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Influence of stirrup spacing in concrete column on its dynamic characteristics

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Preliminary report

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Influence of stirrup spacing in concrete column on its dynamic characteristics

Changes in natural frequencies, modal shapes, and damping ratios of a two story single span reinforced concrete building having different stirrup spacing in columns are analysed in the paper. Two building models measuring 150 x 150 x 135 cm were manufactured for the testing. Dynamic properties of both buildings were experimentally determined using the operational modal analysis. The ABAQUS finite element software was used to numerically determine dynamic properties of the buildings. The effect of stirrup densification in columns on dynamic properties of the building was defined by comparing experimental and numerical analysis results.

Key words:
Dynamic properties, operational modal analysis, ABAQUS, column stirrup spacing

Prethodno priopćenje

Hakan Başaran

Utjecaj razmaka spona u betonskom stupu na njegova dinamička svojstva

U radu je provedena analiza promjene vlastitih frekvencija, modalnih oblika te koeficijenata prigušenja armiranobetonske dvokatne jednorasponske konstrukcije s različitim razmakom spona u stupovima. Za potrebe ispitivanja izgrađena su dva modela zgrada dimenzija 150 x 150 x 135 cm. Dinamička svojstva građevina eksperimentalno su određena primjenom operacionalne modalne analize. Za numeričko određivanje dinamičkih svojstava građevina, upotrijebljen je računalni program ABAQUS. Utjecaj progušćenja spona u stupovima na dinamička svojstva građevine određen je pomoću usporedbe rezultata dobivenih eksperimentalnom i numeričkom analizom.

Ključne riječi:
dinamička svojstva, operacionalna modalna analiza, ABAQUS, razmak spona u stupovima

Vorherige Mitteilung

Hakan Başaran

Einfluss von Bügelabständen bei Stützen auf dynamische Eigenschaften

In dieser Arbeit wurden Unterschiede in Eigenfrequenzen, Modalformen und Dämpfungskoeffizienten einer zweistöckigen einspännigen Stahlbetonkonstruktion für verschiedene Bügelabstände in den Stützen analysiert. Dafür sind zwei 150x150x135 cm große Modelle des Gebäudes erstellt worden. Die dynamischen Gebäudeeigenschaften wurden durch experimentelle Versuche mittels der operationellen Modalanalyse ermittelt. Um dynamische Eigenschaften numerisch zu erfassen, wurde das Finite-Elemente-Programm ABAQUS angewandt. Der Einfluss verdichteter Bewehrung der Stützen auf dynamische Eigenschaften wurde durch den Vergleich von Resultaten numerischer und experimenteller Analysen ermittelt.

Schlüsselwörter:
dynamische Eigenschaften, operationelle Modalanalyse, ABAQUS, Bügelabstand bei Stützen

1. Introduction

The behaviour of structures under dynamic loads is determined using natural frequencies, modal shapes, and damping ratios, which are dynamic characteristics of each structure. These characteristics are determined depending on present structural properties and material characteristics of a given structure and boundary conditions. Dynamic characteristics are then used to determine the efficiency of analytical models and earthquake forces affecting the structure. By using integrated approaches, dynamic analyses are also carried out depending on the first period value [1]. Moreover, the rigidity distribution and torsional irregularities can be established by evaluating modal behaviour of the structure. Therefore, dynamic characteristics must be determined realistically.

Dynamic characteristics of structures are determined using analytical models or approximate methods [2]. Thus, both natural frequencies and modal shapes can be obtained, and dynamic behaviour of the structure can approximately be ascertained. Several software programs are available for analytical modelling. Approximate solutions to determine first frequency values of structures can be found in several technical standards. The first period value for the buildings built according to technical standards can be defined based on the dimensions of such buildings. Modal behaviour of buildings of regular geometry, built based on technical standards, appear as translation displacement in the longitudinal and transverse directions in the first and second modes, and as torsion in the third mode [3]. The behaviour of structures under dynamic load is characterized by numerous uncertainties. Apart from dynamic load uncertainties, the uncertainties in parameters defining dynamic behaviour prevent us from determining dynamic behaviour realistically. Therefore, experimental methods need to be used to enable a more realistic determination of the dynamic behaviour of structures.

