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IDENTIFICTION OF DYNAMIC CHARACTERISTICS OF A CONTINUOUS DYNAMIC SYSTEM: CASE STUDY FOR A FLEXIBLE STEEL STAIRWAY

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Abstract

In this work, a modal shape identification procedure for a flexible steel stairway located within a building complex at Aristotle University in Thessaloniki, Greece is presented. The aforementioned stairway is a system with continuous distribution of mass and stiffness, a fact that makes structural identification challenging as compared to structures where these two basic parameters are observed to be lumped at certain locations such as the floors and the vertical support elements. More specifically, this stairway was instrumented using a local multi-channel network of accelerometers. Two twelve-bit nominal resolution, digital uniaxial accelerometers, connected by cables and with 'common time' and 'common start' characteristics were installed on the stairway. Dynamic input to the stairway was provided by pedestrian traffic. The dominant modes of vibration of the stairway were computed by the 'modal response acceleration time history' methodology, as developed by the authors over the last few years. In parallel, a detailed finite element method model of the stairway was built and calibrated according to the ambient vibration results. The present identification procedure used for the dynamic characteristics of spatial structures yields results that can be used to develop a family of numerical models for the stairway ranging from the simple single-degree-of-freedom system to highly detailed multiple-degree-of-freedom models. Finally, some useful information on the theoretical procedure for the identification of modal shapes is included in this work.

Keywords: *Modal identification; mode shapes; modal response; acceleration time histories; finite element models;*

1. Introduction

Steel stairways are used mainly as emergency exits in hotels, hospitals and public buildings. Experimental and numerical studies of their static and dynamic behavior is important for various reasons. For instance, steel stairways are usually attached to a pre-existing structure made of different structural material, which is usually reinforced concrete. Furthermore, they are open-air structural elements and thus their loads are mainly generated from environmental conditions. Moreover, in case of an emergency, humans ascend and descend at a pace higher than walking, which results in a high frequency loading. In many cases, steel stairways are slender structures, which makes them vulnerable to vibrations. Therefore, any information concerning the dynamic properties in terms of eigenmodes and eigenfrequencies of the stairway is important for both design and maintenance.

In the last few years, issues such as 'monitoring' and 'structural integrity' of structures is being developed by employing suitable, multi-channel networks for measuring acceleration response time-histories, followed by appropriate data processing techniques. If the structural response remains within the linear elastic range, then the recorded acceleration response time-histories contain the structure's modal response. It is well known that a clear deterministic relationship between ambient vibration loading or ground excitations as input and the ensuing structural response as output does not exist. Furthermore, the methodologies used to identify the dynamic characteristics (i.e., natural frequencies, mode shapes and modal damping ratios) of a structure must take into account the instrumentation configuration that is used for monitoring. Thus, many methodologies are adapted to investigate dynamic structural response on a case-by-case basis. The main objective in all cases is to identify the dynamic characteristics of the structure through an analytic processing of the measured response. In the past, various deterministic and stochastic methods have been proposed [1-8]. Although there are many techniques available for structural identification, as well as commercial software packages for general use, the structural engineering community has yet to agree on a universally accepted procedure for identifying the dynamic characteristics of structures and structural systems (e.g, buildings, bridges, towers, dams, plus other categories of structures such as automobile and aircraft frames) from their measured response.

Despite advances in analysis provided by various numerical methods, there still exist challenges regarding the prediction of the actual dynamic behavior of stairways. Some of the most crucial uncertainties concerning the behavior of an existing stairway refer to the lack of information on the as-built structure (architectural plans, material properties, foundation design, etc.), the boundary conditions and the effects of non-structural elements [9]. The gap between real structural behavior and numerical model prediction can be bridged by performing various modal tests on the existing structure, see [10]. More specifically, various researchers have recently studied the behavior of steel stairways numerically [11-14].

