

Article

Structural Behavior of Reactive Powder Concrete under Harmonic Loading

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Abstract: Industrial buildings usually are designed to sustain several types of load systems, such as dead, live, and dynamic loads (especially the harmonic load produced by rotary motors). In general, these buildings require high-strength structural elements to carry the applied loads. Moreover, Reactive Powder Concrete (RPC) has been used for this purpose because of its excellent mechanical strength and endurance. Therefore, this study provides an experimental analysis of the structural behaviors of reinforced RPC beams under harmonic loads. The experimental program consisted of testing six simply supported RPC beams with lengths of 1500 mm, widths of 150 mm, and thicknesses of 200 mm under harmonic loading with varied frequencies between 10 and 20 Hz. Different steel fiber ratios of 0%, 0.5%, 0.75%, 1.0%, 1.5%, and 1.75% were provided in the concrete mixes to explore the effect of steel fibers on the dynamic behavior of these beams. Except for the steel fiber volume fraction, all of the examined specimens shared the same material attributes and reinforcing details. The outcomes proved the positive effect of adding steel fibers on the dynamic response under the effect of harmonic loading. The optimum volume fraction of steel fibers was characterized by a percentage of 1.5%. Moreover, the vibration amplitude was more affected by the steel fibers than the support reactions. The inertial force increased as the harmonic loading duration increased. This increase in the inertial force by the load duration was enhanced after adding the steel fibers. However, this enhancement started to decline after increasing the steel fiber content to 1.75%.

Keywords: reactive powder concrete; harmonic loading; steel fiber; frequency; load duration effect



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1. Introduction

The maximum density theory inspired the development of Reactive Powder Concrete (RPC) as an example of ultra-high-strength concrete. Because of its excellent mechanical strength and endurance, this form of concrete has been used in many construction projects [1,2]. Many studies have discussed the benefits of RPC over normal-weight concrete due to its higher compressive and tensile strengths and lower permeability. The coarse material was removed from the concrete to eliminate the weakest link [3]. RPC is usually formed from extremely fine powder materials (cement, sand, quartz powder, and silica fume), steel fibers (optional), and a superplasticizer [4,5]. Conventional aggregate is completely replaced by fine sand, whose particle size is less than 0.6 mm. It was also indicated that the RPC's compressive stress-strain relation has a linear ascent stage until the ultimate strain, and at that point, the strength drops sharply and an explosive failure occurs suddenly. Hence, it is so difficult to observe a complete descending stage. To solve this problem, steel fibers are usually added to improve ductility [6]. Many studies collectively demonstrated that adding steel fibers to RPC can significantly improve its mechanical properties, including compressive strength, flexural strength, toughness, and

crack resistance; moreover, highlighting the positive influence of steel fibers on enhancing the performance and durability of RPC [2,5,7–11]. Concrete can be made with special mechanical properties to withstand different types of loading and reduce the dead load by reducing the geometrical dimensions and increasing the strength. Additive materials largely carry out this process of improving concrete's durability, strength, and ductility with serviceability control. RPC is used to create a composite material that is advantageous for creating strong structural components. Using RPC could replace the reinforcement steel bars, and thus, it simplifies the construction procedure. Furthermore, the excellent durability of RPC could prolong the service life of the bridge [12].

Chen et al. [13] developed a thin plate of RPC reinforced by steel welded wire mesh to investigate its behavior under reversed cyclic bending. The effects of the steel welded wire meshes and steel fiber volume fractions were investigated under static and cyclic loads. The study concentrated on energy dissipation, particularly during reversed cyclic bending. The results showed that the energy dissipation capacity of the specimens reinforced by four layers of steel welded wire and a 2% volume fraction of steel fibers was found to have the best performance. RPC beams subjected to harmonic loads exhibit favorable characteristics such as high strength, durability, stiffness, crack control, and damping properties. These properties make RPC beams a promising choice for structures that experience cyclic loading, such as bridges, offshore platforms, and high-rise buildings [13,14]. Many researchers have studied the effect of harmonic loading on beams of different material types (concrete, steel, and composite). They analytically studied the effect of a moving harmonic load on beams with different boundary conditions. Several parameters had been thought out, such as the type of support, excitation frequency, and speed of the harmonic load [15–17]. Minh et al. [16] studied experimentally the vibration characteristics of cantilever sandwich beams and panels under the harmonic force applied at the free edge based on the response history of the accelerometer signal and displacement signal. The results concluded that experiments should be conducted with a load cell to measure the harmonic force and the fundamental frequency of the live load. Makki [17] studied analytically the responses of continuous deep beams under harmonic loading using Timoshenko beam theory and dynamic equations and then verified the results with a numerical analysis using ANSYS APDL V.15.0 software. It was concluded that minimizing the shear span of the beam-to-depth ratio decreased the deflection wave amplitudes and that replacement provided more ductility due to the rubber's elasticity. Dakhel and Mohammed [18] studied the behaviors of composite cellular beams with lightweight reinforced concrete deck slabs under harmonic loading. The experimental program involved three fixed-end supported beams. Three different types of concrete, e.g., Normal Weight Concrete, Lightweight Aggregate Concrete, and Lightweight Fiber-Reinforced Aggregate Concrete were investigated. The frequencies taken into consideration were 5, 10, 15, 20, 25, and 30 Hz. It is important to note that the study used Lightweight Fiber-Reinforced Aggregate Concrete as a deck slab for the cellular specimens, resulting in a lightweight structure that resisted harmonic vibrations with a minor strength reduction and provided a structural element with a smaller density, presenting an advantage of the cellular beam that is used for low-loaded structures. The effect of lap splices in reinforcing bars on the behavior, strength, and deflection of steel fiber-reinforced RPC beams under harmonic loading was investigated [19]. The results showed that the increase in the lap splice length under the effect of harmonic loading resulted in a decrease in the deflection of the beams, especially in the case of a medium frequency. Concrete beams strengthened with an RPC layer in the compression zone were investigated under monotonic loading [20]. The process of concrete cover delamination in the compression zone was significantly reduced, the high ductility of the rebars was fully utilized during the formation of plastic hinges, and the bending capacity was increased.

RPC proved to be a recommended choice for special functionality buildings like bridges, factories, and fortified structures through various research studies. These types of structures are usually subjected to the effects of severe loading systems during their service life. Studying the structural behaviors of RPC under the effect of harmonic loading

is a very significant aspect of investigating the adequacy of using such a type of concrete in special functionality buildings. Currently, experimental investigation of RPC beams considering different parameters like steel fibers under the effect of harmonic loading is limited. Further research and practical applications are needed to fully explore the potential and optimize the design of RPC structures under harmonic loading conditions. Therefore, this research investigated experimentally the behaviors of RPC beams under harmonic loading conditions, focusing on analyzing factors such as the amplitude, frequency, and duration of the harmonic load and their effects on the responses of RPC beams. The effect of using different steel fiber ratios (0%, 0.5%, 0.75%, 1%, 1.5%, and 1.75%) was investigated, and the applied harmonic loading frequencies varied between 10 and 20 Hz. Such research contributes to a better understanding of the dynamic behaviors of RPC structures and aids in developing design guidelines and recommendations.

