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NATURAL CHARACTERISTICS AND NONLINEAR BEHAVIOR OF A NEW RC FORMWORK SYSTEM

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ABSTRACT

Reinforced concrete (RC) products poured directly at sites or prefabricated are still popular choices in civil engineering field around the world. In the present study, prefabricated RC formwork possibly decreasing project duration remarkably and mostly keeping the monolithic behavior of frames are introduced. A RC prefabricated formwork system not only plays the same role as classical kinds of formwork, particularly wood, plastic or steel but also contributes to the strength of structures. The natural characteristics and the nonlinear performance of a single three-dimensional frame built using a RC formwork system are evaluated by comparing with those of a reference frame constructed traditionally. The natural frequencies are determined experimentally using shaker test and by numerical modeling using finite element method (FEM) whereas the nonlinear performance of the structures is computed by nonlinear static pushover analysis (NSPA) using the software package ABAQUS (2013). Based on the results of the empirical vibration test and numerical modeling, the natural characteristics of both structures are approximately similar to each other. However, in case of nonlinear performance, although the frame built using the RC formwork system performs a lower bending capacity, about 70% of the ultimate flexural strength of the monotonic frame, its ductility ratio is higher, 13.3% in comparison with 8.2% of the classical frame.

Keywords: Concrete-to-concrete interface, RC Formwork, Shaker Test, natural characteristics, Pushover analysis

1. INTRODUCTION

Formworks play an important role in forming the shape of structures and supporting concrete until its required age is reached. The shape and dimensions of structural elements such as columns, beams, slabs, and walls are flexible so that forming using wood, steel or plastic formworks is considered as convenient and effective methods. Some traditional types of formwork are shown in Figure 1. Moreover, RC structures poured directly at construction sites work monolithically while buildings constructed using prefabricated elements do not. Conversely, workmanship at construction sites possibly causes some issues. Firstly, some mistakes coming from workmanship cause erroneous dimensions in comparison with original plans. Consequently, these errors lead to some potential problems because the original structures are changed. Secondly, the cost paid for workmanship at construction sites and keeping the environment around sites clean also are remarkable issues.

As the classical formworks, a new RC formwork system that can be seen in Figure 2 is used to not only form the core concrete but also solve the aforementioned negative aspects inherent in the traditional methods. The monolithic properties of the structure are able to be mostly kept. First of all, the RC formworks are formed in factories so that their dimensions and the quality of materials are controlled under strict conditions. That can ensure that a final project will be identical to the original one and save vast of time for workmanship. Besides that, the transportation at sites will be easy when there is less stuff used under construction. According to engineering aspect, although a RC formwork system is produced in factories, the main structure is poured in-situ so that it works better than a completely prefabricated structure due to the fact that its monolithic properties mostly still are kept. In the other view, this kind of structure definitely cannot work as well as a monolithic one. This study

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evaluates this important point by investigating the difference between a three-dimensional single story frame built RC formworks and a one constructed traditionally when they are applied to shaker test and pushover analysis.

Figure1. Classical kinds of formwork [1]

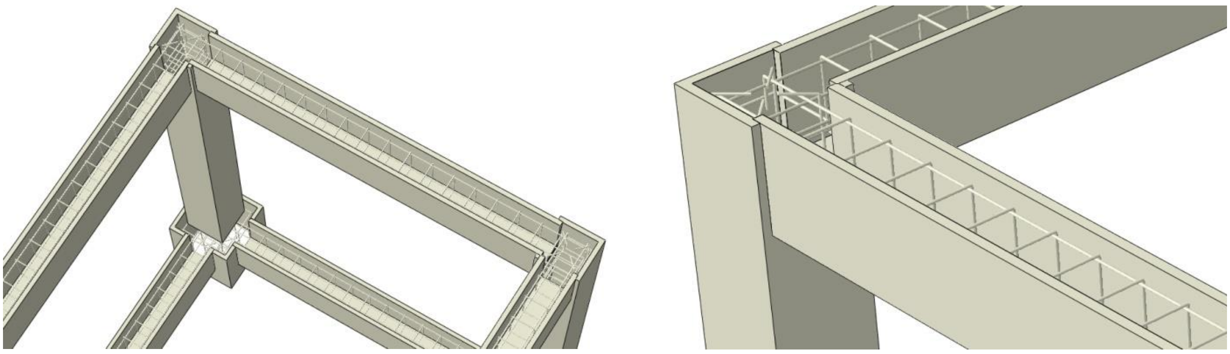


Figure2. (RC) formworks

2. MODAL ANALYSIS WITH SHAKER TEST

Modal analysis is used in order to find out the natural characteristics of structures such as natural frequencies, damping, and mode shapes according to Peter et al. [2]. Modal analysis can be carried out by using both mathematical methods and vibration test. Vibration test is considered as an effective method to identify natural properties and help engineers to control unwanted vibrations that are shown clearly under the motion of structures throughout vibrating and to find suitable ways to reduce the response of structures effectively. Shaker test is also known as one of the most common vibration methods in order to identify the modal parameters of structures based on the driving acceleration levels collected from accelerometers that are attached to the considered structures.

