Behaviour of Reinforced Fibrous Concrete Beams under Reversed Cyclic Loading

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Abstract

When earthquakes occur, energy released by the earthquake gets induced into the structure as ground motion and this energy has to be dissipated for safety reasons. To release seismic energy, the structure should damage in such a way that on one hand, collapse of structure should not occur and on the other hand, after the earthquake, damage should be economically feasible to repair. To avoid the collapse of the structures and also to reduce the repair cost after the earthquake, most design codes focus on providing sufficient ductility to structure. Dissipation of large part of injected seismic energy is an important factor for a structure to be seismically resistant. In this contribution, use of metallic-fiber to improve the behaviour of reinforced concrete beams subjected to cyclic loading is investigated. RC beams containing metallic fibers of two different types in mono and hybrid forms were constructed and tested under reverse cyclic loading to investigate the possibility of obtaining ductile and energy dissipating RC beams to be used in seismically active area. Reverse flexural cyclic loading tests were performed on beams of cross section 150 x 200 mm with a clear span of 1 m. In all tested compositions of concrete containing fibers, metallic fibers were investigated at maximum content of 40 kg/m^3 and 80 kg/m^3 in mono and hybrid forms, respectively. Experimental results showed that metallic fibers act as energy dissipater in the concrete and significantly improve the energy dissipation capacity of RC beams. Moreover, from the results obtained in terms of energy dissipation for RC beam containing fibers in hybrid form, positive interaction between two different metallic fibers used in this study has also been underscored.

Key Words: RC Beams; metallic fibers; hybridization; cyclic loading; energy dissipation, synergy

1. Introduction

Brittle matrix such as concrete loses its tensile load capacity almost immediately after the formation of first crack [1]. Addition of ductile fibers can improve several mechanical properties, such as cracking resistance, ductility, impact strength, fatigue strength. When the brittle matrix incorporating fibers are subjected to flexural loading, the cracks developed are bridged by the fibers [2]. When the fibers are used along with the longitudinal steel reinforcement, because of the high capacity of the composite, high tensile deformation in the longitudinal reinforcement are involved and as a result, high ductility of the structural member is achieved [3].

Under seismic loading, stress arises in the structural member may lead to a brittle response in the absence of adequate reinforcement. If in any case, reduced brittleness is achieved, pronounced non-linear fracture behaviour is exhibited until strain localization predominates. After this stage, sufficient residual strength is required to ensure that the structure can withstand the possible subsequent severe loading conditions involving large deformation, which may result from earthquake [4].

An important aspect of structural performance under cyclic loading is the ability of the structure to dissipate energy adequately. Energy dissipation capacity has been used as a measure of the ability of a structural member to withstand cyclic inelastic loading [5]. To enhance the structural performance under seismic loading, use of steel fiber reinforced concrete has been a subject of many research projects in last recent years [6,7]. Under reverse cyclic loading, concrete is subjected to more severe damage and the presence of fibers can reduce the strain magnitude and arrest the cracks [8]. The most important benefits of adding steel fibers in the concrete are the hindrance of the development of micro-cracks, delay in propagation of micro-cracks to form macro-cracks and better ductility after the formation of macro-cracks [9].

To evaluate the response of structure to a seismic event, determination of structural properties such as secant stiffness, ultimate capacity, ductility demands, energy dissipation and residual load carrying capacity is essential. In order to assess the complete response of a structure, non-linear dynamic analyses is sometime required. Due to complex interaction between the different structural components, scale effect between real structure and prototype structure, it is difficult to draw complete picture of the dynamic characteristics of a structure even from a non linear dynamic analysis. Moreover, the cost associated with the testing equipments and construction of large scale test specimens is also another hurdle in performing these types of testes [10]. Such type of laboratory testing also involves some approximation. Since the seismic action can be simulated by a series of alternating loading cycles of variable amplitude [11], the difficulties faced in non linear dynamic testing of structures have been overcome by performing reversible cyclic loading tests on structural components or assemblage of structural components (such as column-beam joint).

The research reported herein is concerned with the behaviour of reinforced fibrous concrete beams subjected to reverse cyclic bending. Main objective of this study has been to examine experimentally influence of metallic fibers on energy dissipation capacity of reinforced concrete beam. Two different kinds of metallic fibers are investigated: amorphous metallic and carbon steel fibers. As a tradeoff between loss of workability, cost of fibers and improvement in the structural performance, both fibers have been used at content of 40 kg/m^3 and 80 kg/m^3 in mono and hybrid forms, respectively. Basic purpose of studying fibers in hybrid form is to investigate the positive synergetic effect between the fibers for energy dissipation.

2. Experimental Program

2.1 Concrete Composition

One control concrete (without fibers) and three concrete mixes containing fibers were investigated. The average compressive strength of plain and fiber-reinforced concrete varied between 41 MPa and 45 MPa. For all concretes, CEM I 52.5 R type cement was used. Locally available natural sand with round particles having maximum particle size of 4 mm was used. Round gravels with size range of 4 -10 mm were used as coarse aggregates. To improve the workability of the each fibrous concrete mix, Super-plasticizer was used as an admixture. Mix proportion of control concrete is given in Table 1.

Table 1: Control concrete mix proportion (values in kg/m^3)

Cement	Sand	Gravel	Water	Super-Plasticizer
322	872	967	193	1.61

2.2 Types of metallic fibres used

Two types of macro-metallic fibres, 30 mm in length were used (Figure 1):

- *FibraFlex fibers* are amorphous metallic fibers produced by Saint-Gobain Seva, France. According to C. Redon; and J-L Chermant [12], no corrosion is observed when these fibers are immersed in HCl (0.1 N) for 24 hours or in $FeCl_3$ (0.4N) for 24 hour. These fibers develop very high bond strength with concrete matrix due to their rough surface and large specific surface area.