2. Experimental Work Details

2.1. Constituent Materials

The considered RPC mix comprised different constituent materials that included ordinary Portland cement that was marked as Al-Mass and classified as CEM I 42.5R according to the Iraqi Specification No. 5/2019 [21], fine aggregate of maximum particle size not greater than 0.6 mm, tap water, silica fume (SF) that conformed to the ASTM C1240 [22], and SikaViscocrete-5930 superplasticizer (SP). Tables 1 and 2 summarize the properties of the cement and fine aggregate, respectively, while Table 3 illustrates the parameters of the superplasticizer SikaViscocrete-5930 at 5–35 °C. Intermittent isolated straight steel fibers of 0.25 mm diameter, 14 mm length (i.e., an aspect ratio of 56), and tensile strength of 2500 MPa were utilized with different ratios (0%, 0.5%, 0.75%, 1.0%, 1.5%, and 1.75%). The considered mix proportions of the RPC are illustrated in Table 4. The concrete mix was the same for all the specimens, except the steel fiber volume fractions, as listed in Table 5. The RPC mixes were obtained using a water–cement ratio of 0.21.

Table 1. Physical properties of the cement.

Physical Characteristics	Test Outcomes	Limits of Iraqi Specification No. 5/2019
Specific surface area (Blaine method) (m^2/kg)	367	≥ 250
Setting time (Vicat method)		
Initial setting time (h: min)	1:10	≥ 45 min
Final setting time (h: min)	4:50	≤ 10 h
Compressive strength (MPa)		
for 2 days	16.22	≥ 10 MPa
for 28 days	48.80	≥ 42.5 MPa
Expansion (autoclave method)	0.03%	$\leq 0.8\%$

Table 2. Sieve analysis and physical test results of the fine aggregate.

Sieve Size (mm)	% Passing by Weight	Limit of Iraqi Specification No. 45/1984 and Its Modifications			
		Zone 1	Zone 2	Zone 3	Zone 4
10	100	100	100	100	100
4.75	100	90–100	90–100	90–100	95–100
2.36	100	60–95	75–100	85–100	95–100
1.18	100	60–90	55–90	75–10	90–100
0.60	80.1	30–70	35–59	60–79	80–100

Table 2. Cont.

Sieve Size (mm)	% Passing by Weight	Limit of Iraqi Specification No. 45/1984 and Its Modifications			
		Zone 1	Zone 2	Zone 3	Zone 4
0.30	39.2	5–34	8–30	12–40	15–50
0.15	7.8	5–20	0–10	0–10	0–15
Finer than 0.075 mm	2.90		Max. 5		
Clay lumps and friable particles	0.10		Max. 1		
SO ₃ content (%)	0.102		Max. 0.5		
Specific gravity	2.60		-----		
Sulfate contained (%)	0.20		Max. 0.5		
Absorption	0.62		-----		

Table 3. Technical parameters of SikaViscocrete-5930 at 5–35 °C.

Form	Viscous Liquid
Color	Turbid
Freezing point	≈3 °C
Specific gravity	1.095 ± 0.02
Air entrainment	Typically, less than 2% additional air is entrained
Dosage	0.8–2% liter by weight
Cleaning	Washed with water
Fire	Non-flammable
Health and Safety	Not classified as hazardous material

Table 4. Reactive powder concrete mix proportions.

Constituent Materials	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Silica Fume (kg/m ³)	Water (kg/m ³)	Superplasticizer
Proportion	750	900	200	160	0.2% binder weight

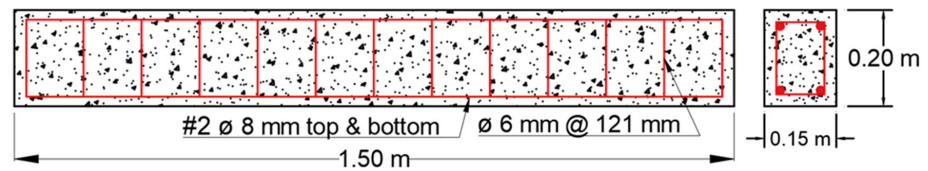
Table 5. The mechanical properties of the concrete.

Designation	V _f (%)	V _f (kg/m ³)	Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (MPa)
B-NF	0	0	105	5.5	43,050
B-F0.5	0.5	39.25	107	7.2	43,260
B-F0.75	0.75	58.88	111	9.2	43,750
B-F1.0	1.0	78.50	113	10.8	44,100
B-F1.5	1.5	117.75	115	12.5	44,200
B-F1.75	1.75	137.38	118	15.2	44,600

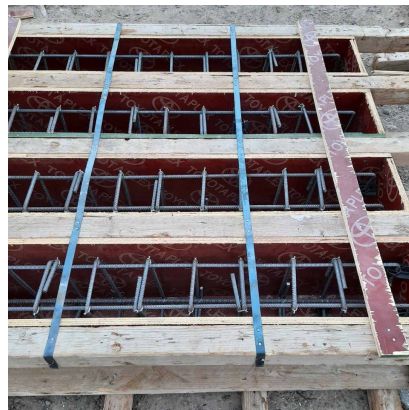
2.2. Details of the Tested Specimens

The experimental program of this research included the casting and testing of six fixed-ended RPC beams (see Figure 1). The total beam length was 1.5 m, with an overall depth of 0.2 m and width of 0.15 m. The clear span of the tested specimens was 1.2 m. All the beams were identical regarding their geometric layout, concrete mechanical properties, and steel reinforcement details, excluding their steel fiber volume fractions (V_f %). All

the specimens were reinforced by $\varnothing 6$ and $\varnothing 8$ deformed steel bars for the transverse and longitudinal reinforcement, respectively (see Figure 1a). The transverse reinforcement was closed stirrups that were arranged at a longitudinal spacing of 121 mm. The considered steel fiber volume fractions were 0%, 0.5%, 0.75%, 1.0%, 1.5%, and 1.75%. The designations of the tested specimens are listed in Table 5.



(a) Reinforcement details of the tested specimens



(b) Molds and reinforcements



(c) Reactive powder concrete beams

Figure 1. Details of the tested specimens.



(a) Compressive strength test



(b) Modulus of elasticity test



(c) Splitting tensile strength test

Figure 2. Tests of the concrete mechanical properties.

To evaluate the concrete's compressive strength, three standard cylinders measuring 150 mm in diameter $\times$ 300 mm in height were utilized according to the ASTM C39 requirements [23], while the splitting tensile strength of the concrete was determined by testing three standard concrete cylinders of 150 mm in diameter $\times$ 300 mm in height by following ASTM C496-96 [24] (see Figure 2). The modulus of elasticity of the concrete was tested at a constant strain according to the standard of ASTM-C469 [25] using three standard concrete cylinders (150 mm $\times$ 300 mm), as shown in Figure 2. Table 5 summarizes the mechanical characteristics of the concrete. The mechanical properties of the steel reinforcement were obtained according to ASTM A370-19 [26] by conducting tension tests. The tensile strengths of the $\varnothing 6$ and $\varnothing 8$ steel rebars were 480 MPa and 490 MPa, respectively.

2.3. Test Setup and Instrumentations

The testing steps were identical for all the specimens. Generally, the specimen was first positioned in the tested rig, so a fixed-end condition was applicable for both ends of the beam. Thereafter, the harmonic load system was centered on the top surface of the beam. This system included a steel mass of 150 kg that was firmly connected to a rotary motor of 3 HP capacity. The electrical supplier unit of this motor had a controller to change the capacity of the supplied electrical current so that the rotation speed of the motor was organized, as shown in Figure 3. Five piezoelectric transducers (type KPSG100) were used to capture the dynamic response of the tested specimens. Two of them were installed to detect the vertical and the lateral harmonic load (Pz3 and Pz4), respectively. The characterized responses of the tested beams in terms of the vertical and lateral vibrations were also measured by two other piezoelectric transducers (Pz1 and Pz2), respectively. Moreover, the vertical reaction in one of the fixed supports was measured by the fifth piece of the piezoelectric transducer (Pz5). All the outcome data were recorded by an advanced digital data logger with 24 channels and 1000 records/s.

