11th International Operational Modal Analysis Conference
20 - 23 May 2025 | Rennes, France

Vibration and Modal Analysis of the Roman Wall of Lugo

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ABSTRACT

This study focuses on the vibration and modal analysis of the Roman Walls of Lugo, a UNESCO World Heritage Site known for its historical and architectural significance. The wall is one of the most important structures of Hispania Romana, since it is the only fortification which has preserved its entire perimeter and it is the only one on the peninsula possessing a maintenance plan. The research involved vibration tests and modal identification in three areas of the walls: Porta San Fernando, Porta Bispo Odoario, and Porta San Pedro. The aim was to assess the dynamic behavior of the structure, analyze vibration levels, and identify low-frequency vibration modes across the different measurement zones.

Triaxial and uniaxial acceleration sensors were placed at various points, including the base and upper sections of the wall. Data were collected at a sampling frequency of 50 Hz, enabling the determination of natural frequencies, acceleration amplitudes, and vibration transmission characteristics. Modal analysis revealed consistent low-frequency modes across the studied sections, providing valuable insights into the structural response.

The results indicated that, despite vibrations caused by external factors such as vehicular traffic, the measured levels remain within acceptable thresholds as defined by international standards. These findings affirm the structural integrity of the walls and highlight the importance of vibration and modal monitoring in the preservation of historical structures, particularly those exposed to urban and environmental influences

Keywords: Cultural Heritage, Structural Vibrations. OMA.

1. INTRODUCTION

The preservation of cultural heritage is currently a topic of great interest due to specific maintenance programs designed for historical structures, primarily supported by public entities as well as private foundations and organizations. The main objective is to safeguard these monuments, which not only provide economic benefits through tourism but also contribute to the cultural identity and legacy of a region or country

While a comprehensive maintenance plan for this type of historical structures involve studies in many fields, vibration measurements and Operational Modal Analysis (OMA) are widely used tools for assessing the structural health of historical buildings. The method has been successfully applied to historic monuments, including masonry towers, medieval churches, and large-scale fortifications, to assess their stability and to calibrate numerical models used in conservation planning [1], [2], [3].

The Roman Walls of Lugo (see Figure 1) represent one of the best-preserved examples of late Roman military architecture. Built between 263 and 276 AD, the walls enclose an area of 34.4 hectares, with a perimeter of approximately 2,117 meters. The structure is composed of external stone facings with an internal core made of earth, stone fragments, and recycled masonry. Originally, the walls featured 85 defensive towers, of which 71 remain standing, along with ten access gates—five from the Roman era and five added in later centuries [4]. Due to their historical and architectural significance, the walls were designated a UNESCO World Heritage Site in 2000, and they remain the only Roman fortification in Spain with a dedicated maintenance plan [5].

The conservation of the Lugo walls has been supported by various intervention strategies. One of the key aspects has been the geometric documentation of the structure using terrestrial laser scanning (TLS) and unmanned aerial vehicle (UAV) photogrammetry. These techniques have enabled the creation of a high-resolution 3D model, which provides accurate data on the geometry and current state of the walls, supporting further structural analysis and conservation planning [4]. In addition, conservation efforts have focused on essential interventions such as the removal of attached buildings and the restoration of internal staircases, which have improved both structural stability and accessibility [6]. The comprehensive maintenance plan implemented in recent decades includes periodic inspections, vegetation control, and structural reinforcements to mitigate long-term deterioration [5].

This study aims to analyze the effects of traffic-induced vibrations on selected sections of the Lugo walls. Using accelerometers, the dynamic response of the structure is measured, and an Operational Modal Analysis is performed to extract modal parameters. The findings contribute to understanding the impact of external loads and provide insights for future conservation measures, ensuring the long-term stability of this historical monument.

