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Modal identification for rapid assessment of short span reinforced concrete bridges

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ABSTRACT: Structural condition assessment of bridges is the combination of multiple activities such as visual inspections, field and lab testing, structural modeling among others. Therefore, it implies not only structural resistance and static analyses but also dynamic behavior. Dynamic testing techniques as a non-destructive structural assessment is commonly used in bridge engineering. However, different challenges arise when mathematical modeling is involved for rapid evaluation, including modes and frequency validation. The vibration record is a procedure that allows the evaluation of the real behavior of a structure without affecting its own operation. Calibrating numerical models from field data allows to know the real structural behavior during operation. This investigation focuses on the difference between the real behavior and the idealized numerical model built with field structural data in terms of natural frequency and mode shapes. For this study, forty-five simply supported bridges located in Colombia were instrumented and modeled. Visual inspections and proper photographic records were available for all bridges. Different mathematical models were examined including single beam elements, beam elements in conjunction with shell elements and only shell elements. Flexural frequencies and mode shapes were compared using field data and mathematical models. Results suggest that the consideration of the dynamic modulus of elasticity instead of the static modulus in numerical analysis led to more accurate results compared with those obtained from analysis of field data.

1 INTRODUCTION

Dynamic monitoring of structures is a common practice since late 70´s. Those records commonly had been used to estimate the real behavior of a structure such as fatigue analyses observed from dynamic parameters (Doebling et al., 1996) among others. In many cases, researchers focus on the comparison between the real response of the structure (identified in the dynamic records) and the simulated response through numerical models.

This investigation was focused on the study of a simply supported reinforced concrete bridge located in Colombia and part of the main road system. There were two reasons for choosing those structures: Firstly, the huge importance of this type of configuration for the developing of the Colombian infrastructure. Secondly, the potential contribution to the modeling of bridges and their accurate response compared with the real behavior. In addition, the particularity of those structures is that are constantly forced to dynamic forces like the transit of vehicles, characteristic that makes feasible the dynamic characterization with field acceleration records.

Starting from the available field inspections of bridges, numerical models had been created. Additionally, field acceleration records had been used to identify the dynamic behavior of the structure during operation. Comparisons of both results allow to identify the differences between both behaviors. All data including pictures, field inspections (visual and field tests) structural drawings, concrete compression resistance and acceleration records were supplied by INGETEC S.A. – Ingenieros Consultores –.

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This method is commonly known as bridge modal identification (BMI) and has been implemented by different authors. For example, Sadeghi Eshkevari et al., (2020) and Talebi-Kalaleh & Mei, (2023) implemented the method in long-span simply supported bridges, focused on the accurate dynamic response. Other researchers like Li et al., (2022) examined BMI in long-span cable stayed bridges. Finally, Consuegra & Santos, (2015) presents an alternative method to investigate structural condition based on a non-linear elastic mathematic representation of the structure based on BMI. Hence, the current research efforts are focused on complex methods to be used in detailed analyses. Consequently, alternative rapid assessments for dynamic bridge responses could be useful for practitioners and inspectors as an initial tool of analysis and preliminary structural behavior. The analysis aims to determine a rapid relationship between the numerical model and the operation response through the modulus of elasticity of the concrete.

The elastic modulus of elasticity is the relationship between the normal stress and longitudinal strain of any given material under axial load (Neville, 2011). The elastic modulus of elasticity is given by the slope of the stress-strain curve of a given material due to a pseudo-static test; however, this curve is not strictly linear for the concrete behavior (Serrano-Guzmán & Pérez-Ruiz, 2010). The dynamic modulus of elasticity corresponding to a very small instantaneous strain is approximately given by the initial tangential modulus which is the tangent modulus for the line drawn from the origin. It is generally 20, 30 and 40 percent higher than the static modulus of elasticity for high, medium, and low strength concretes respectively (Serrano-Guzmán & Pérez-Ruiz, 2010).

