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Experimental and Numerical Evaluation of Dynamic Characteristics of 3DOF Reduced-Scale Model

Avaliação Experimental e Numérica das Características Dinâmicas de um Modelo em Escala Reduzida de 3DOF

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Abstract

The dynamic behavior of structures subjected to seismic excitations is often predicted by numerical models based on the finite elements method. The reliability of the results of the numerical models must be subject to experimental validation. To achieve this, experimental tests using shaking tables lead to a more realistic prediction of the dynamic behavior of civil engineering structures. The main objective of this work is to develop an experimental procedure to determine the dynamic characteristics of civil engineering structures under seismic excitations. These dynamic characteristics are vital for understanding the real dynamic behavior of structures. For this, a three-degree-of-freedom (3DOF) reduced model of a steel structure adopting a 1:6 scale is developed. It is composed of three-level steel frames. Experimental tests are conducted using the shaking table of the RISAM laboratory (Risk Assessment and Management) at the University of Tlemcen. This work is focused on the two main dynamic characteristics of the reduced model, namely the predominant frequencies and the damping. The predominant frequencies of this reduced model are determined using a frequency sweep under a low-intensity white noise signal. This experimental procedure aims to detect the predominant frequencies by converting the recorded time history response to a signal depending on frequencies. Based on the logarithmic decrement method, the damping ratio is calculated. Next, a three-dimensional finite elements model of the reduced model is established. Several dynamic analyses of the finite elements model are performed. The experimental and numerical results are compared and discussed. The results obtained through these experimental tests show that the procedure used to determine the dynamic characteristics of this reduced model is very effective. Moreover, a perfect similarity is found between the experimental and numerical results.

Keywords: Shaking table. 3DOF reduced model. Dynamic characteristics. Predominant frequencies. Damping ratio.

Resumo

O comportamento dinâmico de estruturas submetidas a excitações sísmicas é frequentemente previsto por modelos numéricos baseados no método dos elementos finitos. A confiabilidade dos resultados dos modelos numéricos deve ser sujeita à validação experimental. Para alcançar isso, testes experimentais utilizando mesas vibratórias levam a uma previsão mais realista do comportamento dinâmico das estruturas de engenharia civil. O principal objetivo deste trabalho é desenvolver um procedimento experimental para determinar as características dinâmicas das estruturas de engenharia civil sob excitações sísmicas. Essas características dinâmicas são vitais para entender o comportamento dinâmico real das estruturas. Para isso, é desenvolvido um modelo reduzido de três graus de liberdade (3DOF) de uma estrutura de aço adotando uma escala de 1:6. É composto por estruturas de aço de três níveis. Os testes experimentais são realizados utilizando a mesa vibratória do laboratório RISAM (Avaliação e Gestão de Risco) da Universidade de Tlemcen. Este trabalho é focado nas duas principais características dinâmicas do modelo reduzido, a saber, as frequências predominantes e a amortecimento. As frequências predominantes deste modelo reduzido são determinadas usando uma varredura de frequência sob um sinal de ruído branco de baixa intensidade. Este procedimento experimental visa detectar as frequências predominantes convertendo a resposta do histórico temporal registrado em um sinal dependente de frequências. Com base no método do decremento logarítmico, a razão de amortecimento é calculada. Em seguida, um modelo tridimensional de elementos finitos do modelo reduzido é estabelecido. Várias análises dinâmicas do modelo de elementos finitos são realizadas. Os resultados experimentais e numéricos são comparados e discutidos. Os resultados obtidos através desses testes experimentais mostram que o procedimento utilizado para determinar as características dinâmicas deste modelo reduzido é muito eficaz. Além disso, uma perfeita semelhança é encontrada entre os resultados experimentais e numéricos.

Palavras-chave: Mesa de sacudidas. Modelo reduzido de 3DOF. Características dinâmicas. Frequências predominantes. Razão de amortecimento.

1. Introduction

Civil engineering structures and infrastructures are responsible for supporting and facilitating the daily lives of individuals and the socio-economic development of communities. However, these structures are subjected to various loads, making them susceptible to damage and collapse at any moment.

Earthquakes are one of the most critical excitations that can affect these civil engineering structures, causing considerable human and economic losses (Ayad, 2012; Benmansour, 2013; Benmansour *et al*., 2012; Derbal, 2021; Derbal *et al*., 2024; Zellat *et al*., 2023; Zerva, 2009).

To avoid these problems, it is important to understand the real dynamic behavior of structures, which allows us to design these structures in accordance with the specified standards and codes through the good representation of seismic excitations. Several effects can affect the seismic loading like the site, SVGM (spatial variability of ground motions) (Benmansour *et al*., 2021; Derbal, 2017; Derbal *et al*., 2007, 2018, 2019, 2022, 2023, 2019, 2021; Djafour *et al*., 2006).