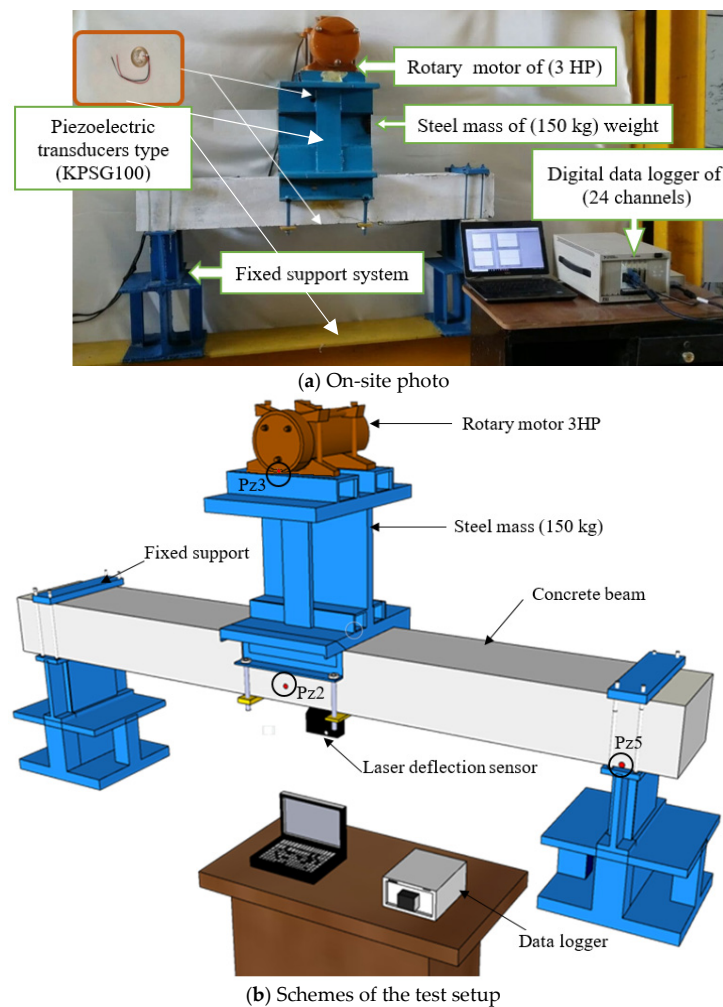


Figure 3. Test setup.

The experimental test comprised two stages. In the first one, each specimen was tested under the effect of different frequencies of 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20 Hz, while the second stage characterized the load duration effect, in which each specimen was subjected to a harmonic load of six-hour duration and the frequency that caused the maximum response in the first stage. Two sets of data were collected in the second stage after 3 h and 6 h.

3. Results and Discussion

Six RPC specimens were tested under the effect of harmonic loading. The adopted experimental program comprised different parameters regarding the beam characteristics (steel fiber volume fraction and the harmonic load properties in terms of the frequency and load time duration).

3.1. Steel Fiber Volume Fraction Effect

The recorded first load stage responses in terms of the vertical vibration and support reaction of the tested specimens under the effect of the considered harmonic load frequencies are illustrated in Figures 4 and 5. It can be seen that adding steel fibers significantly affected the dynamic responses of the RPC beams. The vertical displacement significantly decreased after adding the steel fibers to the concrete mix. This effect slightly vanished as the steel fiber content increased. However, the generated cracks were greater in spread, length, and width in the reference specimen (B-NF), as shown in Figure 6. Specimen B-NF, which characterized the case of no fiber content, generally behaved as the critical case regarding all the recorded responses (vibration amplitude, support reaction, and generated cracks) for all the considered frequencies. Regarding the first load stage, the vertical vibration amplitudes of the specimen B-NF ranged between 0.154 mm and 1.234 mm, as shown in Figure 4, while the support reactions varied from 1.365 kN to 9.117 kN, as detected in Figure 5. The highest dynamic responses were recorded in the case of a harmonic load frequency of 19 Hz.

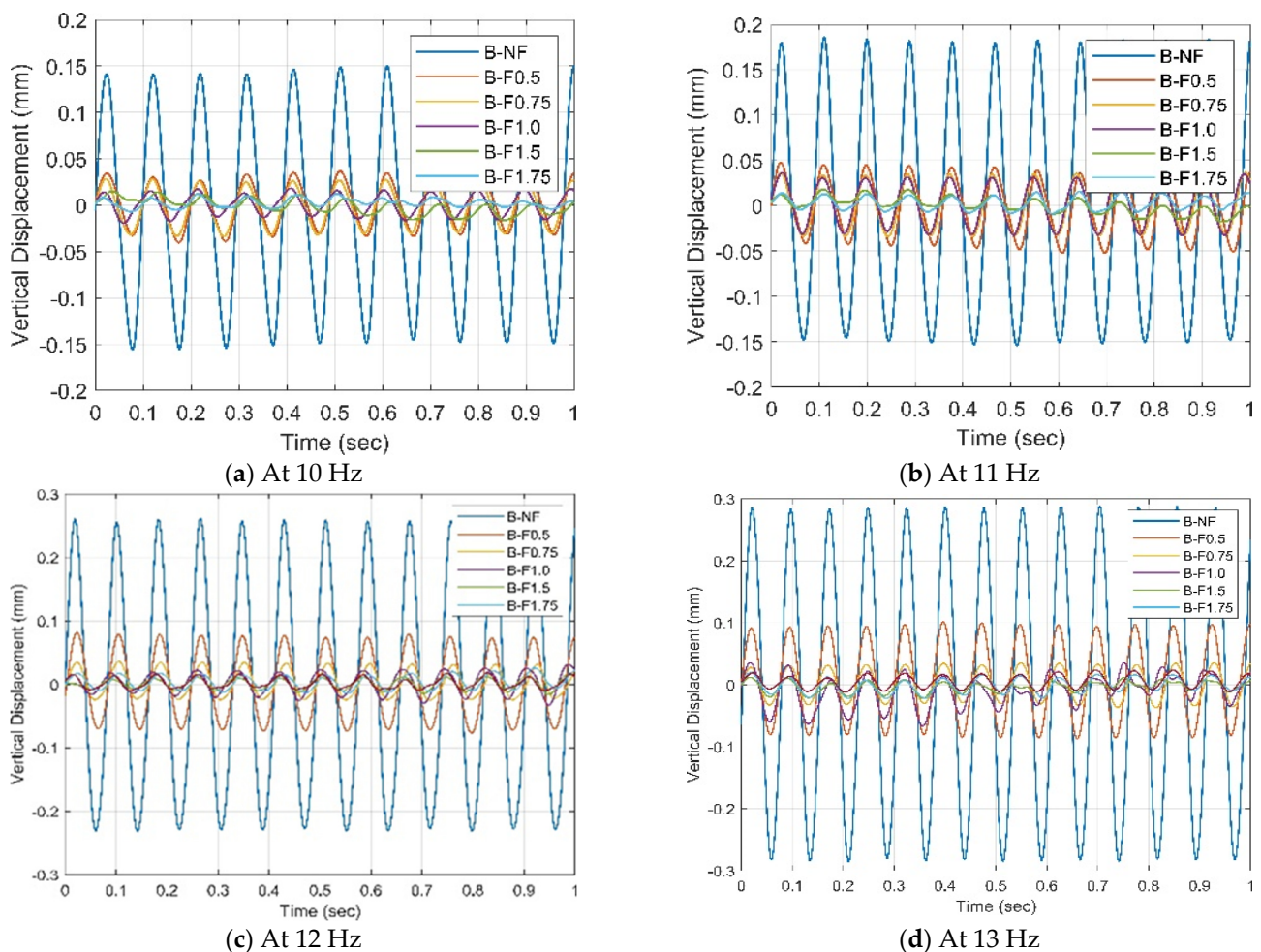
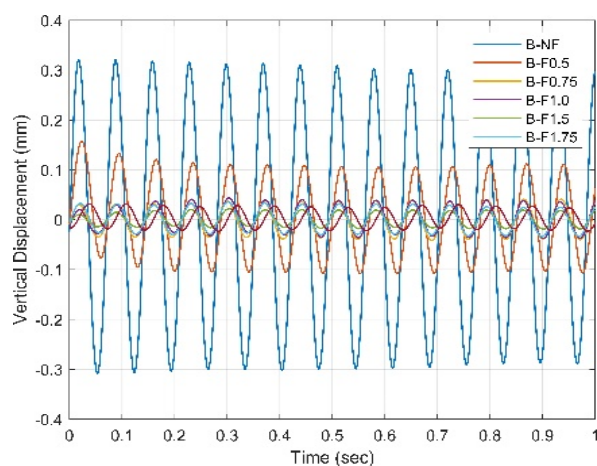
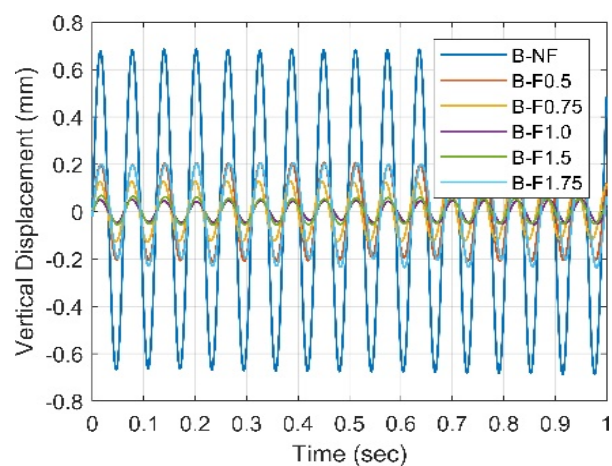


