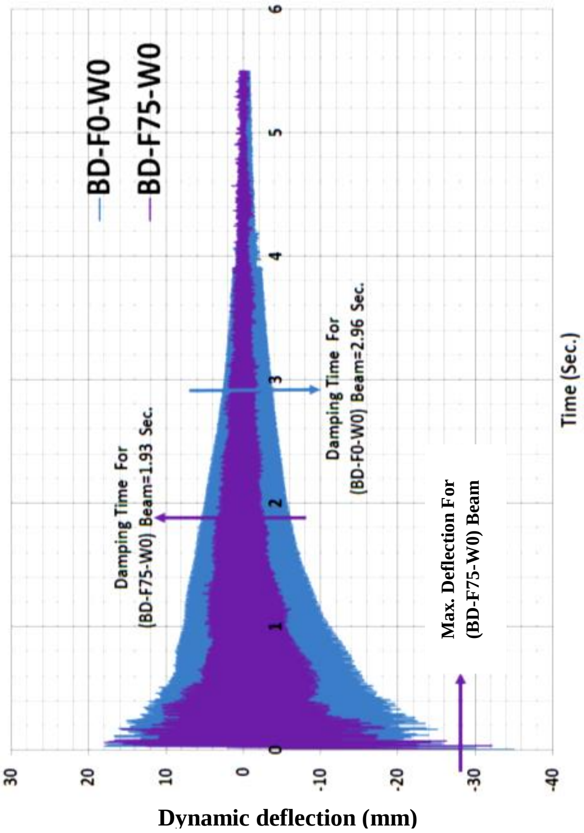
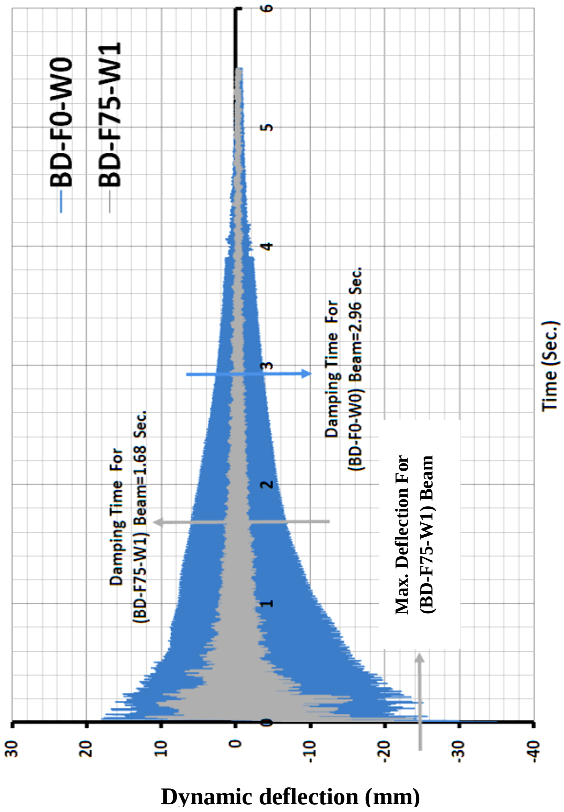
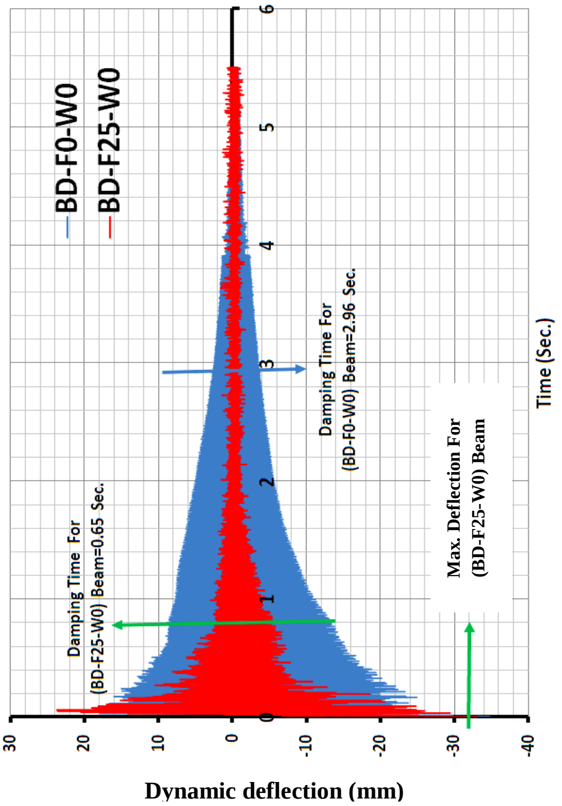


Figure 6: Relationship between impact energy and damping time.


