



Experimental and Numerical Investigation of Hybrid Fiber Reinforced Concrete for Vibration-Based Damage Assessment

Radhika Sridhar,¹ Thanongsak Imjai^{1,*} and Irwanda Laory²

Abstract

Concrete, a widely used building material, has seen significant interest in the incorporation of hybrid fibers for reinforcement, offering advantages over mono fiber reinforced concrete. This study investigates the mechanical and dynamic properties of hybrid fiber reinforced concrete (HFRC) through experimental research. Mechanical parameters such as compressive strength, split tensile strength, and flexural strength were assessed for various mixtures containing steel and polypropylene (PP) fibers at different volume fractions of 0.25%, 0.5%, and 0.75%. Additionally, dynamic properties including mode shape, fundamental frequency, and damping ratio were evaluated to assess HFRC's damage resistance capabilities. Results indicate that the addition of steel and PP fibers enhances the concrete's mechanical properties, with optimal performance observed at a fiber volume fraction of 0.5%. A specific combination of 0.25% total fiber volume with 75% steel and 25% PP fibers exhibited superior performance. The study also found that the natural frequency of HFRC specimens decreases with increasing fiber content and structural damage, while the damping ratio increases. Numerical modeling using ANSYS software was employed to compare experimental results with analytical predictions. The HFRC with a total fiber volume of 0.75% and a composition of 75% steel and 25% PP fibers demonstrated the best damping qualities.

Keywords: Hybrid fiber; Flexure, Frequency; Steel fibers; Polypropylene; Damping; Damage assessment.

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1. Introduction

A composite material is concrete that has seen a lot of application recently since it is cost-effective, hardens at room temperature, can be shaped by casting, and can be consumed and recycled. Although reinforced concrete with short fibers scattered randomly will increase the strength of the cementitious matrices by preventing fracture initiation, propagation, and merging, concrete is typically categorized as a brittle material.^[1] Materials with high densities, charcoal, steel, polypropylene, glass, and natural fibers are a few examples, have been employed for this type of composites.^[2,3] Steel and various non-metallic fibers, which are used in concrete to enhance its mechanical characteristics, are among these elements. To build a novel material with different composites known as hybrid fiber reinforced concrete, and the

incorporation of their combinations have also been done.^[4,5] Steel fibers are the most often utilised fiber due to their high tensile strength and higher elastic modulus.^[6] Steel fiber-reinforced concrete has been utilised extensively in the construction industry for projects including chimneys, commercial buildings, and air pavements.^[7]

Despite the steel fibers are the most utilized fiber material in concrete for the purpose of reinforcement, creative solutions have been achieved in the past ten years by combining various fiber combinations, and cementitious materials are becoming more common.^[8] It has been frequently referred to hybrid fiber reinforced concrete, and their behaviour was specifically studied to better understand how fibers might work together to improve the structure's post-cracking resistance or responsiveness.^[9] Applications based on fiber reinforced concrete with polypropylene is one type of construction that uses hybrid fibers, which makes use of both macro and micro steel fibers, with the combination of short and long fibers with hooked ends, twisted macro and steel fibers, and monofilament and staple fibers.^[10-12] Concrete cracks can vary

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in size and stage, and the employment of numerous fibers of various lengths is a better solution to the issue. The incorporation of two different fibers such as low and high elastic modulus fibers increase the mechanical and durability properties of the structural integrity which is referred to be hybrid fiber reinforced concrete (HFRC). Additionally, HFRC's with the additions of both polypropylene and steel fibers has been experimentally investigated for its permeability and durability properties.^[13,14] Concrete fracture is a multi-scale process from the micro-crack to macro-crack with the progression of load and it will be restrained with the addition of hybrid fibers to the concrete especially in the shear zone and weak zone of interfacial transition zone (ITZ).^[15-17] HFRC also increases the flexural performance under fire of the self-compacting concrete with the addition of supplementary cementitious materials.^[18-20] The examination of the findings reveals the insertion of fibers with hybrid combinations until it enhances the concrete's long-term serviceability. Combining different fiber types is primarily done to control micro and macro fractures in a variety of materials with cementitious zones of various levels in a variety of dynamic loading scenarios.^[21]

In general, a structure's dynamic qualities, like dynamic rigidity modulus, dynamic elasticity modulus, and dynamic Poisson's ratio, and mode shape, all have distinct values from those of the structure's mechanical properties.^[22,23] According to the method outlined in ASTM C-215, these dynamic property characteristics can be empirically assessed from concrete specimens (standard test method for fundamental resonant frequency). Dynamic attributes often interact with one another because of the characteristics of the material's energy dissipation, dynamic response, and natural frequency, which are all connected to the material and structural system. The changes of natural often be like the frequency of the structure when the state of structure be undamaged, which can also be used to determine damage to any structure.^[24] The decay under free vibrations can be used to determine a system's damping. The benefits of vibration dampening for buildings because it reduces risks from wind, ocean waves, earthquakes, and unintentional loads, which improves the comfort of occupants of apartment buildings and the dependability of the structure.^[25] There are two basic ways for measuring the damping characteristics of structures: the bandwidth method and the decay curve method.^[26] Because of the non-linear behaviour of structures, it is exceedingly challenging to examine the resonance curve approach in most unpractical scenarios with real structures. As a result, the decay curve method is the method that is most frequently recommended and used. Additionally, damping helps reduce

resonance and attenuate vibration to prevent resonance of a certain structure at characteristic modes, whether at the member, material, or structural levels.

Therefore, the aforesaid research work focuses primarily on the mechanical static features of HFRC, while additional research on its dynamic qualities is required. A total of nine combinations were created in this experimental study to examine the effects of combining steel and polypropylene (PP). Total volume fractions fiber of 0.25%, 0.5%, and 0.75% were considered to examine the dynamic and static properties of HFRCs. To determine the ideal level of steel and PP fiber hybridization, Concrete's mechanical qualities, including its flexural, splitting, and compression strengths, were studied. Furthermore, research on the hybrid fiber reinforced concrete's basic resonant frequency and damping ratio has been done. Through experimental and computational analysis, the primary goal of the current work is to investigate how the fiber reinforced concrete with hybrid fibers affects dynamic and static properties, with a particular focus on the characteristics of damage of the material. The main objective of the research work is to study to the influence of steel-polypropylene hybrid fibers on the mechanical (compressive, split tensile and flexural strength) and dynamic properties (natural frequency, mode shape and damping ratio) of concrete under the induced damage state in free-free end conditions.