The determination of the dynamic characteristics of structures is an important task in the field of civil engineering. This characterization allows for understanding the dynamic behavior of structures in response to different loads, such as seismic ground motions.

Several studies have been conducted in this context. Gong *et al*. (2008) and Sanli *et al*. (2001) analyzed the dynamic characteristics of a reinforced concrete building during earthquakes, and the modal frequencies were determined (Gong *et al*., 2008; Sanli & Çelebi, 2001). Another approach uses the Kalman filter to determine the modal parameters (Li *et al*., 2020; Xie *et al*., 2018). Zhou *et al*. (2017) employed hysteresis loops to calculate the frequencies of a reduced-scale reinforced concrete building (Zhou *et al*., 2017).

Recent studies focus on analyzing structural responses generated by the application of white noise excitations. This procedure has become one of the most effective methods commonly used for determining the dynamic characteristics of structures.

White noise, generated by controlled random vibrations using a shaking table, is used to analyze and identify the dynamic characteristics of structures(Gong *et al*., 2008). It allows for the determination of key characteristics such as predominant frequencies, vibration periods, and dynamic responses of structural systems. This approach can improve the design and the accuracy of finite element models.

The Results obtained from numerical models are commonly used to guide the design and construction of real models, but their accuracy and reliability often remain uncertain (Simoen *et al*., 2015).

This study aims to explore this issue by developing a three-story reduced model. The dynamic characteristics of this 3DOF reduced model are measured via the shaking table of the RISAM laboratory.

Then, the dynamic characteristics of this reduced model, evaluated experimentally, are compared with those obtained through numerical simulation. This approach will allow for the evaluation and understanding of potential discrepancies between theoretical and actual results, thereby offering valuable insights for improving the accuracy of models and simulations in the field of engineering, which enables a precise understanding of the exact behavior of structures, as well as the planning of optimal maintenance strategies for infrastructures to ensure the performance and durability of structures (Bassoli *et al*., 2018; Brownjohn *et al*., 2001; Chen, 2017; Chen & Ni, 2018; Jiménez-Alonso & Sáez, 2016; Moravej *et al*., 2017).

2. Description of the shaking table of the RISAM laboratory

The identification of the dynamic characteristics of a system involves the use of means to stimulate the structure and obtain usable vibration signals. Among these means, the shaking table is one of the devices commonly used to generate artificial earthquakes and other excitation signals in the laboratory (MTS Systems Corporation, 2014b, 2014a).

Many shaking tables are used for scientific research purposes in Algeria. Among the most important are the shaking table at the University of Chlef, the shaking table at the Scientific Research Center in Algiers, which is the largest shaking table in Algeria, and the shaking table at the RISAM laboratory at the University of Tlemcen (MTS Systems Corporation, 2014c, 2014a).

On an international scale, there is the shaking table at the University of California, San Diego, which is the largest outdoor shaking table in the world and is used to study the seismic behavior of large structures at their actual dimensions. There is also the shaking table of the University of Nevada, as well as a shaking table at the University of Japan, currently recognized as the largest shake table in the world (20 meters by 15 meters), used to study the behavior of buildings in seismic zones and to develop seismic-resistant structures and systems (Suita *et al*., 2009; Williams *et al*., 2001).

The experiment tests are performed based on the shaking table of the RISAM laboratory (Risk Assessment and Management Lab) at the Faculty of Technology, University of Tlemcen. This shaking table is uniaxial motion.

The main components of the shaking table include a rigid metal platform measuring 1.5 × 1.5 m² (see Figure 1a), resting on a reinforced concrete reaction mass covering an area of 3.5 × 5.5 m² with a depth of 3 m. This arrangement is complemented by the hydraulic power unit (see Figure 1b), a series of high-performance actuators, and a data acquisition system comprising 44 channels.

The maximum sampling rate per channel simultaneously is 512 data samples per second. Table 1 summarizes the main characteristics of the RISAM laboratory's shaking Table.

Table 1 – Main specifications of the shaking table of RISAM laboratory (MTS Systems Corporation, 2014c, 2014a).

