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EXPERIMENTAL CHARACTERIZATION OF VISCOELASTIC MATERIALS

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Abstract. *The present work aims to describe experimental procedures for viscoelastic materials, through the determination of their properties - shear modulus, G, and loss factor, η. The use of viscoelastic materials can increase the structural damping, so that vibrations levels are reduced. These properties and special formulations have permited to write down frequency and damping for structures that are composed by viscoelastic material layer between two metallic layers.*

In this work two known methods were used: the standardized American Society for Testing and Materials (ASTM, 1993) known as Standard Test Method for Measuring Vibration-Damping Properties of Materials and the Indirect Method (Masterson & Miles, 1995). A third technique called Direct Method, was also developed.

To verify the efficiecy of the methodology used in the ASTM Method, tests were accomplished to characterize the viscoelastic self-adhesive 3M-ISD. The obtained results were compared with others technical works and it could be verified that the used methodology is appropriate. Tests were also accomplished for obtaining the properties of the viscoelastic self-adhesive Very High Bond (3M-VHB), manufactured in Brazil, and the three presented methods were used. From the comparison of the obtained results some conclusions relative to the employed methodologies in these methods are presented.

Keywords: *Viscoelastic materials, Structural damping, Vibration damping.*

1. INTRODUCTION

The tendency for projecting lighter and slender structures, either by economical reasons or by new employed materials variety in the current constructions, or also older structures that have been suffering alterations in the acting load due to modifications of human behavior, have generated many dynamic problems, which can commit human comfort, as well as stability, functionality, durability and safety of the structure. Due to these problems, simple and economical ways of solving the excessive vibration problems in structures through the use of viscoelastic materials, which possess properties that increase the damping have been studied. The use of viscoelastic materials as systems of passive damping or as elements placed in strategic points of the structures, has showed a very interesting technique and it has motivated several works, because besides presenting efficiency in vibration damping, it has a very reduced cost with regard to the traditional technique of increasing structural stiffness, besides being a ligther solutions than the previous ones.

One of the most usefull way to describe rheological behavior of viscoelastic materials, is the complex modules representation. Therefore, the complex shear modulus is given by the following equation:

$$G^* = G + i\eta G \tag{1}$$

In this equation the real part represents the rigidity of viscoelastic material that means the stored energy, and the imaginary part divided by the real part represents the loss factor that means the ratio between the dissipated energy per radian and the stored energy.

The main purpose of this article is to characterize viscoelastic materials experimentally through their properties - shear modulus, G, and, loss factor, η.

In order to obtain viscoelastic materials properties, several techniques exist: Standard Test Method for Measuring Vibration-Damping Properties of Materials (ASTM, 1993) and Method for the Determination of Complex Shear Modulus of Viscoelastic Adhesives (denominated in this work Indirect Method, because the force is measured indirectly through the relative acceleration between two accelerometers), developed by Masterson & Miles (1995). In this work, these two techniques are presented and a third technique similar to the last one, is also developed (Faisca, 1998), however the force is measured directly. To verify the efficiency of those experimental techniques, tests were accomplished to characterize two types of viscoelastic adhesives: 3M-ISD, which is commonly used in tests of vibrations and 3M-VHB, that is manufactured in Brazil. This last material was used due to a need to search for vibration damping materials that were manufactured in Brazil with viscoelastic properties. After confronting the methodology used in ASTM tests (ASTM, 1993) with the ISD material, since the results obtained in these tests can be correlated with the one of Nashif *et al.* (1985), ASTM (1993), Masterson & Miles (1995), these tests were accomplished again with the VHB material.

2. METHODS FOR THE DETERMINATION OF VISCOELASTIC MATERIALS PROPERTIES

2.1 ASTM Standard Method

This method uses metallic bars to simulate clamped-free beams, as shown in Fig. 1.

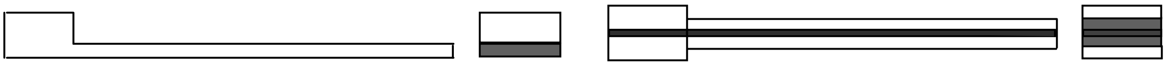

Figure 1 - Simple beam and sandwich beam with viscoelastic material between two bars.