2. Experimental testing programme

2.1 Material properties and mix design

As per Indian Standard Code, grade 53 ordinary Portland cement with 3.15 specific gravity and 1140 kg/m³ bulk density was used in the present investigation. Further, this cement's measured compressive strength at the age of 28 days was 53.5 MPa. To keep the mix workable while adding fibers, fly-ash was added with cement at a rate of around 10% by mass. [Table 1](#) provides physical and chemical characteristics of fly ash and OPC 53 grade cement and the oxidation compounds have been reported by the manufacturing suppliers. Coarse aggregates with a fineness modulus of 6.34 and Specified sizes are 20 mm and 10 mm, respectively, were used. Fine aggregates, 2.86 fineness modulus river sand that is readily available in the area has been employed. To make the combination more workable, the components were combined with water and super-plasticizers.

To generate the HFRC composites in the current research work, various combinations of fibers with hybrid zones were employed. While the polypropylene fibers utilised in this experiment were straight, the steel fibers were hooked end. Steel and PP fibers were made using materials found in the neighborhood. [Table 2](#) shows the properties of fibers used in

the study. A typical view of polypropylene and steel fibers used in the study is shown in Figs. 1a and 1b.

Table 1. Chemical compositions of OPC 53 grade cement and fly ash.

Constituents of chemical (%)	OPC 53 grade cement	Fly-ash
Aluminium oxide (Al ₂ O ₃)	4.84	21.28
Silicon dioxide (SiO ₂)	18.93	52.56
Ferric oxide (Fe ₂ O ₃)	2.92	5.23
Calcium oxide (CaO)	60.25	7.28
Magnesium oxide (MgO)	2.59	2.25
Sodium oxide (Na ₂ O)	0.86	1.02
Potassium oxide (K ₂ O)	0.86	0.93
Sulphur dioxide (SO ₃)	3.02	2.53
Phosphorous oxide (P ₂ O ₂)	0.23	0.06
LOI (%)	2.96	1.05

Mix design has been done based on the properties of materials used in the study as per the IS 10262:2019.^[27] Initially, aggregates are dry mixed for a minute served as the initial step in the mixing process. After adding the cement, it was left for an additional minute. Following the addition of steel fibers, the mixture was stirred for a further two minutes to make certain that the fibers were dispersed uniformly. After adding water, the super-plasticizers were combined for an additional two minutes. To make certain that the PP fibers could distribute equally all around the concrete, after the first procedure, these were included in the mixture after the wet concrete was stirred for an additional three minutes. Fresh concrete was then compressed on a vibration table after being poured into cubes, cylinders, and prisms steel molds. All specimens were demolded after 24 hours and immersed in 28 °C water for the remaining 28 days before testing. Table 3 shows the proportions of mixtures of HFRC composites.

Table 2. Physical and mechanical properties of steel and polypropylene fibers.

Fiber type	Shape of fibers	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Modulus of elasticity (GPa)	Density (kg/m ³)
Steel	Hooked end	35	0.5	70	1100	210	7850
PP	Straight	12	0.038	315	420	5	990

Table 3. Mix proportions of HFRC composites.

S. No	Mix designation	Cement	Fly-ash	Fine aggregate	Coarse aggregate	W/C ratio	Total fibers (%)	Steel Fibers (%)	PP Fibers (%)
1	M ₂₅ C	1	0.10	1.89	2.89	0.42	0	0	0
2	M ₂₅ HY1	1	0.10	1.89	2.89	0.42	0.25	25	75
3	M ₂₅ HY2	1	0.10	1.89	2.89	0.42	0.25	50	50
4	M ₂₅ HY3	1	0.10	1.89	2.89	0.42	0.25	75	25
5	M ₂₅ HY4	1	0.10	1.89	2.89	0.42	0.50	25	75
6	M ₂₅ HY5	1	0.10	1.89	2.89	0.42	0.50	50	50
7	M ₂₅ HY6	1	0.10	1.89	2.89	0.42	0.50	75	25
8	M ₂₅ HY7	1	0.10	1.89	2.89	0.42	0.75	25	75
9	M ₂₅ HY8	1	0.10	1.89	2.89	0.42	0.75	50	50
10	M ₂₅ HY9	1	0.10	1.89	2.89	0.42	0.75	75	25

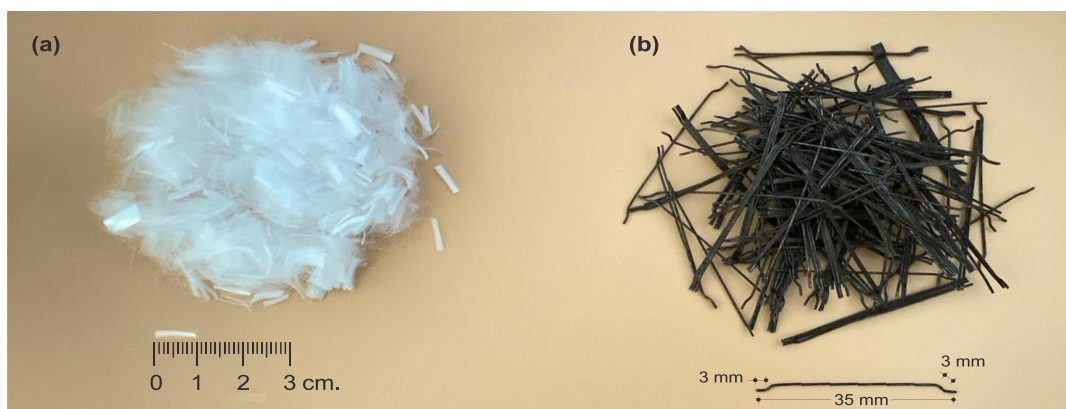


Fig. 1 Typical view of fibers: (a) Polypropylene fibers and (b) Hooked end steel fibers.