2. MEASUREMENT LOCATIONS AND SETUPS

In order to check the vibration levels in the wall due mainly to different traficc conditions, three different locations along the perimeter were selected. The locations are indicated in red squares in Figure 1 being:

- T1: San Fernando Gate
- T2: Bispo Odoario Gate
- T3: San Pedro Gate

Figure 1. Lugo Roman Wall (www.openstreetmap.org: CC BY-SA 2.0).

In each of the test, accelerometers located at the streel level as well as located at the upper part of the wall were used in order to correlated the possible traffic-induced vibrations (see Figure 2).

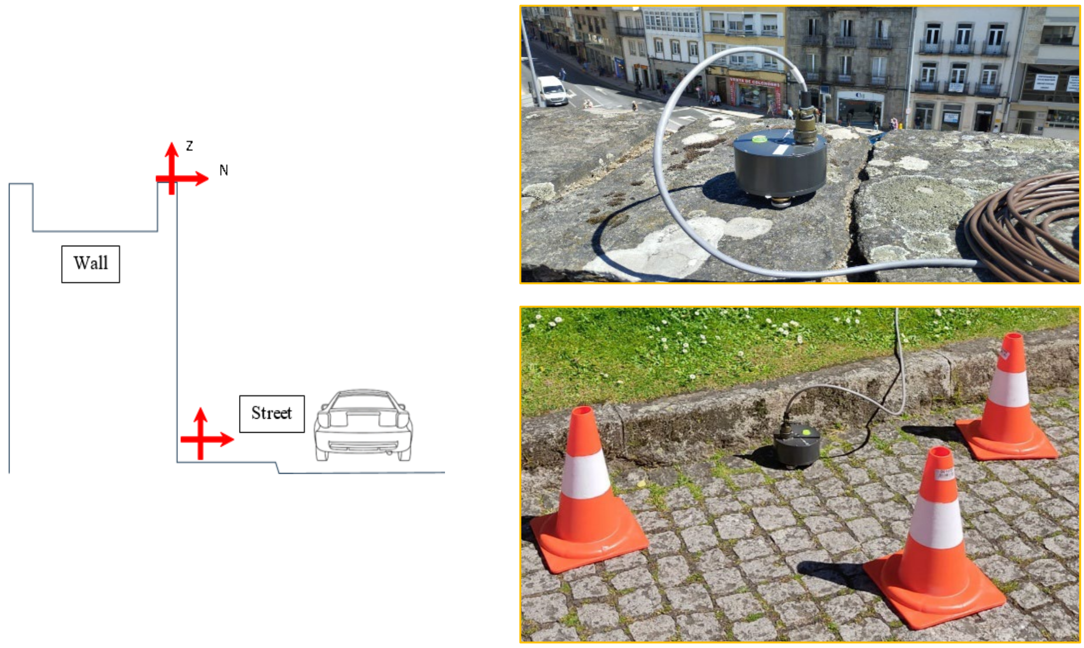

Figure 2. Locatios of the sensors in the street and in the upper part of the wall.

For the measurements, a Gural System with two DAQ equipments, connected with a syncronization cable, was used. The accelerations were measured using 2 Data Sets (17 channels each one) for the three gate locations. A sampling frequency of 50 Hz was used being the registering time about 30-60 minutes depending of the location and the Data Set. The two datasets were used in order to cover more measured points as well to cover more wall distance along each location. As example, in Figure 3, are presented the measurement points at location T1: San Fernando Gate.