In the present experiment, a shaker and three accelerometers are mounted to structures. First, the shaker gives function-dependent forces to the structures directly and accelerometers collect acceleration levels at the certain points that they are mounted. Next, electronic signals from accelerometers are sent to a dynamic signal analyzer (DSA) connecting to a computer where

SignalCalc Dynamic Signal Analyzer software (SDSA software) is installed. Finally, the data is digitized at DSA and then final information like computation of time and frequency measurement will be stored and illustrated visually at the computer.

3. NONLINEAR STATIC PUSHOVER ANALYSIS

RC structures built in areas prone to intense earthquake events experience extremely nonlinear behavior during ground excitation. There are two methods used to evaluate the capacity of a system against a seismic situation, one is considered as an accurate way, called time history nonlinear analysis and the other known as NSPA that widely used in common due to its simplicity even though inherit inaccuracy. The latter procedure commonly considered as an approximate method consists of Capacity Spectrum Method (CSM) and Displacement Coefficient Method (DCM). In the present study, CSM considered more suitable for reinforced concrete structured is applied to evaluate the nonlinear behavior of structures. NSPA, according to Anil et al. [3] and Joseph et al. [4], predicts the inelastic performance of structures by applying a time-invariant monotonically lateral pushing procedure to structures until a predetermined target displacement is reached. The lateral pushing procedure is determined based on the predominant mode of a structure. A line graph of roof displacement on base shear force known as the bending capacity of the structure is the product of NSPA. In the present study, the flexural capacity of structures is compared to each other.

4. SHAKER TEST APPLICATION

4.1. Specimen preparation

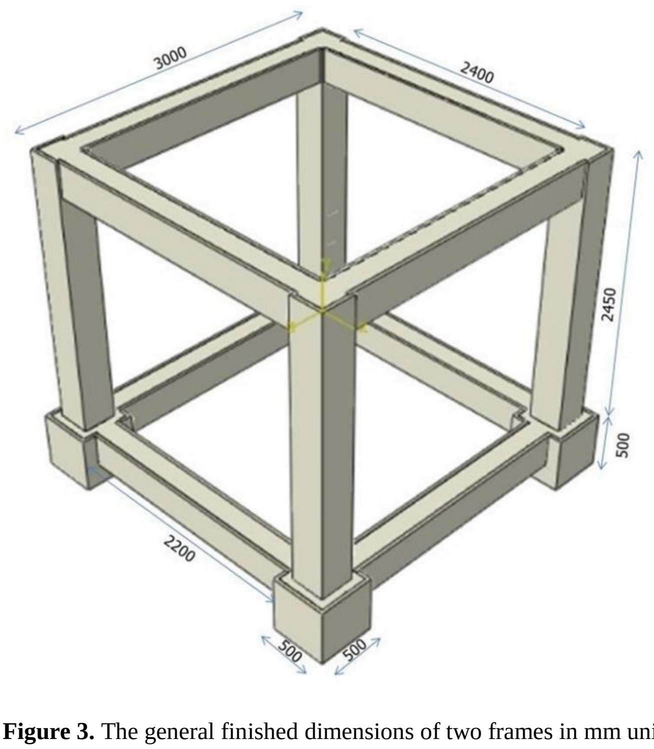
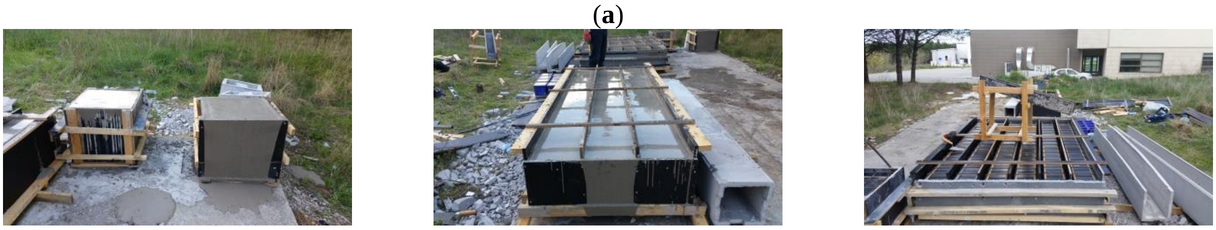