2.3 Static test of HFRC's

To evaluate the flexural performance of HFRC, three cubes and cylinders of (150mmx150mmx150mm and (150mm diameter and 300mm height) standard dimension respectively have been made and evaluated in a compression testing machine with the able capacity of 3000kN. Four-point indirect tensile strength was performed for each % variation of the HFRC mixes to determine the effect of the hybrid fiber addition. All prismatic test specimens were put through a 1000kN capacity universal dynamic testing equipment. In this study, a beam with the dimensions 500 mm x100 mm x100 mm was employed. Using a dynamic universal testing equipment with a 1000kN capacity, all test specimens were loaded at a loading rate of 0.20mm/min until they fully failed under displacement control. The dynamic features of HFRCs and their damage characteristics were evaluated using a total of 30 prismatic beams. The mechanical characteristics of HFRC have been evaluated using 90 specimens, including cubes, cylinders, and prisms.

2.4 Test setup and instrumentation for dynamic test

According to the method outlined in ASTM C-215,^[28] a beam specimen measuring 500 mm x 100 mm x 100 mm has been made and tested to determine their fundamental transverse, longitudinal, and torsional resonant frequencies.^[29] The accelerometer was kept on the samples from three distinct orientations to collect data while vibrating the building as illustrated in the ASTM C-215^[28] standards. The dynamic analyzer was used to do modal analysis. Both an input and an output device are part of it. The signal from the input device will be received by a central unit and sent to the computer for additional processing. The computer will be used to store all the data, which can then be retrieved in whatever format is needed.

In this experiment, each of the three damage levels was created by cutting the specimens at the midpoint of their span. Fig. 2b depicts a typical view of the specimen with an induced damage. The preceding method was used during the experimental investigation, for the dynamic analysis of HFRCs' damage characteristics at various damage levels.

Frequency Response Function (FRF) was generated through the dynamic analyzer that has been entered in the NV smart office solution software to assess the necessary result. Fig. 2a displays a typical view of dynamic properties test setup. Accelerometer has been fixed at a constant node for all the specimens and the FRF's were evaluated under free end conditions. Vibration has been induced to the specimen with the help of impact hammer at any given time, and the resulting FRF's were recorded to examine the transverse frequency for different damage conditions. Similar methods were followed for all the locations without changing the accelerometer's position, hence this technique is known as the "roving impact hammer method". For all mixes, beams of the aforesaid size have been cast and examined at 28 days of age to determine the characteristics of damage of HFRCs in free end conditions. A total of four damage phases considered in this analysis are followed as: (i) Undamaged beam (D_0), (ii) Damage induced at the mid-span of width 10mm and depth 10mm (D_1), (iii) Damage induced at the mid-span of width 10mm and depth 20mm (D_2), and (iv) Damage induced at the mid-span of width 10mm and depth 30mm (D_3).

3. Results and discussions

3.1 Static test results

Table 4 illustrates the mechanical property results of the compressive, split tensile and flexural strength tests. Fig. 3 displays the percentage improvement in flexural, splitting, and compressive strength for various HFRC composites with the

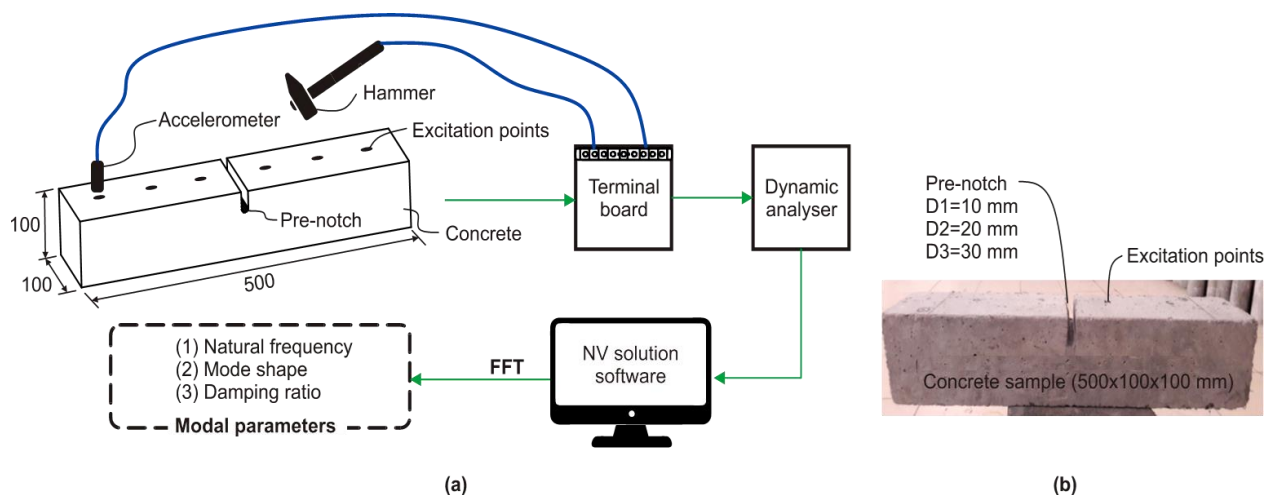


Fig. 2 A typical view of dynamic properties test setup: (a) Schematic view of dynamic analyzer connections and (b) Specimen with an induced damage.