The present work identifies the dynamic characteristics of a specialized type of steel stairway with continuous mass and stiffness distribution. These stairways serve as escape routes from high-rise buildings, are placed externally to the building and can be classified as flexible structures. Also, since low amplitude ambient vibrations are used as the external excitation, the assumption of viscously damped modes is acceptable. The analysis procedure presented in this work is adapted to the particular instrumentation configuration used on the steel stairway, supplemented by the method of 'modal time-histories' [6-7]. This methodology has been applied in modal characteristics identification of pedestrian bridges, where the source of excitation is ambient vibrations induced by ordinary, daily use of the stairway by people [15-16]. Within this framework, a parallel modeling procedure using the finite element method (FEM) based SAP 2000 [17] software was developed and the results obtained were calibrated against the experimental data. The FEM. models were then recalibrated and used to reproduce details in the dynamic response of the stairway. This way, the numerical models help extend the results of the experimental effort and can be used to trace the ageing and deterioration phenomena expected during the useful service life of the stairway.

2. Case Study Outline and Modeling

The steel stairway under study is located in the courtyard behind the main building of the Civil Engineering Department at Aristotle University, Thessaloniki, Greece (see Fig. 1 for an architectural plan). The stairway was constructed in 1982 and comprises three spans which terminate at three landing levels of a low rise annex building housing laboratories. The central span is supported by two beams (IPN140 cross section), while the beams supporting the other two end spans, as well as the landings, are IPN100 cross sections. The columns supporting the beams at the second landing, as well as the main column of the third landing, are IPN140 cross sections. All remaining columns of the structure are IPN100 cross sections. As illustrated in Fig.1, the IPN140 columns are connected by cross diagonal bars with an RHS 60x40 cross section. These cross bars supplement the lateral stiffness of the stairway and reduce the buckling length in the columns. The vertical stiffness of the landing is reinforced by the contribution of T50 beams on the first landing and IPN beams on the other two. Finally, the landings, the treads and the risers are made of sheet metal plates of 3mm thickness. The same material is used as protective sideway cover for the beams.

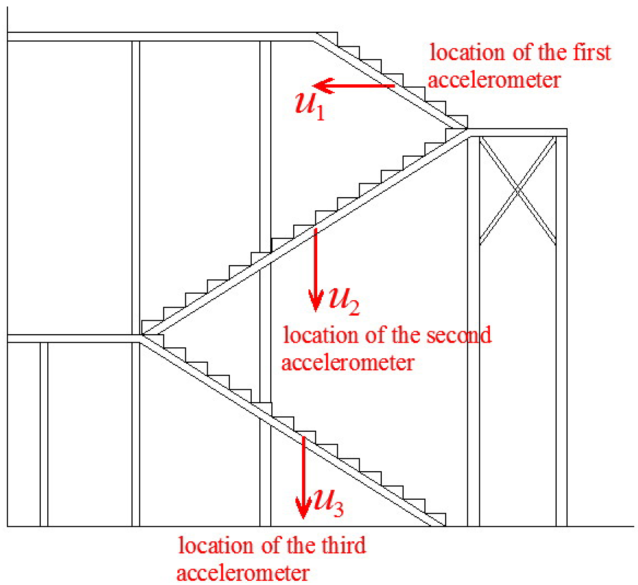

Fig. 1 - Location of accelerometers at key points in the three-story steel stairway

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Next, the instrumentation scheme used during a two week time period for conducting the measurements comprised three uniaxial accelerometers, see Fig. 1. We note that the stairway under study cannot be modeled as a lumped mass system, since there is no detectable concentration of mass at any floor level. Therefore, the structural system is continuous in terms of the mass and stiffness distributions, and this causes difficulties in the identification of the eigenmodes. In accordance to the accelerometer placement scheme, the vector **u** corresponds to three basic degrees of freedom (DOF), and the generalized matrices for the mass **M**, the stiffness **K** and the damping **C** of the steel stairway are fully populated, as shown below.

$$\mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}, \quad \mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix}, \ \mathbf{C} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \tag{1}$$

The equation of motion of the steel stairway subjected to environmentally-induced dynamic loads is now the following:

$$\mathbf{M}\,\ddot{\mathbf{u}}(t) + \mathbf{C}\,\dot{\mathbf{u}}(t) + \mathbf{K}\,\mathbf{u}(t) = \mathbf{W}(t) \tag{2}$$