Table dimensions	1.5 × 1.5 m²
Shaking direction	Unidirectional
Maximum specimen weight	2 tons
Real-time bandwidth	2048 Hz
Maximal acceleration	±1.0 g
Maximal speed	±1.0 m/s
Maximum displacement	±0.25 m
Maximum actuator force	42 KN
Maximum overturning moment	10 tm
Operating frequency	0-50 Hz

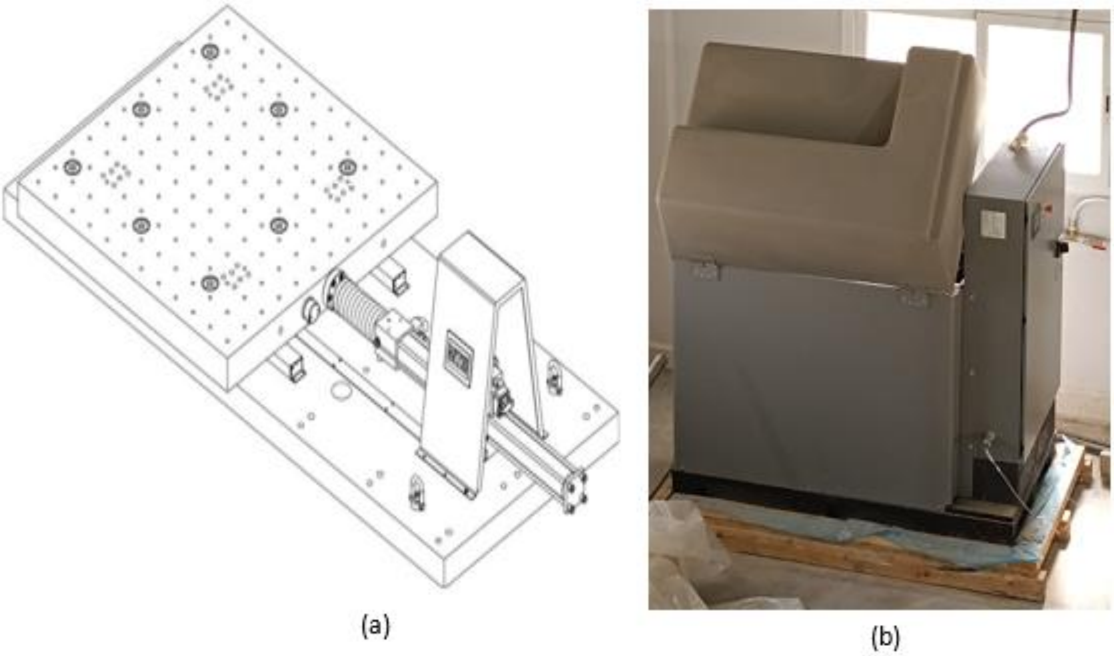

Figure 1 – The main components of the shaking table of the RISAM laboratory

3. Description of the reduced scale model

Figure 2 provides an overview of the 3DOF reduced model adopted with a scale of 1:6 fixed at the shaking table. It is composed of three-level steel frames, and each level measures 500 mm in height, with steel plates separating the levels over a span of 500 mm. The total mass of this structure amounts to 14.50142 kg.

The composition of this reduced model is divided into two main elements: the columns and the plates, which are connected by electric welding. The metal plates act as floors, with a cross-section of 80.33 × 8.4 mm² and a weight equal to 2.6539 kg, ensuring an adequate weight distribution across the entire structure. The columns have rectangular sections measuring 82 × 3 mm², thereby providing the stability and strength required for the tests on the shaking table. The reduced model proprieties are given in Table 2.

Figure 2 – The 1:6 reduced-scale model fixed at the shaking table

Table 2 – The mechanical properties of the model.

Proprieties	Specification
Density (Kg/m^3)	7800
Modulus of elasticity (N/m^2)	2.1×10^9
Poisson's ratio	0.2

4. Experimental test procedure

4.1. Experimental predominant frequencies identification

Predominant frequency is one of the most important dynamic characteristics of a structure. To determine experimentally the predominant frequencies of the 1:6 reduced model, a low-intensity frequency sweep is performed. This is conducted by applying a white noise signal to the reduced model by sweeping a large interval of frequency between 0 and 50 Hz. Then, the measured response is converted from the time domain to the frequency domain using the Fast Fourier Transform technique (FFT).

The reduced model is subjected to white noise excitation with an amplitude of 0.05 g. The dynamic response is recorded using uniaxial accelerometers placed on top of the reduced model. The data is sampled at 512 records per second, which is 1.953×10^{-3} s. This allowed the collection of a maximum amount of data for precise signal identification.

The response, in uniaxial accelerations following the direction of excitation, was recorded over 88 seconds. Figure 3 illustrates the input signal according to the accelerometer built into the shaking table, and Figure 4 gives the response signal recorded by the accelerometer on top of the reduced model.