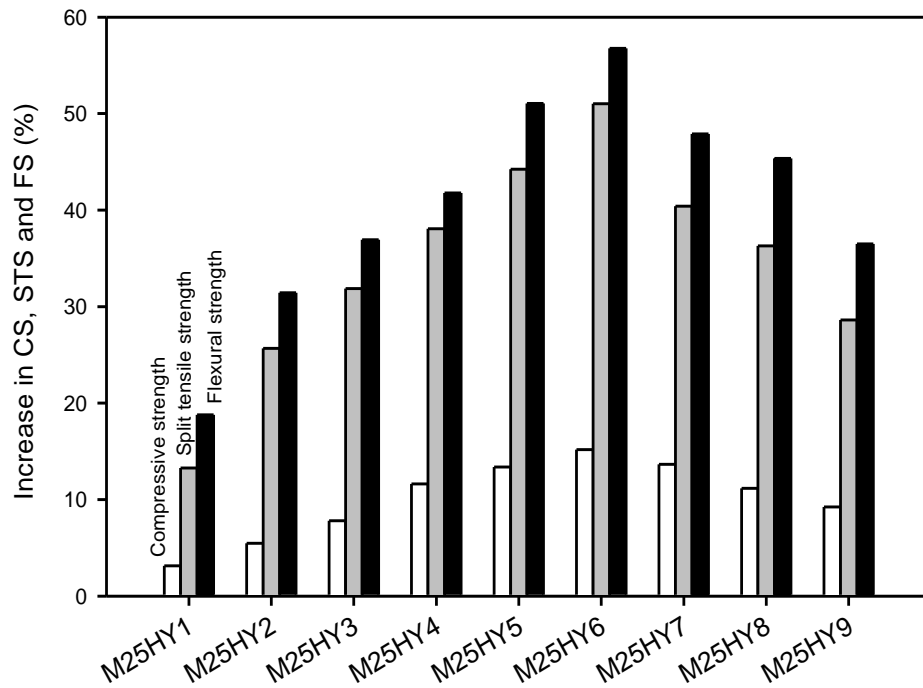


Fig. 3 Comparison of the HFRCs CS, STS, and FS with conventional concrete.

Table 4. Mechanical property test results of HFRC composites.

S. No	Mix designation	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)
1	M25c	34.87	3.39	4.74
2	M25HY1	35.96	3.84	5.63
3	M25HY2	36.78	4.26	6.23
4	M25HY3	37.59	4.47	6.49
5	M25HY4	38.92	4.68	6.72
6	M25HY5	39.53	4.89	7.16
7	M25HY6	40.16	5.12	7.43
8	M25HY7	39.63	4.76	7.01
9	M25HY8	38.76	4.62	6.89
10	M25HY9	38.09	4.36	6.47

comparison of conventional concrete. The findings highlight the inherent improvement in compressive strength above control concrete occurred because of the volume fractional addition of hybrid fibers like steel and PP.

Testing revealed that when total fiber volume increases, HFRCs compressive strength increased. The concrete strength was increased up to 13.7% with hybrid fibers for M25HY7 combination in contrast to control concrete. Out of the many percentage variations of steel and PP hybrid fibers taken into consideration in this experiment, the best compressive strength was found for the mix M25HY6 comprising 0.5 percent of total fiber volume fraction. Because plain concrete is known to be brittle in tension and ductile in compression, its tensile strength result was roughly 36% lower comparable to the maximum value over all type of HFRC (7.25 MPa for M25HY6).

Therefore, determining the load at which concrete members may begin to break requires knowledge about the concrete's tensile strength. According to the results, adding 25% steel and 75% PP fibers to a combination that had 0.5 percent concrete overall caused a 51 percent rise in the mixture's volume. According to the findings, hybrid fibers added to concrete performed better than that of the control concrete without fibers. For mixes M25HY1 and M25HY6, adding hybrid fibers improved M25 grade concrete's split tensile strength by 13.3 percent to 51 percent, respectively. The increase in indirect tensile strength was about 25.7 percent, 44.2 percent, and 33.6 percent when 0.25 percent, 0.5 percent, and 0.75 percent volume fractions are added, compared to non-fibrous concrete, respectively. The major cracking stage of the concrete was being stopped by a few staple fibers that were crossing the

microcracks. The tensile stress was transferred to steel fibers when it became clear that the specimens would continue to be harmed.

3.2 Dynamic property test results

The resonant frequencies of the HFRC beam specimens at 28 days are displayed in Table 5 for each mode of vibration. All mixes have undergone ASTM C215-compliant fundamental longitudinal, transverse, and torsional frequency tests in all three dimensions. The test findings highlight that, when compared to control concrete, HFRCs achieve the greatest resonant frequencies for all three modes of vibration. Additionally, it has been shown that the natural frequency falls as the fiber concentration rises. When compared to control concrete, The basic transverse frequency was discovered to the M_{25HY1} combination rose by roughly 4.5 percent. The test findings showed that HFRCs had a higher dynamic modulus of elasticity compared to control concrete. For 0.25 percent fiber content, the increases in dynamic modulus of elasticity were around 8.9 percent, 11.6 percent, and 11.2 percent for 25-75, 50-50, and 75-25 percentages of steel and PP fibers, respectively.

Tables 6 and 7 present the basic transverse frequency and

damping ratio derived for HFRCs and control concrete mixes, respectively, for both damaged and undamaged circumstances. This has been done to assess how damage from HFRC beams in the free hanging condition. The table shows that, as compared to control concrete with the addition of fiber content, the damping ratio of HFRC rose. In comparison to the damping values of plain concrete achieved are enhanced by 18.75, 20.8, and 25 percent for a total volume fraction of hybrid fibers of 0.5 percent, with adding steel-PP fibers in ratios of 25:75, 50:50, and 75:25, respectively. The bridging effect may be the cause of the increased damping ratio in HFRC. According to the table, the fundamental frequency reduces as fiber content and structural damage rise but damping increases relative to the characteristics of an undamaged stage as fiber content and damage grow. Figs. 4a and 4b show the comparison of HFRC’s fundamental frequency of damaged specimens to that of undamaged specimens for three damage levels for the primary and secondary vibrational modes, respectively. Figs. 5a and 5b demonstrate accordingly, for the 1st and the 2nd mode, the percentage increase of the damping ratio for HFRC composites.

From the results, it has been clearly observed that the

Table 5. Test results for dynamic properties of HFRC composites.