In the above, $\mathbf{W}(t)$ is the loading vector of the unknown environmental dynamic loading on the specified DOF. For this case, the solution of Eq.(2) is of the following form:

$$\mathbf{u}(t) = \boldsymbol{\varphi}_1 q_1(t) + \boldsymbol{\varphi}_2 q_2(t) + \boldsymbol{\varphi}_3 q_3(t) = [\boldsymbol{\varphi}_1 \quad \boldsymbol{\varphi}_2 \quad \boldsymbol{\varphi}_3] \begin{bmatrix} q_1(t) \\ q_2(t) \\ q_3(t) \end{bmatrix} = \boldsymbol{\Phi}\, \mathbf{q}(t) \tag{3}$$

where

$$\boldsymbol{\Phi} = [\boldsymbol{\varphi}_1 \quad \boldsymbol{\varphi}_2 \quad \boldsymbol{\varphi}_3] = \begin{bmatrix} \varphi_{11} & \varphi_{12} & \varphi_{13} \\ \varphi_{21} & \varphi_{22} & \varphi_{23} \\ \varphi_{31} & \varphi_{32} & \varphi_{33} \end{bmatrix}, \qquad \mathbf{q}(t) = \begin{bmatrix} q_1(t) \\ q_2(t) \\ q_3(t) \end{bmatrix} \tag{4}$$

More specifically, $\boldsymbol{\varphi}_1$, $\boldsymbol{\varphi}_2$, $\boldsymbol{\varphi}_3$ are the basic three eigenmodes; $\boldsymbol{\Phi}$ is the modal matrix of the steel stairway and $q_i(t), i = 1,2,3$ are the corresponding generalized time functions of vibration for each eigenmode.

It can been proven that the system of Eq.(2), which is particular to the placement scheme of the three accelerometers, is equivalent to a single degree of freedom (SDOF) vibrator response for each eigne-mode i and is described below (see [6-7]) as follows:

$$\ddot{q}_i(t) + 2\xi\omega_i\dot{q}_i(t) + \omega_i^2 q_i(t) = \frac{\boldsymbol{\varphi}_i^T\, \mathbf{W}(t)}{\boldsymbol{\varphi}_i^T \mathbf{M}\, \boldsymbol{\varphi}_i} \tag{5}$$

Equation (5) shows that any solution for the calculation of the time varying modal functions $q_i(t)$ requires a known environmentally-induced dynamic loading vector $\mathbf{W}(t)$, which is of course impossible to estimate a priori. However, it is clear that its exact solution is a superposition of the solution $q_{o,i}(t)$ to the homogenous equation and of the particular solution$q_{w,i}(t)$, which in turn depends on the dynamic loading $\mathbf{W}(t)$:

$$q_i(t) = q_{o,i}(t) + q_{w,i}(t) \tag{6}$$

Moreover, it is known that for free vibrations, the exact solution $q_{o,i}(t)$ for the homogenous equation coincides with the final solution. Consequently, suppose a theoretical situation where the structure vibrates, then the action of the dynamic loading $\mathbf{W}(t)$ ceases and its free vibration response is now being recorded. In this case, the condition that the solution $q_{o,i}(t)$ of the homogenous equation is also the final solution of the problem is fulfilled:

$$q_i(t) = q_{o,i}(t) \tag{7}$$

More specifically, each term in the summation of Eq. (3) represents the modal response movements $\mathbf{u}_i(t)$ for each *i*=1,2,3 eigenmode:

$$\mathbf{u}_i(t) = \boldsymbol{\varphi}_i\, q_i(t) \quad \Rightarrow \quad \begin{bmatrix} u_{1i}(t) \\ u_{2i}(t) \\ u_{3i}(t) \end{bmatrix} = \begin{bmatrix} \varphi_{1i}\, q_i(t) \\ \varphi_{2i}\, q_i(t) \\ \varphi_{3i}\, q_i(t) \end{bmatrix} \tag{8}$$

From the combination of Eqs.(7) and (8), the following conclusion is drawn: If dissociation of the modal responses $\boldsymbol{\varphi}_\mathrm{i}\, \mathrm{q_i(t)}$ for each DOF of the system is feasible, then the direct estimation of the components of each one of the eigenmodes by elimination of the time function $\mathrm{q_i(t)}$, which is common to all the degrees of freedom of the same eigenmode, would also be feasible. Indeed, referring at the instant of the simultaneous extreme amplitudes of vibration (a, b, c) for all DOF ($\mathrm{u_1}$,$\mathrm{u_2}$, $\mathrm{u_3}$) as shown in Fig. 2, the components of the *ith*-eigenmode are directly described by the following equation:

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} \Rightarrow \begin{bmatrix} a/a \\ b/a \\ c/a \end{bmatrix} = \begin{bmatrix} \varphi_{1i} \\ \varphi_{2i} \\ \varphi_{3i} \end{bmatrix} = \begin{bmatrix} 1 \\ \varphi_{2i} \\ \varphi_{3i} \end{bmatrix} \tag{9}$$

The uncoupling of the modal response is achieved numerically by truncation of the harmonic having a frequency equal to the *ith*-eigenfrequency of the structure. This truncation uses an appropriate digital filter applied to the initial recordings, which permits only the transmission of one specific frequency, that which equals the eigenfrequency of the structure, so long as the latter is already known. The eigenfrequency of the structure can be determined by the combination of the “peak-picking” technique applied to the Fast Fourier

Transform (FFT) diagrams of the recordings, followed by an examination of the phase difference between the extreme response values. This last point must take into account, as a phase difference of 0 or π (rad) between different recordings corresponds to an eigenmode. The aforementioned method is known as the 'modal time-history method' and has been recently developed in [6,7]. This the method is now applied to the steel stairway, which is a system with infinite DOF having a continuous mass and stiffness distribution and this makes the identification of the basic eigenfrequencies quite difficult.

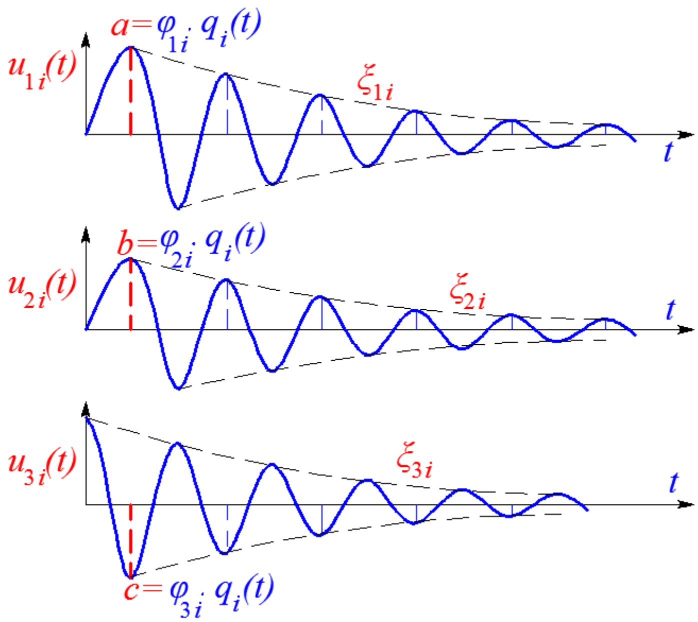

Fig. 2 - Modal time-histories of the three DOF system

3. Steel Stairway Instrumentation Blueprint

The stairway was instrumented by a system of two 12 bit-nominal resolution, digital uniaxial accelerometers of the type KYOWA-PCD-30A. One sensor (channel 1) was used for the recording of the vertical accelerations, while the second sensor (channel 2) was used for the recording of the horizontal accelerations, see Fig. 1. The fastening of the sensors on the lower surface of the treads was achieved by the use of silicon adhesives. The sensor recording the horizontal accelerations (reference accelerometer) was installed in the middle of the third span, while the sensor recording the vertical accelerations was alternately installed in the middle of the first and second spans. The ambient vibration loading was realized during regular use, with people ascending and descending the steel stairway. Usually people did not stay put on the stairway, but merely went up and down in a short time interval. A sufficient number of response recordings was made, and durations of two (2), five (5) and fifteen (15) minutes were considered, including the free vibration part of the response as well. The two accelerometers were connected to a logging unit for receiving data, which in turn was connected to a laptop computer. Using the appropriate software, visualization and calibration of the recordings took place. By selecting a range of 10000 μm/m and a calibration factor of 0.000829, the accelerometer in the vertical vibration direction was capable of recording the acceleration of gravity g=9.81m/s^2 under calm conditions. The software used also offers the ability of exporting data in the .xls format. Therefore, the recordings were easily imported and processed in a spreadsheet (e.g., MS Excel program).