Figure 3. The general finished dimensions of two frames in mm unit

The experiment was held at the faculty of Civil Engineering at Bursa Uludağ University. Two single spatial frames that own same outlook dimensions and use the same materials. 35 MPa strength concrete was used for formworks and the core system. On the other hand, the type of steel S420 whose yielding strength is 420 MPa was selected for reinforcing bars. Firstly, both of kinds of formwork were prepared at sites. Wooden formworks were used to form Classical Frame (CF) while RC formworks formed the second frame namely New Frame (NF). The same finished dimensions of two symmetric frames are depicted in Figure 3. Besides that, in both cases, the cross-sectional of columns is 300x300 mm and 250x300 mm is the sectional dimensions of beams.

The next consideration was forming 30 mm thick formworks whose dimensions were calculated carefully to make the same shape as the classical frame as Figures 4. After that, the RC formworks were localized before pouring concrete as Figure 5.

(**a**)



(**b**)

Figure 4. RC formworks for foot, columns, and beams. (a) preparation; (b) products.

Figure 5. Pouring concrete into the integrated formwork system

The most remarkable difference after pouring concrete can be seen in Figure 6 is that the construction site of both frames is so different from each other. The site surrounding the structure using the RC formwork system is cleaner than the site around CF.

Figure 6. The construction site around two frames

4.2. Shaker Test's Installation and Storing Data

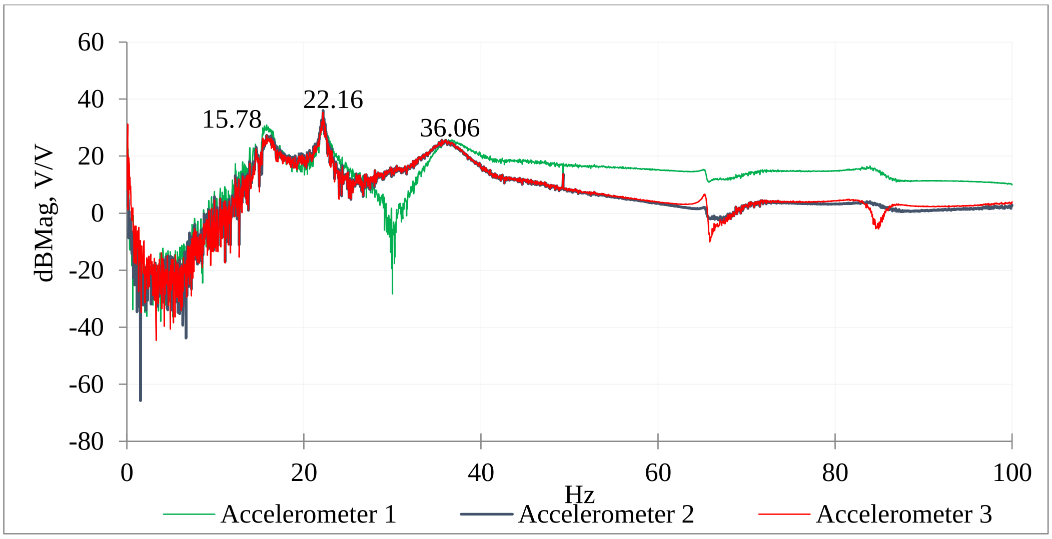
The shaker test was installed to both of structures to investigate the differences in natural frequencies. The test was done from a frame by frame and in two perpendicular horizontal directions (x and z) of each structure. Besides that, for accuracy reasons, there was two digital information that was collected in every direction by mounting shaker at two positions, particularly at the top of two columns as shown in Figure 7.

Figure 7. Two positions in one direction of the electrodynamic shaker on NF.