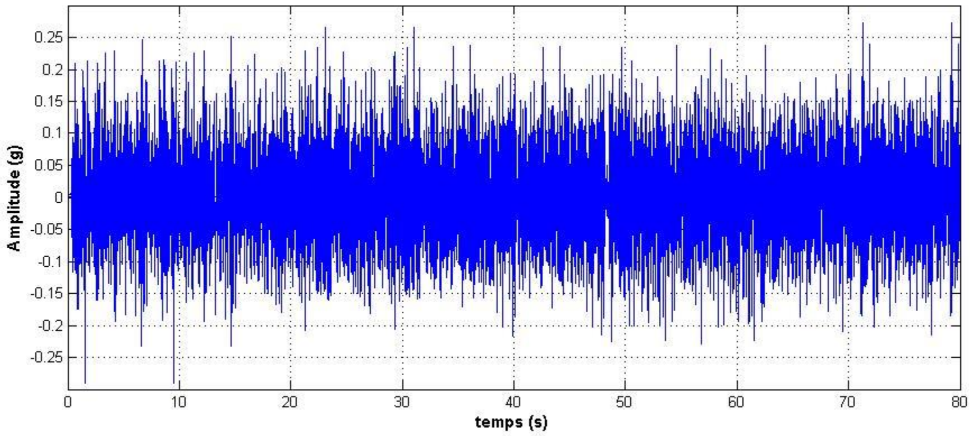

Figure 4 – Adopted white noise input signal

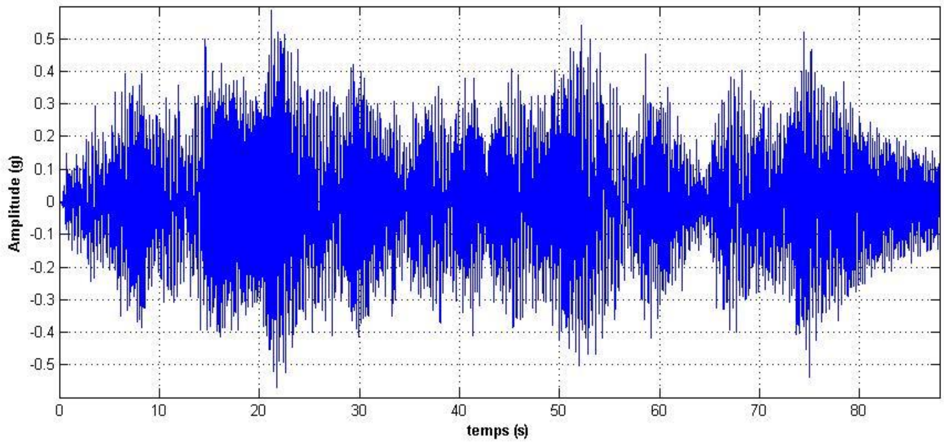

Figure 5 – Measured reduced model response in terms of acceleration

4.2. Experimental damping determination

The damping is an effect that reduces the amplitude of oscillations under dynamic excitations. In this work, the damping ratio is calculated experimentally using the logarithmic decrement method. It is determined based on the first mode because this mode accounts for more than 90% of the mass participation. This means that the dynamic behavior of the reduced model is characterized by the first mode of vibration.

To determine the damping ratio experimentally through free vibration tests. For this purpose, several tests are conducted using the shaking table.

<u>The logarithmic decrement method principle</u>

The structure oscillates with free vibration when the external excitation is annulled, which means that the second part of the motion equation is zero (Eq. 1). Thus, the equation of motion can be written as follows (Anil K, 2012):

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = 0 \quad (1)$$

By dividing by the mass m, we obtain:

$$\ddot{u}(t) + \left(\frac{c}{m}\right)\dot{u}(t) + \left(\frac{k}{m}\right)u(t) = 0 \quad (2)$$

With:

$\ddot{u}(t)$, $\dot{u}(t)$, and $u(t)$, which are the vectors of acceleration, velocity, and displacement, respectively.

k is the stiffness of the system, and c is the damping ratio.

Knowing that:

$$\xi = c/c_r \tag{3}$$

With:

ξ is the damping ratio and c_r the critical damping ratio.

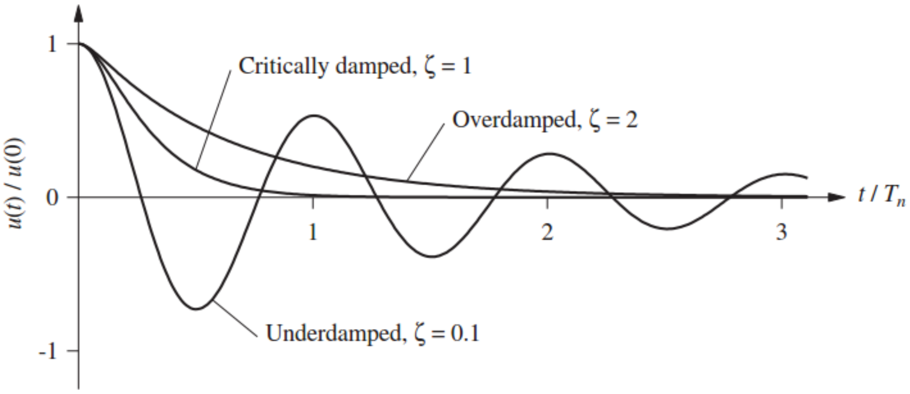

Figure 6 – Free vibration response (Anil K, 2012)

To determine the value of the damping ratio, two successive values of the maximum displacement of the structure are taken into account, which leads to the definition of the concept of logarithmic decay (Anil K, 2012):

$$\delta m = ln\,(u_n / u_{n+m}) \approx 2\pi m\, \xi \tag{4}$$

So, Eq. (1) can be written as follows:

$$\xi = \left(\frac{1}{2m\pi}\right) * ln\left(\frac{u_n}{u_{n+m}}\right) \tag{5}$$

With:

u_n and u_{n+m} represent the maximum displacements at time n and time $n+m$.