- *Dramix fibers*, produced by Bekaert Belgium, are made using carbon steel wires. These fibers develop weak bond strength with concrete matrix due to smooth surface and less specific surface area. Cross section of these fibers is circular and they have hooked-ends. They are usually available in clips of certain number of wires as shown in Figure 1. When these fibers are added in the concrete during mixing satge, the adhesive material by which the wires are bonded together is dissolved and individual fibres are distributed evenly in the concrete mix.

Figure 1: Metallic fibers used in this study

The characteristics of the two fibers used (i.e., FibraFlex and Dramix) are given in Table 2 where L, W, T, D and E are length, width, thickness, diameter and modulus of elasticity, respectively.

Table 2: Characteristics of metallic fibres

Fiber Type	Dimension (mm)				E, GPa	Tensile strength (MPa)
	L	W	T	D		
FF	30	1.6	0.03	-	140	2000
DF	30	-	-	0.5	210	1200

FF stands for FibraFlex fibers
DF stands for Dramix fibers

2.3 Test Specimen

Concrete beam reinforced with longitudinal steel bars and randomly distributed short fibers is named as reinforced fibrous concrete beam. In this experimental study, test specimens (Beams) having cross section of 150 x 200 mm and effective span of 1000 mm were tested in reverse cyclic bending. Two steel bars of 6 mm diameter (ρ = 0.19%) with characteristic yield strength of 500 MPa were used as conventional reinforcement. Flexural failure of the beam was ensured by providing necessary shear reinforcement (i.e., 6 mm Ø @100 mm C/C). Geometry and reinforcement details of the test specimen are shown in Figure 2. Details of all tested beams regarding concrete type, conventional steel ratio, fiber type and dosage are given in Table 3. For each concrete composition, two beams were cast and tested. The results presented in this paper are average of the two specimens.

2.4 Nomenclature of Tested Beams

Each tested beam was given a name according to type and dosage of fiber. For example, RC beam containing FibraFlex fibers was named as Beam-FF40, where FF stands for FibraFlex fibers and 40 is quantity of fibers in kg/m^3. Similarly RC beam containing Dramix fibers was designated as Beam-DF40, where DF stands for Dramix fibers. RC beam without any type of fiber (control beam) was designated as Beam-cont. Beam containing fibers in hybrid form was named as Beam-80HyF, where 80 is total quantity of two fibers in kg/m^3 (40 kg/m^3 of each fiber) and HyF stands for hybrid fiber concrete.

2.5 Casting of Test Specimens

In the pan type concrete mixer cement, sand and coarse aggregates were mixed for 2 minutes, and then fibers were added. Dry mixing of all the constituents was again carried out for 3 minutes. Water and super-plastizer were then added and mixing was done again for 3 minutes.

Since internal vibration method is not recommended for fiber reinforced concrete because it changes random distribution of fibers. To compact the concrete in the mould, external vibration method was adopted in this study. In this external vibration method, vibrator is pushed against the wall of the mould to transmit vibration to the concrete. Concrete was placed in the mould in two layers. In all cases, mould was vibrated on both faces at each 200 mm along the beam length for 8 to 10 seconds for each layer. Total time required for the compaction of one sample was 4 to 6 minutes. Generally, no difficulty in the casting of beam samples was faced using the external vibration method adopted in this study except for the beams constructed using concrete containing FibraFlex fibers for which more compaction time (i.e., up to 8 minutes for one sample) was required.

2.6 Testing Setup

Cyclic tests were performed using SCHENCK Standard PS 3007 B Hydroplus Machine with maximum capacity of 100 kN in static loading and 80 kN in dynamic loading. In order to ensure the same rigidity of the experimental setup in both directional bending (positive & negative bending), a model of the experimental setup was made and analyzed using finite element code CASTEM. From this modelling, sizing of the each component of experimental setup was done keeping in mind that during reverse cyclic test, each component of setup should remain in elastic range. Schematic diagram of the experimental setup is shown in Figure 3.

2.7 Testing Procedure

Displacement controlled reverse cyclic bending tests were performed. Numbers of loading cycles for each amplitude value of the imposed displacement were kept three. Amplitude of imposed displacement was gradually increased from 1 mm to 10 mm. History of reverse cyclic loading is shown in Figure 4.

The loading rate of imposed deflection was kept as 0.2 mm/second. The frequency of the reverse cyclic loading was calculated based on loading rate and amplitude value. During each loading cycle, mid span deflection of the beam was measured using external LVDT as shown in Figure 5. Data of the test was recorded automatically on a computer using a data acquisition system.

2.8 Measurements

During each test, followings were measured; (1) Mid span deflection of the beam; (2) Maximum load corresponding to each deflection value.

3. Test Results and Discussion

3.1 Cracking and Spalling

Due to rough surface which results in good bond with concrete matrix, FibraFlex fibers always act immediately after the crack initiation and try to stop the crack to open through bridging action between the crack edges. As a result, it was visually observed in the beams containing FibraFlex fibers (Beam-FF40) that the crack width was small at a given deflection compared to Beam-cont and Beam-DF40. At larger crack opening, when stress in FibraFlex fibers becomes high and exceeds their tensile strength, they break instead of pulling out from the matrix due to high bond strength

Dramix fibers have round smooth surface which results in poor bond strength with concrete matrix and their action to bridge the crack is mainly due to the anchorage in the concrete matrix because of their hooked ends. These fibers require a certain value of crack opening to come in action to arrest propagation of macro-cracks. At larger crack opening, they are pulled out from the concrete matrix instead of breaking due to anchorage failure.

