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A Comparative Study of the Behaviour of Hybrid Fiber-Reinforced Concrete (HFRC) Beams Subjected to Low-Velocity Impact Loads under Various Boundary Conditions

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ABSTRACT: This study investigates the structural behaviour of Hybrid Fiber-Reinforced Concrete (HFRC) beams with the incorporation of steel and polypropylene fibers, considering various boundary conditions under low-velocity impact loading. Forty-eight beams, each measuring (150x200x1800) mm, were modeled and analyzed using ABAQUS software. Half of these beams were subjected to simply supported conditions, while the other half were under fixed support. Two types of fibers were employed, with aspect ratios of 60 for steel fibers and 231 for polypropylene fibers, while maintaining a constant fiber volume fraction of 1% of the specimen's total volume. The impact load was applied using a 100 kg hammer with a tip diameter of 16 mm, resulting in a hemispherical contact area of 201 mm², at four different velocities: 3.13 m/s, 4.42 m/s, 5.43 m/s, and 6.11 m/s. The findings indicate that the addition of hybrid fibers led to a reduction in beam deflection for both boundary conditions studied. When subjected to different impact velocities, the response of the beams followed a distinct pattern. In the case of fixed supported beams, the deflection initially exhibited a linear behaviour, followed by a sinusoidal waveform. Conversely, for simply supported beams, the deflection INITIALLY DISPLAYED A LINEAR RESPONSE BEFORE TRANSITIONING INTO THE PLASTIC DEFORMATION STAGE.

KEYWORDS: HFRC beams, steel fibers, polypropylene fibers, low-velocity impact, ABAQUS analysis, structural behaviour, boundary conditions.

1. INTRODUCTION

An impact load refers to a sudden force or load applied to a structure or system that can result in a rapid change in stress, deformation, or movement. It is often characterized by its short duration and high magnitude. Impact loads can have substantial effects on the structural integrity and performance of objects, ranging from buildings to mechanical components. Engineering and design considerations are essential to confirm that structures can withstand and absorb the effects of such loads without failure. To design the structure to withstand the action low velocity impact load is a major issue, due to the risks associated with natural hazards or accidental or manmade damage (i.e., ice ship impact, falling of heavy weights on structures, natural threats such as falling rocks in mountain areas, atomic power plant accidents, motor vehicle, chemical plant bursts and other acts related to terrorism). There is still a lot of demand in the improvement of the performance of infrastructures subjected to extreme loads, such as blast loads and impact load (High velocity impact as well as low velocity impact). However, till date the performance of RC structures, subjected to impact loading has not been suitably defined by civil engineers. As a result of this, many low velocity impact tests have been conducted to understand and study the response of concrete beams subjected to impact loading.

Hybrid fiber-reinforced concrete beams are structural elements made by combining different types of fibers, such as steel and synthetic fibers, with concrete to enhance their mechanical properties and performance. This combination can provide improved strength, ductility, durability, and crack resistance compared to traditional concrete beams. Steel and polypropylene fibers are used in this work as hybrid fiber-reinforced concrete beams. Steel fibers provide tensile strength and ductility, while polypropylene fibers improve crack resistance and durability. The combination of these fibers in concrete can lead to a more balanced and enhanced performance in terms of mechanical properties and overall structural behavior. The combination of steel and polypropylene fibers in the concrete enhances its ability to withstand such impact loads. Steel fibers contribute to the beam's toughness and energy absorption, while polypropylene fibers help control crack propagation. This can result in reduced damage and better post-impact performance of the beam, making it suitable for applications where impact resistance is important, such as in structures prone to accidental collisions or vibrations.

In the present study, steel, and polypropylene fibers with aspect ratio of 60 and 231 respectively were used as reinforcing materials in concrete, these results in hybrid fiber reinforced concrete (HFRC). These fibers were chosen because of their advantages; the steel fibers are large compared to PP fibers, as it will arrest the growth of macro cracks thereby improving the fracture energy of concrete, while the PP fibers are short, thin, flexible, and smooth and helps in resisting the development of micro cracks.

Further, PP fibers with low modulus of elasticity are ductile and flexible; it can be effectively improving the toughness and resistance to elongation in the cracking zone. Meanwhile, the steel fiber is stronger, more rigid, has a high modulus of elasticity and can improve the final strength before it is cracked for the first time. Vahid and Togay studied experimentally the durability and mechanical properties of high strength concrete on adding steel and PP fibers. They employed polypropylene fibers with a 12 mm length and hooked end steel fibers with a 60 mm length in a variety of volume fractions while keeping the total fiber volume fraction at 1.0%. They discovered that among the many fiber combinations investigated, a mixture containing 0.85% steel and 0.15% polypropylene fiber performed best in terms of mechanical and durability qualities [2]. According to the numerical analysis, impacts from large masses traveling at low speeds resulted in lower maximum impacts but higher maximum beam deflections in the middle of the span, and vice versa [4]. For fixed end boundary conditions, the maximum impact load was also high while the mid-span deflection was lower than for pinned-end boundary conditions. Higher reinforcement ratio led to improved deflection recovery in the anticipated impact. The recovery of deflection after impact is significantly impacted by variations in the reinforcement ratio. It was discovered that the greatest deflection in the center of the span dropped by 37% as the proportion of steel reinforcement grew from 0% to 2.28% [10].