Stirrups are elements that are used in columns and beams as transverse reinforcement and as a means to provide strength against shear forces. This means that the bending resistance of elements is increased. Moreover, they are used to improve ductility of densification and prevent buckling in longitudinal reinforcement. Various experimental studies about the use and arrangement of stirrups are available in literature [4]. According to the results of these studies, the stirrup arrangement affects the system behaviour under lateral loads; when arranged properly, stirrups improve the horizontal displacement capacity, ductility, energy consumption ability, and lateral load capacity of the system. With the densification of stirrups, the buckling length in columns and beams decreases and an instantaneous brittle failure is prevented. By manufacturing stirrups as a 135 degree hook, the confining effect of stirrups increases. Thus, the loading capacity of elements subjected to axial load improves considerably.

With the use of stirrups, the displacement profile of the building is modified and it becomes a function of dynamic forces. The effect of stirrups on the behaviour of buildings is of great concern. Dynamic characteristics are nowadays determined either using the design data or real time on-site measurements, or analytically, using the finite element model, which makes use of element dimensions, material properties, and boundary conditions. Dynamic characteristics are determined either numerically or experimentally. In the numerical analysis, a finite element model is developed, suitable material properties and boundary conditions are established and, lastly, natural frequencies and modal shapes of a building are assessed. However, several researchers have concluded that dynamic characteristics obtained by numerical analysis do not necessarily represent real condition of a building [5-6]. Therefore, the use of numerical data in determining earthquake behaviour of a building may result in inaccurate analysis. Thus, experimental studies are needed to confirm numerical studies as to determination of dynamic properties. Experimental methods are directly applied to a building and the resulting dynamic properties exhibit the present condition of a building. One of the most widely used methods for determining dynamic characteristics is the Operational Modal Analysis (OMA). In the OMA, vibrations caused by environmental effects are recorded by accelerometers, and the results are used to determine dynamic parameters [7-14]. The OMA is almost universally used in the dynamic characterization of every engineering structure because it is easily applicable, cost effective, and presents minimum interference during measurements. Several studies have been presented in literature about dynamic characterization of buildings using the OMA. Dynamic characteristics of concrete and steel buildings, bridges, dams, silos, stadiums, historical buildings, and nuclear power plants, have been investigated in such studies [15-26].

The objective of our study was to investigate dynamic characteristics, including natural frequencies, modal shapes, and damping ratios, of a concrete building subjected to dynamic loads. Two scaled up single span two-story concrete buildings measuring 150 x 150 x135 cm were manufactured. The first building (B1) was constructed to have 8 and 4 cm transverse reinforcement spacing in the central and confinement zones of the column, respectively. All first floor columns of the second building (B2) were designed to be 4 cm. The effects of stirrup densification on dynamic characteristics of the structure were experimentally determined using the OMA. The numerical analysis was carried out by means of the ABAQUS finite element software. Experimental and numerical results were compared.

2. Materials and methods

2.1. Theoretical and experimental modal analysis

Frequencies and periods were determined using the undamped free vibrations equation of motion as an eigenvalue problem.

$$[K- \omega^2 M] = 0 \quad (1)$$

where

M - the mass matrix

K - he rigidity matrix

By solving this equation, undamped natural angular frequencies (ω_1, ω_2, ω_3,...., ω_n), whose number is equal to the degree of freedom, are obtained. For each frequency value, the modal shape the building assumes is determined using the following equation:

$$[K- \omega^2 M]\,\Phi = 0 \tag{2}$$

where
Φ - is the modal amplitude vector.