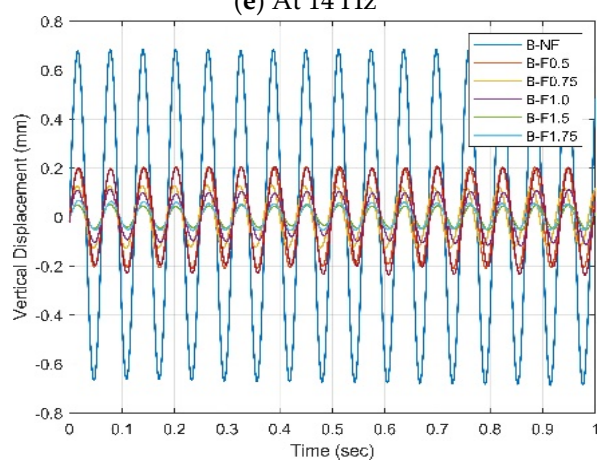
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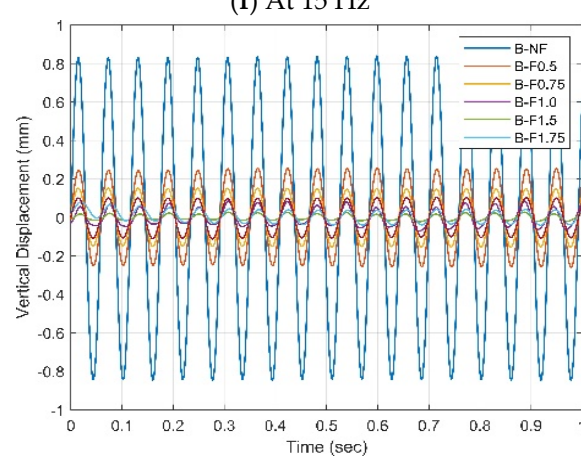
(e) At 14 Hz



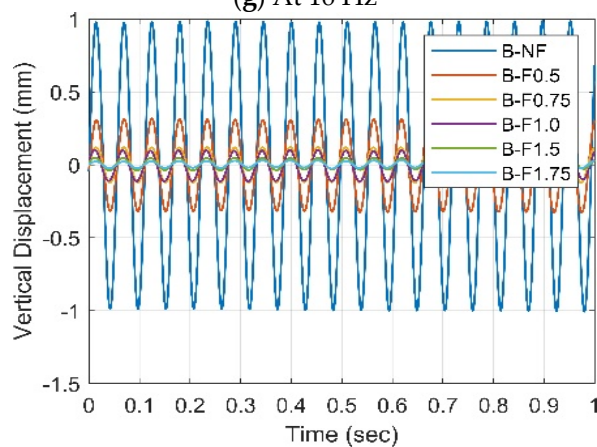
(f) At 15 Hz



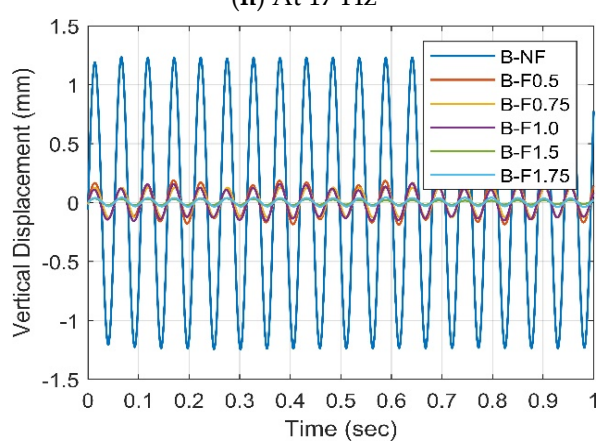
(g) At 16 Hz



(h) At 17 Hz



(i) At 18 Hz



(j) At 19 Hz

Figure 4. Cont.

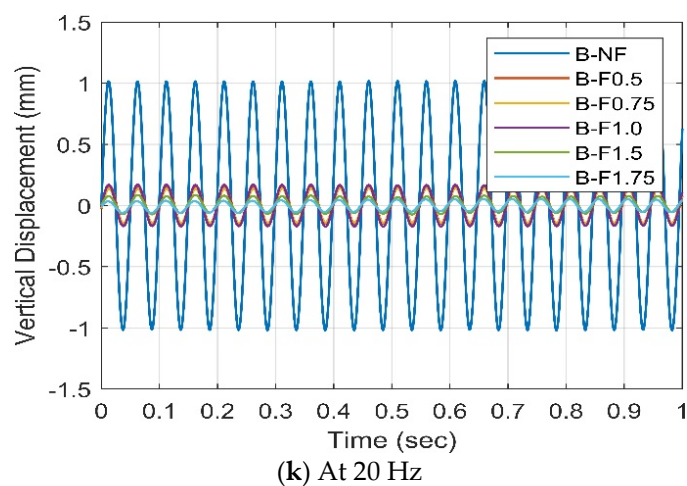


Figure 4. Specimens' responses to different frequencies in the first test stage.