5. Finite elements model

A three-dimensional finite elements model of the 3DOF steel frame is developed. The beams and columns were represented by the "frame" element. The numerical model is illustrated in Figure 7.

6. Results and discussions

6.1. Numerical determination of predominant frequencies

Figure 8 presents the first three vibration modes of the numerical model, while Table 3 summarizes the periods and frequencies of these modes.

Table 3 – Frequencies and periods of the first three vibration modes of the finite elements model

Mode	Frequency (Hz)	Period (s)
1st Mode	3.043	0.328
2nd Mode	8.755	0.114
3rd Mode	12.543	0.079

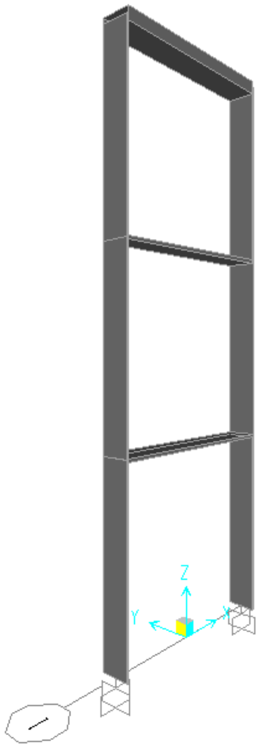

Figure 7 – Three-dimensional finite elements model

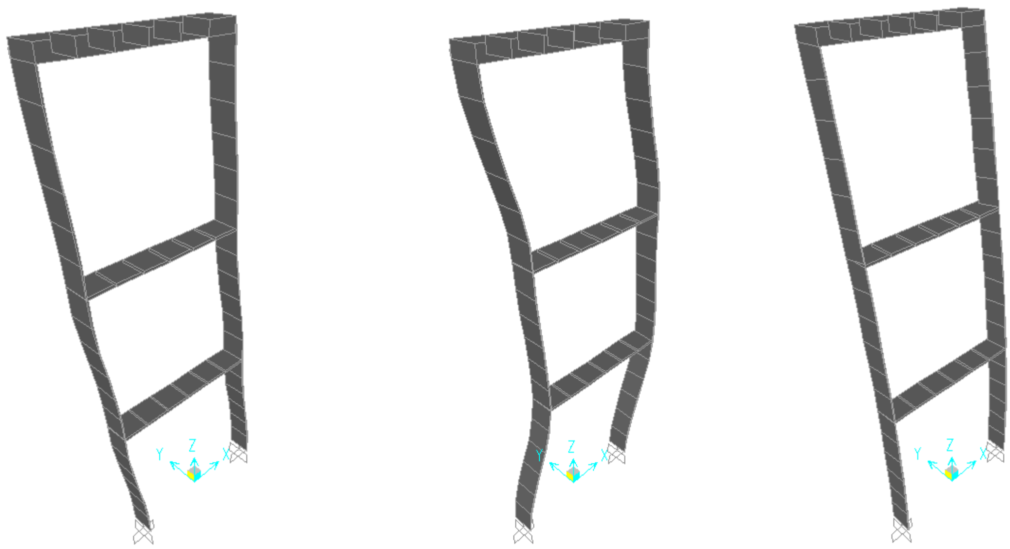

Figure 8 – The three first vibration modes of the finite elements model

6.2. *Experimental determination of predominant frequencies*

Using the shaking table of the laboratory of RISAM, the reduced model is subjected to white noise excitation for a duration of 88 seconds. The Fast Fourier Transform is used to convert the measured time history response in terms of acceleration (illustrated in Figure 5) is used to calculate the predominant frequencies of the reduced model (see Figure 9).

The peaks observed in Figure 9 represent the three predominant frequencies detected in the measured response under the white noise excitation. Table 4 summarizes the first three frequencies and periods of the vibration modes determined experimentally.