By ranking natural frequencies from smallest to highest, the minimum frequency is assumed to be the fundamental frequency and the modal shape corresponding to this frequency is called the first mode [27].
Another dynamic property of a structure is its damping ratio. In the Turkish Earthquake Code, the acceptable friction ratio for the idealized elastic acceleration spectrum is 5% in structural design. In our study, the damping ratio was calculated using the Fourier spectrum obtained from earthquake acceleration records. In this calculation, the self-vibration frequency was the frequency at which the spectrum amplitude attained its maximum.
As shown in Figure 1, the amplitude at this frequency was assumed as being A, and the damping ratio was calculated from the following equation. f1 and f2 were frequencies where the amplitude was reduced to.

$$\gamma = \frac{f_2 - f_1}{f_2 + f_1} \tag{3}$$

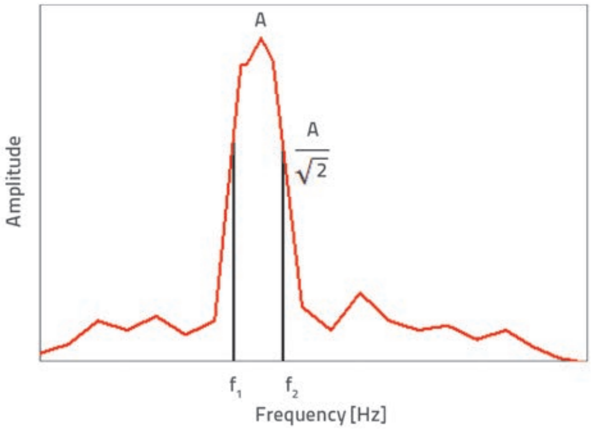


Figure 1. Amplitude and frequency values used for damping ratio in Fourier transform

The Experimental Modal Analysis (EMA) and the Operational Modal Analysis (OMA) are presently widely used to determine dynamic parameters of structures. EMA can be used to confirm dynamic parameters of structures obtained by numerical analysis. However, measurements according to the EMA method have to be obtained using an external effect, and so this method cannot be used for a real building. Therefore, OMA is preferred to EMA for real time situations. The principle of OMA method is to obtain real time data by using acceleration values observed in the building due to environmental effects. With the help of computer, dynamic modal parameters are obtained. Stimulating effects needed for OMA are environmental factors such as the vehicle load, wind load and machine vibrations. Since environmental effects are not definitely known, modal parameters are established using different algorithms in OMA. A widely cited time-dependent "Stochastic Subspace Identification (SSI) technique", was used in our study. This method is able to process data without the need for transformation such as the correlation or spectral transformation. A detailed description of equations and formulas used can be found in literature [28]. SSI method is preferred because it uses real time data and does not need transformation at any step of the process.

2.2. Description of buildings

Figure 2 shows single span two-story scaled buildings that were used in our study. Both buildings have identical beams, columns, floor dimensions, and reinforcement.

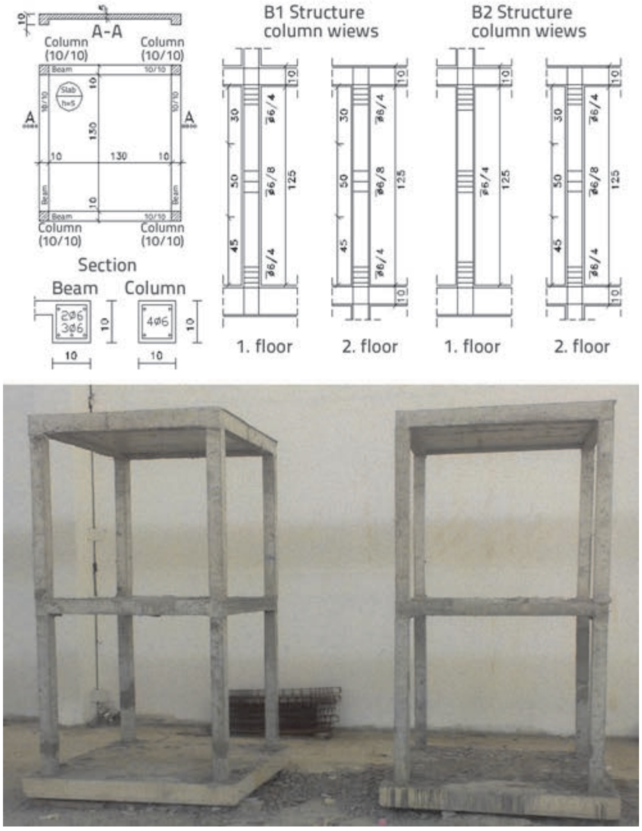


Figure 2. Scaled concrete building

The only difference between the two buildings is that the stirrups densification was applied to the first floor columns of B2. Floor heights were 135 cm and the other two dimensions were 150 x 150 cm. The column and beam dimensions were 10 x 10 cm,