Equation 1 shows the numerical expression used by "Norma Colombiana de Diseno de Puentes (CCP14)" which is the official normative used for the analysis and design of bridges in Colombia. This equation stablishes a relationship between the compressive resistance of the concrete ($f'c$) and the value of the elastic modulus of elasticity.

$$E_c = 4800(f'c)^{0.5}\ [MPa] \tag{1}$$

Several attempts have been made to correlate static (E_c) and dynamic (E_d) moduli of elasticity for concrete. The simplest of these empirical relations was given by Lydon & Balendran, (1986), and it is presented in equation (2):

$$E_c = 0.83E_d\ [MPa] \tag{2}$$

Therefore, it can be determined that the dynamic modulus of elasticity for concretes above 18.00MPa (considered as structural concrete) is 1.20 times higher than the elastic modulus of elasticity. Additionally, and as specified by Serrano-Guzmán & Pérez-Ruiz, (2010), for lower compressive strengths, it could be 1.40 times larger.

2 DESCRIPTION OF BRIDGE DATABASE AND FIELD INSTRUMENTATION

All the bridges analyzed can be comprised in the following superstructure categorization: 35 reinforced concrete beam bridges (RC), 1 reinforced concrete beams bridge with external post-tensioning (RC-ET), and 9 prestressed concrete beams bridges (PC). There are 37 bridges with one simply supported span, 5 with two simply supported spans and 1 with three simply supported spans; it means that there are 50 different acceleration records. Geometrically there are bridges with 3 to 9 principal beams, widths from 8.00m to 14.70m including the handrails, and lengths between 5.00m to 42.20m. Average values of concrete compression strength varies between 7.85MPa to 31.90 MPa.

A simply supported reinforced concrete beams bridge is presented for the explanation of the method. The geometry of the structure is presented in Figure 1. The bridge is 11.02m long (10.00m between supports), 8.57m wide, the superstructure is composed of four main 0.41x0.82m beams with principal reinforcement of 2 layers of 8#8 plain reinforcing steel. Reinforced steel distribution and concrete compressive strength (11.80MPa) were obtained from non-destructive testing, visual inspections and extracted concrete core samples.

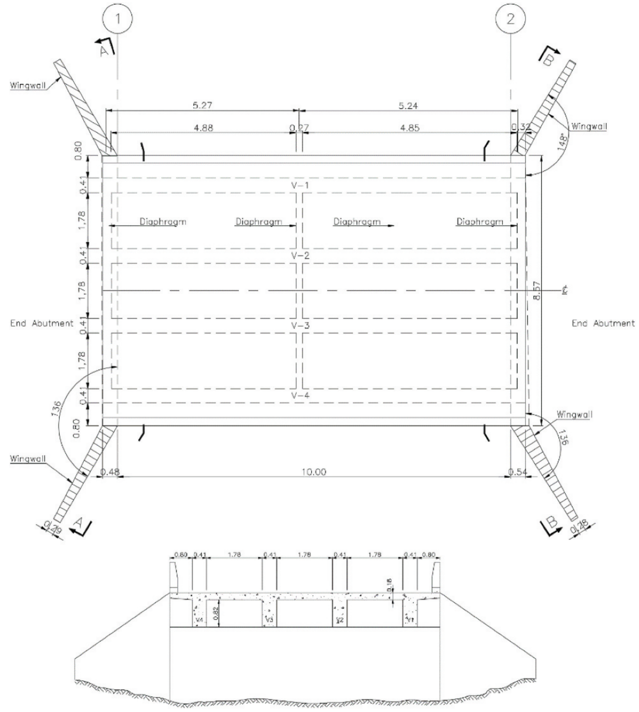

Figure 1. Reinforced concrete bridge geometry.

All field records were made with 3 accelerometers located at the extreme points of the external beams of the bridge in a straight parallel line to the longitudinal direction. Accelerometers #1 and #3 were installed in the end quarters of the total bridge length, and accelerometer #2 in the midspan as shown in Figure 2. Data was recorded at 2,000sps for a maximum period of 3 minutes. Data were collected with micro-vibration accelerometers with a scale range of ±0.50g, and an acquisition equip of 24bits. Measurements were collected at both sides of the