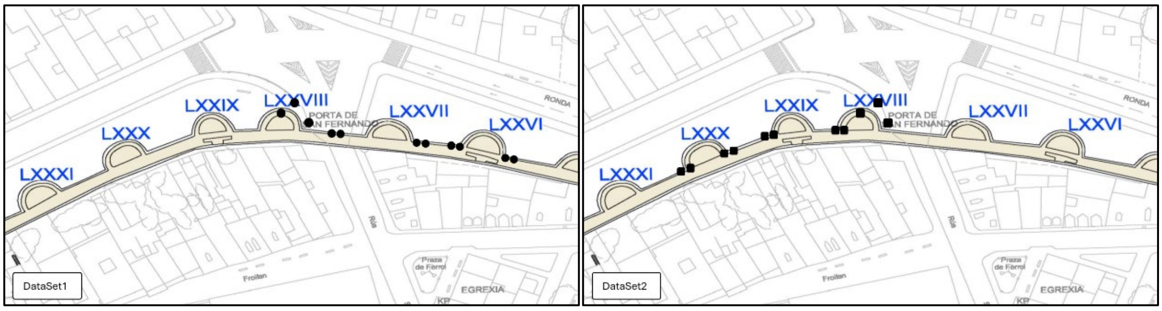

Figure 3. Datasets and location of measurement points at T1 location.

The accelerometers were located in order to measure de vertical direction (Z) and normal to the wall (outward oriented) (N). Some of sensors were triaxial so data in the wall's contour direction (E) was also measured

3. ANALYSIS OF THE VIBRATION LEVELS

Since similar results were obtained for the different measured locations along the wall, only the analysis of the results for the location T2: Bispo Odoario Gate are presented in this section.

At T2 location, the road is quite close to the wall, and the street is relatively straight. At the beginning of the street, there is a traffic light; when it's green, a large number of vehicles drive along the street for about 1-2 minutes.

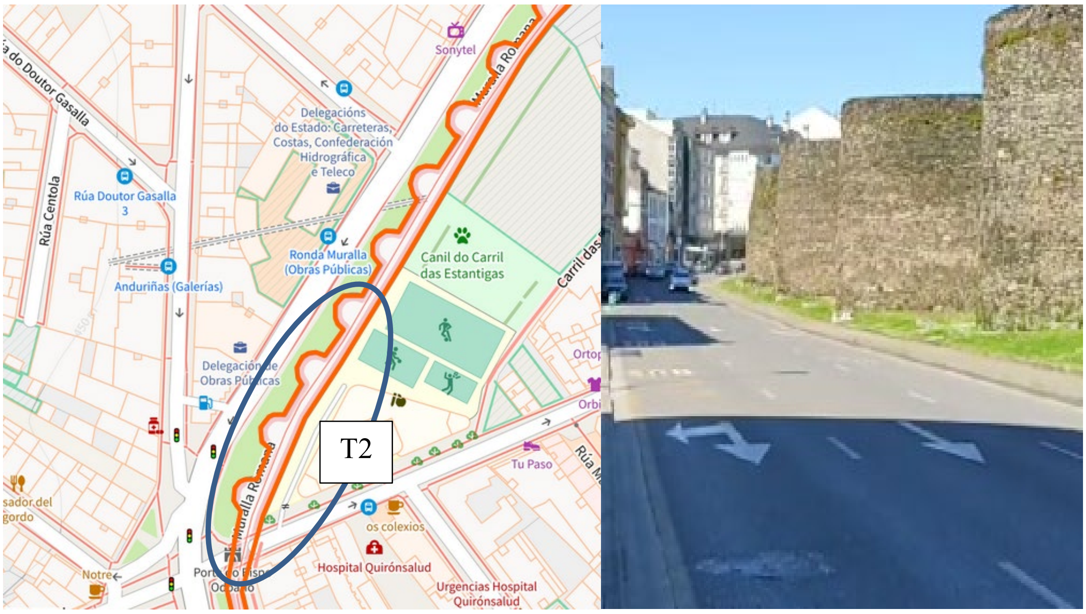

Figure 4. Area of measurement at T2 location (left) and a picture of the traffic road close to the wall.

From the direct view of the time acceleration series, it can be inferred the induced vibrations on to the wall structure. An example of the accelerations measurement when traffic is passing through the street is presented in Figure 5 for triaxial sensors T30 (street) and T29 (top of the wall). From the figure it can be observed how the amplitude level of acceleration increase when the traffic is passing along the street.