Spalling of concrete cover is a common problem with structural element subjected to reverse cyclic loading, because each element comes alternatively in compression and tension. It was observed in this study that the spalling of concrete cover of the fibrous RC beams (Beam-FF40, Beam-DF40 and Beam-80HyF) was not severe compared to control RC beam (Figure 6b) due to the fact that fibers always hold the concrete matrix. Severe spalling of concrete cover was observed in RC beam without fibers (Beam-cont) as shown in Figure 6a. The photographs shown in Figure 6 were taken after the displacement amplitude of 10 mm. Reduction in the spalling of concrete by the use of metallic fibers in the concrete structural member subjected to reverse cyclic loading could lead to less maintenance and rehabilitation cost after the earthquake of small magnitude.

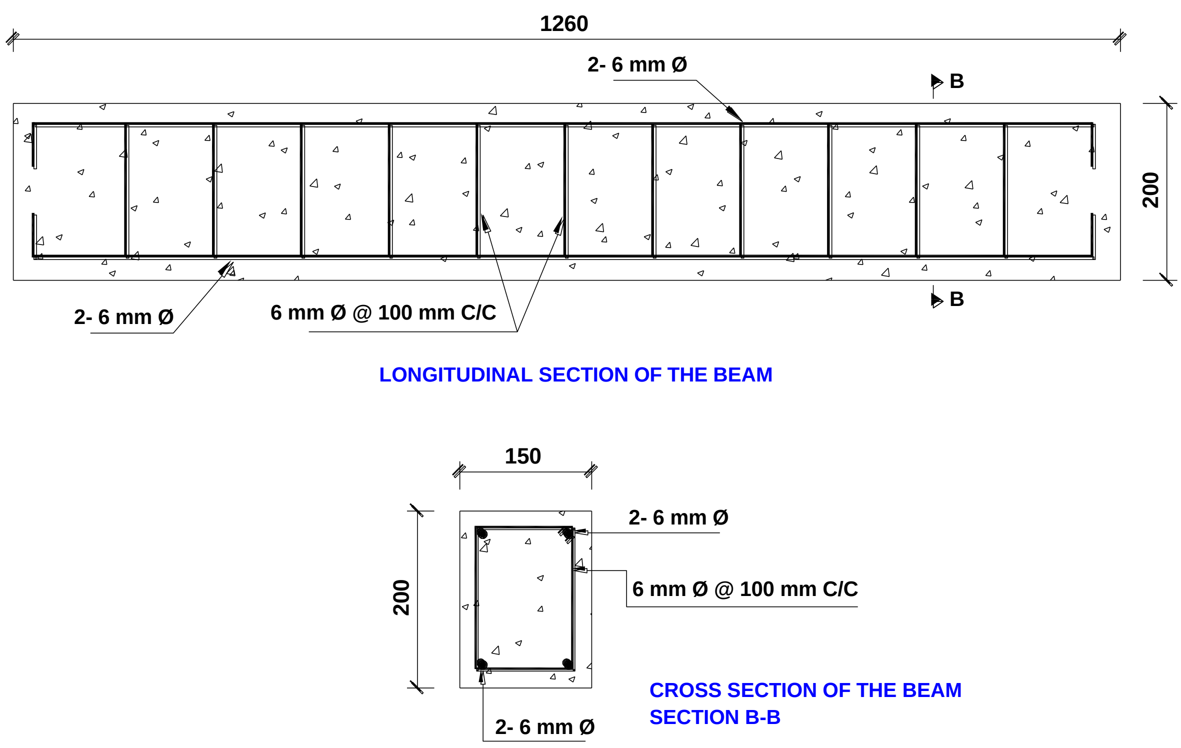

Figure 2: Reinforcement details of test specimen

Table 3: Details of tested beams

Beam Type	Concrete	Steel ratio ρ, Ø	Dosage of Fibers, (kg/m^3)		Total quantity of fibers, kg/m^3
			FibraFlex	Dramix	
Beam-cont	Control	0.19 % (6 mm)	--	--	--
Beam-FF40	Mono fiber		40	--	40
Beam-DR40			--	40	40
Beam-80HyF	Hybrid fiber		40	40	80

