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IN-SITU EXPERIMENTAL TESTS OF PIPING SYSTEMS IN HOSPITALS AND HEALTH FACILITIES

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Abstract

Non-structural component failures due to earthquake events can cause significant economic losses and even life-threatening hazards to occupants. For buildings with special occupancies and functions, such as hospitals, a higher level of performance is required to address the life safety issues, since patients often have limited mobility and are dependent on caregivers or specialized medical equipment. In addition, non-structural damage is often the main cause of health service interruption as a result of seismic events.
The complexity of non-structural components in hospitals and health facilities is due to the presence of extensive networks of mechanical, electrical and piping systems necessary for essential functions. These systems are critical services on which the operation of a hospital depends.
In order to conduct a more accurate seismic analysis or damage assessment of the piping systems, it is necessary to establish reliable numerical models. From this point of view it has been shown that dynamic identification techniques are nowadays a reliable method for the dynamic characterization of the piping systems.
In this work, the results of two experimental ambient vibration tests are reported to determine the dynamic properties, such as the natural frequencies and mode shapes, of a fire-fighting system and a heat water piping system, located in a health facility in the South of Italy. The dynamic in situ tests have been carried out in the framework of the PRIN research project ENRICH- "ENhancing the Resilience of Italian healthCare and Hospital facilities".

Keywords: Ambient vibration test; piping systems; health facility; non-structural components; model updating.

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1 INTRODUCTION

Non-structural components constitute a major portion of the construction costs of a building and play a fundamental role in maintaining the functionality of a building facility [1]. These elements have been found to be more susceptible to damage in comparison to structural elements because of improper design and construction practices. Moreover, it is note that financial loss due to earthquake-damaged non-structural components can be significantly more than the structural damage repair costs [2].

Often, critical facilities, such as hospitals, have been shut down following an earthquake due to non-structural damage [3]. The latter can also pose threats to life-safety, either due to the falling of non-structural components on the residents or the blocking of exit routes in buildings during seismic shaking [4]. In general, they do not receive the required attention during the design and installation phase and consequently this is the reason of the poor performance of non-structural components during past seismic events. Moreover, as stated by Filiatrault and Sullivan [5], the design methods for non-structural elements are mostly empirical in nature and are conceived based on past seismic performance and intuition.

Some of the essential non-structural elements in a building are the utility systems among which the fire sprinkler system. Damage to fire sprinkler systems during an earthquake can result in property loss and can enforce evacuation either due to the flooding of buildings or a compromised fire protection system. The above aspects are particularly important in critical facilities such as hospitals that are required to be operative after a seismic event. In general the failure of a fire protection piping system can be linked to a damage occurred before the seismic event caused, for example, by construction imperfections and material shortcomings or deterioration or to a damage occurred during the seismic event. For instance in the 2010 Chile earthquake, many hospitals lost their functionality due to non-structural failures that included fire sprinkler piping [6]. An extensive water damage resulting from sprinkler pipes along with other utilities have forced the patients evacuating in some acute care hospitals during 1994 Northridge earthquake [7]. Seismic performance of sprinkler piping systems has been the subject of some comprehensive experimental and numerical research studies [9, 8, 10].

Generally the determination of the seismic demands is performed through the equivalent static force approach. According to Eurocode 8 [11], unlike other standards [12, 13, 14], the component amplification factor is dependent on the proximity of the component and supporting structure vibration period (Ta/T1). Therefore, the reliability of the estimated demands depends on the dynamic properties. However, manufacturers provide no information on the period of vibration of these elements and few studies have been conducted to determine these values experimentally on-site.

The modal responses (natural frequencies, mode shapes and damping) of a fire-surpression piping system, depending on the diameter of the pipe and restraint conditions, were obtained by means of the Enhanced Frequency Domain Decomposition by Archila et al. [15] and different OMA techniques by De Angelis et al, [17]. Similarly, the determination of the natural vibration modes by means of a hammer impact modal test was performed by Yang [16] on several secondary elements including a steel pipe.

This work, carried out in the framework of the PRIN research project ENRICH- “ENhancing the Resilience of Italian healthCare and Hospital facilities, aims to understand the dynamic behaviour of piping systems to provide grounds for a better estimation of seismic demands.

In particular, an operational modal analysis using an ambient vibration test AVT has been employed to determine the dynamic properties such as natural frequencies and mode shapes of two utility systems, a fire-fighting system and a heat water piping system.