5. Ambient Vibration Recorded Signal Processing

During the processing of the recordings, multiple time windows were examined. The forced vibration part was truncated and only the part of the free vibration was taken into consideration. The noise was removed from the free vibration recordings by the use of appropriate filters using the SeismoSignal software [18]. Finally, the FFT of each DOF was calculated. The main observation concerning the FFT diagrams refers to the lack of the usual 'spikes' for certain eigenfrequencies due to the fact that the steel stairway does not respond as a discrete system, since it does not contain any sizeable lumped masses, see Figs. 3 and 4.

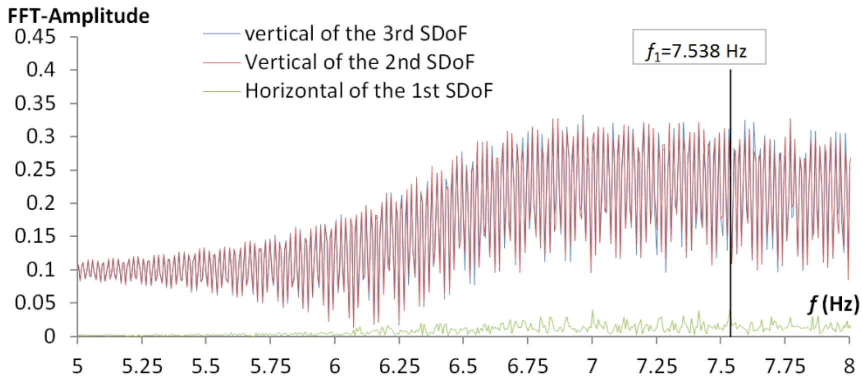

Fig. 3 - FFT of the three displacement components from 5 Hz to 8 Hz

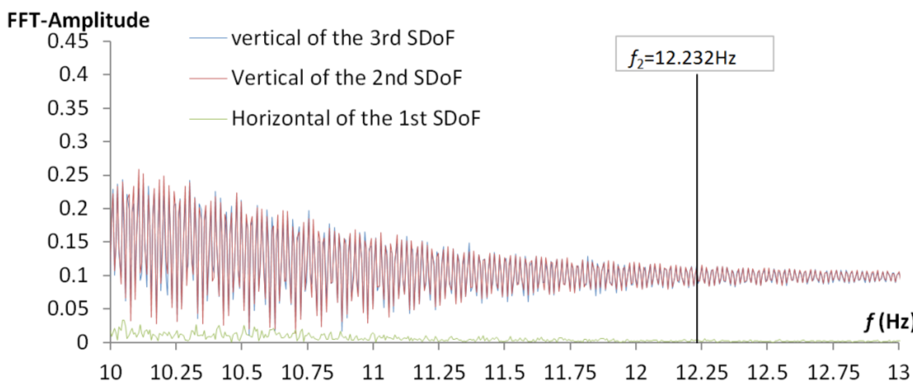

Fig 4 - FFT of the three displacement components from 10Hz to 13 Hz

More specifically, the FFT displacement amplitudes present a rather smooth uniformity, due to the fact that that the structure performs as a system with continuous mass and stiffness distribution. Combining the 'peak-picking' technique with an estimation of the phase difference between the modal response histories, it is possible to detect whether or not the peaks observed refer to the modal response of the structure or simply stem from the external dynamic loading. This way, the peaks in the entire frequency range of FFT diagrams were sequentially examined. As a result, two frequencies, at f_1=7.538Hz and f_2=12.232Hz, were identified as being the most likely eigenfrequencies of the structure. Indeed, the time histories corresponding to these two frequencies, present a phase difference of 0 and π rad respectively, as illustrated in Figs. 5 and 6.

According to Figs. 3, 4 and Eq.(9), the modal components of the two eigenmodes of the stairway were computed by suitable filtering via the SeismoSignal software[18] and the following values were recovered

$$\boldsymbol{\varphi}_1 = \begin{bmatrix} \varphi_{11} \\ \varphi_{21} \\ \varphi_{31} \end{bmatrix} = \begin{bmatrix} 1 \\ 41.405 \\ 47.50 \end{bmatrix}, \ \boldsymbol{\varphi}_2 = \begin{bmatrix} \varphi_{12} \\ \varphi_{22} \\ \varphi_{32} \end{bmatrix} = \begin{bmatrix} -1 \\ 51.16 \\ 44.00 \end{bmatrix} \tag{10}$$