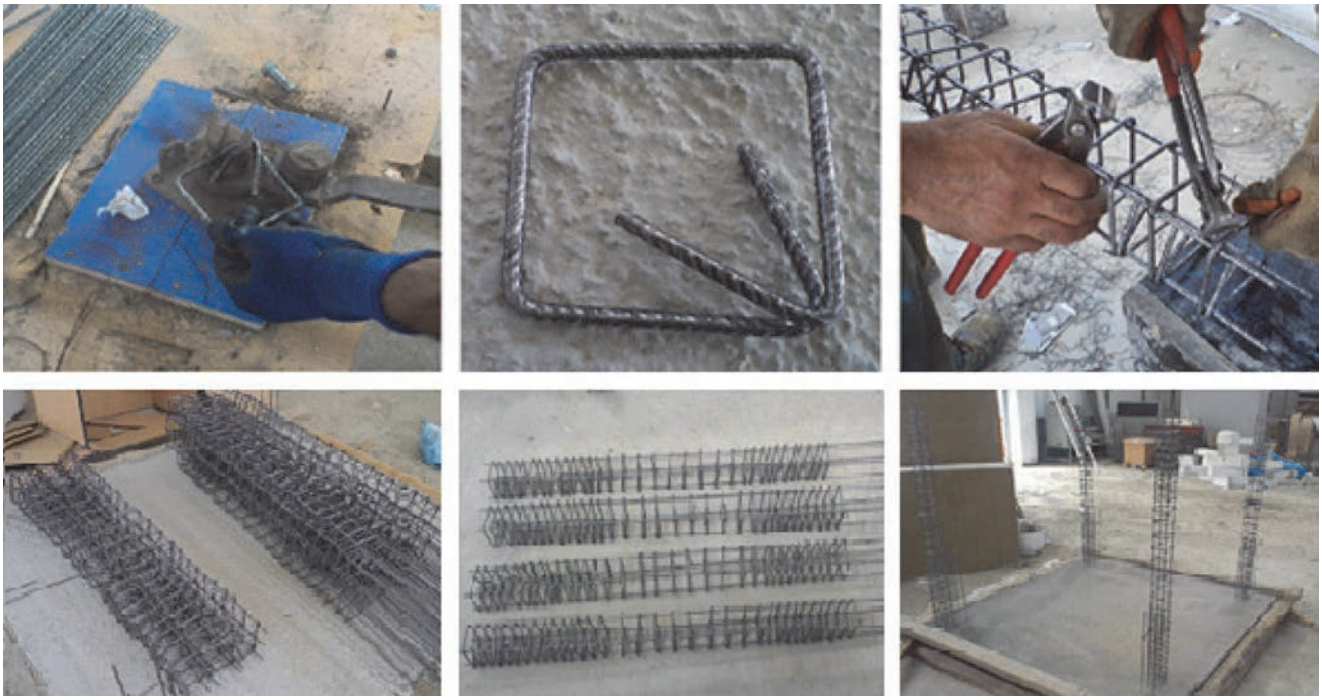


Figure 3. A detailed schematic of stirrups

and the floor was 5 cm in thickness. A 15 cm raft foundation was applied to both buildings and the ground floor columns were anchored to the base. The longitudinal reinforcement of 4Ø6 was applied to the columns, 3Ø6 to the bottom, and 2Ø6 to the top of the building. Ø6/8-4 stirrups were used in beams. Ø6/4 stirrups were used in the first floor columns of B1, and Ø6/8-4 stirrups were applied to the remaining columns. Ø6/10 stirrups were applied to the top and bottom of floors in both directions. The S420 reinforcing steel was used in the buildings. The strength of samples taken during pouring of concrete amounted to 30 MPa. A 1,0 cm concrete cover was used in the manufacture of stirrups. The end of stirrups was bent as 135° hook (Figure 3).