2 MODAL IDENTIFICATION TEST

In this section a brief background of Modal Testing Technique is reported. The basis of the modal identification tests is that the relation between the input force exerted on a structure and the resulting linear responses is a reflection of the structure's modal properties [18]. The Newton's equations of motion for a multiple degrees-of freedom system are given by:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \tag{1}$$

Where M, C and K are the mass, damping and stiffness matrices respectively and x(t) is the response displacement of the structure subjected to external forces f(t). Transforming this equation into a frequency-domain equivalent, the time variant response becomes:

$$X(s) = H(s)F(s) \tag{2}$$

$$H(s) = X(s)F^{-1}(s) \tag{3}$$

$$H(s) = (Ms^2 + Cs + K)^{-1} \tag{4}$$

Where H(s) is defined as a frequency response function (FRF) matrix, also known as a transfer function, and X(s) and F(s) are the output response and input force expressed in the frequency domain, respectively. The time-domain-to-frequency-domain transformation can be performed based on the Faster Fourier Transfer (FFT) algorithm [19]. The FRF can be plotted as the frequency domain relationship between the input and output signals. Now, consider the transfer function H(s) in the modal format:

$$H(j\omega) = \sum_{j=1}^{n} \left(\frac{1}{j\omega - \lambda_i}\right) \{v_i\} \langle l_i^T \rangle \tag{5}$$

Where ω is the circular frequency; n is the number of modes; {vi} are the modal vectors; $\langle l_i^T \rangle$ are the modal participation vectors; and λi are the eigenvalues that are related to natural frequencies ωi and damping ratios ξi as follows:

$$\lambda_i, \lambda_i^* = -\xi_i\omega_i \pm j\sqrt{1 - \xi_i^2}\,\omega_i \tag{6}$$

From the above equations, the FRF is related to the mode shapes, modal participation factors, modal frequencies and the damping ratios of the structure. These parameters can be determined once the FRF plots are obtained from the input-output spectrum relationship. This modal identification method is classified as an "input-output approach". The Hammer Impact Modal Testing is a typical input-output approach. A Hammer Impact Modal Testing (HIMT) approach involves applying an impact force to the tested object by an instrumented hammer with a built-in force transducer. The input signals are measured by the built-in force transducer, and the output signals are measured by external vibration sensors. The recorded input-force and output signals are then processed to extract the fundamental frequency and damping of the tested object.

The other type of modal identification testing method is the "output-only approach". Under some conditions where it is not feasible to excite the structure with a measurable impact due to cost, safety issues and/or undesired disturbance of the structure's operation, the input-output approach cannot apply. Only the response vibration can be measured and this type of modal identification method is so called the output-only approach.

The most common application of an output-only method is the Ambient Vibration Testing (AVT) approach that have been employed in this work. The AVT procedure includes:

- measuring the acceleration time-hisories of interest using uniaxial accelerometers during the normal operation of the non-structural component;
- constructing the PSD plots using the FFT algorithms;
- Identifying the natural frequencies of the non-structural component using peak-picking (PP) technique.

The AVT is defined as a measure to record only the response of the structure under ambient excitations such as wind, traffic, environmental noise. Ideally, the ambient excitation can be treated as white noise, which corresponds to a constant power spectral density within any frequency band, so that the response spectrum is reflective to the modal properties of the structure. The excitation with limited bandwidth and low amplitudes can lead to the extraction of inaccurate modal properties [20]. Therefore, the response signals should be recorded over a long duration to ensure that the excitation contains a broad range of vibration frequencies.

3 DYNAMIC IDENTIFICATION OF TWO UTILITY SYSTEM

In this section first of all, the selected utility systems located in a health facility, in the South of Italy, are described. Then the dynamic identification, including the development of a preliminary numerical model, the ambient vibration tests and data processing, are detailed.

3.1 Description of the case study

Two utility systems, i.e., a fire-fighting system and a heat water piping system located in a health facility named “Clinica Villa del Sole” (Figure 1), in South of Italy has been studied through operational modal analysis.

Figure 1: Top view of the health facility “Villa del Sole”.

The selected fire-protection piping system is the fire surpression piping system with fire extinguishing equipments like Naspo. The selected segment of the piping system analysed is presented in Figure 2. The epoxy powder-coated steel piping system has a main line with a nominal diameter of 3''. Great attention has been paid to the points where the piping system connects to the structure and crosses vertical structural and/or nonstructural elements.