S. No	Mix designation	Transverse frequency (Hz)	Longitudinal frequency (Hz)	Torsional frequency (Hz)	Dynamic modulus of elasticity	Dynamic modulus of rigidity	Dynamic Poisson’s ratio
1	M _{25C}	1398	3374	2327	35.63	15.43	0.155
2	M _{25HY1}	1461	3458	2432	38.82	16.81	0.155
3	M _{25HY2}	1455	3452	2389	39.78	16.76	0.187
4	M _{25HY3}	1448	3443	2379	39.62	16.71	0.185
5	M _{25HY4}	1441	3431	2372	39.43	16.69	0.181
6	M _{25HY5}	1434	3426	2367	38.33	16.32	0.174
7	M _{25HY6}	1429	3418	2359	37.97	16.17	0.174
8	M _{25HY7}	1421	3406	2352	37.67	16.13	0.168
9	M _{25HY8}	1415	3396	2345	37.53	16.11	0.165
10	M _{25HY9}	1409	3385	2338	37.43	16.10	0.162

Table 6. Experimental natural frequency (ω) values of control and HFRCs composites.

Mix No	Designation	D ₀		D ₁		D ₂		D ₃	
		Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
1	M _{25C}	1398	3428	1384	3411	1372	3394	1359	3383
2	M _{25HY1}	1461	3504	1456	3492	1437	3483	1419	3469
3	M _{25HY2}	1455	3493	1439	3481	1417	3473	1402	3459
4	M _{25HY3}	1448	3486	1425	3472	1408	3465	1394	3452
5	M _{25HY4}	1441	3481	1414	3469	1403	3452	1389	3443
6	M _{25HY5}	1434	3474	1416	3461	1398	3448	1375	3438
7	M _{25HY6}	1429	3469	1409	3453	1384	3441	1372	3428
8	M _{25HY7}	1421	3452	1398	3442	1381	3437	1372	3426
9	M _{25HY8}	1415	3448	1381	3437	1373	3428	1368	3419
10	M _{25HY9}	1409	3439	1375	3428	1367	3423	1358	3404

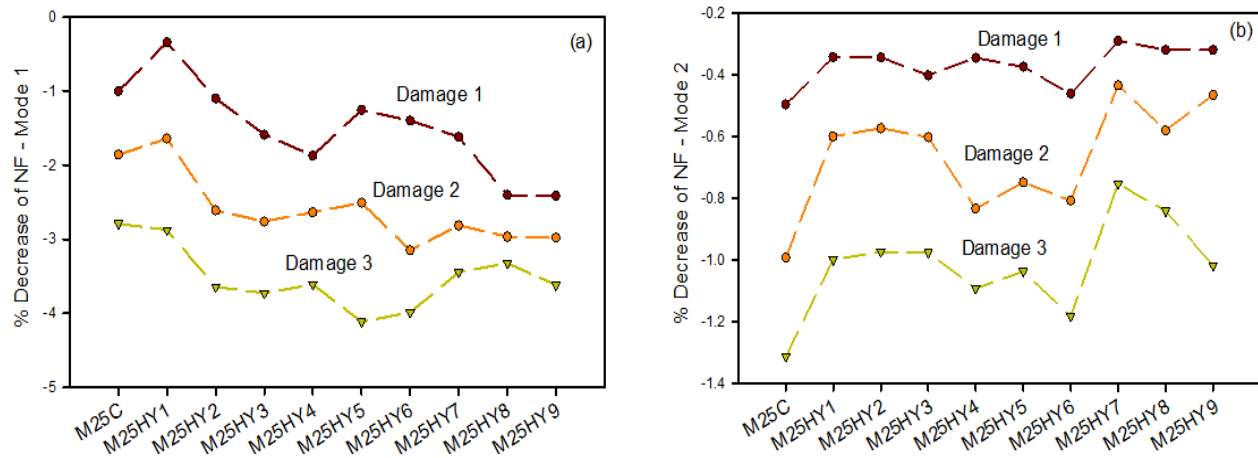


Fig. 4 Percentage decrease in natural frequency values for all the three damage levels: (a) Mode 1 and (b) Mode 2.

Table 7. Experimental damping ratio values of control and HFRC composites.

Mix No	Designation	D ₀		D ₁		D ₂		D ₃	
		Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
1	M ₂₅ C	0.48	0.34	0.51	0.36	0.54	0.42	0.59	0.46
2	M ₂₅ HY1	0.51	0.36	0.54	0.37	0.57	0.45	0.63	0.49
3	M ₂₅ HY2	0.52	0.39	0.56	0.41	0.59	0.47	0.65	0.53
4	M ₂₅ HY3	0.54	0.41	0.59	0.43	0.63	0.51	0.68	0.56
5	M ₂₅ HY4	0.57	0.42	0.62	0.47	0.66	0.54	0.71	0.6
6	M ₂₅ HY5	0.58	0.45	0.64	0.49	0.68	0.57	0.74	0.63
7	M ₂₅ HY6	0.6	0.47	0.67	0.53	0.72	0.61	0.76	0.65
8	M ₂₅ HY7	0.61	0.49	0.71	0.56	0.75	0.63	0.79	0.67
9	M ₂₅ HY8	0.63	0.51	0.73	0.58	0.77	0.65	0.82	0.72
10	M ₂₅ HY9	0.65	0.52	0.74	0.61	0.81	0.68	0.85	0.75

values of damping ratio for the 1st mode was larger in each of the mixes due to the frequency of the 2nd mode is consistently greater than that of the 1st mode. The HFRCs with the variation of 0.75 percent in total volume fractions, have the best dynamic properties and the highest damping ratio, as shown in the comparison figures. Fig. 6 shows the experimental mode shapes of prismatic beam specimens. The frequency response

function of the HFRC is depicted in Fig. 7 under both damaged and undamaged conditions.