Table 4 – The experimental frequencies and periods of the first three modes of the reduced model

Mode	Frequency (Hz)	Period (s)
1st Mode	3.045	0.328
2nd Mode	8.636	0.115
3rd Mode	12.760	0.078

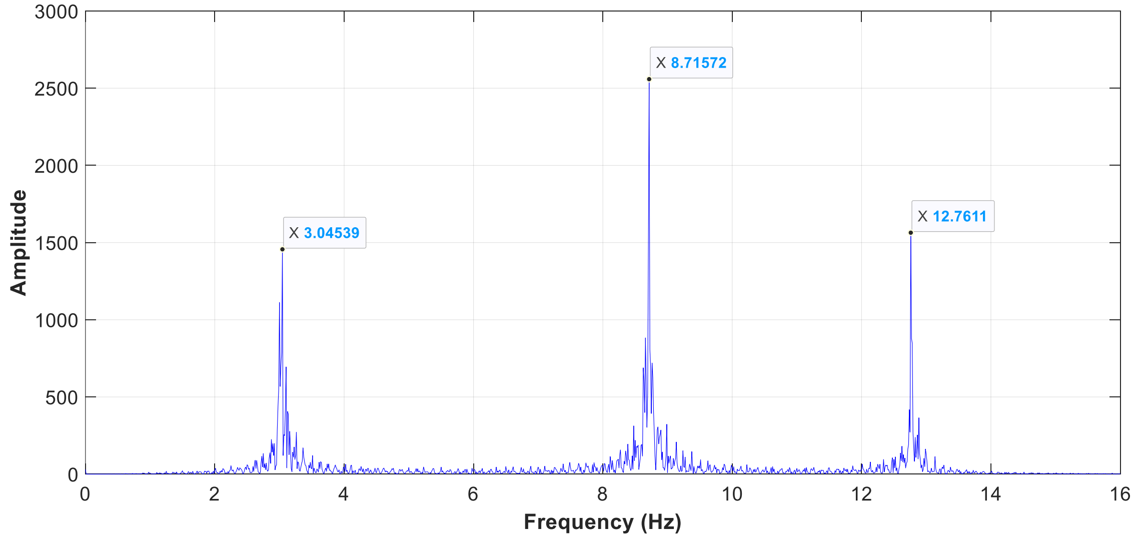

Figure 9 – The predominant frequencies calculated by the Fast Fourier transform

6.3. *Comparison of predominant frequencies*

In this section, the experimental and numerical predominant frequencies for the three vibration modes of the reduced model are compared. The results of this comparison are presented in Table 6 and illustrated in Figure 12.

Table 6 – Numerical and experimental frequencies and periods

Mode	Numerical	Experimental	Error
	Frequency (Hz)	Frequency (Hz)	
1st Mode	3.043	3.045	**1.00%**
2nd Mode	8.755	8.715	**1.00%**
3rd Mode	12.543	12.761	**1.02%**