In particular, it is mainly anchored to the structure with rod hangers to ensure stability for vertical loads and crosses a nonstructural element (partition) in one point (Figure 3).

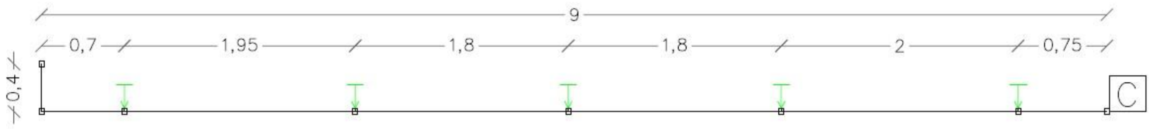
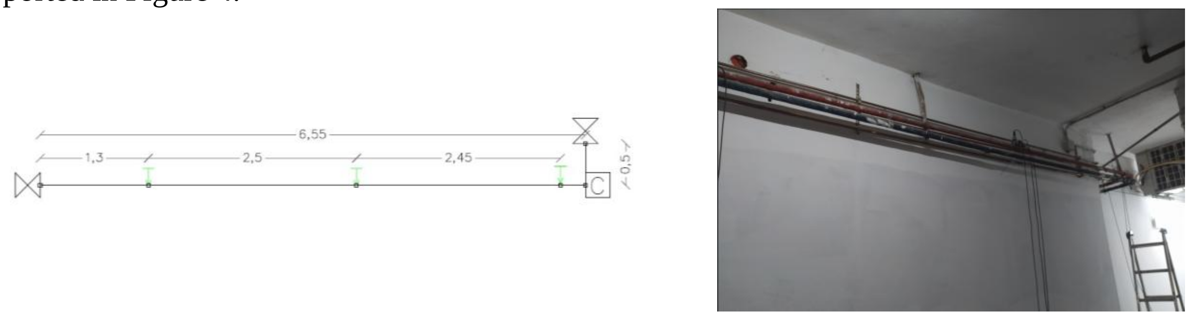


Figure 2: Schematic plan of the piping system (dimensions in meter).

Figure 3: In-situ constraint conditions: Vertical supports and crossing in walls.

The second utility system studied is a heat water piping system. The steel piping system has a main line with a nominal diameter of 1' and 1/2 and it is anchored to the wall with vertical brackets. A schematic view and a picture of the analysed part of the system are reported in Figure 4.



a) b)

Figure 4: a) Schematic view and b) picture of the heat water piping system (dimensions in meter).

3.2 Finite element model

This section has the primary objective of numerically simulate the response of the utility systems tested to investigate if the commonly used analysis tools can reliably predict the recorded experimental responses.

Prior to the experimental modal testing preliminary FEM-analyses was carried out to find out the frequency range of interest as well as the associated mode shapes. The 3D finite element model of the selected segment of the piping system was developed with the software SAP2000 [22] to simulate the elastic response of the piping system.

All components of the sample piping system (pipes, elbows, rod hangers) were modeled properly. Pipes were modelled with frame elements. The properties of the sections were calculated automatically and assigned to the different pipes using as input the external diameter and the thickness of the pipe, detected during the inspection. Distributed masses that include the weight of the pipe and the water were assigned to each element. The fittings and or elbows were modeled through rigid link elements. All steel rod hangers were modeled by means of steel elements with a solid section of diameter equal to 1.2 cm, modulus of elasticity of 200 GPa and Poisson module of 0.3. For the vertical supports, a pendular connection between the piping and the hanger was assumed. A 3D view of the models are shown in Figure 5 for the fire protection piping system and Figure 6 for the water pipe system.