2.1 Modeling

For the analysis of hybrid fiber reinforced concrete beams, the commercially available finite element analysis program ABAQUS is used. Both the beam and the hammer are built individually while modeling. Eight-nodded solid elements (C3D8R) are used to model the beam component. Like that, the steel hammer is similarly modeled using solid parts. C3D8R element is formulated based on Lagrangian assumption of the element deforms with material deformation. While modeling the hammer used is of size 51 mm diameters with cylindrical body which intern connected with hemisphere tip (striking tip) of 16 mm diameter at the bottom. The two parts are then put together as depicted in Figure 1.

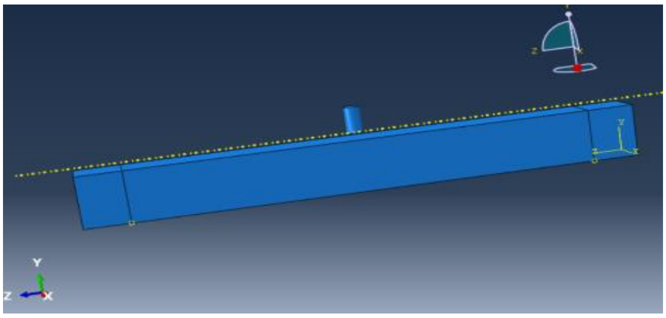


Figure 1. Assembled model.

2.2 Material Properties

The hybrid fiber used is of two types of fiber: Polypropylene fiber with aspect ratio 60 (length = 3 mm, diameter = 0.013 mm) having elastic modulus = 4.7 GPa similarly steel fibers are of aspect ratio 231 (length = 21 mm and diameter = 0.35 mm) with elastic modulus is 200 GPa. The tensile strength of the PP and MS fibers were 550 and 2800 MPa, respectively. HFRC beams are modeled by using their combined material properties and are tested for impact resistance. The HFRC materials properties required for the analysis are compressive and tensile strength, along with elasticity, poisons ratio and concrete damage plasticity. Table1 shows the input parameters used for defining concrete [11].

Table1: Material properties for different concrete mixes

Mixture Designation	Steel fiber (%)	PP fiber (%)	Total Volume (%)	Density (kg/m^3)	Compressive Strength (MPa)	Tensile Strength (MPa)	Young’s modulus (E) (MPa)
P C1	0	0	0	2293.33	38.5	3.5	31024.2
P C2	1	0	1	2304.44	37.4	3.8	32372.0
P C3	0.9	0.1	1	2337.8	48.4	5.1	36335.2

P C4	0.825	0.175	1	2322.73	41.8	4.6	33749.7
P C5	0.75	0.25	1	2240.33	35.6	3.9	31129.5
P C6	0	1	1	2166.37	24.7	2.4	24681.1

2.2.1 Concrete Damaged Plasticity Model

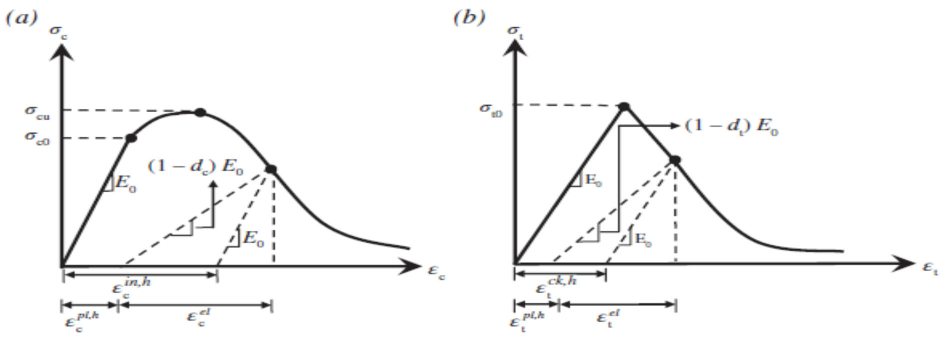


Figure 2. Response of concrete to a Uniaxial loading condition: (a) Compression (b) Tension