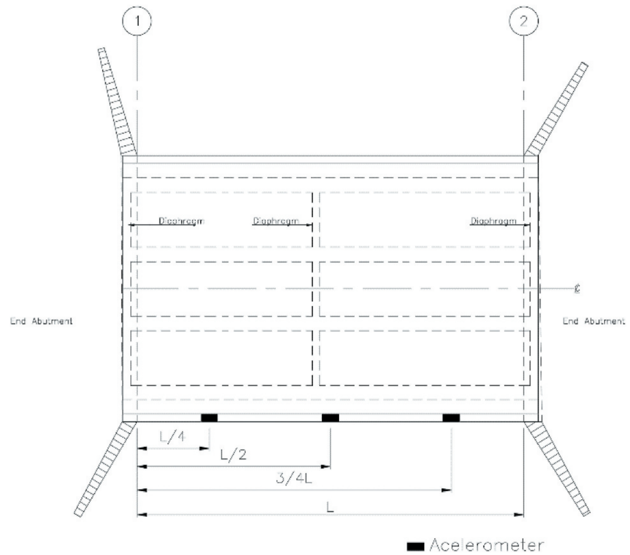

Figure 2. Accelerometer location for dynamic monitoring.

bridge independently. There are no records of the type and periodicity of the traffic, however, all tests were made during operation.

3 ANALYSIS OF FIELD RECORDS

Vibrations inherently are time-domain data, however, for engineering purposes, frequency-domain data are preferable. Hence, the fast Fourier transform (FFT), understood as a computational tool to transform time-domain data to frequency-domain outputs, is a feasible method to analyze acceleration field records. Complementary, flexural, and torsional frequencies were found using the "Peak-Pick" method, filtering the original signal as proposed by other authors (F. Consuegra & Irfanoglu, 2012; Bindi et al., 2015; Naderpour & Fakharian, 2016; Jin et al., 2021). For this study Chevychev type I filter was used due to the frequency attenuations of records higher than the filter frequency parameter established. To identify and compare the vibration modal shapes due to flexion and torsion, an acceleration normalization was used, taking as the norm the maximum value among the accelerations filtered.

Moreover, due to the nature of the acceleration records, the response shown in the acceleration spectrum is highly influenced by interpretation. The most common challenge faced in these analyses is the frequency picking among multiple peaks close together. Figure 4 (b) shows the frequency spectrum of an acceleration record test (a). As can be seen, there are multiple identifiable frequency peaks that could be interpreted as flexural or torsional frequencies. Therefore, filters for each peak were performed for all the accelerometers positioned (c, e and g) and the modal shapes identified from the filtered signals (d, f and h). Hence, the modal shape that best fits the flexural or torsional expected modal shape (verified with the numerical model) was selected as the frequency for each phenomenon. The definitive frequency used for the comparison with the numerical model is the mean of the frequency values obtained for all the acceleration tests available for each bridge.

4 NUMERICAL MODELATION

Based on the geometry, material properties and visual inspections made for all the bridge database, 3D models using only shell elements were constructed using SAP2000® software (see Figure 3). In addition, other models were considered, including 2D single-frame models, 3D

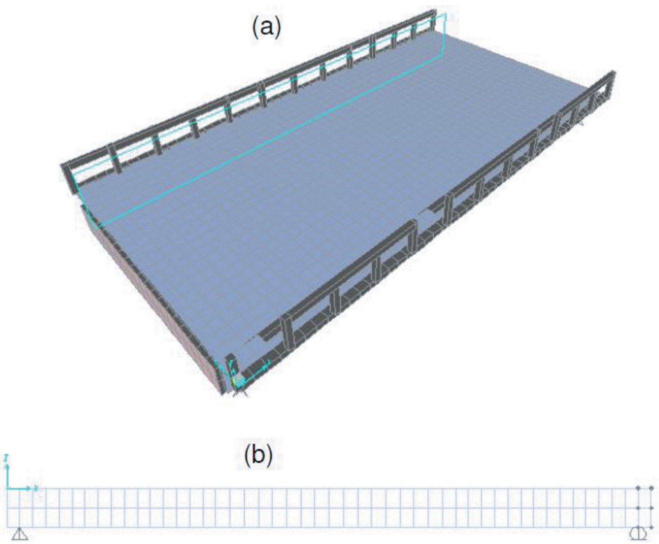

Figure 3. 3D shell only model. (a) Isometric general view. (b) General profile.