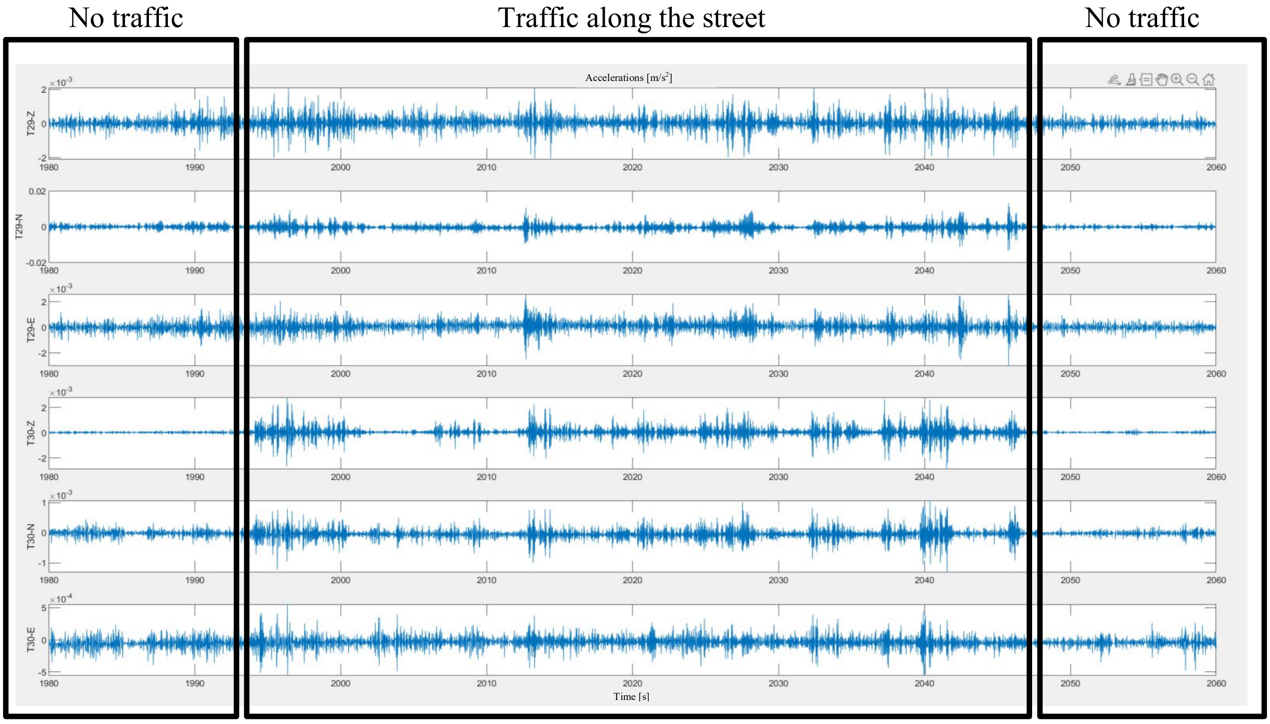

Figure 5. Acceleration measurements during the opening period of the traffic light.

In order to quantify the ratio between vibrations at the street and the wall, two triaxial sensors, one in the street and the other in the wall were used. From the Power Spectral Density (PSD) of the vertical direction (see Figure 6), it can be obtain that an average amplification factor of 5.5 is present in the range 0-25 Hz. On the other hand, Table 1 presents the maximun acceleration during the register in Z direction for both accelerometers. Moreover, in order to obtain an average value of the maximun signal amplitudes, a normal statistic distribution was fitted at 3 different probabilities to the measured data.

Figure 6. Comparison of PSD [dB] of the Z direction measurements at T2 (T30: street level and T29: upper part of the wall).

Table 1. Maximum accelerations in Z direction at T2.

Sensor	a_{max} $[m/s^2]$	Acceleration $[m/s^2]$		
		$p = 99\%$	$p = 95\%$	$p = 90\%$
T30 (street)	0.0237	0.0008	0.0006	0.0005
T29 (wall)	0.0131	0.0010	0.0007	0.0006

In both PSDs and maximun accelerations in Z (Table 1) can be observed that higher values are measured in the top part of the wall. Similar results were obtain for the rest of the measured locations along the wall. It can be noted that, in all the cases, the normal to wall direction acceleration presents a higher amplification factor (even double) when comparing wall to street ratio.