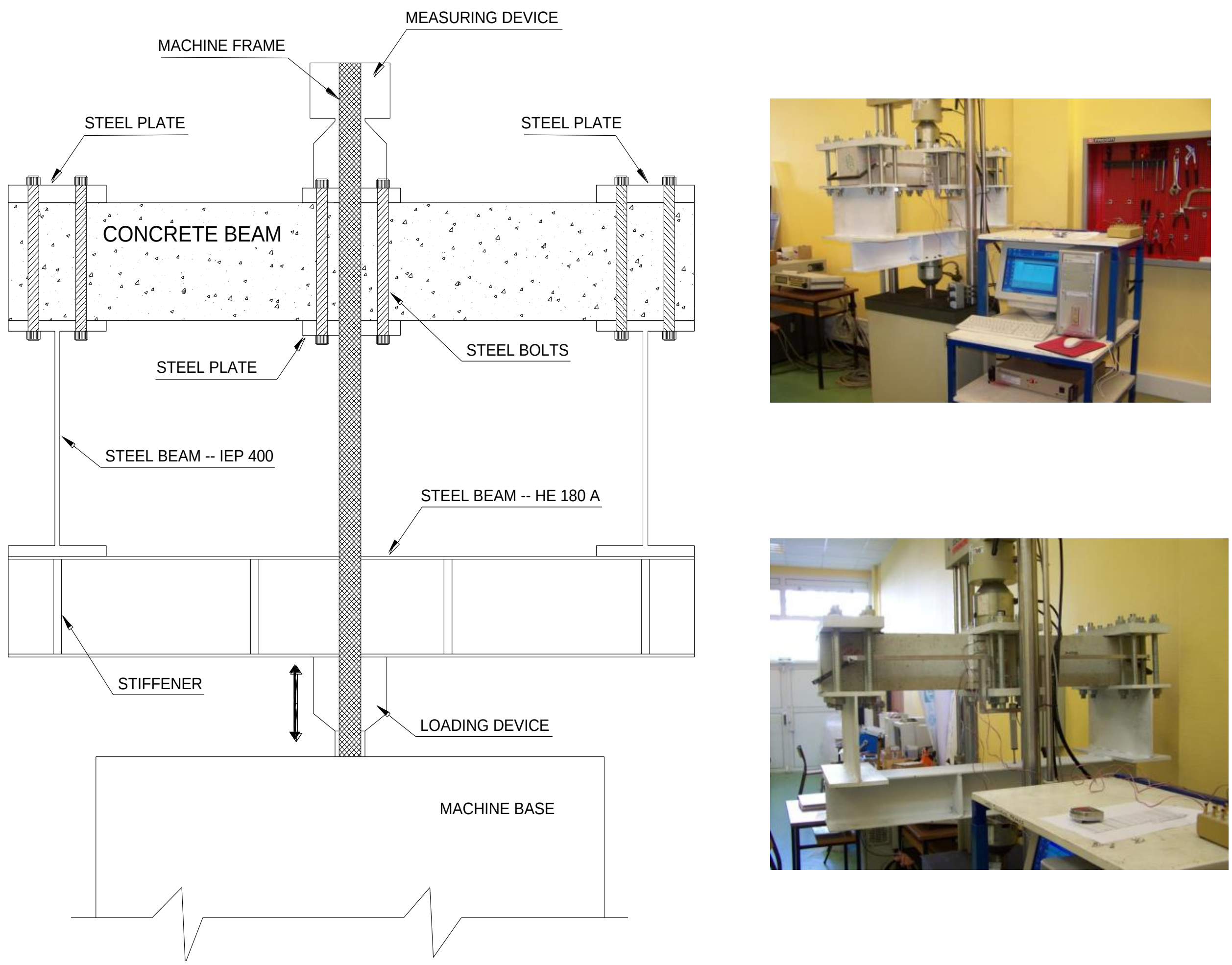

Figure 3: Experimental setup for reverse cyclic bending test on beam

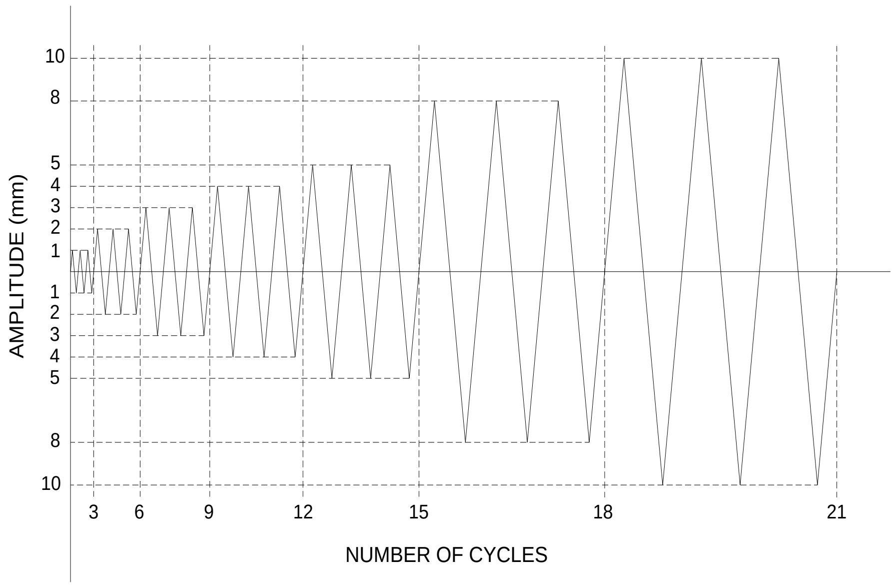

Figure 4: History of the displacement controlled reverse cyclic loading

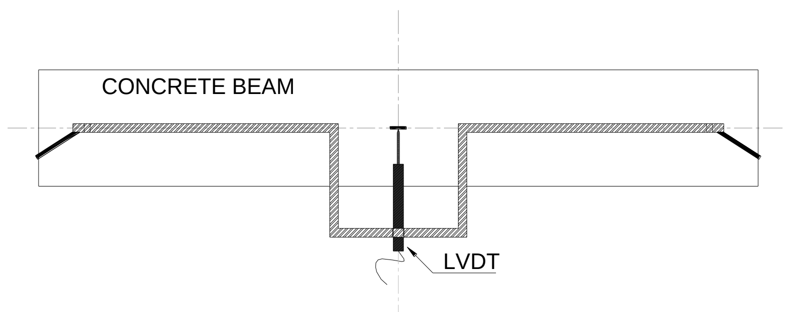

Figure 5: Deflection measurement scheme

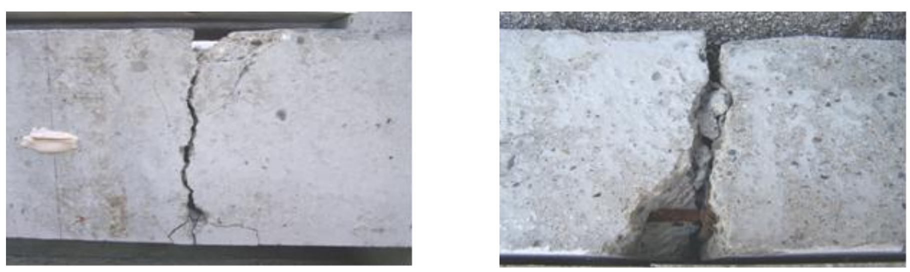

Figure 6a: Spalling of concrete cover (Control Beam)

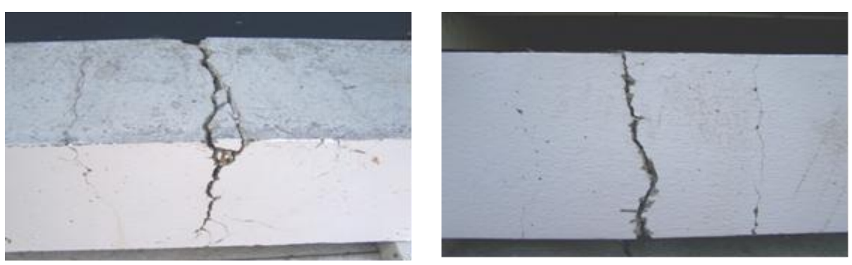

Figure 6b: Spalling of concrete cover (Fibrous Beam)

3.2 Load Deflection Hysteresis Loops

An important figure that must be generated to evaluate the structural seismic performance is the load-deflection hysteresis loops. Structures are expected to enter in elasto-plastic range during the strong earthquake and the hysteresis loops can provide good understanding for the analysis of seismic elasto-plastic response [13]. The Load-deflection hysteresis response indicates the energy dissipation capacity of the structure by considering the area enclosed by the hysteresis loops. Load-deflection hysteresis loops of all four beams are shown in Figure 7. The following could be observed in the load-deflection hysteresis loops of RC beams with and without fibers:

- The relationship between load and deflection of all the tested beams was observed to be linear before cracking of the concrete. After cracking, slope of the hysteresis curves (secant stiffness) degrades with increase of deflection.

- By comparing the maximum load attained by the RC beams containing FibraFlex fibers (Beam-FF40) in the first cycle of loading, it was noticed that at same deflection, there was strength decay after the first cycle of loading in the subsequent cycles. This shows that the effect of these fibers is more concentrated in first cycle of loading. The decay in strength after the first cycle was also observed in the RC beams without fibers (Beam-cont) and with Dramix fibers (Beam-DF40), but with these beams, decay in strength in the subsequent cycle was not significant as for the beam containing FibraFlex fibers

- After cracking, it was observed up to deflection of 3 mm that the hysteresis loops of the RC beam containing FibraFlex fibers were fatter than RC beams without fibers showing larger area enclosed by the curves. After 3 mm, hysteresis loops of the RC beam containing Dramix fibers were fatter than the RC beam without fibers.

- In all types of beams, no pinching of hysteresis loops was observed.

3.3 Dissipated Energy