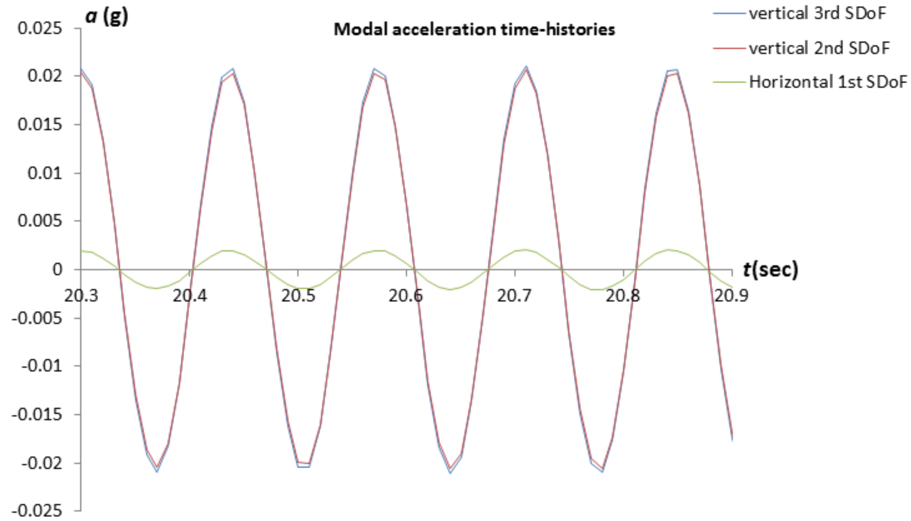

Fig. 5 - Modal acceleration time-histories for frequency f_1=7.54 Hz, where the phases between the three components are zero

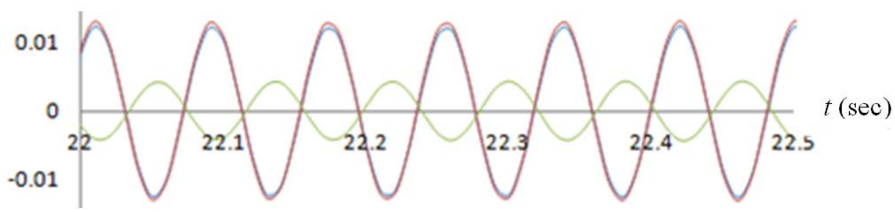

Fig. 6 - Modal acceleration time-histories for frequency f_2=12.23 Hz, where the phase between the first component and the other two is π

Finally, the free vibration part of the modal time histories components was used in order to calculate the equivalent modal damping ratios ξ^{mod}, by applying the equation of the logarithmic decrement in each of the three modal components. As shown in Table 1, the final averaged equivalent modal damping ξ corresponds to the mean value of the aforementioned ξ^{mod}.

4. FEM Model of the Steel Stairway

In the present study, the FEM modeling of the steel stairway is based only on information provided and/or estimated by appropriate engineering judgment regarding the as-built structure from architectural plans and from actual measurements. In what follows, we list all necessary assumptions regarding the built-up of the FEM model of the steel stairway (see Fig. 7) using the commercial program SAP 2000, version 6.1 [17].

(1) Each structural element is considered to behave as a linear, elastic and isotropic material.

(2) The structure is built of structural steel (span beams and landing beams, columns and guardrails) and of sheet metal (risers, treads and landings).

(3) Frame elements are used to model all beams, the supporting columns and the columns of the guardrails. These frame element in SAP2000 [17] correspond to the general, three-dimensional, beam-column formulation which includes the effects of biaxial bending and shear, of torsion and of axial action.

(4) Existing overlapping and/or eccentricities in the frame elements cross sections coming at a joint is taken into account by the 'end offsets' formulation provided by SAP 2000.

(5) Four-node shell elements are used to model all the surface elements of the stairway, such as the landings, the risers and the treads.