Although measurements and their comparison provide evidence that traffic induces vibrations in the wall, it is important to have a reference value to determine whether these vibrations are acceptable or not. For this purpose, the recommendations of the standard DIN 4150-3 [7] were followed. This standard stablishes maximun velocites for frequency ranges that could be allowed for different types of structures. To check with the standard recomendations the accelerations signals were integrated in MATLAB. The obtained values for location T2 for the same triaxial sensors (T30: street and T29: wall) are presented in Table 2. In the table is also included a column with the maximun velocity obtained from the rest of the sensors used in the datasets. From the table, it can be observed that the maximum velocities for all the cases are below the maximun value according to DIN-4150.

Table 2. Maximum velocities according to DIN 4150-3.

Direction	Sensor	v_{max} $[mm/s]$	v_{max} $[mm/s]$ DIN-4150 range 1 to 10 Hz	v_{max} $[mm/s]$ Other channels
Vertical (Z)	T30 (street)	0.139	3	0.013
	T29 (wall)	0.166	8	0.016
Normal to wall (N)	T30 (street)	0.065	3	0.005
	T29 (wall)	0.522	8	0.035
Transversal (E)	T30 (street)	0.034	3	--
	T29 (wall)	0.121	8	--

For the rest of locations measured, the obtained velocities are also below the maximuns according to DIN-4150 being the higher values those presented for the location T2 (see Table 2).

4. OPERATIONAL MODAL ANALYSIS (OMA)

The data obtained for the induced vibration analysis can be also used to perform an OMA of the structure. In this case, the OMA for the location T3: San Pedro Gate is presented in this section. After a first analysis, it could be determined that both vertical direction (Z) and countor wall direction (E) can be neglected for the OMA, since the identified mode shapes were in the normal to wall direction. For the modal identification the ARTeMIS Modal software was used. The Singular Value Decomposition (SVD) with the modes that stabilize are presented in Figure 7. The estimated natural frequencies of the wall, obtained with the SSI-UPC Merge technique are presented in Table 3.

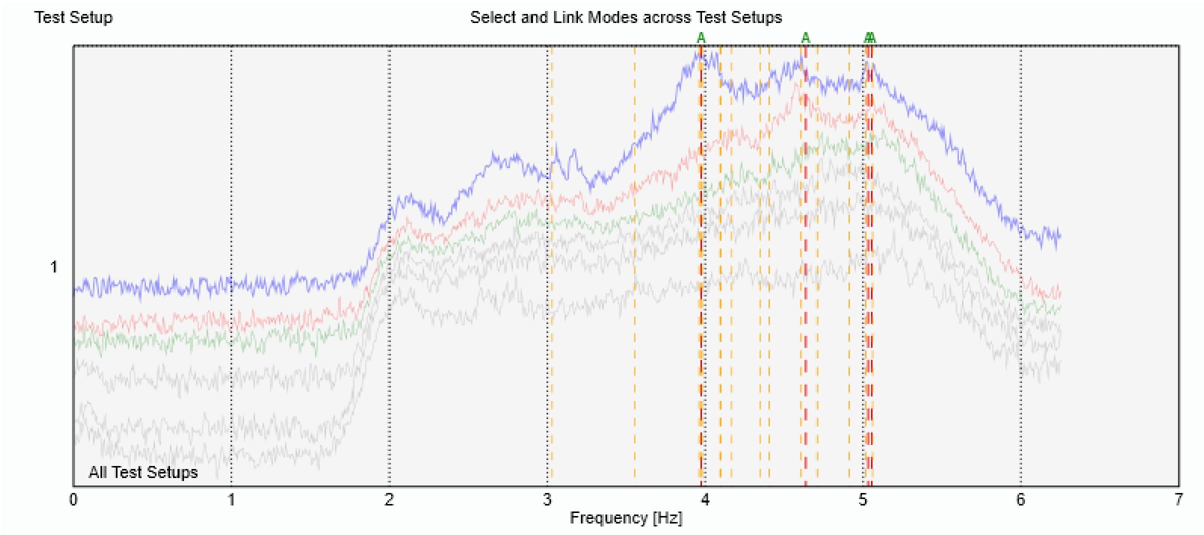

Figure 7. SVD and Identified modes of the wall.