Initially, impacts are given with an instrumented hammer that had a piezoelectric transducer in the simple and sandwich beams, and the responses are captured by a noncontacting transducer, which measures the displacement of the beams. This was necessary, since the models used were very slender, and any additional mass, just as the one of the accelerometers, could modify the mass of the bars, affecting their responses.

The frequency response functions (FRF) of the simple and sandwich beams are obtained and then, the natural frequencies and respective damping rates of the two beams are estimated. Through these values it is possible to obtain the viscoelastic materials properties, the dynamical shear modulus and loss factor, being used the equations (ASTM, 1993):

$$G_{2n} = \frac{(A-B)-2(A-B)^2-2(A\eta_n)^2}{(1-2A+2B)^2+4(A\eta_n)^2} \times \frac{E_1 H_1 H_2 a_n}{L^2} \tag{2}$$

$$\eta_{2n} = \frac{A\eta_n}{A-B-2(A-B)^2-2(A\eta_n)^2} \tag{3}$$

where,

$$A = \left(\frac{\omega_n}{\omega_{1n}}\right)^2 \left(2+\rho_r h_2\right)\left(\frac{B}{2}\right) \tag{4}$$

$$B = \frac{1}{6(1+h_2)^2} \tag{5}$$

G_{2n} is the shear modulus and η_{2n} is the loss factor of the viscoelastic material in the nth mode; a_n is a coefficient of a clamped-free beam in the nth mode; L is the length of the viscoelastic material; $h_2 = H_2/H_1$, H_2 is the thickness of the viscoelastic material, H_1 is the thickness of the simple beam; $\rho_r = \rho_2/\rho_1$, ρ_2 is the density of the viscoelastic material, ρ_1 is the density of the simple beam material; E_1 is the Young's modulus of elasticity of the simple beam; η_n is the damping rate of the sandwich beam in the nth mode; ω_n is the nth angular frequency of the sandwich beam; ω_{1n} is the nth angular frequency of the simple beam.

In spite of being a method that presents simplified test procedures (obtaining of FRFs), it is very limited, because it only allows one to obtain a few points for the viscoelastic properties, in other words, just in relationship to the natural frequencies of the simple beams.

2.2 Indirect Stiffness Method

The device used in this method is shown in Fig. 2, the shaker used, that is fixed to the remaining of the assembly, provides white noise base excitation that will induce shear in the viscoelastic material and relative movement between the base and the metallic block. The dynamic force is measured indirectly through an accelerometer fixed to the base (ac.1) and the response through another accelerometer fixed to the metallic block (ac.2). Due to this reason, this method is called indirect.

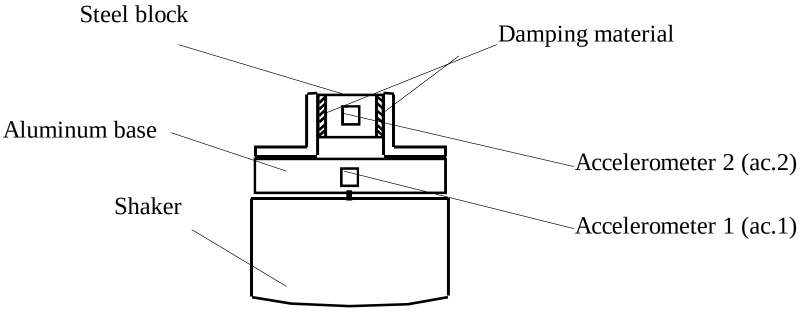

Figure 2 - Block diagram of the Indirect Method.

Obtaining experimentally the transfer function $H_{xy}(\omega)$, between $x(t)$ and $y(t)$, using the H_1 technique (Andrade, 1997), the effective complex stiffness of the viscoelastic material can be calculated by the equation (Masterson & Miles, 1995):

$$K(\omega) = \frac{\omega^2 m}{\left(1 - \frac{1}{H_{xy}(\omega)}\right)} \tag{6}$$

where, m = block mass, ω = frequency of excitation (angular).

The relationship between the complex shear modulus and complex stiffness can be given by:

$$G(\omega) = \frac{K(\omega)h}{2bl} \tag{7}$$

where the factor of *2* accounts for the fact that there is a viscoelastic material fixed in two sides of the block, h is the thickness, b is the width and l is the length of the viscoelastic material.

Therefore, with the real and imaginary parts of the FRF obtained from input and output transducers follows the calculation of the stiffness through Eq. (6) and the complex shear modulus through Eq. (7). The real part of this modulus is just G and the imaginary part divided by the real part is η.