For all mixes, damage evaluation of HFRCs has been conducted using the use of the ANSYS FEM tool and input from experimental findings. Table 8 shows the natural frequency findings for damaged and undamaged conditions at various damage levels as determined by the FEM-based

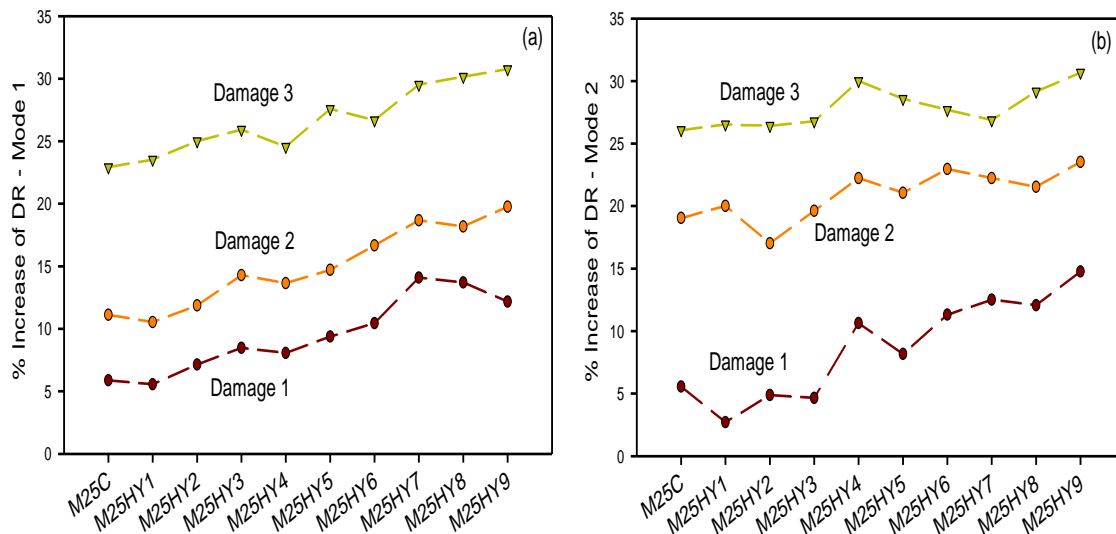


Fig. 5 Percentage increase in damping ratio values for all the three damage levels: (a) Mode 1 and (b) Mode 2.

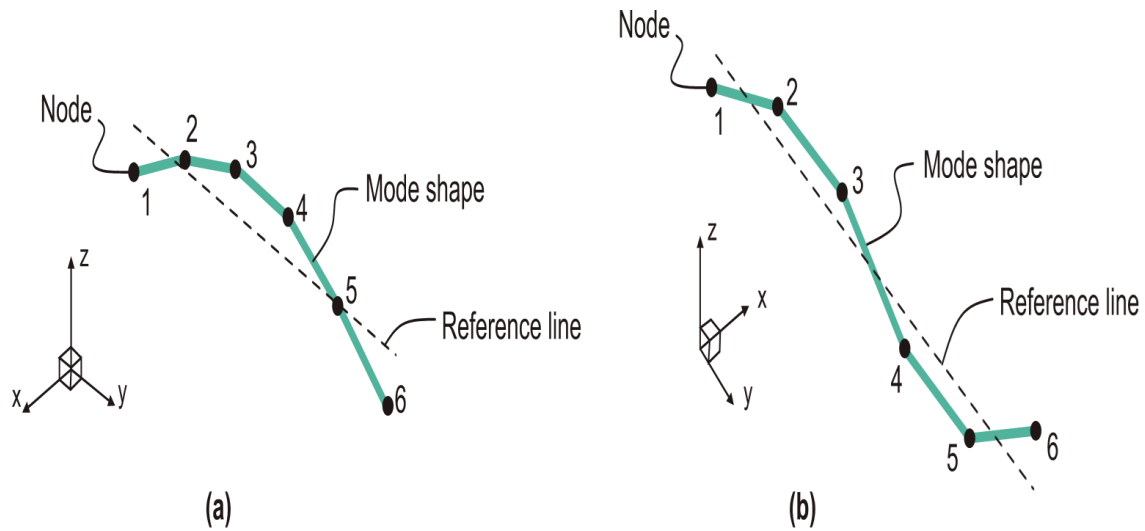


Fig. 6 Experimental prismatic beam – mode shapes: (a) Mode shape 1 and (b) Mode shape 2.

Program. Fig. 8 depicts the appropriate 1st and 2nd vibrational modes for various damage levels in addition to the undamaged level.

4. Numerical Study for vibration response

The FEM Program ANSYS workbench has been used to develop and perform numerical modelling. The analyses were performed with the inclusion of both geometry and mechanical properties. The concrete beam was modelled using tetrahedron elements with a modified second-order integration scheme. The optimization mesh sensitivity was performed in ANSYS, and a mesh size of 10 mm has been used. This function is automatically implemented by the software to minimize errors due to distortions during the analysis. To establish the inherent periodicity and mode forms concrete composite under supervision, a rectangular prism measuring

size was initially constructed, and the inputs have been given from the result. Separate models of HFRC specimens with D0, D1, D2, and D3 damage levels have also been developed to analysis the natural frequencies and mode shapes (Table 8). In the end, experimental results have been compared to those predicted by the numerical model. The figures show that the transverse frequency decline in the first mode has a bigger percentage decrease than the frequency decrease in the second mode in the experimental results as shown in Fig. 8.