For structures, surviving a seismic event depends mainly on their capacity for energy dissipation. Greater the energy dissipated, better the specimen performance [14]. Energy dissipation is also a relevant parameter in order to analyze the performance of reinforced concrete member subjected to cyclic loading [15].

The injected energy into the structure has two forms: dissipated energy; and recoverable energy as shown in Figure 8 of a typical loading cycle. Total energy absorbed by the system is the sum of dissipated energy and recoverable energy [16].

The dissipated energy is the area enclosed by the hysteresis loop (Figure 8) and represents the structural element capacity to mitigate the earthquake effect in-elastically through inelastic behaviour of reinforcing steel which causes excessive cracking and permanent deformation. In fiber reinforced concrete, fibers inside the matrix also act as energy dissipater because inelastic behaviour due to fiber deformation, fiber slip and fiber breaking or pulling out are also main factors along with inelastic behaviour of steel bars and cracking of concrete to dissipate major part of the injected energy into the structures during seismic excitation.

The energy dissipated during each loading cycle was calculated using the trapezoidal rule to determine the area within the load-deflection hysteresis loop. The average value of dissipated energy in three cycles at same deflection was determined. The values of average dissipated energy (ADE) of each type of beam are given in Table 4 and are graphically shown in Figure 9.

In Table 4, it can be observed that for all the beams, the energy dissipated in the first cycle of each displacement level was greater than in the subsequent cycles. This is because that the crack development, widening or propagation occurred in first cycle while in the subsequent cycles, the cracks marginally extended in their length but open and close in alternate loading. The variation in the energy dissipation in first and repeated cycles was severe in case of beam containing FibraFlex fibers (Beam-FF40) which indicated that their action is more concentrated in first cycle. The possible explanation of greater value of dissipated energy in first cycle of loading is that when deflection is increased, crack is extended and the fibers present in the path of the crack resist their propagation causing much energy dissipation. Due to high stress level, the fibers break in first cycle and no more or little damage of fibers occur in subsequent cycles of loading at the same deflection value.