2.3. Experimental setup for operational modal analysis

The OMA was used to determine dynamic characteristics of the buildings. Measurements were taken using uniaxial SENSEBOX-7021 accelerometers. These signals were collected using a TESTBOX-6501 data logger and transferred to a computer (Figure 4). After processing of the signals, dynamic characteristics were obtained using the OMA software.

To accurately measure vibrational modes of the building, accelerometers were placed at eight nodal points. Three accelerometers were used in nodal points for each direction. The measurement process was realized in two steps. In the first step,

Figure 4. Accelerometers (left) and data logger (right)

twelve accelerometers were placed at four different locations on the first floor. In the second step, the other four locations on the second floor were used by taking a reference point. To account for ambient temperature and other environmental factors in the building, the two tests were conducted at two different dates. An approximate building model was drawn using the ARTEMIS Modal Pro (AMP) software, and the data from accelerometers were assigned to appropriate points (Figure 5).

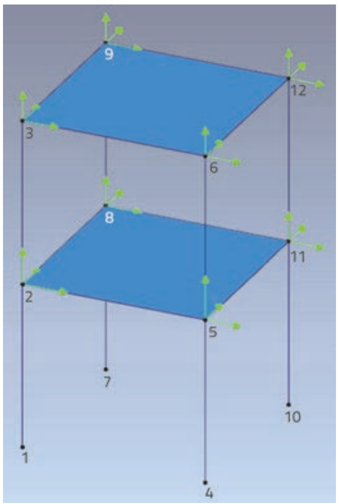


Figure 5. Locations and directions of accelerometers

2.4. Numerical model

The finite element model of the building was obtained using the ABAQUS software. A solid tetrahedral (C3D4) element having 3264105 four-nodal points was used in the development of this finite element model. The finite element model of the structure, and the C3D4 element used in the model, are presented in Figure 6. The building was supported and fixed from the bottom of columns. The linear perturbation-frequency module, which can perform eigenvalue and eigenvector analyses of natural frequencies, was used in our study. Material properties used in the finite element modelling are given in Table 1.

Table 1. Material properties

Property / Material	Elastic modulus [MPa]	Poisson's ratio	Mass density [N/m^3]
Concrete	31000	0.2	25000
Steel	200000	0.3	78000

The convergence analysis was conducted to determine an optimum mesh size for the building. Mesh sizes ranging from 0.009 m to 0.1 m were used in the convergence analysis. The optimum mesh size was found to be 0.009 m. Frequencies for the first six modes are given in Table 2.

Table 2. Frequency values obtained by numerical analysis

Mode	Frequency [Hz]	Mode	Frequency [Hz]
1	6.586	4	19.935
2	6.586	5	19.935
3	11.795	6	30.366