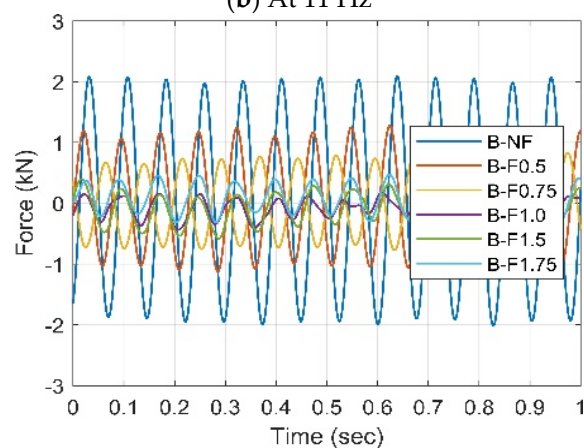
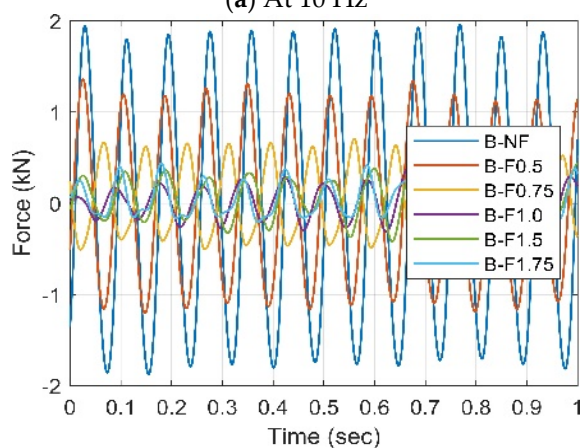
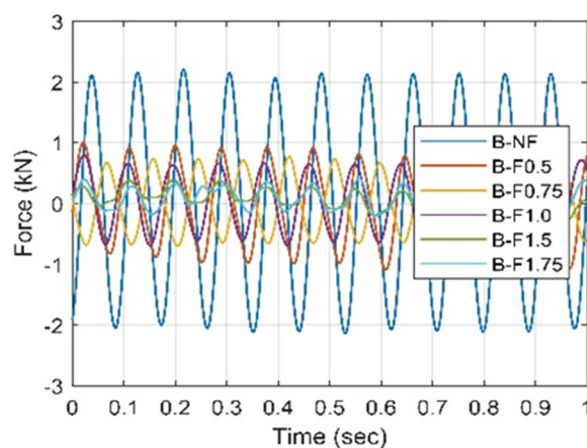
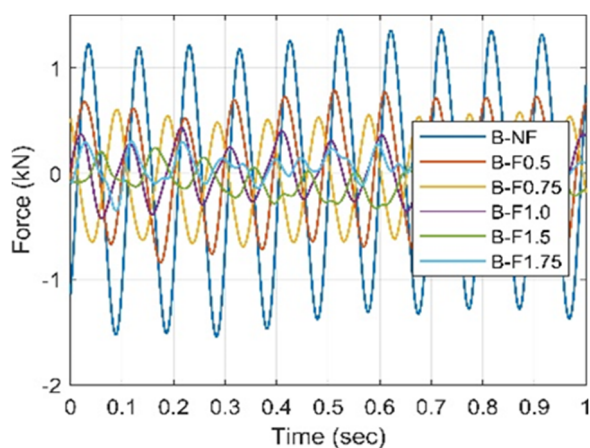
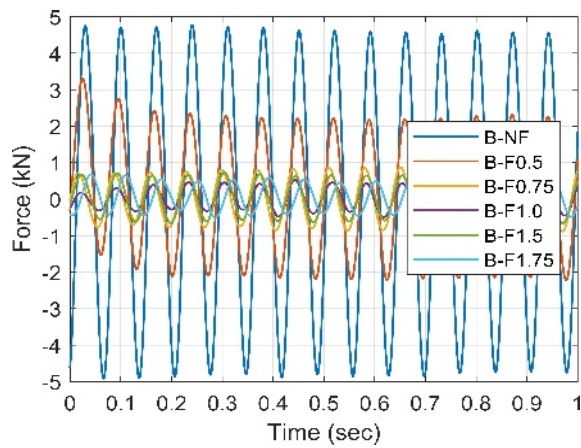
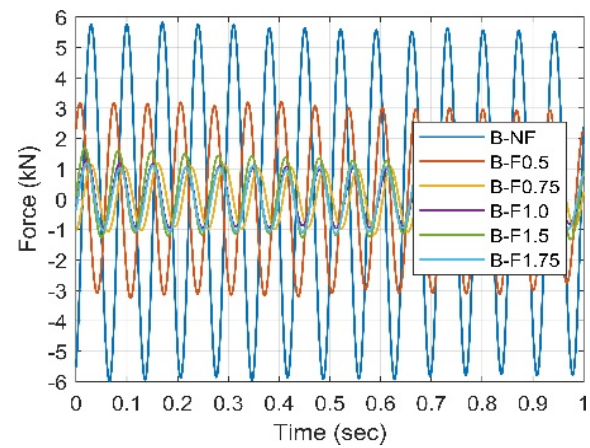


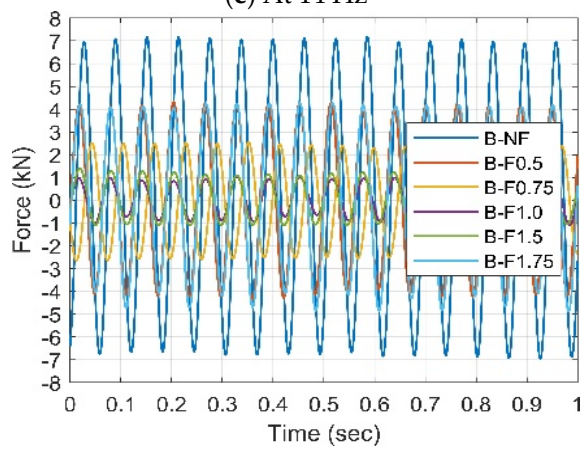
Figure 5. Cont.



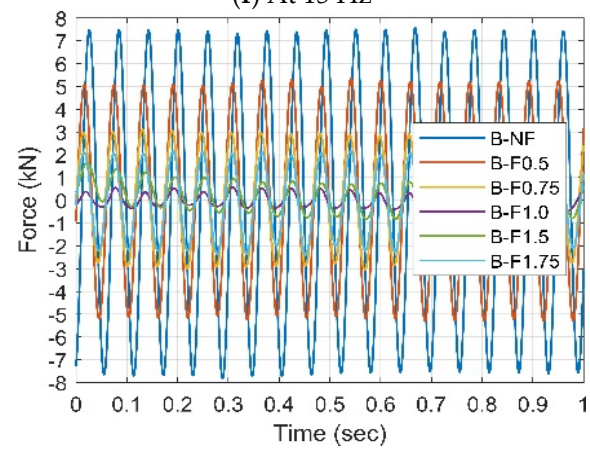
(e) At 14 Hz



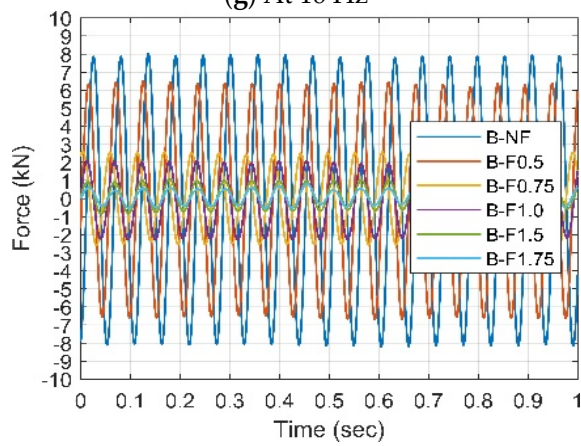
(f) At 15 Hz



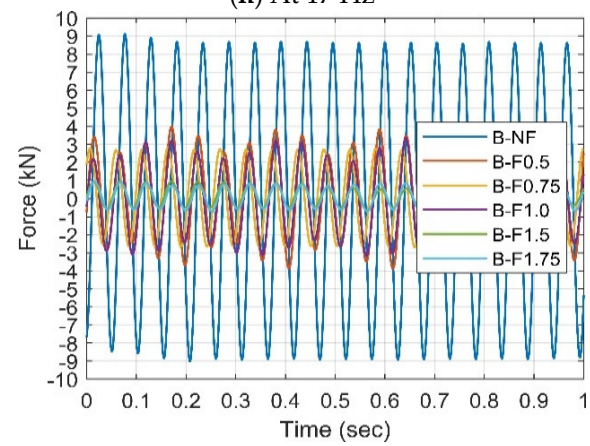
(g) At 16 Hz



(h) At 17 Hz



(i) At 18 Hz



(j) At 19 Hz

Figure 5. Cont.