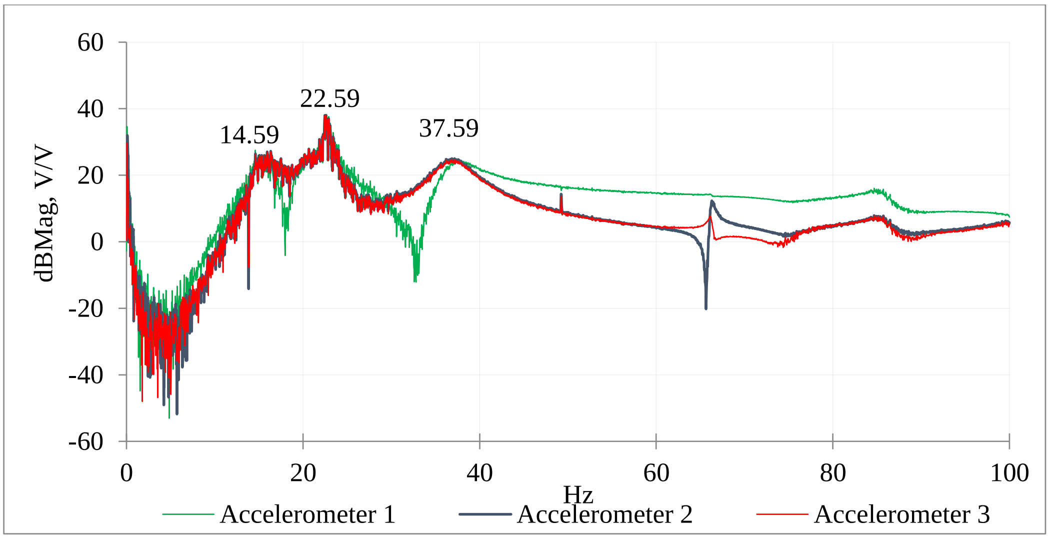
At the beginning of the test, some forms of vibrating force such as sine, random, impulse and pink were applied respectively. The forces that were applied to the structures were controlled by SignalCalc Dynamic Signal Analyzer software and the data was stored to the computer's hard disk. Simultaneously, electronic data is collected from three accelerometers that were attached to the top of the three other columns. The accelerometers must be parallel to the considered axis and mounted stably at the columns to avoid noise. A DSA system collected and computed the electronic signal completely and saved them to the computer.

4.3. Shaker Test Results

The frequency response functions (FRFs) were obtained from SDSA software based on the electronic signal collected from three accelerometers during the external excitation. The data was digitalized by SDSA software by using Fast Fourier Transform (FFT). There is no doubt saying that the first three frequencies are clearly identified through three peaks in each frequency response spectrum shown in Figure 8 and Figure 9. Although both of two frames are symmetric, the experiment was observed in two perpendicular directions in order to control possible significant deviations so that there are two results plotted in x and z directions. The values of natural frequencies are extracted based on coincided peaks of three FRFs obtained by the three accelerometers corresponding to three different colorful lines. In the present experiment, after the third peaks, no natural frequency is possibly extracted as a consequence of the fact that the external vibrating forces cannot excite the next higher natural frequencies of the structures. It can be seen that, after the third coincided peak no convergence is witnessed.

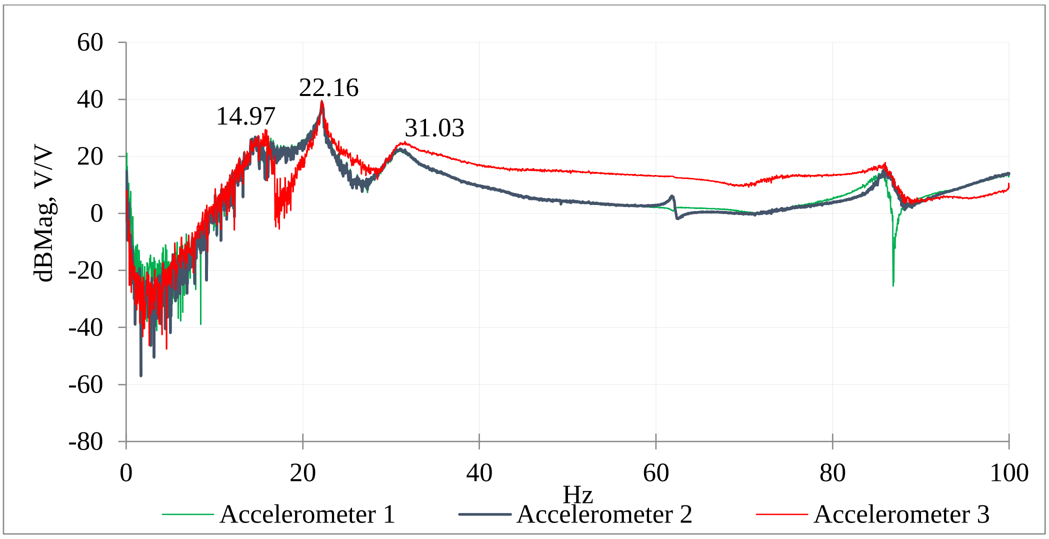


(a)