Properties of steel hammer

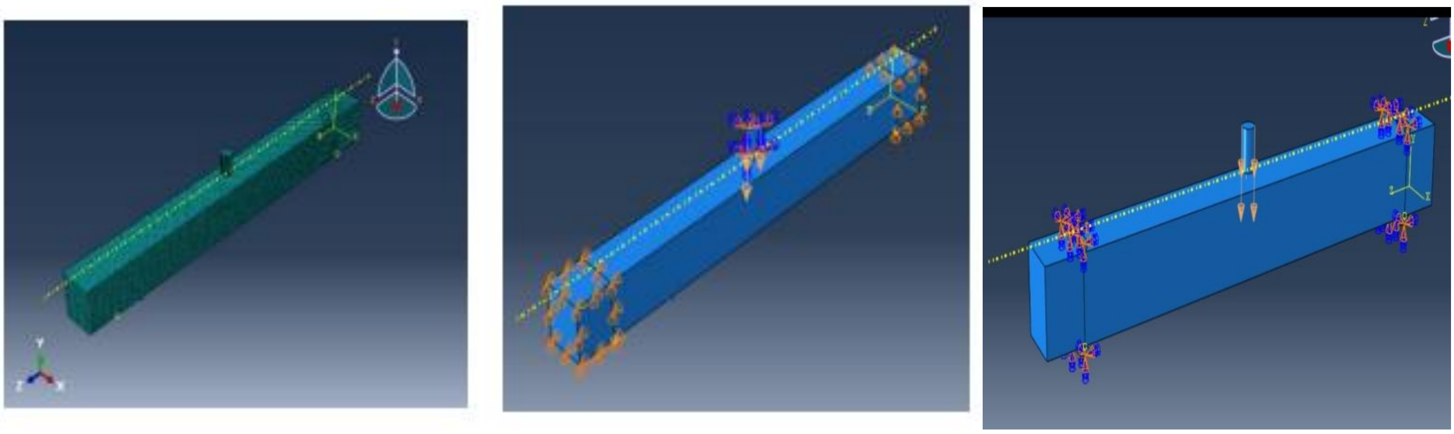
Modulus of Velocity (E) : 210 GPa

Poisons ratio : 0.3

Density hammer : 486964 kg/m^3 (just to maintain the tip diameter and total mass of hammer as 16 mm and 100 kg respectively)

2.3 Mesh Configuration, Load And Boundary Condition

In order to ensure that the model generates a mathematical solution that is virtually precise, and that computing time is kept to a minimum, it is crucial to employ a mesh that has been appropriately developed. In general, numerical result of FE model tends toward a unique value as the mesh density increased. In this study mesh size of 10 mm is used for beam. The drop-weight is modeled with initial position very close to the specimen surface (5 mm away) and assigned with mass of hammer i.e., 100 kg. Each beam specimen is impacted with four different velocities. The hammer is assigned with initial impact velocity of 3.43 m/s, 4.43 m/s, 5.42 m/s and 6.11 m/s. for the drop heights of 0.5 m, 1 m, 1.5 m, and 2.0 m respectively. The specified impact velocities, which are derived from the equation V = (2gh) where g = 9.81 m/s2 and h = height of fall, are utilized in the simulations. Both ends of the beam cannot move or rotate in any direction, so the beam acts as a fixed supported beam. One end of the beam is only allowed to move in the y and x directions (hinged support), while the other end is only allowed to move in the y direction (roller support).



(a) (b) (c)

Figure 3. (a) Beam and hammer mesh (b) Load and simply support beam (c) Load and fixed support beam