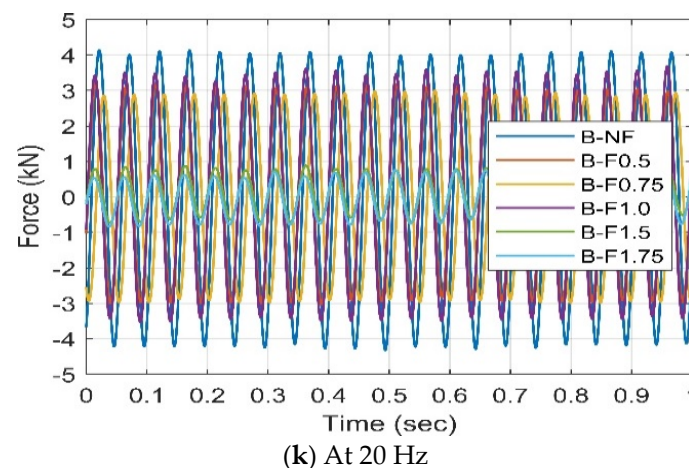


Figure 5. Support reactions to different frequencies in the first test stage.

Specimen B-F1.5 presented the optimum improved dynamic responses among the tested specimens. This was reflected by the outcomes, where the vertical amplitudes extended between 0.0151 mm and 0.087 mm, as shown in Figure 4a,e, and the recorded support reactions ranged between 0.418 kN and 2.138 kN, as presented in Figure 5a,e. The vibration amplitudes and generated cracks in this specimen (B-F1.5) were compatible with the detected behaviors, as shown in Figure 6. The effect of the steel fiber volumetric ratio on cracking can be recognized from the crack patterns of the tested specimens in Figure 6. It can be noted that the beams with higher steel fiber volumetric ratios were associated with lower numbers of cracks. This was attributed to the crack arrest mechanism of the fibers, as it holds the part of the crushed concrete and prevents its disintegration. The multiple cracking in specimen B-NF led to lower stiffness.

It was also detected that the improving effect of adding steel fibers was more significant in reducing the vibration amplitudes than the support reactions. The different percentages between specimens B-NF and B-F1.5 corresponding to the vibration amplitude and support reaction at the upper response limit were 92.95% and 76.55%, respectively. This can be interpreted as the steel fibers' impact on increasing the unit mass, which caused an increase in the generated inertial force. The increased rate of the dynamic response enhancement caused by the steel fiber volume fraction vanished in specimen B-F1.75, as illustrated in Table 6. In comparison to specimen B-F1.5, the response of specimen B-F1.75 increased. The vertical vibration amplitudes ranged between 0.0124 mm and 0.2050 mm, as seen in Figure 4a,g, and the support reactions varied from 0.385 kN to 5.374 kN, as shown in Figure 5a,g. The increases in the vertical vibration amplitude and support reaction reached 57.56% and 60.22%, respectively, compared to specimen B-F1.5. After a specified limit of the fiber volume fraction, the enhancement effect on the mechanical properties of RPC starts to decrease due to the reduction in the concrete mix's workability, which directly reduces the stiffness and increases the dynamic response [27].



Figure 6. Cont.

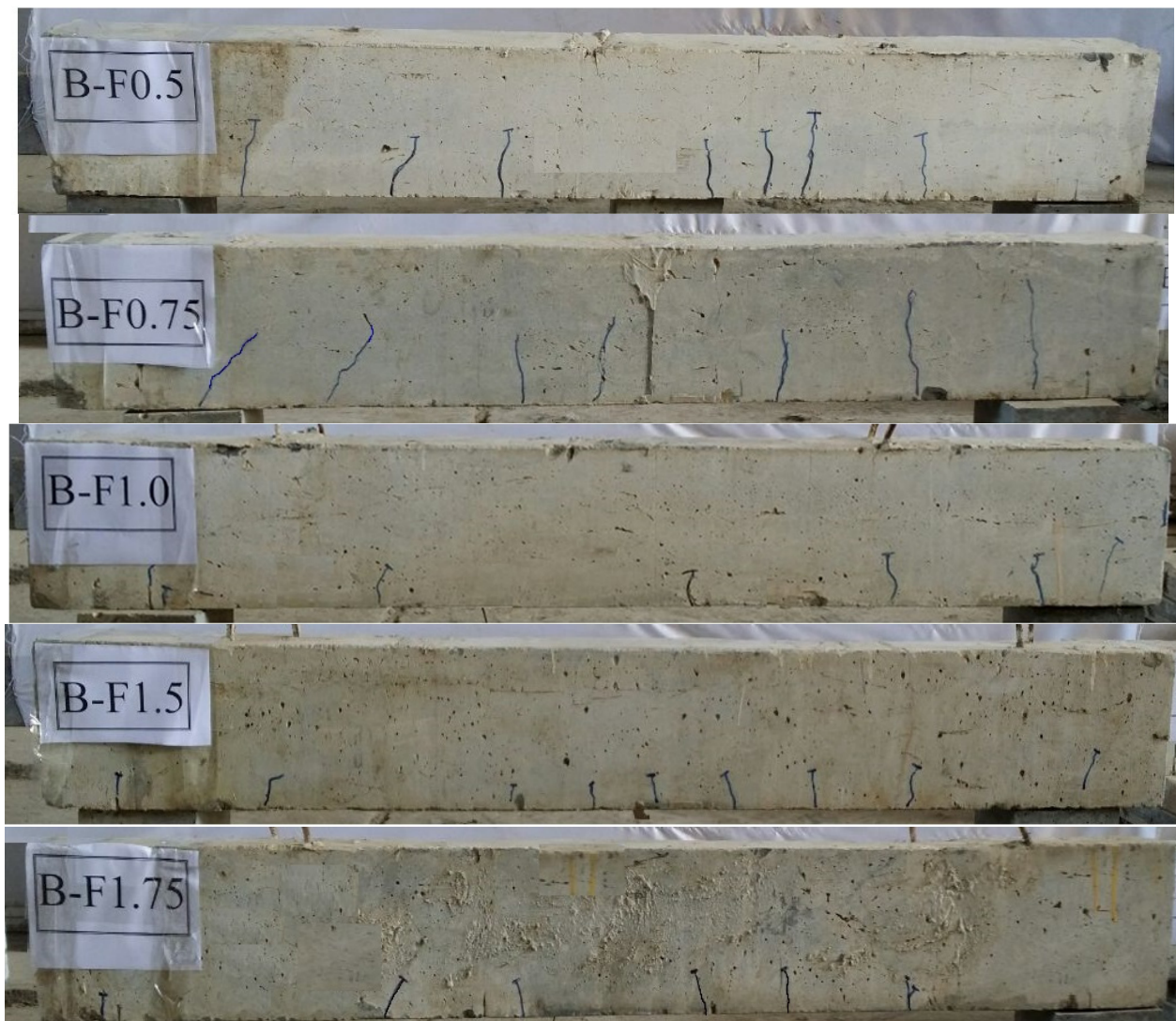


Figure 6. The crack patterns of the tested specimens.