This method has as advantage in relation to the ASTM Method, that it is possible to obtain a continuous curve for viscoelastic materials in a wide range of frequencies.

2.3 Direct Stiffness Method

In order to avoid the difficulties presented in the Indirect Method, which measures force indirectly through the acceleration, the scheme ilustrated in Fig. 3 was proposed, where the excitation force becomes one of the controlled variables in the tests, making this method more advantageous than the previous ones. The dynamic force is measured directly by a load cell and the response, through an accelerometer or a noncontacting transducer.

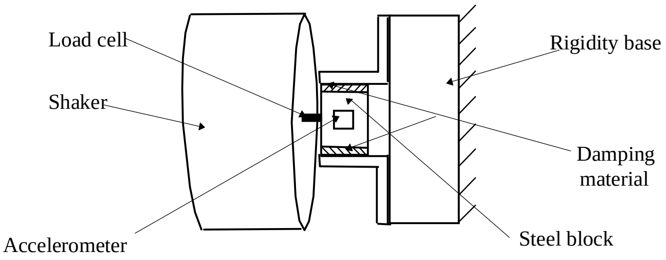

Figure 3 - Block diagram of the Direct Method.

Obtaining experimentally the transfer function $H_{xy}(\omega)$, between $x(t)$ and $y(t)$, using the H_1 technique (Andrade, 1997), the effective complex stiffness of the viscoelastic material can be calculated by the equation (Faisca, 1998):

$$K(\omega) = \frac{1}{H_{xf}(\omega)} + m\omega^2 \tag{8}$$

The complex shear modulus is obtained as the previous method, through Eq.(7).

3. EXPERIMENTAL RESULTS

3.1 Tests using the ASTM Standard Method

Initially, tests were made using ISD material in order to verify the accuracy of the device and the methodology used in it. These tests presented similar responses shown in others works, like Nashif *et al.*(1985) and Masterson & Miles (1995). After confronting the used methodology, it was proceeded to perform the tests with VHB material, and through equations (2) and (3), the values for G and η were calculated.

The dimensions of the aluminum bars used in these tests are: for A bar - 0,225 m x 0,0127 m x 0,0021 m with VHB thickness 0,00064 m; for B bar - 0,450 m x 0,0127 m x 0,00625 m with VHB thickness 0,00064 m and for C bar - 0,705 m x 0,0255 m x 0,0032 m with VHB thickness 0,0023 m.

Figures 4 and 5 show the results for G and η for VHB material, using the aluminum bars.

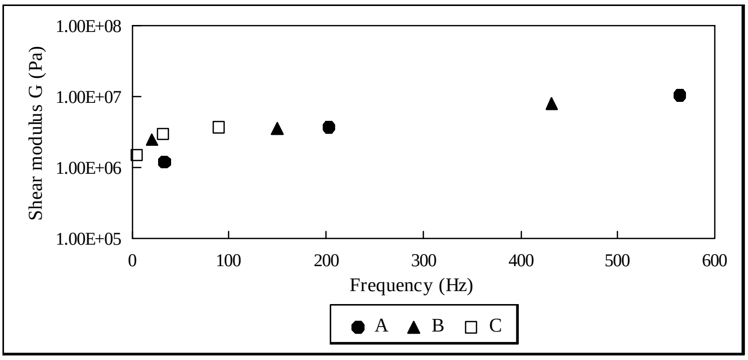

Figure 4 - Shear modulus G for VHB material.

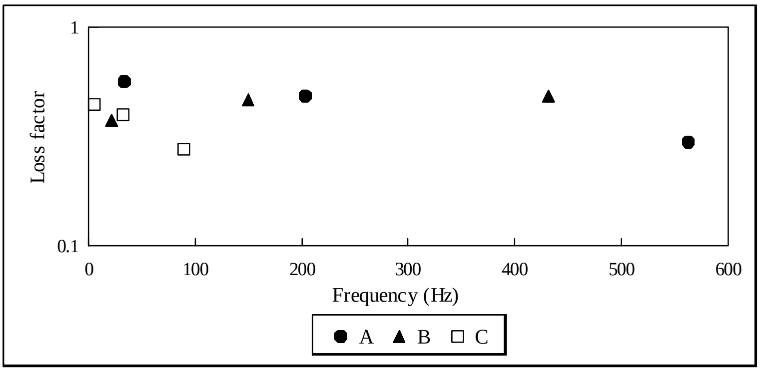

Figure 5 - Loss factor η for VHB material.