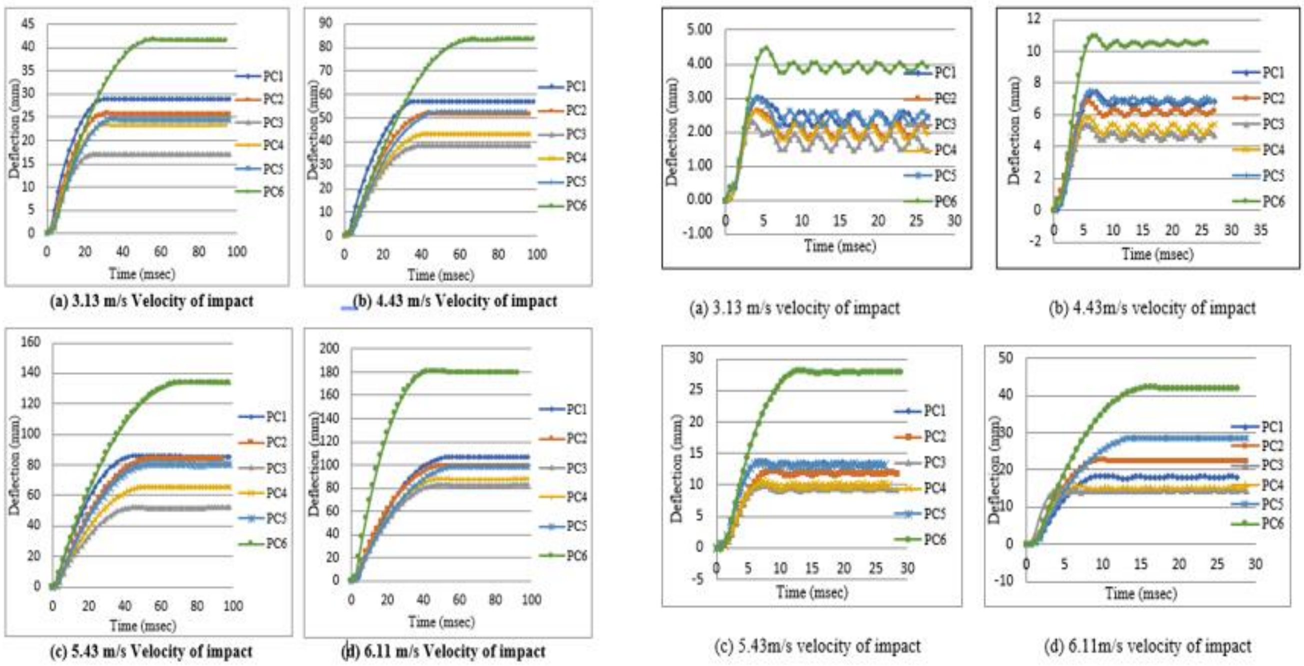
3. RESULTS AND DISCUSSION

To determine the mid span deflection of beams subjected to low velocity impact stress, twenty-four beams with fixed support and another twenty-four beams that were simply supported were tested numerically. The deflection - time histories, impact load with time, impact energy with deflection, stress with time, strain with time, and damage with time for different impact velocities. All specimens are showing a similar response with fixed supported hybrid fiber reinforced concrete beams as well as in simply supported beam.

3.1 Deflection of Beams

Table 2: The max mid span deflection of fixed support (FS) and simply supported (SS) beams subjected to different impact velocities.

Velocity of impact (m/s)	Max. Deflection (mm)											
	PC1 (FS)	PC1 (SS)	PC2 (FS)	PC2 (SS)	PC3 (FS)	PC3 (SS)	PC4 (FS)	PC4 (SS)	PC5 (FS)	PC5 (SS)	PC6 (FS)	PC6 (SS)
3.13	3.02	29.03	2.63	25.76	2.32	17.28	2.59	23.41	2.99	24.44	4.46	41.67
4.43	7.4	57.42	6.68	51.87	5.38	38.37	5.86	43.44	7.33	53.08	10.95	83.28
5.43	13.85	85.8	12.35	83.87	9.88	52.5	10.45	65.67	13.62	80.53	28.17	133.83
6.11	18.54	107.02	22.73	100.25	14.48	83.1	15.71	87.94	28.69	98.18	42.43	180.03



(a) (b)

Figure 4. Variation of mid span deflection with time for simply supported (a) and fixed supported (b) beams subjected to different velocity of impact load.

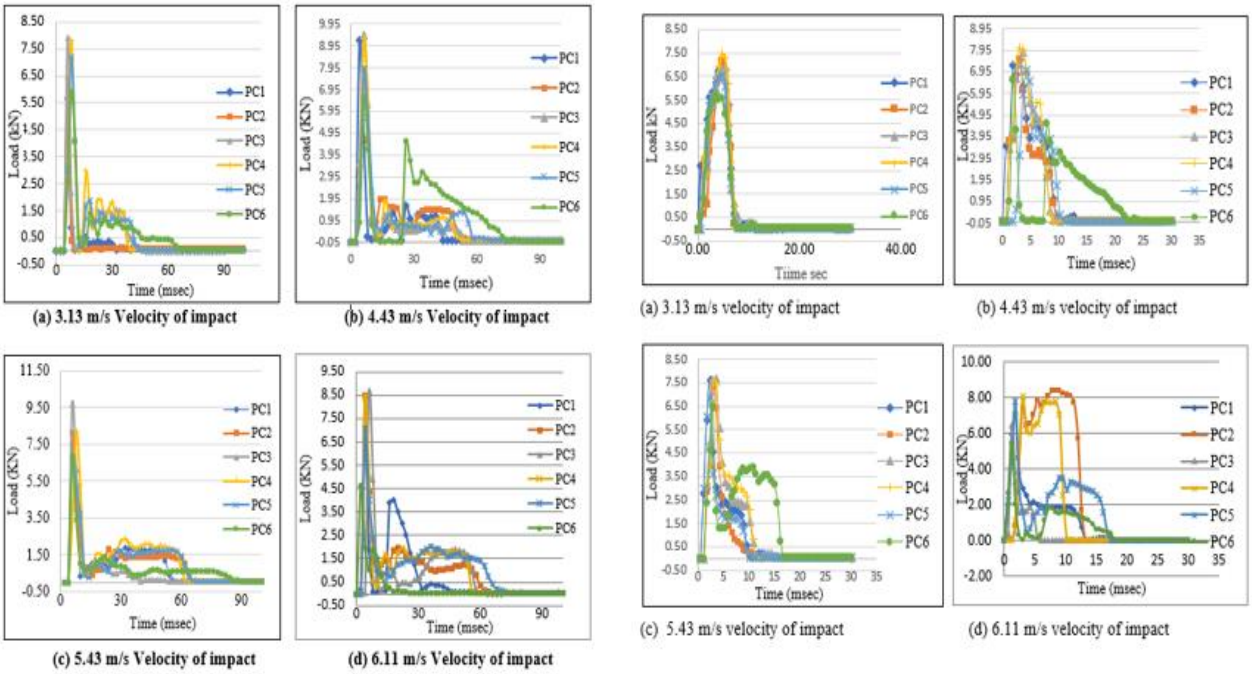
The maximum mid span deflection of beams under various impact velocities is shown in Table 2. All HFRC beams' mid-span deflection - time histories, as determined by mid-span impact, are shown in Figures 4(a) and (b). In reaction to an impact at 3.13 m/s, fixed-supported beams exhibit linear deflection up to 04 msec before taking on a sinusoidal waveform, while simply supported beams exhibit linear deflection up to 17 msec before reaching the plastic stage for 33 msec. When it reaches its maximum deflection after that, it stays constant.