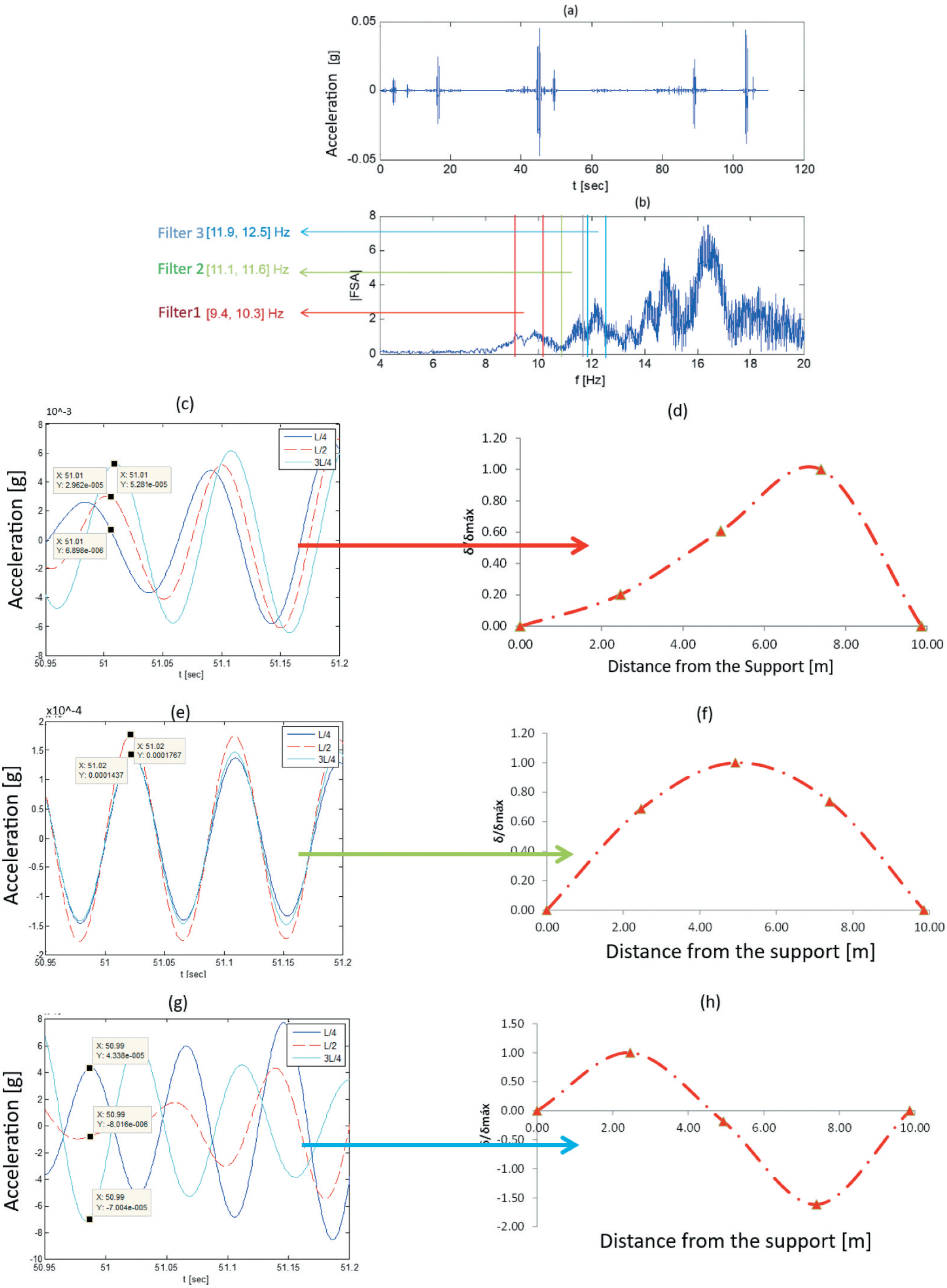

Figure 4. Signal processing. (a) Acceleration record. (b) Frequency spectrum. (c) Filtered signal (Filter 1). (d) Modal shape filtered signal (filter 1). (e) Filtered signal (Filter 2). (f) Modal shape filtered signal (filter 2). (g) Filtered signal (Filter 3). (h) Modal shape filtered signal (filter 3).

shell-frame models with wearing surfaces and barriers (as additional masses), and mathematical expressions for flexural and torsional frequencies based on Euler-Bernoulli beam vibrations theory. Nevertheless, contemplating the feasibility of the model development for rapid assessment, 3D shell models are commonly used in the analysis of bridges, and therefore, chosen for this study. Non-linearity of materials cracked cross sections or additional support stiffness were not included in the numerical models, to simplify the application of this procedure.