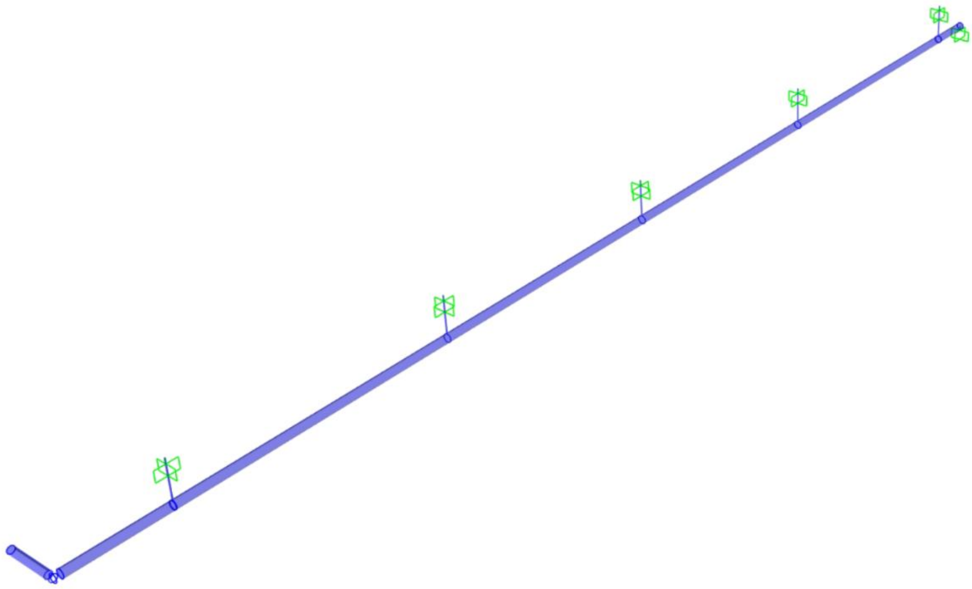


Figure 5: Model of the selected segment of the fire piping system.

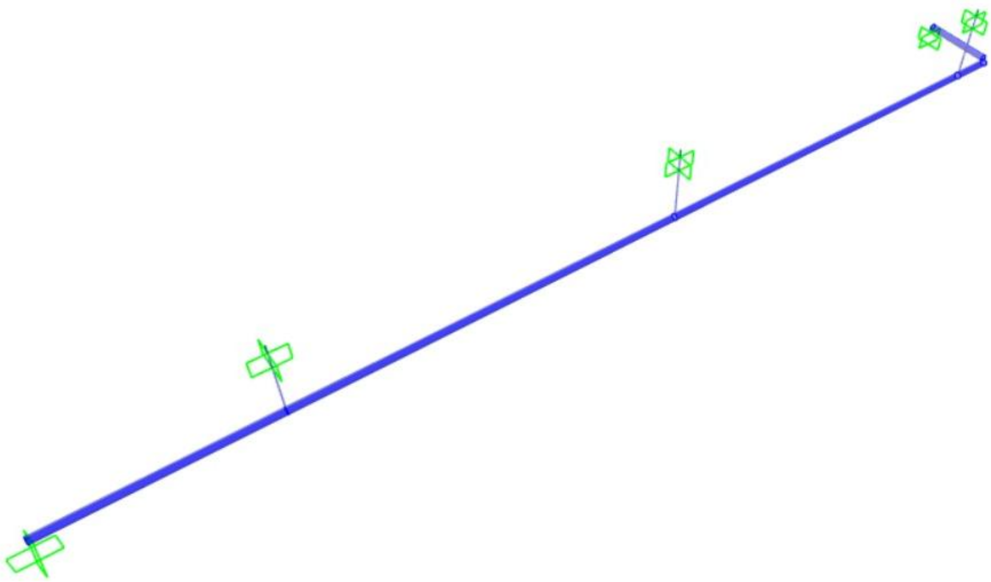
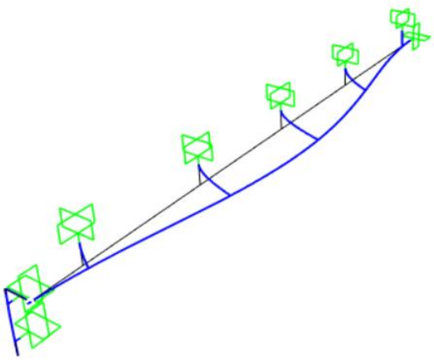
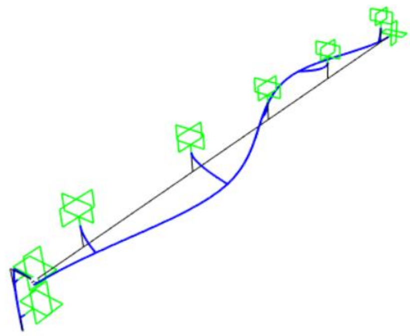


Figure 6: Model of the selected segment of the water piping system.

The modal analysis was carried out to determine the modal shapes, the period, the frequency and the participating mass ratios involved. The first three modal shapes of the section of the fire piping system analyzed are shown in the Figure 7. It is possible to observe that the three main modal shapes refer to translational motions in the xy plane, which is plausible since the hangers act as pendulums for the pipeline in this plane while as fixed constraints in the xz and yz planes.