In both the case the addition of fibres to concrete, the mid-span deflection in beams is reduced. The maximum mid-span deflection of beam PC2, PC3, PC4 and PC5 is considerably less compared to PC1, whereas the beam PC6 is showing more mid span deflection. The beam PC3 shows less mid span deflection because it is having more tensile strength. It can be shown from Table 2 that fixed supported beams have a lower maximum mid span deflection than simply supported beams.

3.2 Impact Load

Table 3: The maximum Load of fixed support (FS) and simply supported (SS) beams subjected to mid span impact with different velocity.

Velocity of impact (m/s)	Max. Load (KN)											
	PC1 (FS)	PC1 (SS)	PC2 (FS)	PC2 (SS)	PC3 (FS)	PC3 (SS)	PC4 (FS)	PC4 (SS)	PC5 (FS)	PC5 (SS)	PC6 (FS)	PC6 (SS)
3.13	6.99	5.66	6.68	6.39	6.84	7.91	7.49	7.82	6.54	7.19	5.66	5.9
4.43	7.48	9.18	7.49	7.35	7.85	9.46	8.03	9.29	6.99	7.88	6.62	6.61
5.43	7.61	7.52	7.33	8.07	7.65	9.66	7.64	3.25	6.88	6.66	6.46	6.87
6.11	7.13	6.61	8.42	8.48	6.49	8.66	8.07	8.4	7.8	7.06	5.46	4.62



(a) (b)

Figure 5. Variation of mid span load with time for simply support (a) and fixed supported (b) beams subjected to different velocity of impact load.

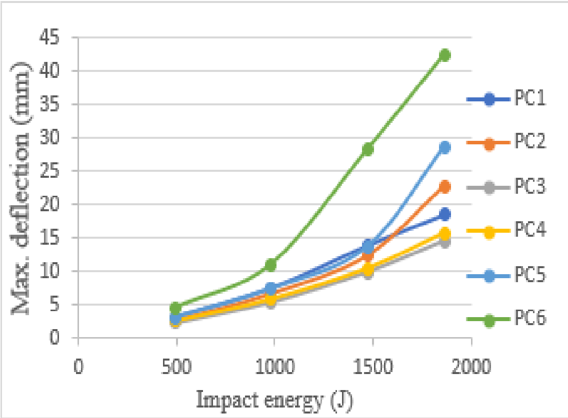
Table 3 shows the maximum load values of all beams subjected to mid span impact with different velocities. Figure 5 shows the impact load with time relationships of all beams are plotted and it is observed that the applied impact loads affect the specimens in a very small-time interval. The load – time curve is increased rapidly initially due to the hammer hitting on the beam surface then due to the residual energy in the hammer which makes it move further in the direction of fall. After that when hammer starts to move away from the beam, the load is reducing and reaches to zero. The maximum load value of beam PC1, PC2, PC4, PC5 and PC6 is less compared to PC3. The beam PC3 is sustaining high loads, due to its high stiffness in simply supported beams whereas, in fixed supported beam, the maximum load value of beam PC1, PC2, PC3, PC5 and PC6 is less compared to PC4. The beam PC4 is sustaining high loads.

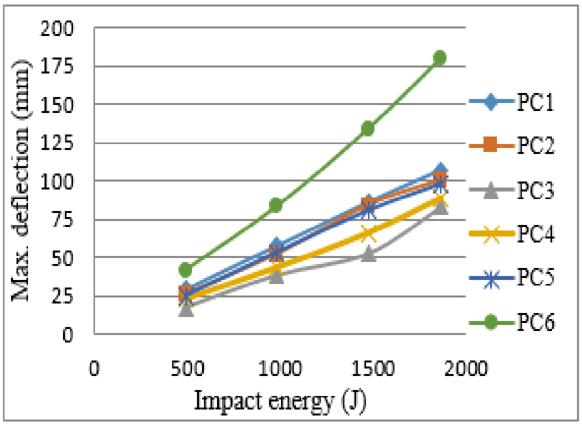
3.3 Impact energy

Table 4: Variation of impact energy and deflection of beams

Impact energy (J)	Max. Deflection (mm)											
	PC1 (FS)	PC1 (SS)	PC2 (FS)	PC2 (SS)	PC3 (FS)	PC3 (SS)	PC4 (FS)	PC4 (SS)	PC5 (FS)	PC5 (SS)	PC6 (FS)	PC6 (SS)