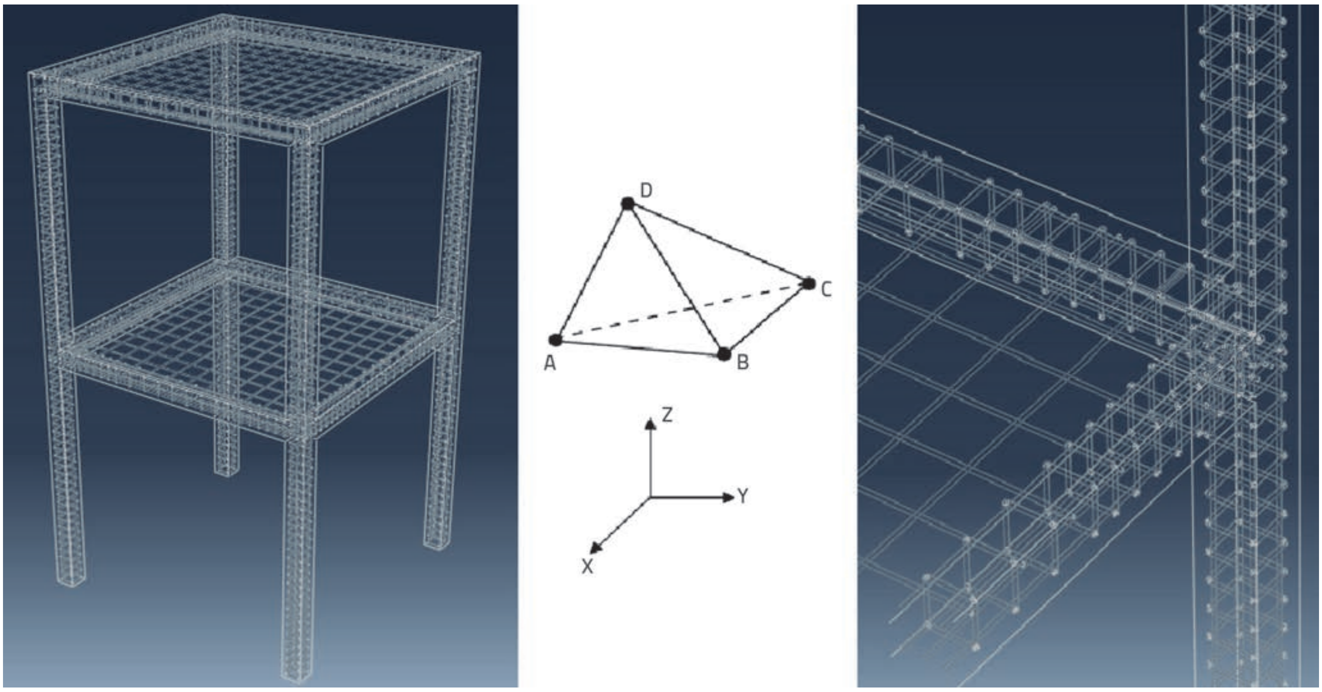


Figure 6. Finite element modelling and solid tetrahedral element (C3D4)

3. Results

Based on experimental data, modal parameters for the damaged and repaired building were determined by the SSI method using the AMP software. Stabilization diagrams were also obtained using the SSI method. Experimental and numerical modal shapes are given in Figure 7.

Modal shapes obtained numerically and experimentally were in good harmony. Both numerically and experimentally, the first mode was in x- direction, the second mode was in y-direction, and the third mode appeared as torsion. The other three modes exhibited the same pattern. Figure 8 shows experimental dynamic modal parameters and stabilization diagrams of B1 building.

Since the building was symmetrical, frequency values for the first and second modes, and those for the fourth and fifth modes, were approximately the same. Dynamic modal parameters and stabilization diagrams of B2 building are given in Figure 9.