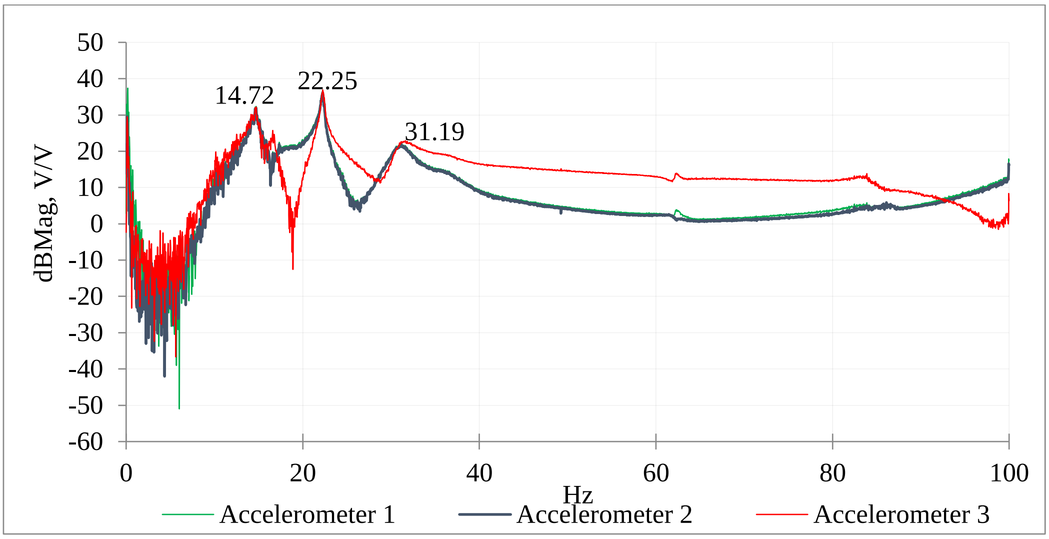


(b)

Figure 8. The frequency response function of CF respect to (a) x direction; (b) z direction



(a)



(b)

Figure 9. The frequency response function of NF respect to (a) x direction; (b) z direction.

According to Figure 8 and Figure 9, it is observed that the result in each direction is approximately similar to the one of perpendicular direction. The slight differences between them are possibly due to the errors coming from workmanship or the setup during vibration test.

It is be observed that the natural frequencies of CF is slightly higher than those of NF in most cases. There are some obvious reasons to explain the slight deviation between them. Initially, the difference of cross sections between NF and CF, especially the reinforcement ratio and the position of longitudinal bars, causes the different masses as well as the stiffness of structures. Moreover, CF works as a monolithic system whereas in NF just the core inside with smaller dimensions response as a monolithic system. Consequently, the stiffness of NF is assumed to be smaller than the stiffness of CF regardless of the existence of the RC formwork system. Furthermore, the friction mechanism at concrete-to-concrete interface can transfer the shear stress between two layers but cannot make NF behave as a monolithic structure. However, it is noted that the small deviation is not meaningful in the terms of the first frequency, the most important one, particularly only 5.1% and 0.9%, in x and z-direction respectively.

5. ABAQUS SIMULATION

According to the materials and the dimensions of the frames, two structures are modeled in ABAQUS for modal analysis and NSPA. It is noted that in case of modal analysis, structures work in elastic states while in NSPA the nonlinear behavior of materials is defined. In nonlinear stages, concrete damage plasticity model (CDPM) is built according to Hsu and Hsu [5] and Aslani [6] for compressive and tensile branch respectively. On the other hand, an elastoplastic model was applied on reinforcement. Moreover, at the “left-as-cast” interface surfaces the frictional mechanism consisting of tangential and normal behavior was defined in detail based on Mohr-Coulomb friction model. The frictional model allows users to define a limitation of shear stress, widely known as critical shear stress. Furthermore, hard contact option was used for normal behavior while in tangential behavior, as shown in Figure 10, the constant friction coefficient and the critical shear stress are chosen as 0.6 and 9.093 MPa respectively. Furthermore, the separation is allowed at the contact between concrete substrates. It is worth noting that the slippage mechanism at interfacial surfaces consists of both elastic and inelastic sliding. Detailed information about required parameters used to define the friction model can be followed according to “11.6.4.3 Coefficient of Friction” in PCI Notes ACI 318-08 [7] and Abaqus 6.13 Analysis User’s Guides [8].

In terms of NSPA, the lateral monotonic pushing is applied at the top of two columns using lateral displacement control procedure. Besides that, normal distributed load is also applied on the top surfaces of four columns during pushing. In case of NF, the axial load is applied only on the core parts of columns.