490.5	3.02	29.03	2.63	25.76	2.32	17.28	2.59	23.41	2.99	24.44	4.46	41.67
981	7.4	57.42	6.68	51.87	5.38	38.37	5.86	43.44	7.33	53.08	10.95	83.28
1471.5	13.85	85.8	12.35	83.87	9.88	52.5	10.45	65.67	13.62	80.53	28.17	133.83
1863.9	18.54	107.02	22.73	100.25	14.48	83.1	15.71	87.94	28.69	98.18	42.43	180.03





(a) (b)

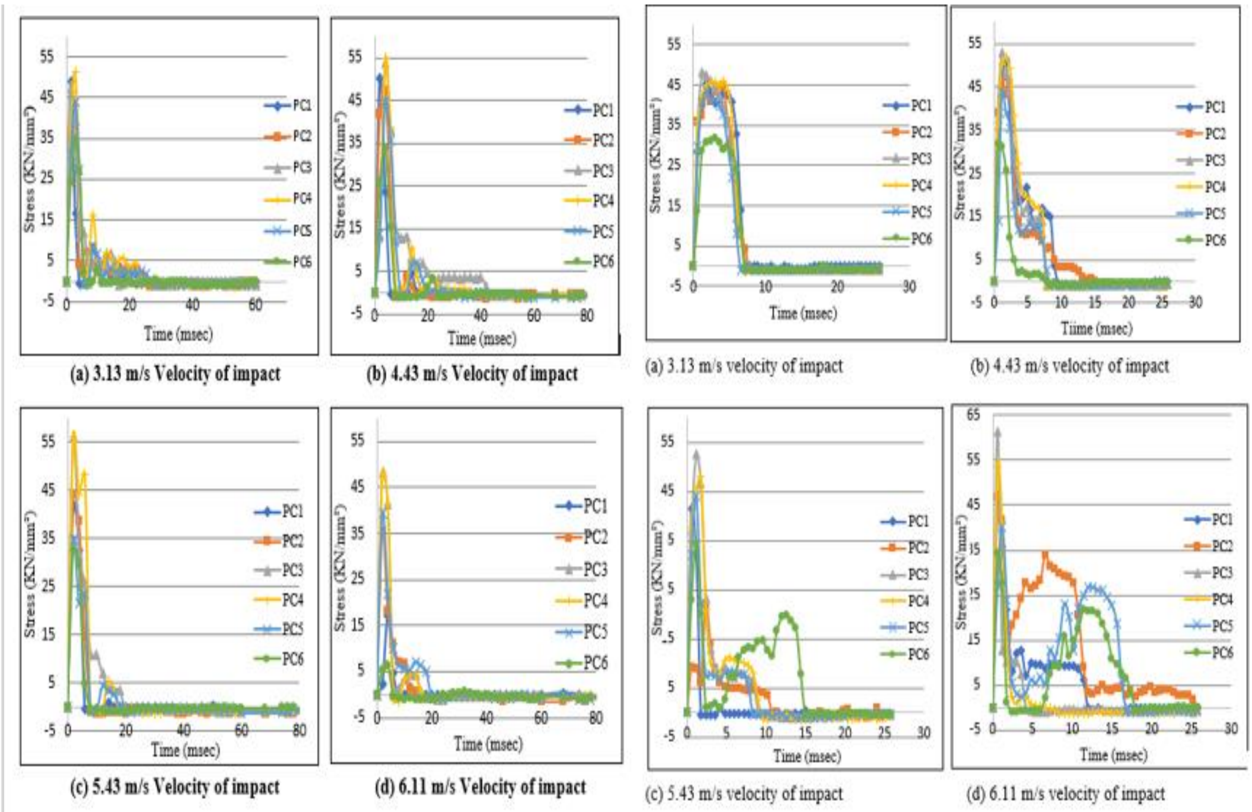
Figure 6. Variation of maximum deflection with impact energy for fixed support (a) and simply supported (b) beams.

The values of the maximum mid span deflections for all beams exposed to four different impact energy are shown in Table 4. All the beams were showing similar response. The fluctuation of impact energy with deflection is depicted in Figure 8. In both scenarios, the beam PC3 has the lowest maximum deflection values for all four impact energies.

3.4 Stress

Table 5: The maximum stress values of fixed support (FS) and simply supported beams (SS) subjected to mid span impact with different velocities.