Table 3. Natural frequencies and damping ratios identified in the wall.

Mode	Natural Frequeny [Hz]	Damping Ratio [%]
1	3.975	2.983
2	4.638	3.357
3	5.056	1.874

The identified modes correspond to bending at the top of the wall. Some lower frequency peaks are observed below the first frequency that cannot be identified as structural modes of the wall. The mode shapes corresponding to modes 1-3 of Table 3 are presented in Figures 8, 9 and 10.

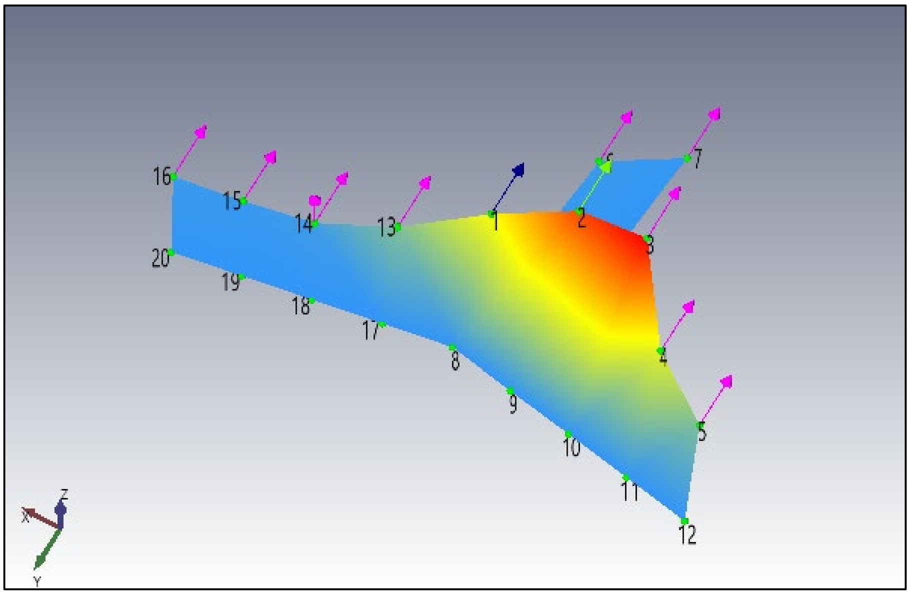

Figure 8. Mode 1 of the wall at T3 location: 3.975 Hz.