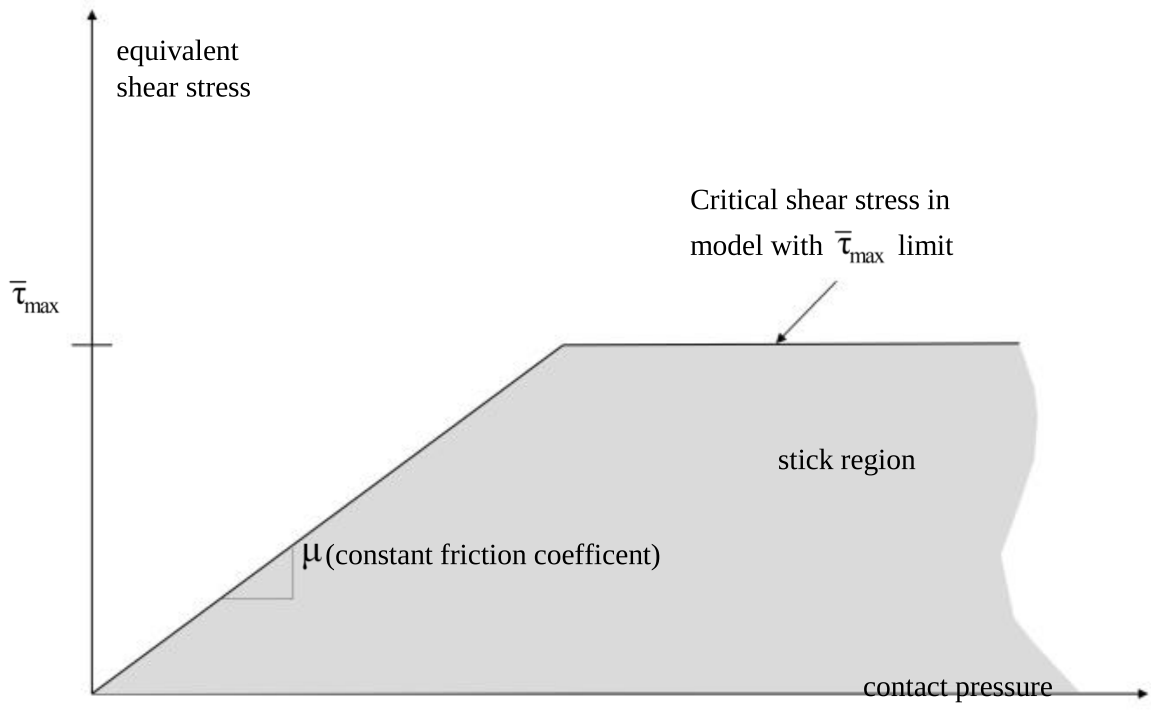
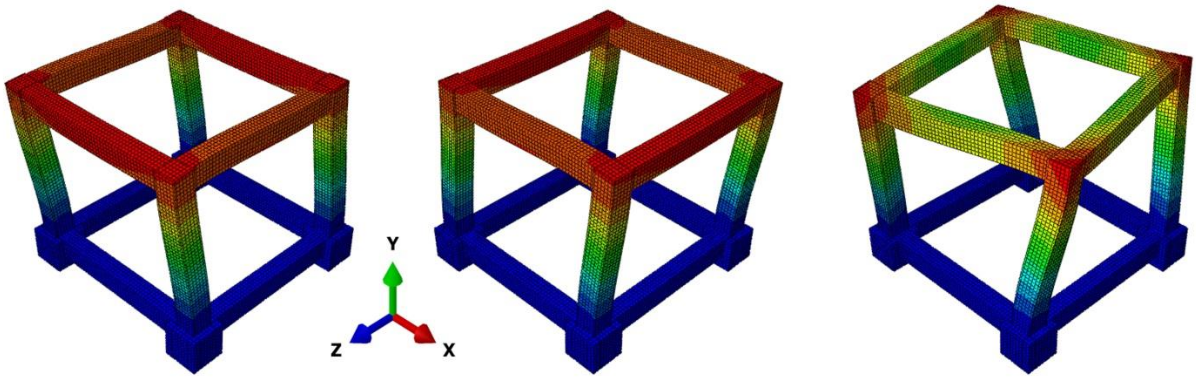


Figure10. Stick region for the friction model with a limitation of the critical shear stress