Velocity of impact (m/s)	Max. Stress (KN/mm2)											
	PC1 (FS)	PC1 (SS)	PC2 (FS)	PC2 (SS)	PC3 (FS)	PC3 (SS)	PC4 (FS)	PC4 (SS)	PC5 (FS)	PC5 (SS)	PC6 (FS)	PC6 (SS)
3.13	45.36	48.87	44.67	37.39	48.08	47.56	45.83	51.09	43.48	44.11	31.75	34.42
4.43	50.93	50.26	46.06	47.46	52.8	53.97	51.82	54.9	43.74	44.9	31.09	33.83
5.43	41.63	41.63	22.03	44.26	52.7	56.22	47.97	56.07	44.01	34.77	34.38	32.59
6.11	46.79	17.01	46.54	35.4	61.25	48.19	53.4	48.19	40.22	39.28	34.33	5.32



(a) (b)

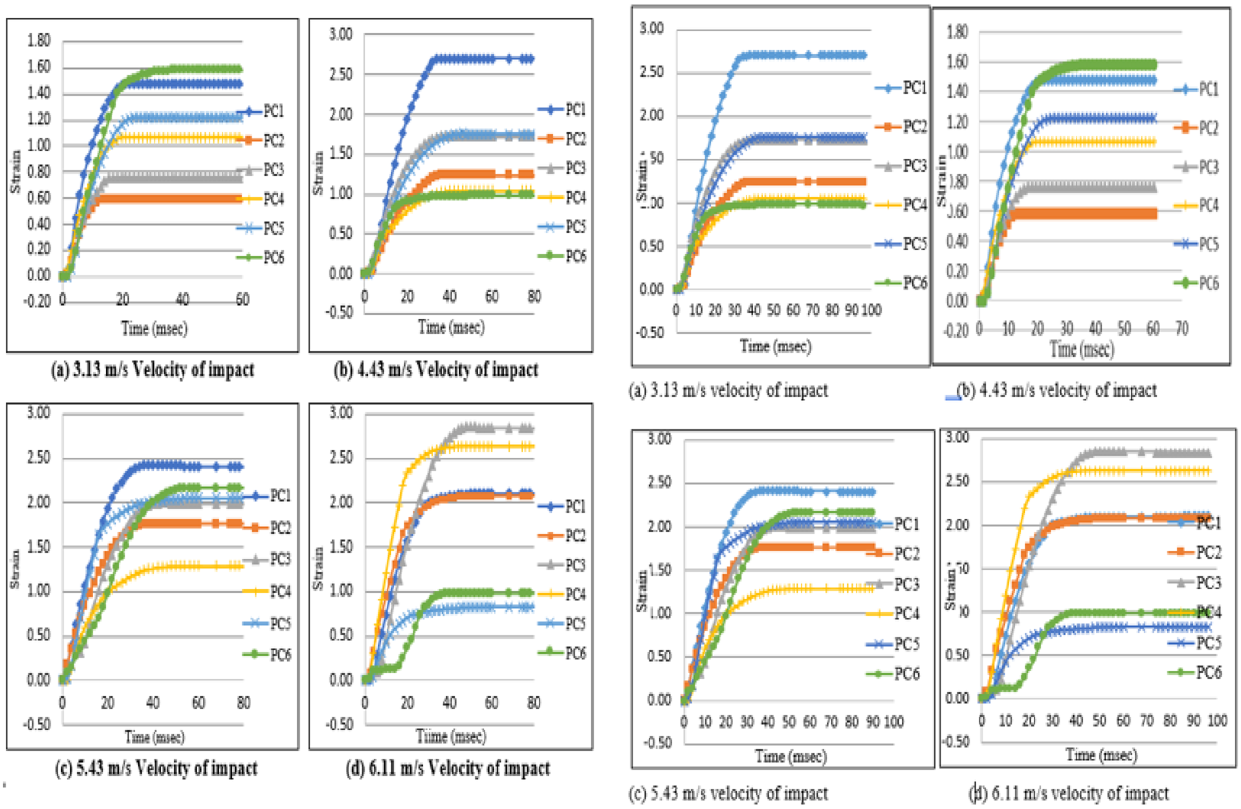
Figure 7. Variation of stress with time for simply support (a) and fixed supported (b) beams subjected to mid span impact with different velocity.

Table 5 shows the maximum stress values of all beams subjected to mid span impact with different velocities. All the specimens are exhibited a similar type of the stresses. Figure6. it is observed that the stress is increased rapidly initially due to the hammer strikes the beam surface and within a short time stress is reached maximum level. When hammer starts to move away from the beam, the stresses are reducing and reaches to zero which means the specimens behaves as nonlinear. In both the cases the stress values are nearly similar.

3.5 Strain

Table 6. Maximum strain values of fixed support (FS) and simply supported (SS) beams subjected to mid span impact with different velocities.