One can observe, through Figs. 4 and 5, that the obtained values come in very close areas for the different dimensions of the bars, allowing the observation of a curve with very coherent values for *G* and η for the VHB material.

3.2 Tests using the Indirect Method

The characteristics of these tests were similar to the ones used by Masterson & Miles (1995). The material of the block is steel, with dimensions of 0,025 m x 0,025 m x 0,040 m and mass 0,1181 Kg. The viscoelastic material used as vibration damping, was the VHB-4970 with the following dimensions: 0,010 m of width, 0,025 m of length and 0,0023 m of thickness.

For obtaining the frequency response function (FRF), tests using random excitation were performed. The input and output signs were measured through resistive accelerometers.

Figures 6 and 7 illustrate, respectively, shear modulus *G* and loss factor η of the VHB material, obtained through equations (6) and (7).

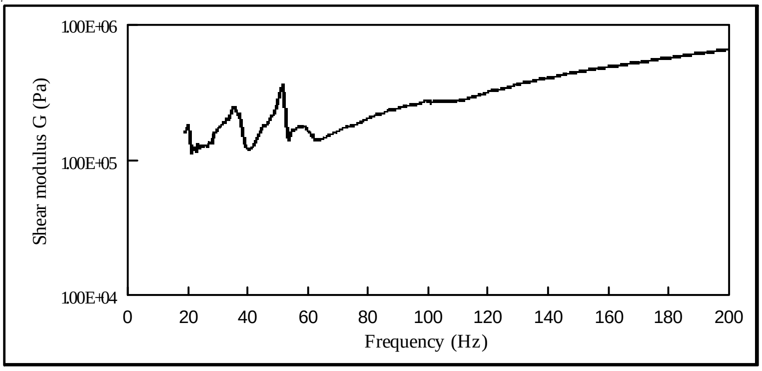

Figure 6 - Shear modulus *G* for VHB material.

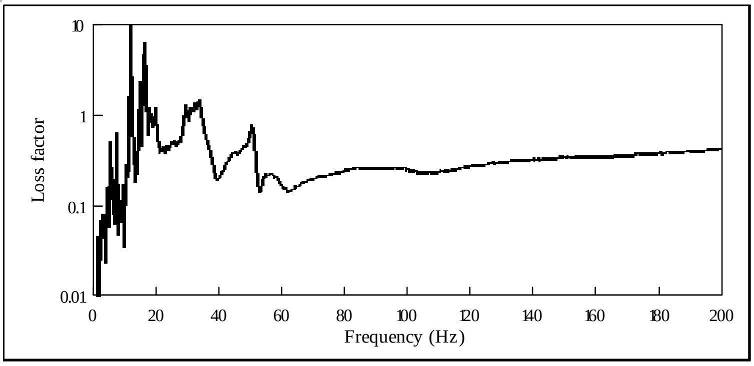

Figure 7 - Loss factor η for VHB material.

In these figures, one can observe that the resistive accelerometers obtain stable measures for frequency range between 50 and 200 Hz.

Some tests using piezoelectric accelerometers were also made, which did not present good results for frequencies below 300 Hz, because these transducers can only obtain good response for higher frequencies.

3.3 Tests using the Direct Method

The methodology used in this test is similar to the one mentioned in item 3.2. The VHB block and the material used have the same characteristics and dimensions described in the previous item.

In order to obtain the frequency response function (FRF), tests using random excitation like white noise were performed. The input sign was measured through a piezoelectric load cell and the output was measured through a noncontacting transducer.

Using this output transducer the shear modulus G and the loss factor η presented values very different from those found in the previous methods. To understand the reason of this great difference, a parametric study was accomplished where it was verified that the parameters G, and mainly η are quite sensitive to the fase angle. This study was motivated by the fact of both the noncontacting transducer and the usual techniques of estimating FRFs introduce mistakes when measuring the phase angle.