Once the model is analyzed, modal shapes and frequencies for both flexural and torsional behavior can be obtained, as shown in Figure 5.

5 ANALYSIS OF RESULTS

As derived from the Euler-Bernoulli vibration theory, frequencies are dependent on variables such as modulus of inertia, element length, cross sectional area, density, and modulus of elasticity. Since all geometrical properties are constant, frequencies are directly correlated with the square root of the modulus of elasticity. Therefore, the relationship between experimental and numerical model frequencies can be expressed in terms of the modulus of elasticity ratio of the experimental and numerical models as described in Equation (3) for the flexural behavior.

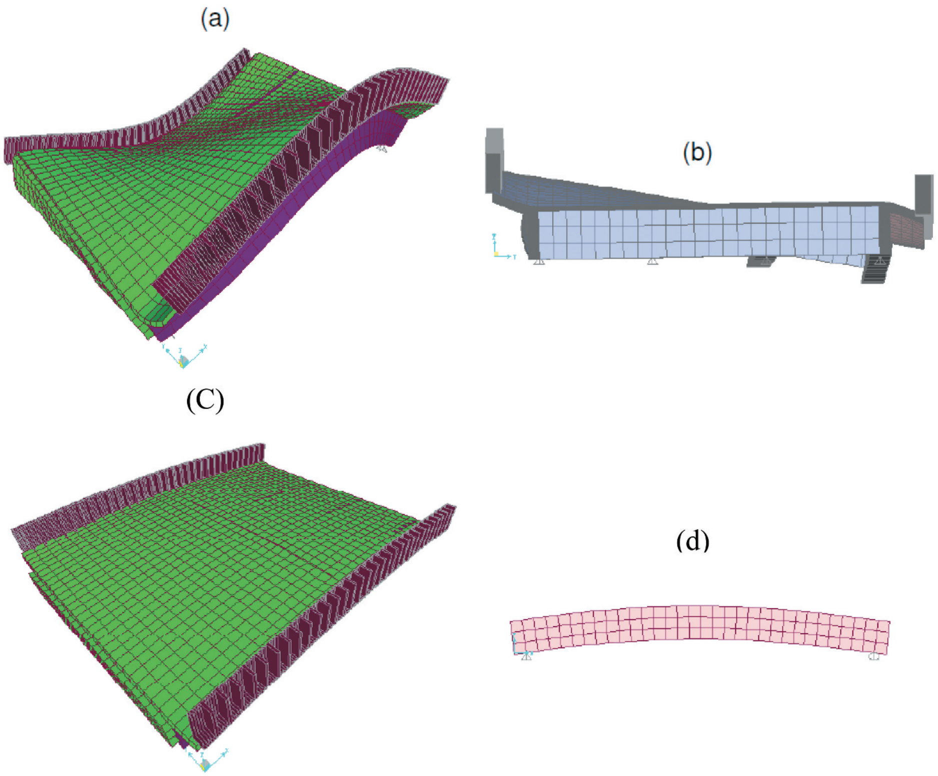

Figure 5. Modal Shapes. (a) and (b) Flexural modal shape. (c) and (d) Torsional modal shape.