Velocity of impact (m/s)	Max. Strain											
	PC1 (FS)	PC1 (SS)	PC2 (FS)	PC2 (SS)	PC3 (FS)	PC3 (SS)	PC4 (FS)	PC4 (SS)	PC5 (FS)	PC5 (SS)	PC6 (FS)	PC6 (SS)
3.13	1.48	1.47	0.58	0.58	0.75	0.76	1.064	1.06	1.2199	1.22	1.5821	1.58
4.43	2.7	2.7	1.24	1.24	1.73	1.73	1.05	1.05	1.76	1.76	0.98	0.98
5.43	1.76	2.4	1.99	1.76	1.29	1.98	2.05	1.29	2.16	2.05	1.76	2.16
6.11	2.1	2.11	2.08	2.08	2.85	2.83	2.63	2.63	0.83	0.83	0.99	0.99



(a) (b)

Figure 8. Variation of strain with time for simply support (a) and fixed supported (b) beams subjected to mid span impact with different velocity.

All the test specimens exhibited a similar response in terms of strain–time relation. During impact, the strains show the linear variation in all specimens’ upto failure. Table 6 shows the maximum strain of beams with variation of impact velocities. The elements which are present in lower portion of the beams (mid span) undergo higher strain. Figure 8 shows the strain v/s time curve are same as that of deflection v/s time curves i.e. the strain in element node gradually increases till certain time and then remains constant thereafter. The gradual increase in strain was seen until the hammer was in contact with beam.

3.6 Damage

Table 7: Damage values of fixed support (FS) and simply supported (SS) beams subjected to mid span impact with different velocities.

Velocity of impact (m/s)	Damage (%) (FS and SS)					
	P C1	P C2	P C3	P C4	P C5	P C6
3.13	68	63	60.5	62	65	71
4.43	73	70.7	67.3	68.5	69.1	75.1
5.43	78.4	75.6	72.22	73.6	76	80.3
6.11	84	81.2	78.4	80.3	82	89.6

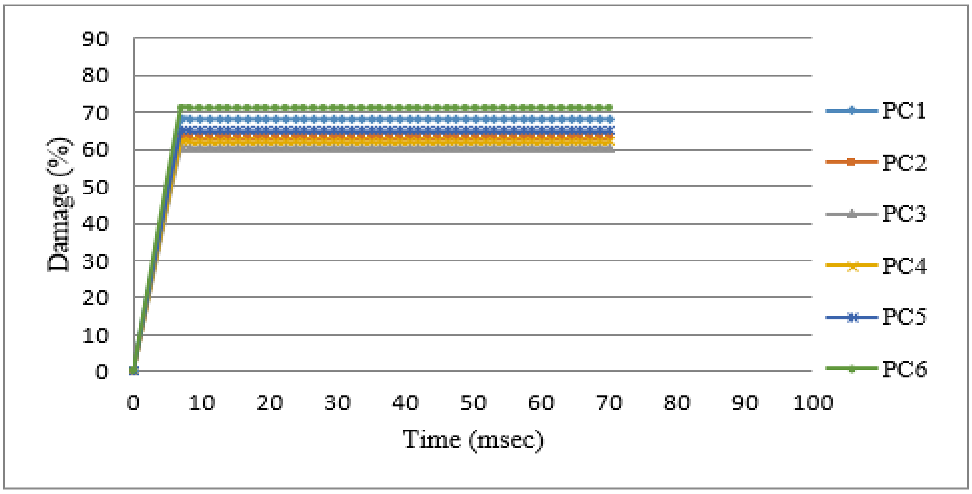


Figure 9. Variation of damage with time for fixed support and simply supported beams subjected to mid span impact with different velocities.

Table 7 shows the damage - time values of beams subjected to mid span impact with different velocities. The damage was zero initially, then increased within small time interval and then reaches to maximum damage. Figure 9. shows the damage values of beam PC2, PC3, PC4 and PC5 is less compared to PC1 whereas PC6 is more. The beam PC3 shows less damage value when compared to all other beams, due to its high tensile strength.

4. CONCLUSIONS

For 24 fixed-supported and 24 simply supported HFRC beams subjected to low-velocity impact at mid-span, the numerical results are described.

1. The variation of deflection during contact period is initially linear as expected subsequently it attains maximum deflection and thereafter it shows the sinusoidal wave form in fixed support beam whereas, in simply supported beam it shows linear initially then attains plastic stage.
2. The maximum Impact loads absorbed were observed in beams containing 0.825% steel and 0.175 % polypropylene fibers, indicating that the beam becoming more stiffer with this percentage in fixed beam whereas in simply supported beam same thing is observed in beam containing 0.9% steel and 0.1% polypropylene fibers.
3. In both cases, with the increase in impact energies the deflection values were seen to be increased. However, the beam containing 0.9% steel and 0.1 % polypropylene fibers shows lower deflection values.
4. The stress is increased rapidly initially due to the hammer strikes the beam surface and within a short time stress is reached maximum level. When hammer starts to move away from the beam, the stresses are reducing and reaches to zero which means the specimens behaves as nonlinear in both FSB and SSB.
5. The strain v/s time curve are same as that of deflection v/s time curves i.e., the strain in element node gradually increases till certain time and then remains constant thereafter in both FSB and SSB.
6. Damage in beams reinforced with 0.9% steel and 0.1 % polypropylene fibers was attained less compared to all other beams, due to its high tensile strength.

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