For the correction of the phase angle, two aspects should be considerate.The first one is related to the positive or negative direction of the measured sign of force (traction and compression) and the displacement, being necessary, a correction in the angle of 180° in case of being in opposite direction. The second factor is associated with the possible phase delays, inherent to the transducers characteristics. The piezoelectric load cell used does not present this problem as verified in work accomplished previously at the Structures Laboratory of COPPE/UFRJ (Roitman *et al.*, 1997). In order to verify if the noncontacting transducer presented some kind of variation in phase measures, a test was accomplished, in which an aleatory sign similar to white noise was used for the excitement.

In this test, the piezoelectric accelerometer was used as reference since this kind of transducer presents small phase variations, as it is shown in (Roitman *et al.*, 1997). From the relative phase between these two transducers for a range between 0 and 400 Hz, it was possible to fit a straight line through the least square method. The result obtained in this fitting for the angular coefficient was 0,15 rad/Hz.

Applying this correction to the measured FRFs in the test with VHB material, one can obtain G and η, that are presented in Figs. 8 and 9.

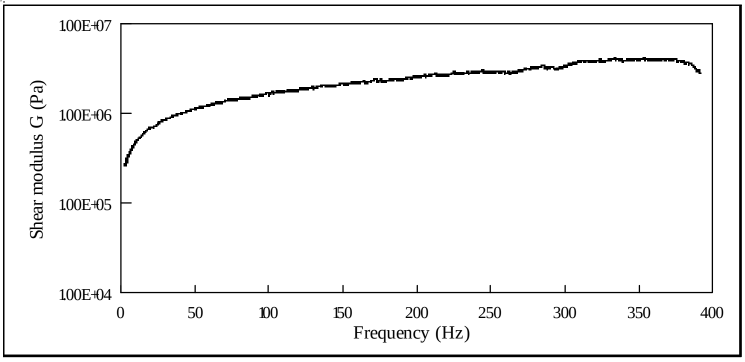

Figure 8 - Shear modulus *G* for VHB material with phase angle correction.

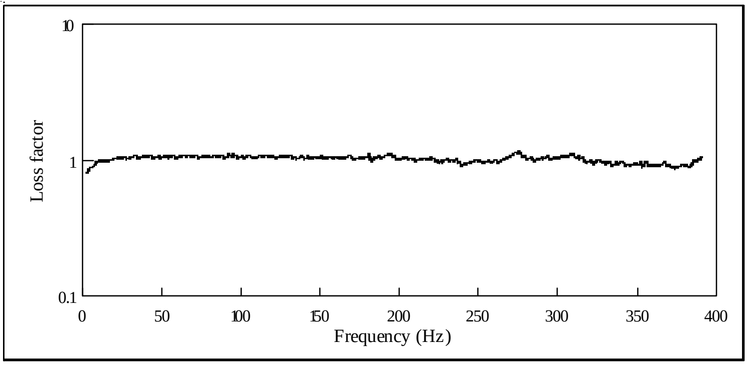

Figure 9 - Loss factor η for VHB material with phase angle correction.

One can notice in Figs. 8 and 9 that the correction imposed to the phase angle eliminates the differences mentioned initially, showing that those tests are quite sensitive to variations in the phase angle, that in turn are difficult to be measured with good accuracy.

4. COMPARISONS AMONG THE TEST METHODS

The ASTM Method is a standard test used internationally, and the necessary experimental data for describing viscoelastic materials can be obtained with good precision, due to this reason it was used as reference to the other two used methods.

Figures 10 and 11 present, respectively, a comparison between the values of shear modulus *G* and loss factor η, among these three presented methods. In these figures, the symbols of the bars *A* to *C* refer to the ASTM Method, and the continuous lines refer to the Indirect and Direct Methods.

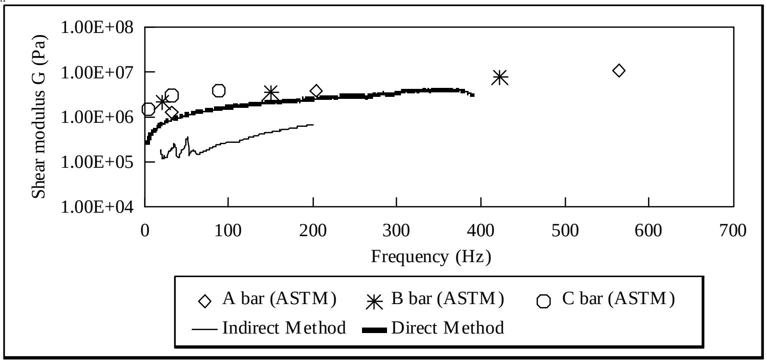

Figure 10 - Comparison between the three methods used to describe *G*.