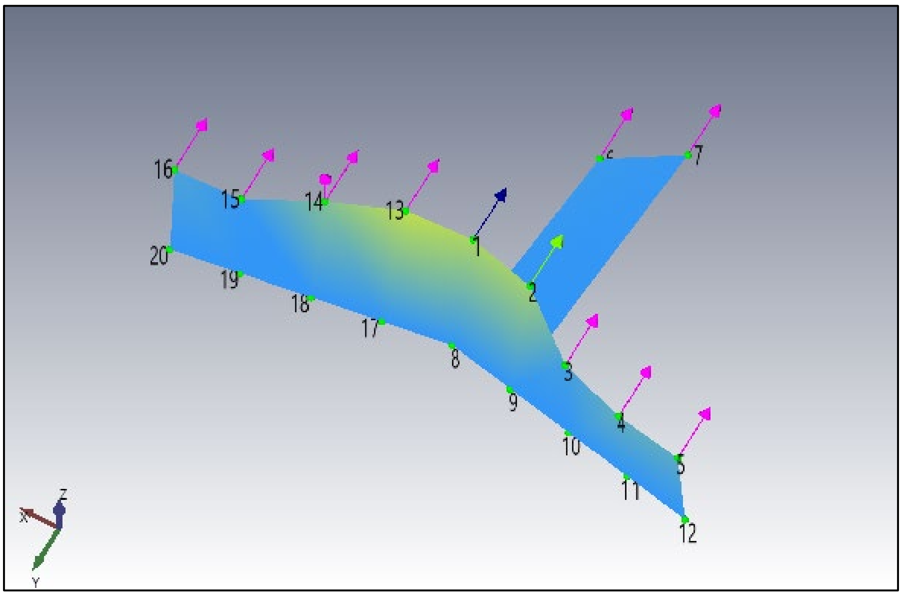

Figure 9. Mode 2 of the wall at T3 location: 4.638 Hz.

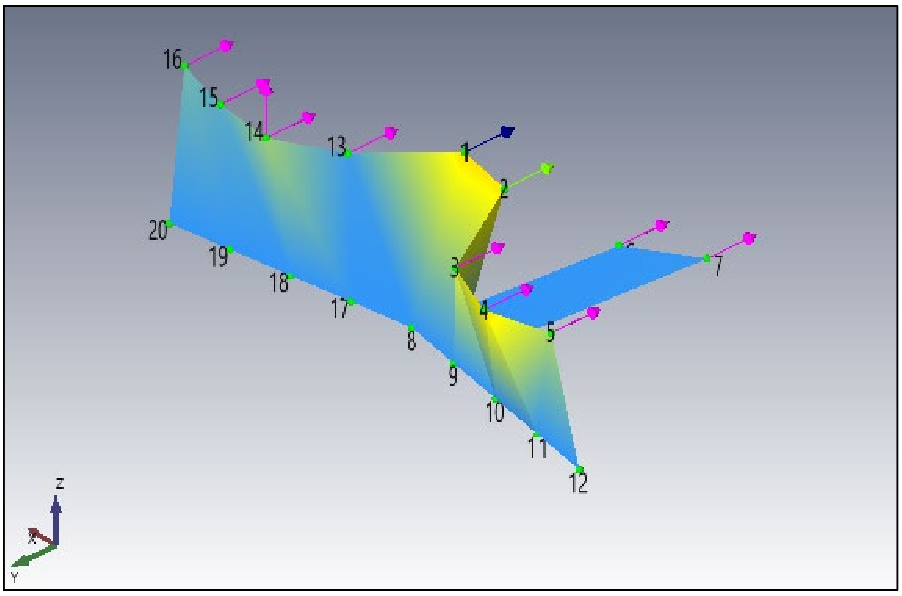

Figure 10. Mode 1 of the wall at T3 location: 5.056 Hz.

As regards the OMA in locations T1 and T2, similar bending modes of the top part of the wall that those presented for T3 locations, can be identified in the range 3-6 Hz.

5. CONCLUSIONS

From the analysis of the different vibration measurements, it has been confirmed that the effect of road traffic near the wall increases the magnitude of vibrations at both the base and the top of the wall. The accelerations are, in all the cases, higher at the top of the wall when comparison with the levels at the base (street levels).

When comparing the obtained velocities during experiments with the maximum velocity levels indicated in the DIN-4150-3 (2016-12) standard for Type 3 structures (high intrinsic value), it is confirmed that the velocity levels recorded during the tests are low in comparison with the values specified in the standard.

On the other hand, the measured data has been also used to perform and OMA identification. Top bending modes of the wall can be identified at the different locations along the wall. The modes identified are in the range 3-6 Hz.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Spanish Ministry of Science and Innovation for the financial support through the following projects: MCI-20-PID2019-105593GB-I00/AEI/10.13039 /5011000-11033, MCI-21-PRE2020-094923, PID2023-147535OB-I00, funded by MCIU/AEI/10. 13039/501100011033, and by FEDER, EU.

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