It has been seen from the numerical data that when structural damage increases from D0 to D3, the natural frequency values drop. From the table, it has also been noted that there is very little variation between experimental and numerical results in terms of error percentatge. Both experimentally and statistically, the percent drop in natural frequency decreases as the fiber concentration increases as

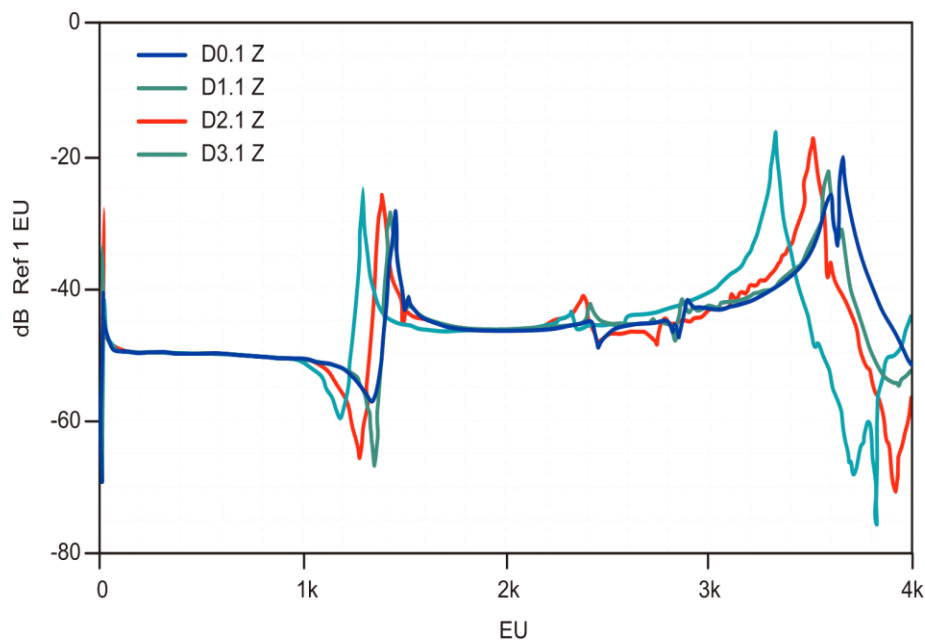


Fig. 7 Damaged versus undamaged levels of the HFRC frequency response functions.

Table 8. Numerical natural frequency values of control and HFRC composites.

Mix No	Designation	D ₀		D ₁		D ₂		D ₃	
		Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
1	M ₂₅ C	1392	3421	1381	3412	1374	3403	1363	3391
2	M ₂₅ HY1	1458	3492	1451	3484	1443	3495	1437	3478
3	M ₂₅ HY2	1453	3485	1438	3474	1427	3462	1418	3447
4	M ₂₅ HY3	1446	3472	1459	3461	1438	3453	1426	3441
5	M ₂₅ HY4	1433	3467	1427	3451	1423	3479	1443	3442
6	M ₂₅ HY5	1438	3478	1425	3492	1444	3461	1425	3453
7	M ₂₅ HY6	1422	3458	1418	3447	1411	3431	1392	3418
8	M ₂₅ HY7	1412	3457	1419	3442	1407	3426	1384	3468
9	M ₂₅ HY8	1407	3441	1394	3432	1418	3448	1379	3452
10	M ₂₅ HY9	1415	3429	1389	3417	1403	3408	1368	3394

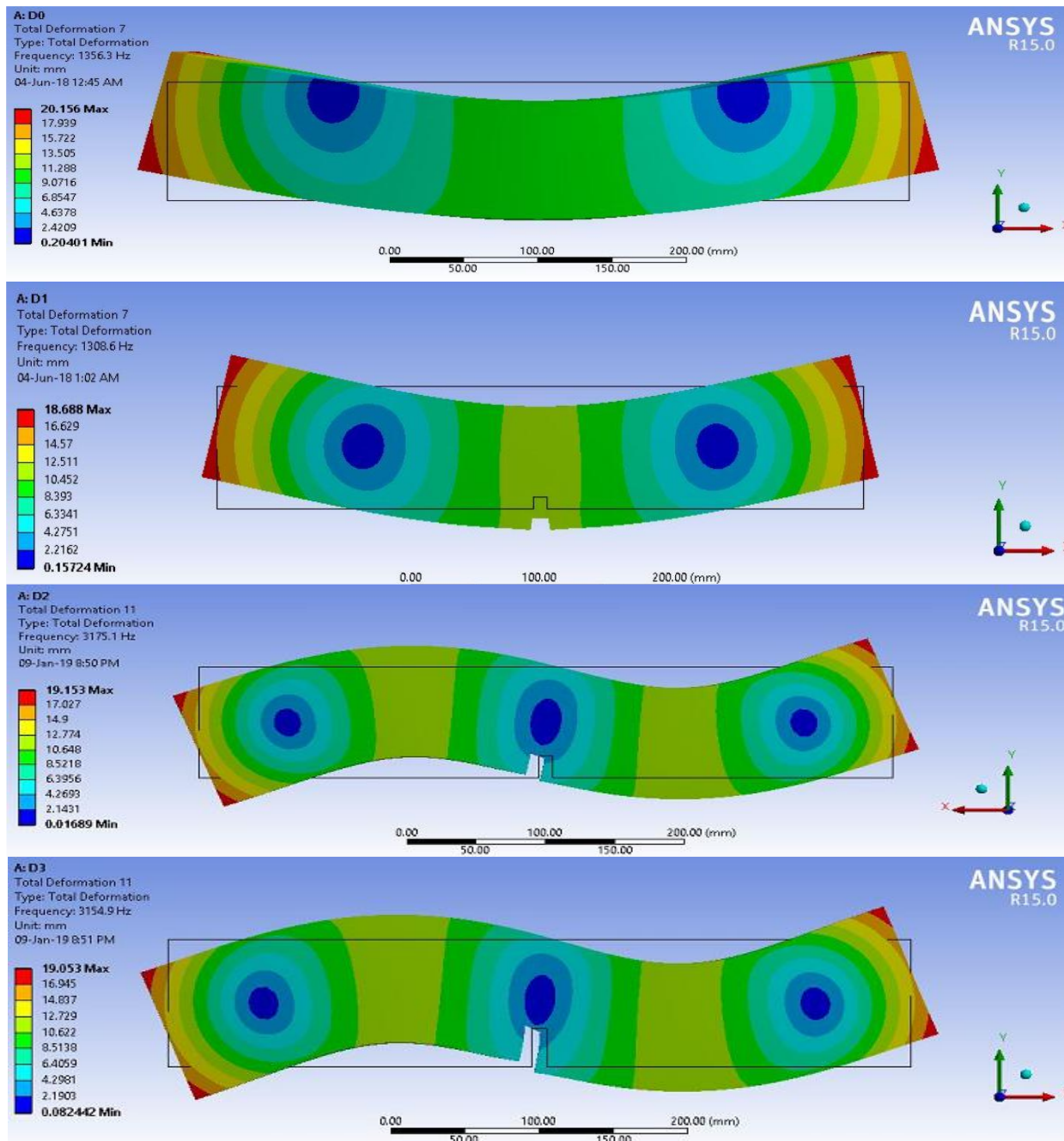


Fig. 8 Numerical first and second modes of vibration of the prismatic beams.