Table 6. Steel fiber volume fraction effect on the deflection amplitude.

Specimens	Amplitude Decreasing (mm)		
	After 1 s	After 3 h	After 6 h
B-NF	----	----	----
B-F0.5	0.917	1.100	1.558
B-F0.75	1.082	1.296	1.743
B-F1.0	1.121	1.336	1.912
B-F1.5	1.147	1.375	1.942
B-F1.75	1.029	1.223	1.716

3.2. Load-Time Duration Effect

The test program was extended by including the time duration effect to achieve a better understanding of the steel fibers' influence. Each specimen was continuously affected by a harmonic loading of the critical frequency that was achieved in the first load stage. The outcomes at 1 s, 3 h, and 6 h were completely compatible with the results of the first load stage, as shown in Figures 7 and 8 and listed in Tables 7 and 8. As the time

duration increased, the dynamic responses of the tested specimens in terms of the vibration amplitude and support reaction increased. The vibration amplitudes of the reference specimen (B-NF) without steel fibers increased from 1.2344 mm after a duration of 1 s to 1.4813 mm and 2.1044 mm after 3 h and 6 h, respectively. Moreover, the support reactions increased from 9.1167 kN at a duration of 1 s to 11.5093 kN and 16.4419 kN at durations of 3 h and 6 h, respectively. This specimen behaved as the critical case, where the vertical amplitude and support reaction increased by 0.2469 mm and 2.3926 kN and 0.8700 mm and 7.3252 kN after 3.0 and 6.0 h, respectively, as listed in Tables 7 and 8.

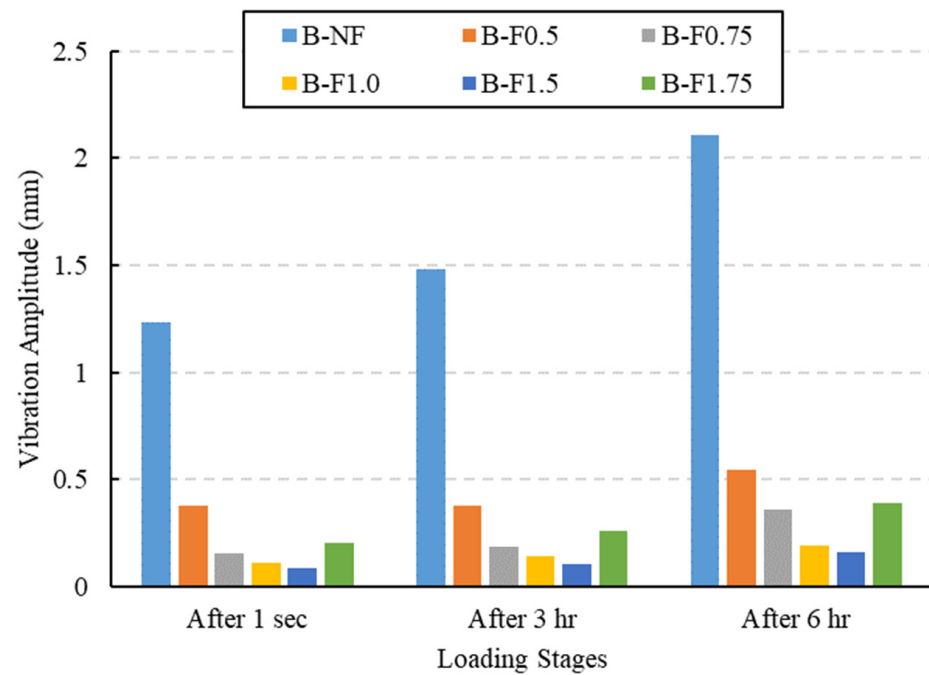


Figure 7. Vibration amplitude comparisons for the load test stages.

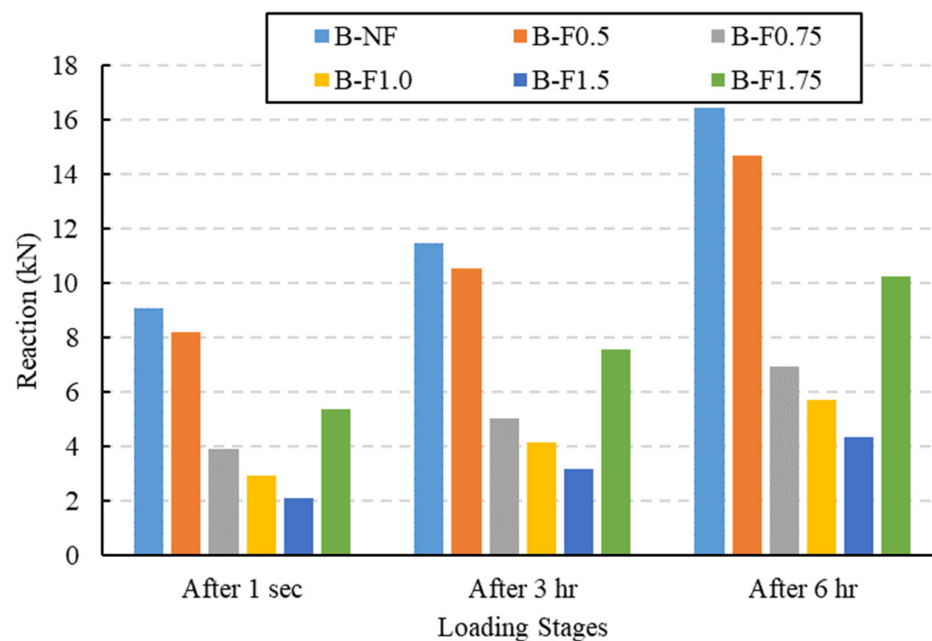


Figure 8. Support reaction comparisons for the test stages.

Table 7. Load duration effect on the deflection amplitudes.

Specimens	Vibration Amplitude (mm)			Amplitude Increasing (mm) *	
	After 1 s	After 3 h	After 6 h	After 3 h	After 6 h
B-NF	1.2344	1.4813	2.1044	0.2469	0.8700
B-F0.5	0.3811	0.3811	0.5468	0.0635	0.2292
B-F0.75	0.1528	0.1857	0.3610	0.0329	0.2082
B-F1.0	0.1134	0.1452	0.1927	0.0318	0.0794
B-F1.5	0.0874	0.1064	0.1625	0.0190	0.0751
B-F1.75	0.2049	0.2580	0.3884	0.0531	0.1835

* This increase is relative to the vibration amplitude after 1 s.

Table 8. Load duration effect on the support reactions.

Specimens	Support Reaction (kN)			Support Reaction Increasing (kN) *	
	After 1 s	After 3 h	After 6 h	After 3 h	After 6 h
B-NF	9.1167	11.5093	16.4419	2.3926	7.3252
B-F0.5	8.2016	10.5736	14.6855	2.3719	6.4839
B-F0.75	3.9156	5.0367	6.9550	1.1207	3.0394
B-F1.0	2.9462	4.1614	5.7302	1.1152	3.0584
B-F1.5	2.1381	3.1927	4.3583	1.0546	2.2202
B-F1.75	5.3744	7.6031	10.2589	2.2292	4.8845

* This increase is relative to the support reaction after 1 s.