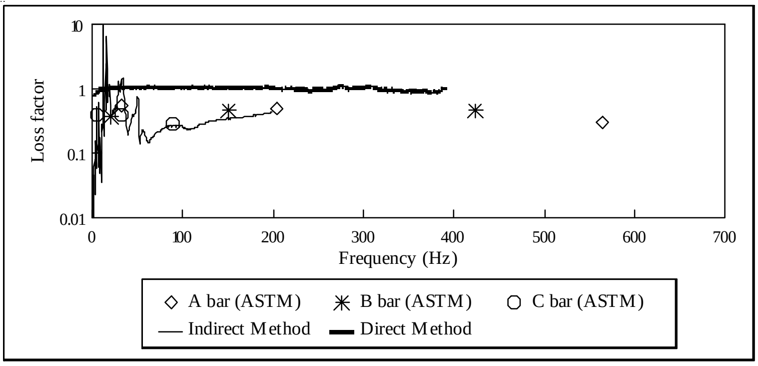

Figure 11 - Comparison between the three methods used to describe η.

One can observe, in Figs. 10 and 11, that in the Indirect Method the values of shear modulus *G* were very inferior to the ones obtained from the other methods. For the loss factor η, in spite of the values below 50 Hz presented great variations for Indirect Method, one can notice a tendency in following the values found by the ASTM Method. It is also observed that, shear modulus *G*, obtained by the Direct Method, presented similar values to the ASTM. With regard to the loss factor, η, the tests using the Direct Method presented values a little higher than the ones obtained with the two other methods.

In spite of the ASTM Method to be a standard method, it only allows to obtain the characteristics of materials for the natural frequencies of the structure that will be used as damping, which is difficult to use in practice. The Direct Method, that has the advantage of obtaining a continuous curve of values for *G* and η, presented a small difference for the values of η due to the great sensitivity to accomplish experimental measures. In case of using this method, a refinement in the assembly of the test and the use of more sensitive equipments for the accomplishment of the experimental measurements are recommended.

5. FINAL COMMENTS

Through the experimental results used for the characterization of viscoelastic materials in the three analyzed methods, one can notice that the necessary ones for the application of the ASTM Method (ASTM, 1993), were shown to be the most reliable. This is because in this method, the necessary data are just the natural frequencies and damping rates, that can be obtained with good precision by several corroborated techniques. Another advantage associated to the ASTM Method, is that it requests a more simplified experimental assembly and the standardization presented by ASTM allows one to minimize possible mistakes associated to the process. Due to these reasons, and for being a standard method and internationally used, it was adopted in this work, as reference for the other analyzed methods. However, this method only allows one to obtain the values of shear modulus, G, and loss factor, η, for a few points in frequency, that is, for the natural frequencies of the test specimen. So, to estimate the values of G and η for the other frequencies, it becomes necessary to do an interpolation among the values obtained for the natural frequencies of the test specimen, being able to induce some imprecisions in the estimates of these values.

The Indirect and Direct Methods, that possess the advantage of obtaining a continuous curve for the characteristics G and η for the viscoelastic materials in a wide range of frequencies, are very influenced by the measured phase angle between the excitation and response, as it was verified through the calculation of these characteristics using these methods. This angle is quite dependent of the transducers, the equipments and the methodology used for estimating the FRFs. This could be proven, through the accomplished tests, in which the difficulty was verified for obtaining this measurement with a good precision. Besides, these two methods present an excessive sensitivity to the accomplished experimental assembly, since when being idealized and mathematically modeled, these methods only consider one degree of freedom (axial displacements) and in practice, this condition is very difficult to attend.

In spite of these problems observed with the Indirect and Direct Methods, the results for shear moduls, G, were close to the results obtained by the ASTM Method, however for the loss factor, η, they were more distant, showing a larger sensitivity to the related problems. It must be regarded that the use of thin viscoelastic adhesives in the tests may cause small imperfections in the assembly. However, for the industry of civil construction, certainly will be necessary materials with a thickness higher than the dimensions used in these tests. And so, the characterization of these materials will also be able in assemblies with greater dimensions than those used here, minimizing the problems verified in the development of the current work.

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