Comparison of RC beams containing FibraFlex fibers and Dramix fibers at content of 40 kg/m^3 in terms of average dissipated energy (ADE) is shown in Figure 10. Percentage increase in ADE compared to control beam by the two reinforced fibrous concrete beams is also shown in Figure 10. In this figure, it can be observed that up to 3 mm deflection, gain in dissipated energy by Beam-FF40 is greater than the Beam-DF40 while after 3 mm deflection, it is reversed and gain provided by the Beam-DF40 is greater than Beam-FF40. Maximum gain registered in energy dissipation by Beam-FF40 and Beam-DF40 compared to Beam-cont is 142% and 70%, respectively. Since the dissipated energy in a loading cycle decreases as the damage levels increases [16], the drop in the energy dissipation in case of beam containing FibraFlex fibers after 5 mm deflection reveals more damage.

Knowing that the fibers inside the matrix act as energy dissipater [17], at smaller crack opening before yielding of steel bars, FibraFlex fibers by developing high bond strength with matrix, are more effective to control propagation of micro-cracks [18] and that is the reason, they provide an important gain in the energy dissipation at smaller deflection (up to 3 mm) due to fiber damage at high stress levels. After yielding of steel bars when the plastic hinge is formed by the extension of crack throughout the cross section of the beam, FibraFlex fibers present in the path of the major cracks are broken and no further gain in energy dissipation is registered with increase of imposed displacement value. On the contrary, Dramix fibers are more effective to bridge macro-cracks [18], with the increase of crack opening after yielding of steel bars, mobilized friction between fiber surface and matrix, yielding of their hooked ends, and finally pulling out mechanism are the main factors which make Dramix fibers a good energy dissipater even up to deflection of 10 mm.

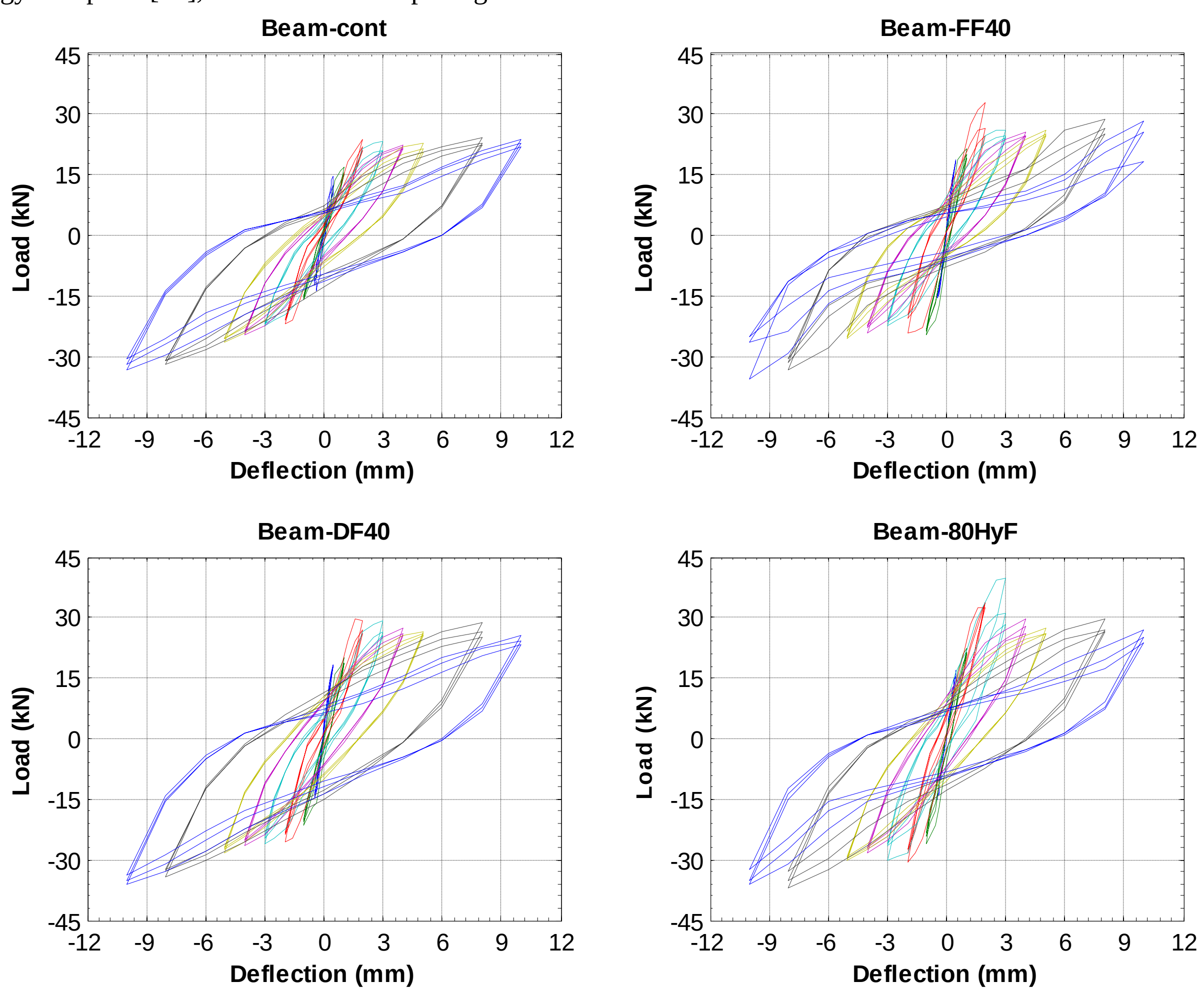

Figure 7: Load-Deflection Hysteresis Loops

Table 4: Average value of Dissipated Energy in three cycles, kN-mm

Beam Type	**Deflection (mm)**						
	1	**2**	**3**	**4**	**5**	**8**	**10**
Beam-cont	4.61	13.84	44.29	76.18	107.95	239.69	285.27
Beam-FF40	8.00	33.50	58.87	84.29	108.91	193.81	180.73
Beam-DF40	7.21	23.59	54.88	96.32	142.58	296.03	334.19
Beam-80HyF	8.53	25.93	69.34	101.86	142.71	262.01	265.51