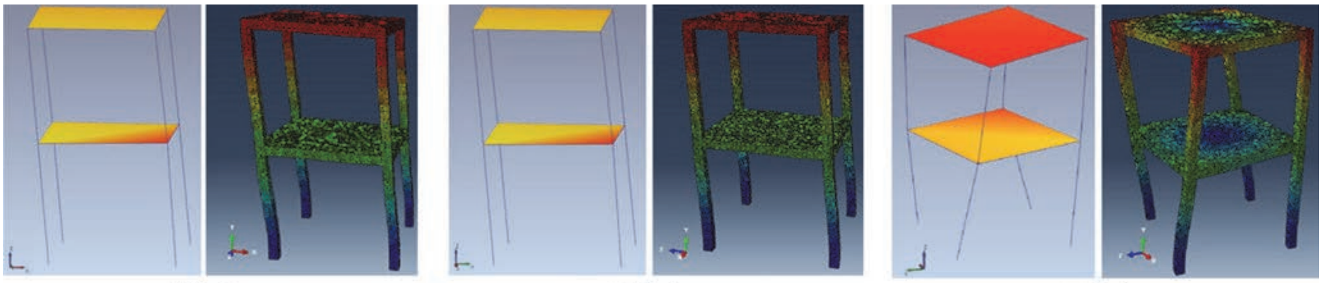
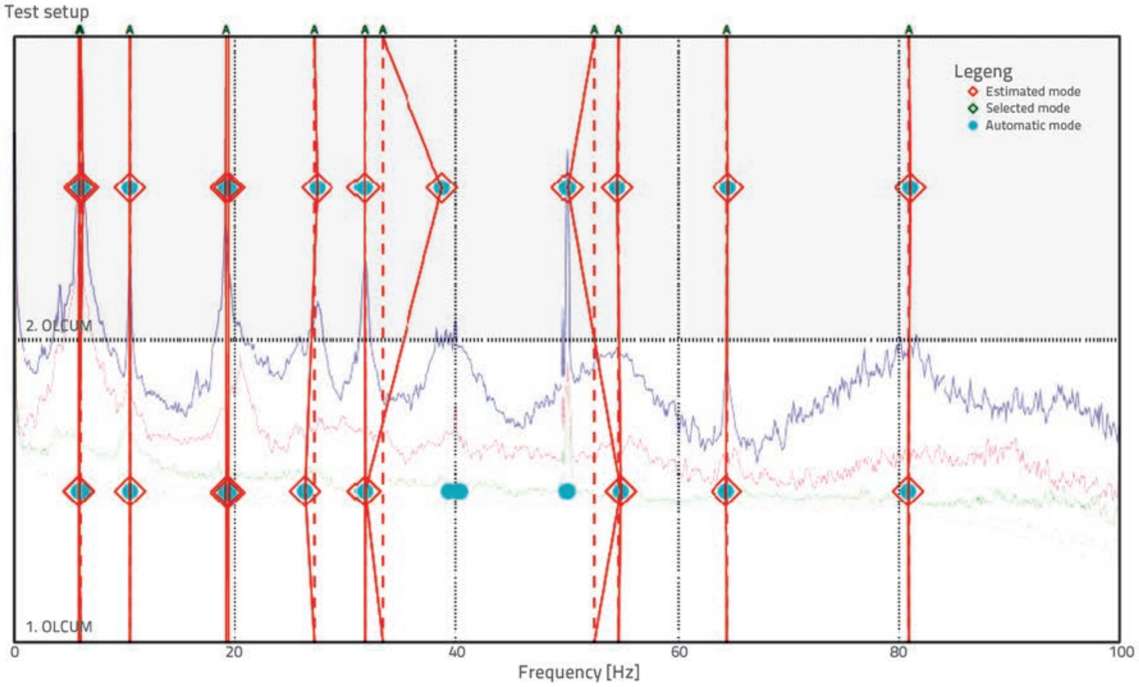
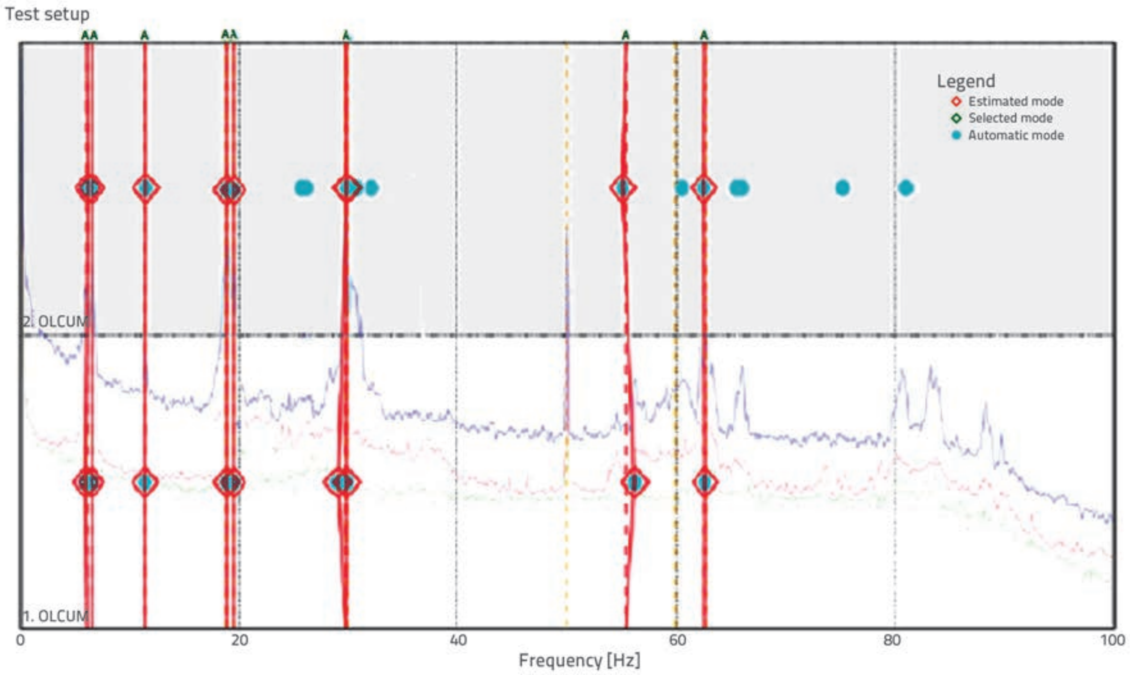