Table 1: Modal and equivalent viscous damping ratios for the stairway

f_1=7.35 Hz	ξ^{mod}	ξ_1=0.0045
1st DOF	0.0037	
2nd DOF	0.0048	
3rd DOF	0.0049	
f_2=12.23 Hz	ξ^{mod}	ξ_2=0.0070
1st DOF	0.0073	
2nd DOF	0.0065	
3rd DOF	0.0071	

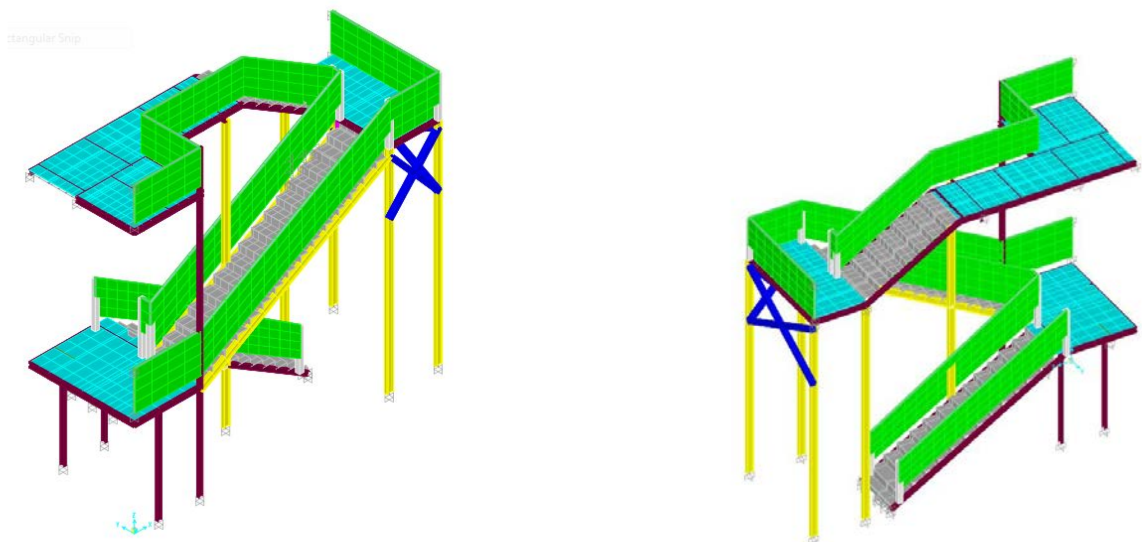

Fig. 7 - FEM model of the steel stairway using SAP2000: (left) front view showing the middle span; (right) back view showing the first and third spans

(6) Four-node shell elements are also used to model the guardrails, as they add stiffness to the adjacent structural elements, see [19].

(7) The homogeneous shell element formulation provided by SAP2000 [17] is selected, which combines independent membrane and plate action.

(8) The selection of isotropic behavior in the aforementioned shell finite elements is based on the investigation conducted [20] for a monumental stair. From the aforementioned study, it was concluded that orthotropic properties in the shell elements do not contribute to the possible discrepancies between the measured and computed natural frequencies.

(9) The existing welded connections between all of the parts of the stairway are modeled as fully continuous connections.

(10) The total mass of the canopy is taken into account under the assumption of lumped masses at the common nodes with the stairway beams.

One of the main modeling uncertainties is the boundary conditions [9]. The steel stairway under study is supported on the ground level by eight steel columns and a concrete surface block, which is in turn connected to the lower level of the first span. Furthermore, the stairway is supported laterally by beam ends, inserted into the adjacent building walls. In order to investigate the effect of the boundary conditions on the dynamic characteristics of the stairway, three different FEM models were created. The first model considers all supports as fixed, the second considers all supports as pinned and the third considers all supports as fixed, except for the lateral ones.

4.1 *Modal analysis*

In order to investigate the dynamic characteristics of the steel stairway, a modal analysis is performed to recover the undamped, free-vibration mode shapes and eigenfrequencies of the system. These natural modes provide insight into the dynamic behavior of the steel stairway, and the first three are depicted in Fig. 8. All three FEM models used yield the same order of eigenmodes. In particular, the first eigenmode refers to the modal deformed shape of the second span of the stairway, the second eigenmode to the first span and the third eigenmode refers to the third span. Therefore, the boundary conditions details do not alert the order of the eigenmodes.

On the other hand, the different boundary conditions affect the numerical values of the eigenfrequencies corresponding to each mode. These values are summarized in Table 2 for the first ten computed eigenfrequencies, as well as their variation under the different boundary condition assumptions. The first eigenfrequency values range between 7.24Hz and 7.26 Hz, the second eigenfrequency values between 7.65 Hz and 7.81Hz and the third eigenfrequency values between 13.27 Hz and 14.23 Hz. In all, the aforementioned eigenfrequencies are in good agreement with the experimental data, i.e., f_1=7.53 Hz and f_2=12.23 Hz.