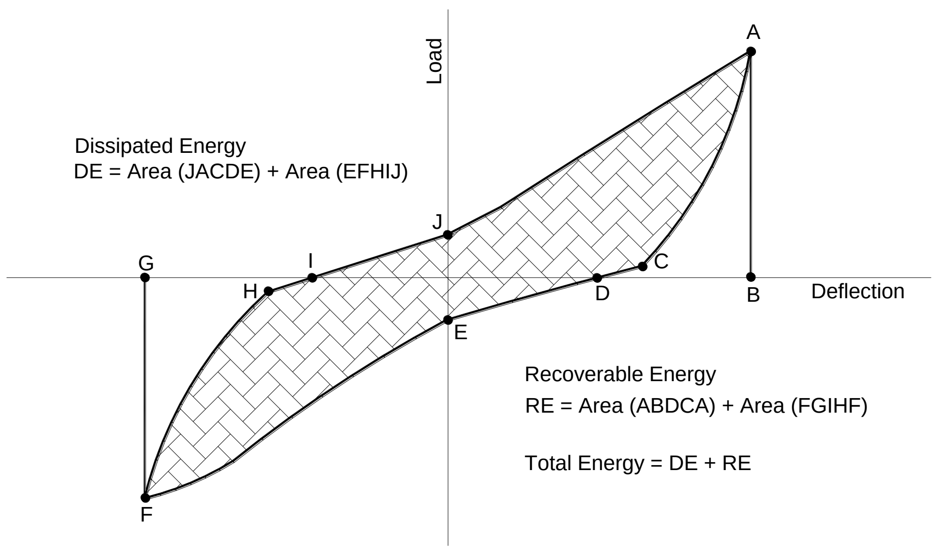

Figure 8: Typical loading cycle for a structural element

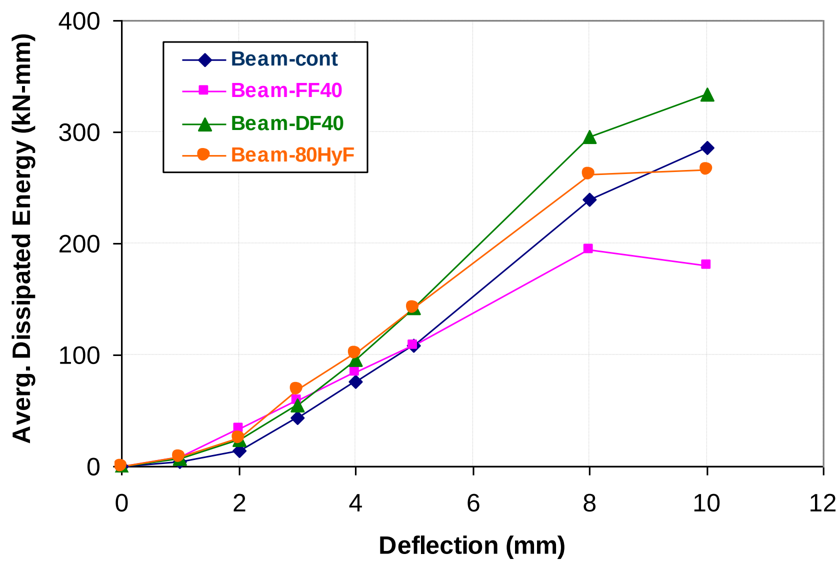

Figure 9: Average dissipated energy of all tested beams

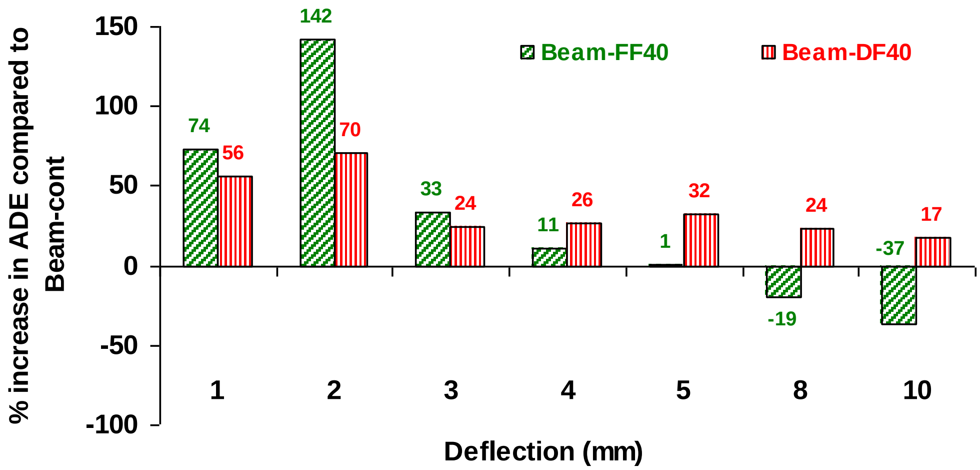

Figure 10: Percentage increase in ADE by the RC beams with fibers compared to Beam-cont

After investigating the effect of each type of fiber (FibraFlex and Dramix fibers) on energy dissipation capacity of RC beam, the same fibers were tested in hybrid form in order to study the benefits of mixing fibers for energy dissipation. The fibers were mixed at 40 to get total quantity of fibers in hybrid form equal to 80 kg/m^3.