1st Mode
2nd Mode
3rd Mode

Figure 7. Experimental and numerical 1st, 2nd and 3rd modal shapes of the building



Mode	Frequency [Hz]	Mode	Frequency [Hz]
1	6.528	4	19.096
2	6.581	5	19.485
3	11.549	6	30.525

Figure 8. Dynamic modal parameters and stabilization diagrams of B1 building and frequency values



Mode	Frequency [Hz]	Mode	Frequency [Hz]
1	5.806	4	18.206
2	5.830	5	18.710
3	10.536	6	27.144

Figure 9. Dynamic modal parameters and stabilization diagrams of B2 building and frequency values

The symmetry between modes #1 and #2, and between modes #4 and #5, was established. Frequency values obtained by numerical solutions and experiments were similar.

4. Discussion

The OMA method was used to experimentally characterize dynamic characteristics of the normal and stirrups densification for buildings. Natural frequencies were measured by accelerometers placed on the building, and these data were transformed to dynamic characteristics using the AMP software. The data obtained and related comparisons are given in Table 3. As can be seen in Table 3, modal frequency values for the first and second modes, obtained by the experimental and numerical analyses, were the same due to symmetry of the building. B2 building, whose columns were treated with stirrups densification, had 12.43, 12.88, and 9.61% difference, respectively, in experimental frequencies for the first, second, and third modes, determined by the SSI method as compared to B1 building. Since measurements were taken in the lab environment, temperature fluctuations and instantaneous loading occurrences were controlled.

Table 3. Numerical and experimental characteristics of building

Mode	Frequency (FEM method) [Hz]			Frequency (SSI method) [Hz]			Damping ratios (SSI method) [%]	
	Structure B1	Structure B2	Difference [%]	Structure B1	Structure B2	Difference [%]	Structure B1	Structure B2
1	6.911	7.841	13.45	5.806	6.528	12.43	0.825	1.854
2	6.905	7.824	13.30	5.830	6.581	12.88	0.910	1.464
3	11.705	13.042	11.42	10.536	11.549	9.61	0.395	0.598

Therefore, any observed difference could be attributed to stirrups densification.

After application of stirrups densification to the building, modal frequencies determined by the SSI method for the first and mode were symmetrical. The difference between numerical and experimental values for the modal frequency was about 20%, which can be attributed to defects in the manufacture of the structure and boundary conditions.

As to numerical modal shapes of the building, the first mode was bending in the x-direction, the second was bending in the y-direction, and the third appeared as torsion. Modal shapes obtained by the SSI method, using the AMP software for the normal and stirrups densification applied to the building, were similar (Figure 8).

5. Conclusions

Our study investigated natural frequencies, modal shapes, and damping ratios of a scaled single-span two story building (with the normal or stirrups densification applied in columns). The solid model of the building, and the linear perturbation frequency analyses, were made using the ABAQUS software. The optimum mesh size was found to be 0.009 m. Frequencies and modal shapes were obtained through numerical analysis. The Operational Modal Analysis (OMA) method was used to experimentally determine dynamic characteristics of the normal or stirrups densification of the building. The following conclusions can be drawn from our study.

The geometry of the building was symmetrical. Therefore, the first and second modal shapes had the same values. The difference in the experimental modal values was about 13% between the stirrups densification and normal building. The stirrup condensed B2 column had higher frequency values, and hence a higher rigidity. With the OMA measurements, accurate data were acquired on dynamic properties of the normal and stirrup densified structures. This study shows that the stirrup densification positively affected dynamic properties of the tested structure.

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