MODE 1 f=6.13 Hz	MODE 2 f=11.58 Hz





MODE 3 f=21.22 Hz

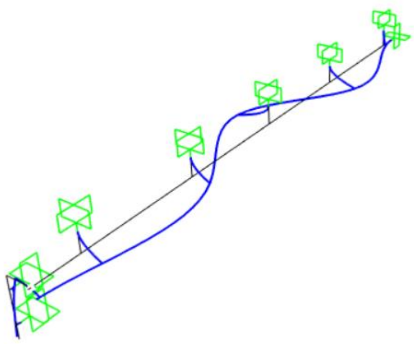
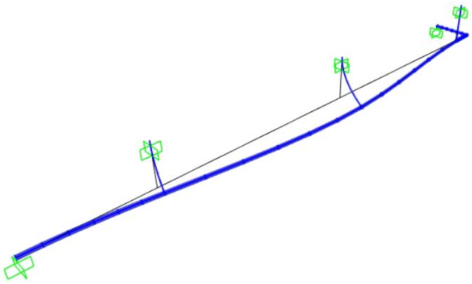


Figure 7: vibration mode of fire piping system.

The first two vibration modes identified for the water piping system are shown in Figure 8, as well as noted for the fire piping system, also in this case the modes are of translation in the xy plane.

MODE 1 f=7.38 Hz	MODE 2 f=20.47 Hz



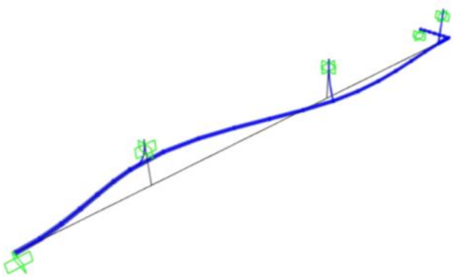
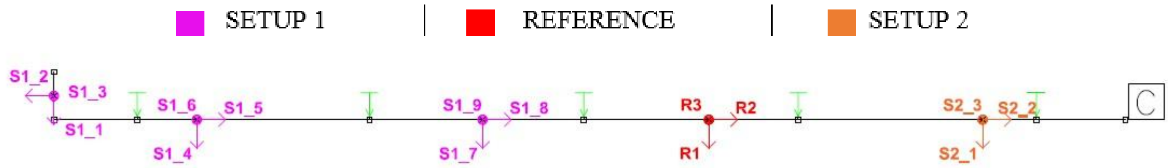


Figure 8: vibration mode of water piping system.

3.3 Ambient vibration tests

The dynamic characteristics of the piping system were assessed through an ambient vibration test (AVT). The accelerations were collected using twelve uniaxial piezoelectric accelerometers with high sensitivity (10 V/g) and low background noise (0.13 µg/√Hz). According to the outcomes of the modal analysis carried out with the preliminary finite element model at least 15 measurements points are necessary. Therefore, in order to study the local dynamic properties of the piping system, three setups were established as shown in Figure 9, adopting 9 accelerometers as roving sensors and 3 as reference sensors. The latter will play an important role in combining the different setups to obtain the global mode shapes of the piping system.

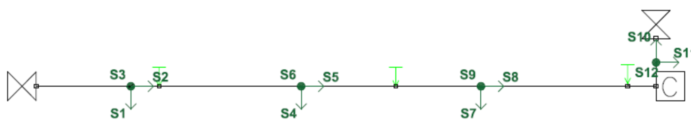


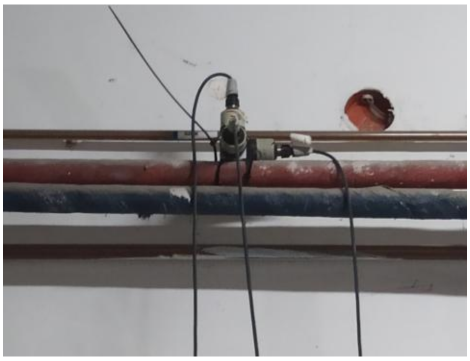
a)

b)

Figure 9: a) Measurement points of the ambient vibration tests for fire piping system and b) picture of the AVT.