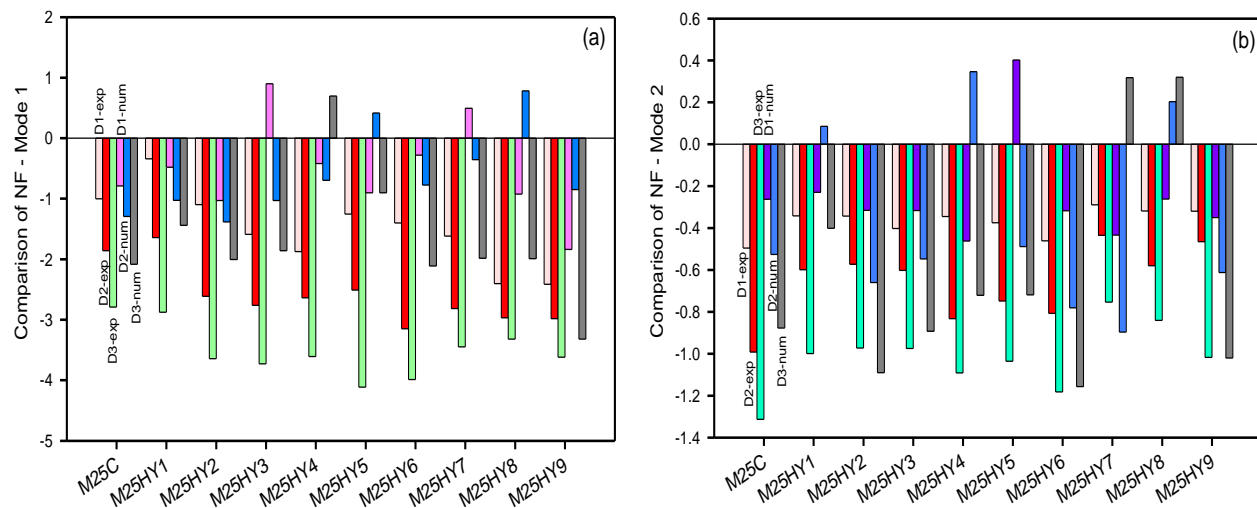


Fig. 9 Comparison between computed and experimental natural frequencies of HFRCs in undamaged and damaged states: (a) Mode 1 and (b) Mode 2.

compared to non-fibrous concrete. The comparison of experimental and numerical results for the primary and secondary vibrational modes, respectively, at damaged and undamaged levels is shown in Figs. 9a and 9b. The chart shows the proportion of natural frequencies calculated using numerical and experimental data. is relatively low.

Based on the findings of this study, it is recommended that construction and design professionals consider the integration of hybrid fiber reinforced concrete (HFRC) with optimal fiber compositions for applications requiring enhanced mechanical properties and improved vibration damping. Specifically, a mix comprising 75% steel and 25% polypropylene fibers at a total volume fraction of 0.50% has demonstrated superior performance and should be prioritized in structural elements subjected to dynamic loads or harsh environmental conditions. Furthermore, results from numerical modeling provide valuable insights into the behavior of HFRC, enabling more informed design decisions. The long-term performance of HFRC under various loading and environmental conditions should be further investigated. Implementing these recommendations can lead to the development of safer, more resilient, and durable structures, thereby advancing the field of civil engineering and construction.

5. Practical implication and recommendations

The study's findings on hybrid fiber reinforced concrete (HFRC) with steel and polypropylene (PP) fibers have significant implications for the construction industry, particularly in designing and constructing structures that require enhanced mechanical properties and improved vibration damping capabilities. The use of HFRC with a fiber volume fraction of up to 0.5% can lead to stronger, tougher, and more durable structural elements. Specifically, the

combination of 0.25% total fiber volume with 75% steel and 25% PP fibers has demonstrated superior performance, making it an ideal choice for applications subjected to dynamic loads or harsh environmental conditions. The observed increase in damping ratio and decrease in natural frequency with higher fiber content and structural damage indicate that HFRC can provide better energy dissipation and vibration control. This is particularly beneficial for structures in seismic zones or those exposed to vibratory loads, as it can help reduce the amplitude of vibrations and prevent resonance.

6. Concluding remarks

Experiments have been carried out to analyze the static and dynamic properties of HFRC's to investigate the damage properties. The observations found from the research work have been followed. From the experimental study, the specific conclusions have been drawn:

- The overall performance of static parameters as well as compressive, splitting tensile, and flexural strength enhanced when fibers were introduced to steel and polypropylene concrete mixtures. Steel fibers' high elastic modulus and polypropylene fibers' low elastic modulus make them the ideal mix for improving mechanical characteristics.
- The variation of both PP-steel hybrid fibers improved the post crack behaviour of concrete and enhanced the flexural bending strength. Flexural strength improved by 47.9%, 45.4%, and 36.5%, respectively, compared to the control concrete.
- HFRC specimens with fiber volume fraction of 0.25% with 75% and 25% of PP and steel fibers compared to control concrete, the natural frequency increased by around 4.5 percent and 2.2 percent for the 1st and 2nd modes, respectively.
- The damping ratio for the 1st and 2nd modes of HFRCs

increases with the increase of fibers compared to control concrete, going from 6.25 percent to 35.4 percent and 5.71 percent to 44.64 percent, respectively.

- The use of numerical modeling to predict the behavior of HFRC has been validated by experimental results, offering a reliable method for designing and optimizing the performance of structures using this advanced material.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable

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