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\begin{gathered}
f_F = \frac{\pi}{2L^2}\sqrt{\frac{EI}{\rho A}} : \{\pi \ L \ A \ I \ \rho\} = const. \therefore f_F \propto \sqrt{E} \\
\frac{f_F Exp}{f_F Mod} = \frac{\sqrt{E_{Exp}}}{\sqrt{E_{Mod}}} = \sqrt{\frac{E_{Exp}}{E_{Mod}}} \therefore \left(\frac{f_F Exp}{f_F Mod}\right)^2 = \frac{E_{Exp}}{E_{Mod}} \rightarrow E_{Exp} = E_{Mod}\left(\frac{f_F Exp}{f_F Mod}\right)^2
\end{gathered}
\tag{3}
$$

Thus, the frequency ratio squared could be related to the ratio between the elastic and the dynamic modulus of elasticity presented in Equation (2). As described before, that relationship depending on the compressive strength of the concrete could vary from 1.20 to 1.40 for high and low strength concretes respectively. Figure 6 Shows the frequency ratios results for all the bridge database, specifying the average ratio and the maximum and minimum extreme values. Taking the average value as the contrast value (ratio=1.10), the final relationship understood as the ratio squared is 1.21, which is consistent with the ratio between modulus of elasticity for structural concrete. Therefore, the inclusion of the dynamic modulus of elasticity in the numerical model for the dynamic analysis of vibrations results in the accurate structural response of the structure analyzed.

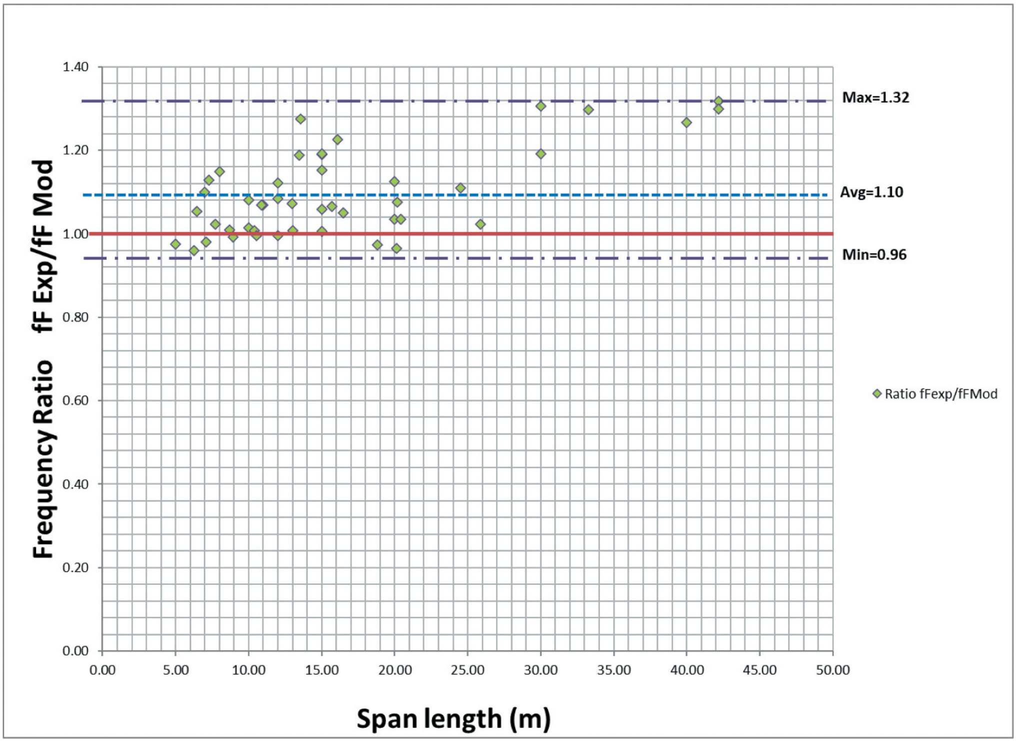

Figure 6. Frequency flexural ratios for different span lengths.

6 CONCLUSIONS

A rapid approach for dynamic analysis and characterization was proposed comparing numerical 3D models and acceleration records from a Colombian bridge database part of the main road system, provided by INGETEC S.A. The analysis suggests that for rapid assessment using acceleration records due to vibrations, a 3D shell-only model can be used, considering the dynamic modulus of elasticity instead of the regular approach which contemplates the elastic modulus. The modulus ratio (1.20) can be compared to the frequency ratio between the experimental and the numerical model squared (1.21). Consequently, findings suggest that the usage of the dynamic modulus of elasticity replicates more accurately the real behavior of the structure and could be used for practitioners and field engineers for rapid assessment. Further analyses and testing could be useful to determine an accurate relationship.

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