Instead, for the heat water piping system, three accelerometers were mounted on a triaxial support to record accelerations in three directions (Figure 10) for a total of four measurement points, 12 sensors and a single setup.





a) b)

Figure 10: a) Measurement points for water piping system and b) picture of the AVT.

In both cases, time series of 15 minutes (900 seconds) were collected at a sampling frequency of 400 Hz. Then the data were low-pass filtered and downsampled at a rate of 100 Hz. This significantly reduces the amount of samples without loss of information in the frequency range of interest.

3.4 Data processing

After acquiring the data, an initial pre-processing step was performed [23] and the data were validated: detection of anomalies such as clipping, spikes, drop-out; recognition of the presence of spurious harmonics. Additionally, any offsets and spurious trends were removed.
After this first step, the data processing and the estimation of modal parameters (frequencies and modal shapes) were carried out through the commercial software Artemis Modal Pro [21] and by employing the Frequency Domain Decomposition (FDD) method [24]. In the FDD method the spectral density matrix is decomposed by Singular Value Decomposition (SVD) to obtain frequency values and mode shapes. The natural frequencies and the modal shapes identified via FDD method are summarized in Figure 11 e Figure 12, it can be observed that three clear translational modes in the xy plane were identified for the fire piping system (Figure11) and two other translational modes in the xy plane for the water piping system (Figure 12).

f=12.31 Hz	f=20.65 Hz	f=30.03 Hz

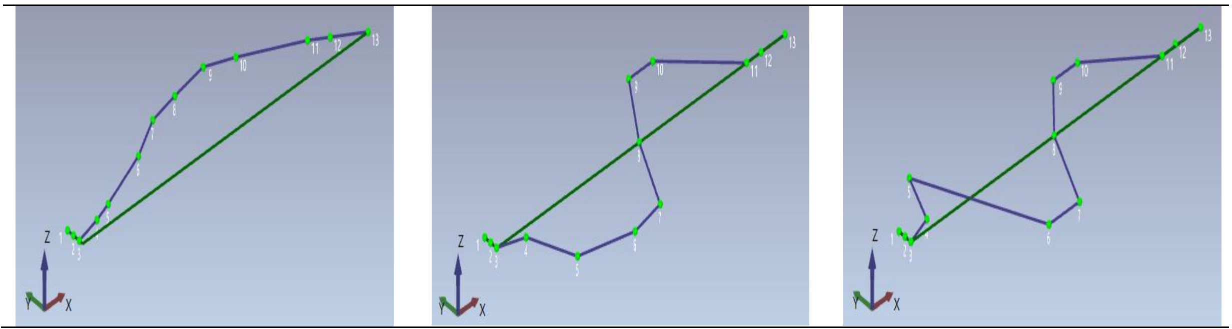


Figure 11: Experimental frequencies and modal shapes for fire piping system.

f=5.85 Hz	f=12.76 Hz

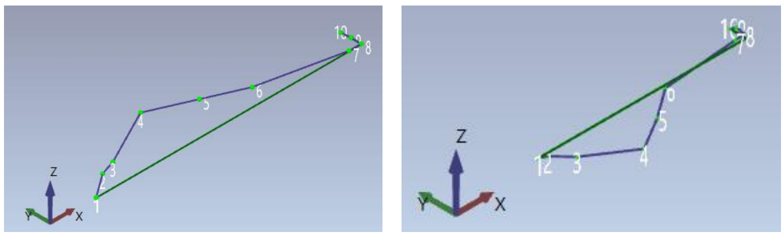


Figure 12: Experimental frequencies and modal shapes for water piping system.

4 CONCLUSIONS

The scientific literature presents a limited number of studies dedicated to the estimation of the dynamic properties of fire protection piping systems. Therefore, the present work examined the dynamic response of two utility systems: a fire extinguishing system and a hot water piping system. The first step of the research was the development of a preliminary model for both systems, with the aim of identifying the expected frequency range and appropriately designing the environmental vibration test (AVT), optimizing both the sampling rate and the configuration of the sensors. Subsequently, the data acquired from the AVT test were analyzed by the Frequency Domain Decomposition (FDD) method, a well-established technique of operational modal analysis in the frequency domain, to determine the dynamic properties of the examined systems, natural frequencies and mode shapes.

The comparison between the frequencies derived from the numerical models and those obtained from the experimental data showed an underestimation of the frequencies by the numerical simulations for the fire piping system.

For the water piping system, the frequencies identified by the experimental data are roughly within the range of frequencies predicted by the numerical model.

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