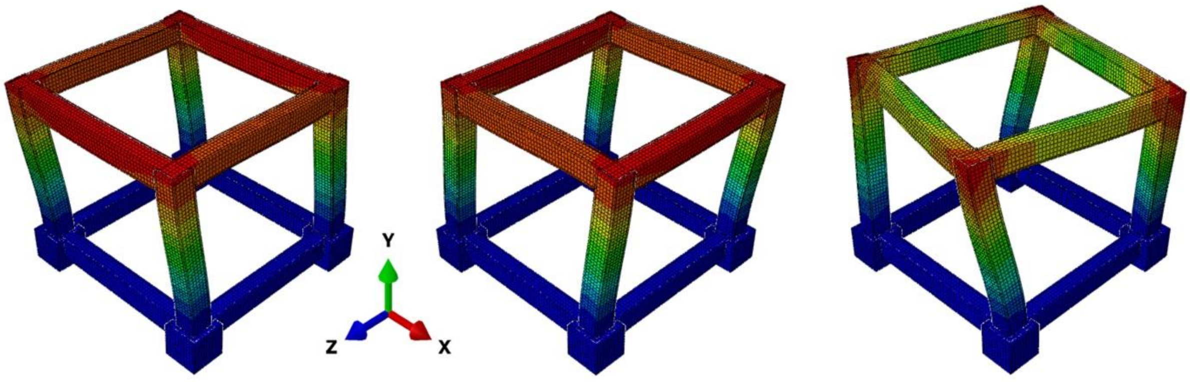
5.1. Modal Analysis Results

The first three natural frequencies as well as their corresponding mode shapes obtained by modal analysis using Abaqus are depicted in Figure 11 and Figure12. It is noted that, the first and second modes of both structures working on lateral axes, x and z, have the same natural frequency due to the symmetric characteristic and the third mode shape rotates around y axis.



(**a**) (**b**) (**c**)

Figure 11. Mode Shapes for classical frame. (a) Mode 1: 15.652 Hz; (b) Mode 2: 15.652Hz; (c) Mode 3: 19.621 Hz.



(**a**) (**b**) (**c**)

Figure 12. Mode Shapes for new frame. (a) Mode 1: 16.756 Hz; (b) Mode 2: 16.756 Hz; (c) Mode 3: 21.067 Hz.

According to experimental and modeling's results, the frequency of every case is compared together in Table 1. The table illustrates the different rate between the results of the simulation and the experimental tests of CF and NF. Vibration test, especially shaker test, was subjected to CF and NF while modal analysis are used in numerical models in order to evaluate the deviation of natural characteristics between them. Based on the results, it could be concluded that there is no meaningful difference between CF and NF in terms of natural frequencies.

The different rates between NF and CF are really slight in the experimental test and in numerical modeling due to the fact of that the forces applied in vibration test just causes linear behavior of materials and there is no nonlinear behavior when using Linear Perturbation procedure type step in ABAQUS. According to numerical results, the noted deviation between two frames is 7.1% in terms of Mode 1 and Mode 2, the two most important modes, is higher than the experimental result, 5.1% and 0.9% for x and z-direction respectively. The higher values of the first frequency can be explained that the finished dimensions of NF are similar to those of CF but the higher reinforcement ratio in NF's elements increases the stiffness of NF.

Compare experimental test and numerical modeling of every frame, NF witnesses a maximum deviation of 12.2% while the CF experiences just 6.8% in case of Mode 2. Moreover, in Mode 3, the torsional mode shape, the deviation reaches 15.1% but it is assumed non-significant because of the small effective mass. The difference between empirical and numerical results could be caused by the parameters used to define materials in the numerical analysis that made the frames not comparable completely as expected. Moreover, the inaccuracy caused by workmanship, materials used in sites, an unsatisfied curing condition etc. is possible affects the quality of the specimens. Besides that, the mass of the shaker attached to the structures during the experimental test could be considered as a reason. Finally, noise caused by environment could affect the accuracy of the results.

Table 1. Comparison of natural frequencies

Direction	MODE	Modal Analysis				Experiment		Different rate, %			
		CF		NF		CF	NF				
		A		B		C	D	B vs A	D vs C	C vs A	D vs B
		f Hz	Effective mass, %	*f* Hz	Effective mass, %	*f* Hz	*f* Hz				
x	1	15.652	60.6	16.756	51.7	15.78	14.97	7.1	-5.1	0.8	-10.7
y	3	19.621	21.6	21.067	19.3	22.16	22.16	7.4	0.0	12.9	5.2
z	2	15.652	60.6	16.756	51.7	14.59	14.72	7.1	0.9	-6.8	-12.2
y	3	19.621	21.6	21.067	19.3	22.59	22.25	7.4	-1.5	15.1	5.6

5.2 NSPA results

Roof-displacement versus base-shear force line graph of NF and CF are plotted in Figure 13. It is noted that the base-shear forces are taken at the bottom sections of columns.