Table 2: FEM model eigenfrequencies of the stairway for three different boundary condition hypotheses

Mode	Fixed Supports	Pinned Supports	Pinned Lateral Supports	Difference between Models 2 &1	Difference between Models 3 &1
	f (Hz)	f (Hz)	f (Hz)	Δf (%)	Δf (%)
1	7.26	7.24	7.26	-0.22%	-0.04%
2	7.71	7.65	7.81	-0.70%	1.35%
3	14.24	13.28	13.28	-6.74%	-7.18%
4	15.22	15.09	15.09	-0.86%	-0.86%
5	15.78	15.72	15.73	-0.39%	-0.32%
6	17.80	17.63	17.63	-0.93%	-0.94%
7	19.20	19.06	19.11	-0.76%	-0.47%
8	19.47	19.44	20.40	-0.14%	4.82%
9	20.46	20.11	20.52	-1.72%	0.28%
10	21.04	20.52	20.53	-2.49%	-2.50%

The pinned support assumption in the second FEM model leads to an even more flexible steel stairway compared to that of fixed supports (the first FEM model). Also, the first two eigenfrequencies are not much affected by the actual support type, whereas the third eigenfrequency is reduced considerably by 6.74%. Therefore, it is the dynamic behavior of the third span that is mostly affected by the boundary conditions, whereas the dynamic behavior of the first and second span is unaffected.

Fig.8 - Eigenmodes of (left) second span; (center) first span; (right) third span

Considering further modeling details, the type of column support at the lower level of the first span due to the presence of the concrete block foundation is modeled as fixed, whereas the beam ends that are inserted in the adjacent building walls are modeled as pinned (third FEM model). Again, the first eigenmode is not affected by this support type. However, the second and the third eigenmodes are quite different from the fixed assumption. In particular, the second eigenmode, which refers to the first span, tends to be stiffer, whereas the third eigenmode, which refers to the third span, tends to be more flexible.

The basic conclusions that can be drawn from the above FEM modal analysis of the three basic steel stairway models are the following:

(1) The first three eigenmodes refer to the modal deformed shape of the second, first and third span of the steel stairway, respectively.

(2) There is a good agreement between the numerical and the experimental results in terms of eigenfrequency values.

(3) The specific boundary conditions of the steel stairway mostly affect the behavior of the first and third spans, which are laterally supported on the adjacent building walls.

(4) The true behavior of the lateral supports can be considered to be somewhere between a fully-fixed and a fully-pinned support.

Finally, taking into account all available experimental data, the present FEM models can be furter upgraded by means of FEM updating techniques.

5. Summary and Conclusions

We present here an identification method for the dynamic characteristics of a flexible steel structure, which responds as a continuous dynamic system to environmentally-induced loads. This is a rather difficult problem in structural dynamics, since there is a spread of closely grouped eigenfrequencies with equivalent response amplitudes. This type of response results in the absence of a dominant frequency that would be detectable in terms of a bell-shaped bump in the FFT plots. Thus, in order to produce reliable results, the method of modal acceleration time histories was applied, which calculates phase differences between the recorded DOF in the total time history response. Next, a discrete-parameter FEM model for the stairway was developed for comparison purposes. Even though this model was based on available design data and appropriate engineering judgment had to be excercised, it succeeded in reproducing the dominant stairway eigenfrequencies, which turned out to be in good agreement with the experimentally measured ones. Also, the ensuing parametric FEM analyses reveal the crucial effect of the boundary conditions on the dynamic response of the steel stairway. Thus, on-site recordings from the multi-channel system of accelerometers, with the appropriate analytic processing, can produce a very good estimate of the true values of the eigenfrequencies and eigenmodes, even in the case of continuous systems. It is of course acknowledged that use of FEM models contributes to the identification of the dominant eigenfrequency range, thus narrowing the search procedure when processing the experimental recordings. However, development of parallel numerical models is not necessary for the identification of the dynamic characteristics of the flexible structure, since the modal time history accelerations method is autonomous. The true value of FEM models in our case lies elsewhere: Once calibrated, they can be used in conjunction with dynamic response recordings to establish the structural ageing over time as the stairway remains under continuous use.

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