An important aspect of hybridization of fibers is synergetic effect between fibers. For the energy dissipation, if the energy dissipation of the RC beam containing fibers in hybrid form is greater then the summation of energy dissipation of RC beams containing fibers in mono form minus the energy dissipation of control beam (refer to Equation 1), one can say there exists positive synergy between the two fibers. In Equation 1, RFCB stands for reinforced fibrous concrete beam and RCB stands for reinforced concrete beam. The value of energy dissipation of the control beam is subtracted because while summing up the energy dissipation of mono fibered concrete beams, effect of matrix and steel bar is added two times. In equation 1, f_1 and f_2 represent two different fiber types, as FibraFlex and Dramix fibers in present study.

$$\left\langle (RFCB)_{f1+f2} \right\rangle_{hybrid\,fiber} > \left\langle \left((RFCB)_{f1} + (RFCB)_{f2} \right)_{mono\,fiber} - (RCB)_{control} \right\rangle \quad (1)$$

Synergy assessment for the beam Beam-80HyF in terms of energy dissipation is shown in Figure 11 where it can be observed that when fibers are mixed at dosage of each fiber equal to 40 kg/m^3, no synergetic effect or positive interaction exists between two metallic fibers used up to displacement amplitude of 5 mm, but it exists at 8 and 10 mm displacement. At displacement amplitude of 4 and 5 mm, although there is no synergy but the values are found to be quite close to each other.

4. Conclusions

The effect of metallic fiber addition on the energy dissipation capacity of the reinforced concrete beam has been investigated. Based on the results obtained, it is possible to draw the following conclusions;

- Through visual observations, it was noticed that addition of metallic fibers in RC beams induces an important reduction in flexural crack width at a given amplitude level.

- Significant reduction in spalling of concrete in RC beams is guaranteed in the presence of metallic fibers.

- Amorphous metallic (FibraFlex) fibers at content of 40 kg/m^3 contribute importantly to enhance the energy dissipation capacity of RC beams at smaller crack width before the yielding of steel. Maximum increase of 142% in energy dissipation capacity is registered by the addition of FibraFlex fibers at content of 40 kg/m^3.

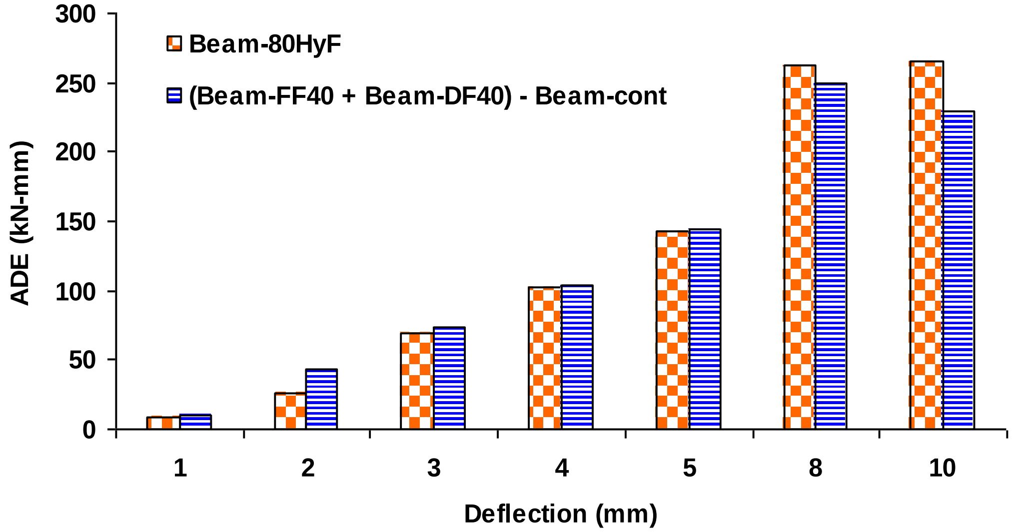

Figure 11: Synergy assessment for Beam-80HyF in terms of dissipated energy

- Addition of carbon steel (Dramix) fibers also improve importantly the energy dissipation capacity of the RC beams. Although gain in energy dissipation by these fibers is less than that of amorphous metallic (FibraFlex) fibers before yielding of steel bar but in comparison with control beam, an important increase in energy dissipation by the addition of these fibers is maintained up to deflection of 10 mm. Maximum increase of 70% in energy dissipation capacity of RC beam is registered by the addition of Dramix fibers at content of 40 kg/m^3.

- At deflection greater than 5 mm, there exists positive synergetic effect between amorphous metallic and carbon steel fibers for energy dissipation when they are mixed at content of 40 kg/m^3 (i.e., total quantity of both fibers equal to 80 kg/m^3).

5. Perspectives

Future study in continuation of the presented work will deal with analytical and finite element modelling of the beam specimens subjected to reverse cyclic loading.

6. Acknowledgments

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