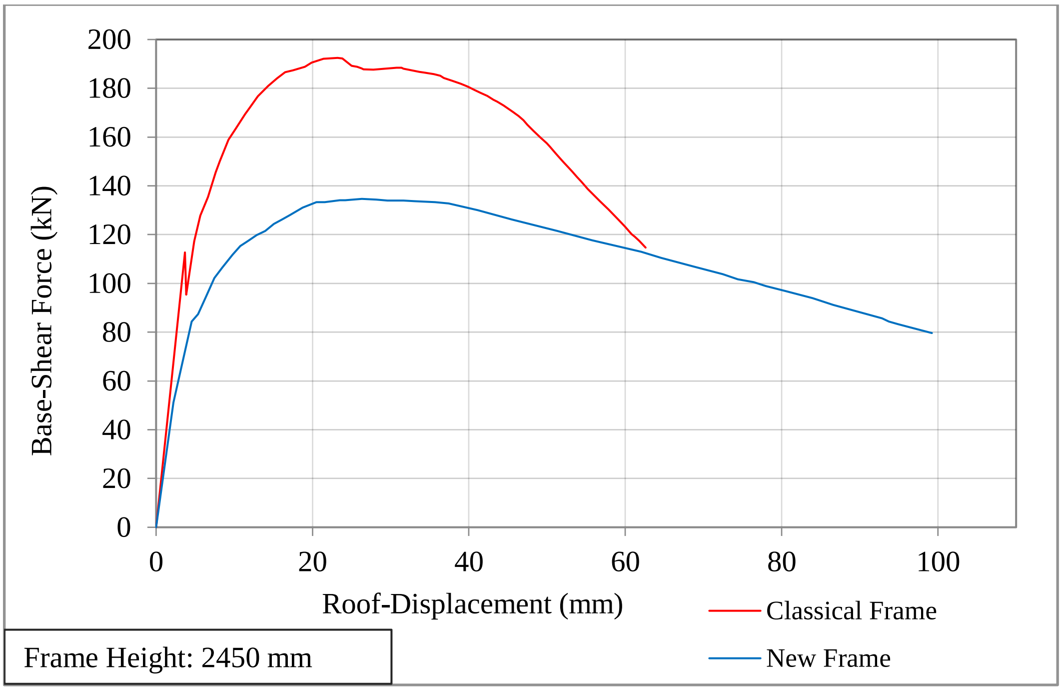


Figure 13. The products of NSPA.

The line graph sheds of light on a comparison of the flexural performance of a single story spatial RC frame formed using prefabricated RC formworks to a reference monolithic frame when the structures fall deeply into nonlinear stages under monotonic pushing.

Based on the base-shear force and top lateral displacement curves, the ultimate value of the bending strength of NF is approximately equal to 70% of the flexural capacity of CF while it performs a more ductile behavior. The lower capacity is possibly predicted due to the fact that only the in-situ poured core system of NF works as a monolithic system. The occurrence of lateral slippage at interfacial surfaces of concrete substrates, covered structural elements are separated into a core part and a covering part and behave as composite elements. Consequently, the stiffness reduction of composite elements compared with monolithic members causes remarkable stiffness degradation of the whole structure.

Notwithstanding the lower bending capacity, a more ductile behavior is witnessed in case of NF. After reaching the ultimate point, 330kNm and 472kNm for NF and CF respectively, the descending branch of NF is less steep and experience a larger displacement before fracture than CF. Although the ultimate bending strength of both structures is witnessed at about 23 mm lateral displacement, the ductility factor of NF is higher, 13.3% compared with 8.2% for CF. The higher ratio of reinforcement is highlighted as the backbone of the more ductile performance of the structure formed using prefabricated formworks in comparison with the traditionally built one.

6. CONCLUSION

The present study evaluates the natural characteristics and the nonlinear behavior of a structure built using RC formwork system by comparing with a reference frame constructed classically.

Firstly, based on both experimental and numerical results, it is clear that there is no significant deviation in terms of natural frequencies between NF and CF. This study witnesses slightly different rates between the numerical results and the experimental results of NF in case of Mode 1. Secondly, in case of nonlinear behavior, based on roof-displacement versus base shear curves, it could be concluded that the flexural capacity of the frame built using a RC formwork system is about 70% of the capacity of the monolithic one. However, due to the higher ratio of reinforcement used in columns and beams, a more ductile performance is witnessed for NF. It is convenient to remind that in the present study, the connecting joint between the formwork and core system is considered as “left-as-cast”, in other words, a smooth surface. The authors recommend that if the surface of old concrete layers is prepared effectively using some common surface treatment methods such as using steel connectors, indented construction joints etc. the flexural capacity of NF possibly increases remarkably according to another study of the writers being under-researched.

ACKNOWLEDGEMENTS

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