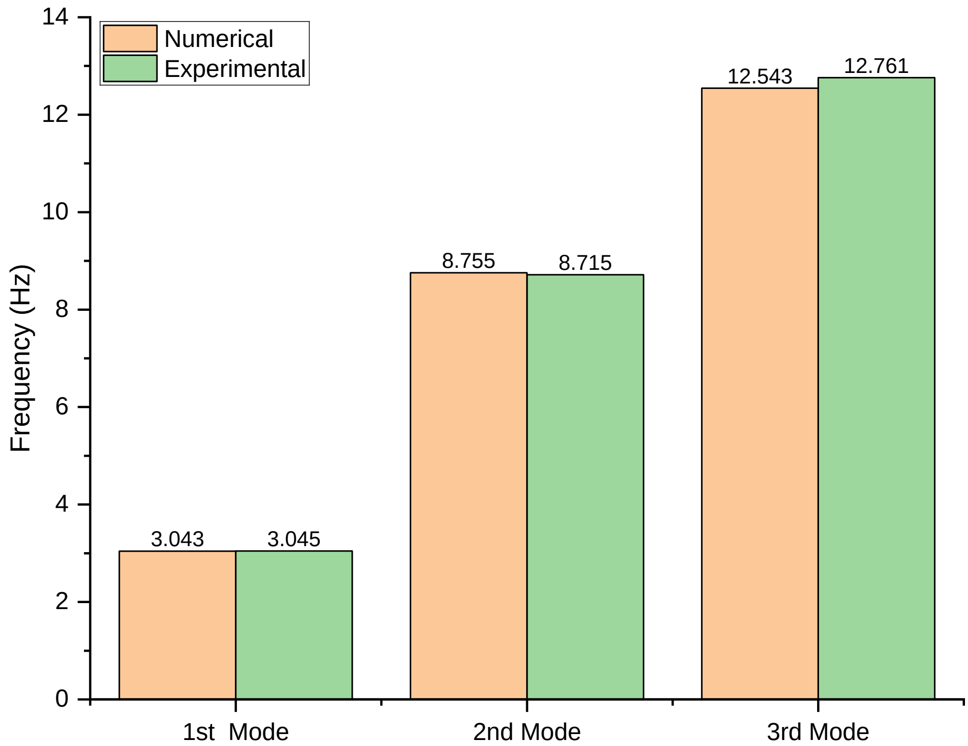

Figure 13 – Comparison of numerical and experimental frequencies

6.4. Experimental identification of damping

To experimentally determine the damping ratio, several free vibration tests are conducted using the shaking table. First, forced vibration tests are performed on the reduced model. After a determined duration to reach the permanent response, the applied excitation to the shaking table is canceled. The structure of the reduced model enters into free vibration (Figures 14, 15, and 16). In these figures, we observe that the acceleration of the shaking table, represented in the blue curve, is zero. At the same time, the reduced model continues to oscillate. The recorded accelerations of the model, described by the red curve, decrease until reaching zero motion after a duration.

Next, equations (4) and (5) are used to calculate the damping ratio for each free test vibration. Based on these tests, its average value is estimated to be around 0.61% (see Table 5).