BD-F0-W0
BD-F50-W0
Damping Time For (BD-F50-W0) Beam=1.07 Sec.
Damping Time For (BD-F0-W0) Beam=2.96 Sec.
Max. Deflection For (BD-F50-W0) Beam
Time (Sec.)
Dynamic deflection (mm)


BD-F0-W0
BD-F75-W0
Damping Time For (BD-F75-W0) Beam=1.93 Sec.
Damping Time For (BD-F0-W0) Beam=2.96 Sec.
Max. Deflection For (BD-F75-W0) Beam
Time (Sec.)
Dynamic deflection (mm)


BD-F0-W0
BD-F75-W1
Damping Time For (BD-F75-W1) Beam=1.68 Sec.
Damping Time For (BD-F0-W0) Beam=2.96 Sec.
Max. Deflection For (BD-F75-W1) Beam
Time (Sec.)
Dynamic deflection (mm)


BD-F0-W0
BD-F25-W0
Damping Time For (BD-F25-W0) Beam=0.65 Sec.
Damping Time For (BD-F0-W0) Beam=2.96 Sec.
Max. Deflection For (BD-F25-W0) Beam
Time (Sec.)
Dynamic deflection (mm)

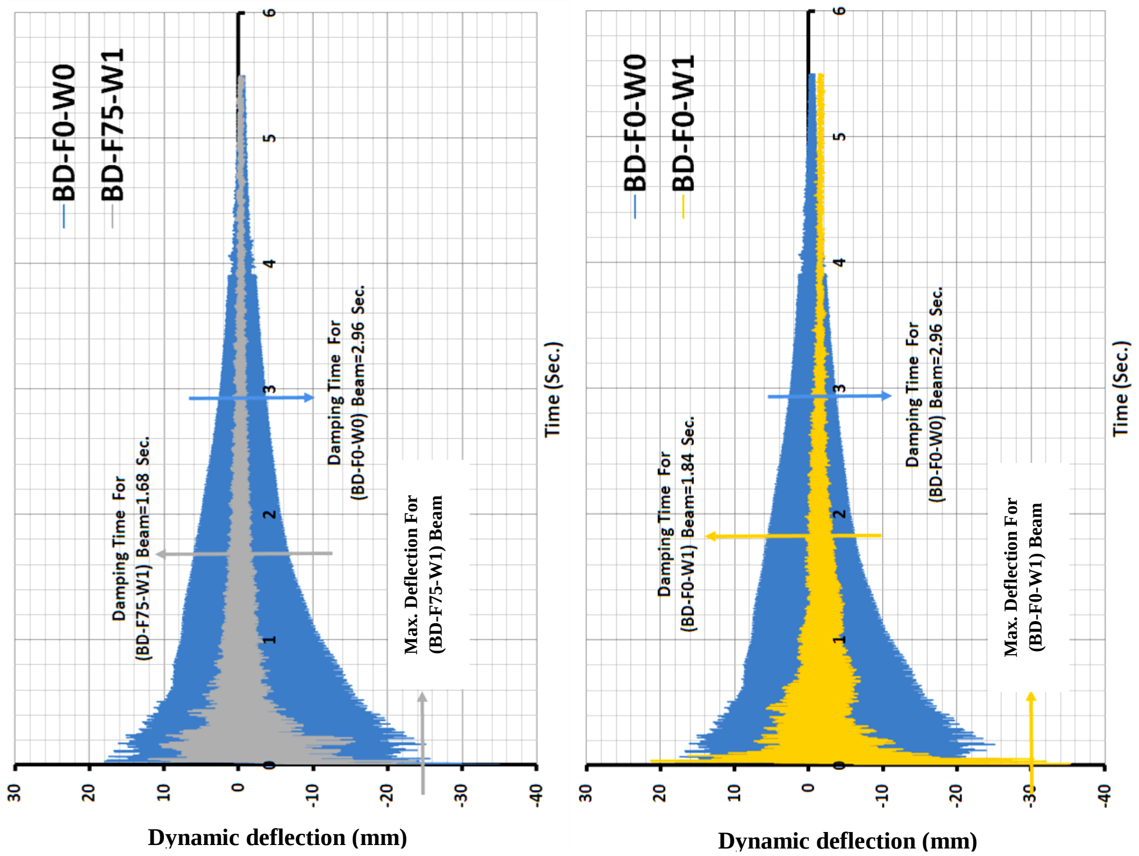


Figure 7: Time-dynamic deflection curve