The minimum increase in the dynamic response was presented by specimen B-F1.5, with a 1.5% steel fiber content. This specimen experienced vibration amplitude values of 0.0874 mm, 0.1064 mm, and 0.1625 mm at the durations of 1 s, 3 h, and 6 h, respectively. In the same sequence, the recorded support reactions were 2.1381 kN, 3.1927 kN, and 4.3583 kN, respectively. The increases in both the vertical vibration and support reaction after 6 h were 0.0751 mm and 2.2202 kN, respectively, which were the minimum increases in the dynamic responses among the tested specimens. However, by increasing the steel fiber volume fraction to 1.75%, specimen B-F1.75 exhibited reductions in the enhancement rates of the dynamic responses due to increasing the steel fiber content. The increases in the vertical vibration and support reaction after 6 h were 0.1835 mm and 4.8845 kN, respectively, as listed in Tables 7 and 8. Adding steel fibers to the concrete mix increased the mass and stiffness of the RPC beams and subsequently raised their natural frequencies away from the excitation frequencies, which improved the dynamic responses of these beams. This improvement in the dynamic response was increased by increasing the steel fiber content to 1.5%. After that, the improvement rate started to decline.

3.3. Inertial Forces and Support Reactions

The differences between the applied harmonic loads (see Figure 9) and the recorded support reactions (see Figure 5) are called inertial forces. These forces are presented in Figure 10 and listed in Table 9 for the three durations of 1 s, 3 h, and 6 h. Firstly, the inertial force increased as the loading duration increased. For specimen B-NF, the inertial force increased by 42.1% and 128.6% after the loading durations of 3 h and 6 h, respectively. This increase in the inertial force by the load duration was enhanced after adding the steel fibers. For specimen B-F1.5, the inertial force increased by 211% and 444%, respectively. However, this enhancement in the inertial force started to decline after increasing the steel fiber content to 1.75%. The increases were only 63.2% and 138.6%, respectively, for specimen B-F1.75.

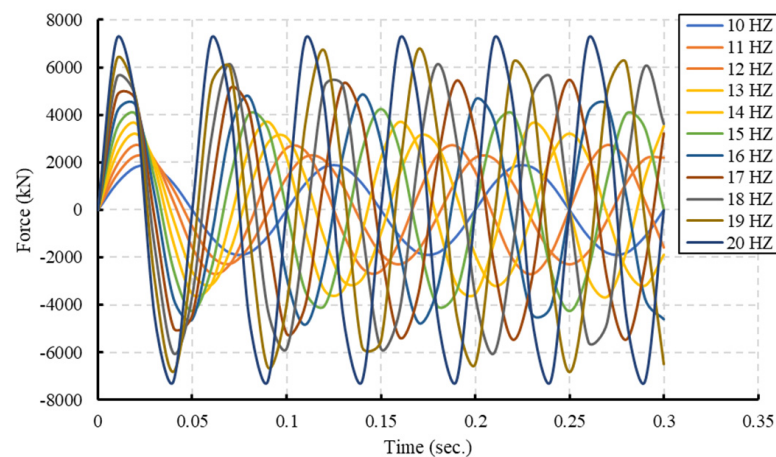


Figure 9. Harmonic load-time histories for the different frequencies.

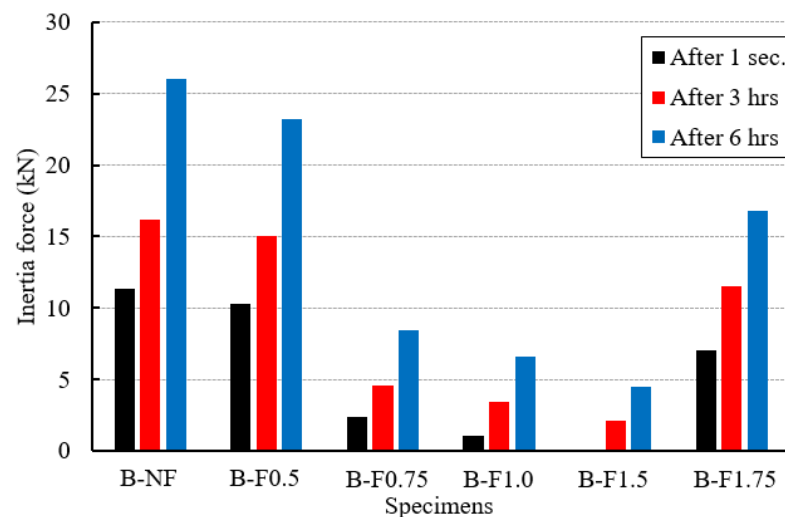


Figure 10. Inertial force comparisons for the test stages.

Table 9. Inertial forces and support reactions.

Specimens	Differences between the Applied Loads and Support Reactions (kN)		
	After 1 s	After 3 h	After 6 h
B-NF	11.39	16.18	26.04
B-F0.5	10.26	15.01	23.23
B-F0.75	2.36	4.60	8.43
B-F1.0	1.04	3.47	6.61
B-F1.5	0.01	2.12	4.45
B-F1.75	7.04	11.49	16.80

Specimens B-NF, B-F1.5, and B-F1.75 presented the critical, optimum, and reflected conditions for the response rate under the effect of the steel fiber fraction. This outcome proved that there were enhancements in the vibration amplitude and acceleration of the RPC beams after adding the steel fibers. The beam deflection depends on the external force, and the relatively large inertial forces induced by the beam's acceleration. This means that the internal moments and shears in the beam need to resist not only the externally applied force but also the inertial forces resulting from the accelerations of the beam. The inertial forces represent a significant portion of the total loading resisted by the

RPC beams with steel fibers. Therefore, a dynamic analysis should be performed as the dynamic characteristics of the beam cannot be ignored and the structural response will vary with time.

4. Conclusions

This study provides an experimental analysis of the structural behaviors of reinforced RPC beams under harmonic loads. The experimental program consisted of testing six simply supported RPC beams with lengths of 1500 mm, widths of 150 mm, and thicknesses of 200 mm under harmonic loading with varied frequencies between 10 and 20 Hz. Different steel fiber ratios of 0%, 0.5%, 0.75%, 1.0%, 1.5%, and 1.75% were provided in the concrete mixes to explore the effect of steel fibers on the dynamic behavior of these beams. Except for the steel fiber volume fraction, all of the examined specimens shared the same material attributes and reinforcing details. The experimental results could lead to the following conclusions:

1. Adding steel fibers significantly influenced the dynamic responses, e.g., vibrations, support reactions, and generated cracks. The recorded dynamic responses in terms of the vibration amplitudes and support reactions were reduced as the steel fibers were added to the RPC beams. The maximum obtained reductions were 92.95% and 76.55% for the vibration amplitude and support reaction, respectively.
2. Adding steel fibers to the concrete mix increased the mass and stiffness of the RPC beams and subsequently raised their natural frequencies away from the excitation frequencies, which improved the dynamic responses of these beams. This improvement in the dynamic response was increased by increasing the steel fiber content to 1.5%. After that, the improvement rate started to decline.
3. The inertial force increased as the harmonic loading duration increased. This increase in the inertial force by the load duration was enhanced after adding the steel fibers. However, this enhancement started to decline after increasing the steel fiber content to 1.75%. This means that the internal moments and shear forces on the beam need to resist not only the externally applied force but also the inertial forces resulting from the accelerations of the beam.
4. There was an optimum fraction for the added steel fibers, after which the enhancing rate would decrease. This volume fraction was 1.5% in this study.
5. RPC beams reinforced by steel fibers can be considered a significant dynamic structural element that endures the effect of harmonic loading. An expanded investigation is essentially recommended to study the dynamic responses and durability of RPC beams reinforced with steel fibers under the effect of real traffic load to be considered as a bridge element. Moreover, full-scale RPC beams under the effect of harmonic loading are recommended for future research work.

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