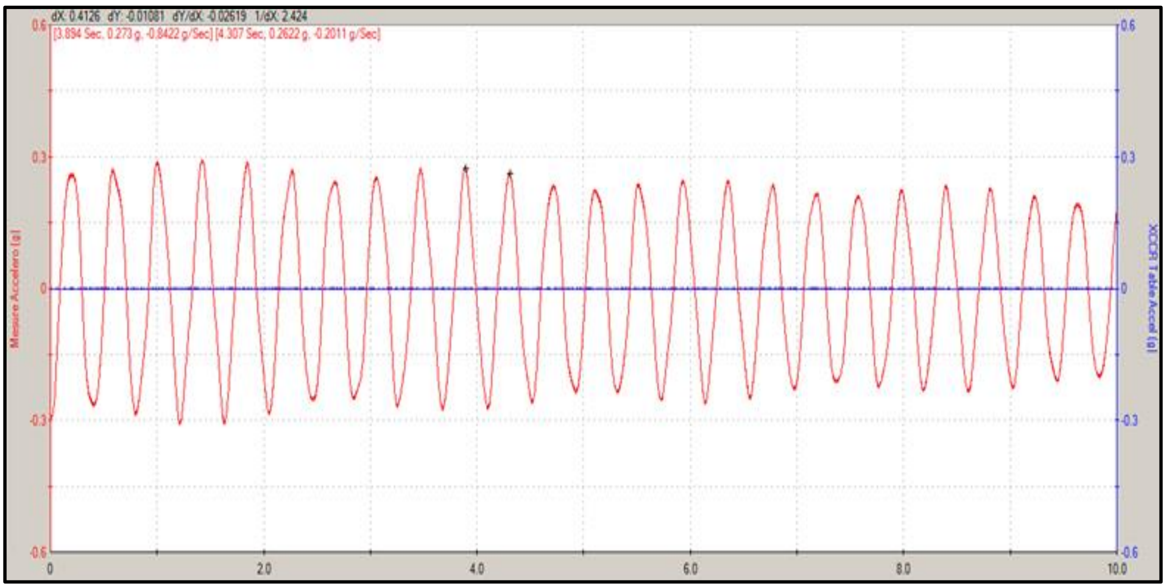

Figure 10 – First free vibration test of the model

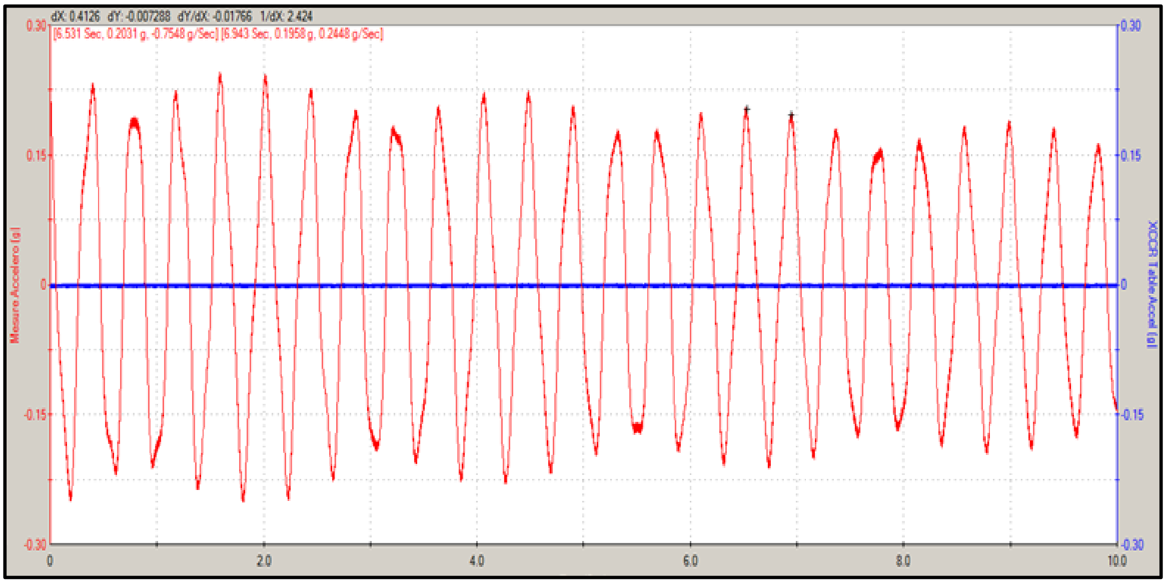

Figure 11 – Second free vibration test of the model

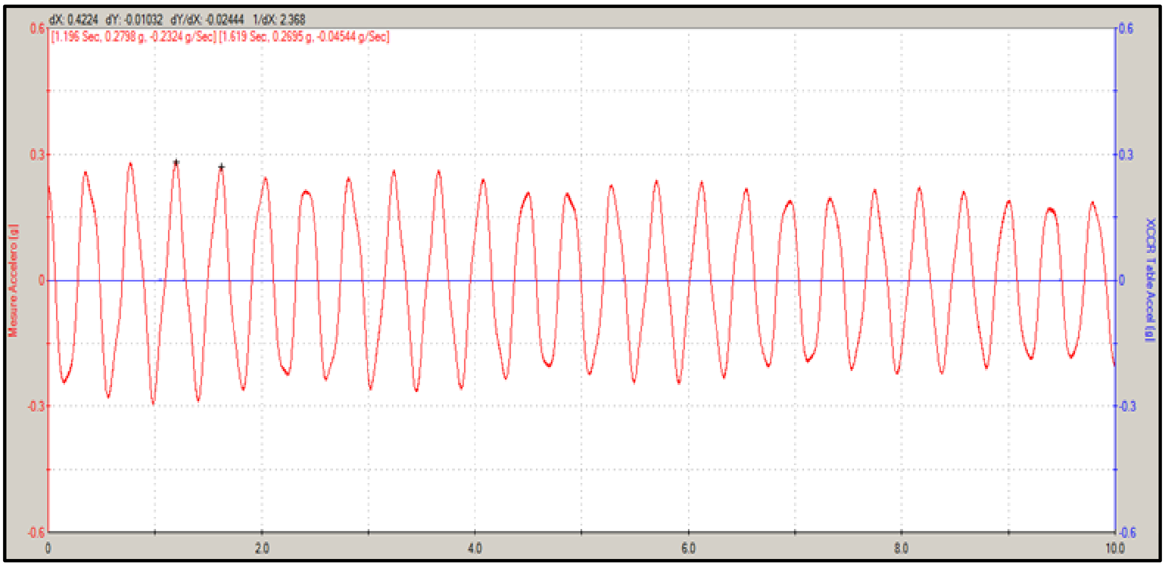

Figure 12 – Third free vibration test of the model

Table 5 – Experimental determination of damping ratio

Tests	Acceleration maximal		ξ (%)	Mean ξ
	U_n (g)	U_{n+m} (g)		
1st Test	0.2730	0.2622	0.64	
2nd Test	0.2031	0.1958	0.58	**0.61%**
3rd Test	0.2798	0.2695	0.60	

6.5. Discussion

The predominant frequencies of the reduced model are determined by the experimental and numerical approaches. The results of these two approaches reveal a remarkable level of concordance.

The first three modes showed remarkable similarity, with a very low error of about 1% between the experimental and numerical results. Furthermore, it is essential to note that numerical methods are designed to generate an approximate simulation of structural behavior.

Nevertheless, despite these considerations, the approaches used to determine the main dynamic characteristics of the reduced model are validated. The calculation of experimental damping led to a very low value, ξ = 0.61%, which indicates that it has no significant influence on the dynamic behavior of this reduced model.

7. Conclusions

The main dynamic characteristics of a 1:6 reduced model is identified by experimental and numerical approaches. First, a white noise signal with a very low amplitude is applied to the reduced model trough the shaking table. Then, the predominant frequencies are determined by the FFT of the measured response of the reduced model.

A three dimensional finite elements model is constructed and the predominant frequencies are calculated by the modal analysis. Then, the damping ratio of this steel model is calculated according on the logarithmic decrement method.

The comparison of the experimental and numerical dynamic characteristics led to a perfect concordance. Indeed, the experimental results demonstrate that the adopted approach is very effective.

The shaking table of the laboratory RISAM, used to perform the experimental dynamic tests for the identification of the reduced model, provides efficient results.

The experimental calculation of damping of the reduced model gives a very low damping ratio. This indicates that this damping ratio have no significant influence on the dynamic behavior of this reduced model.

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