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DAMAGE IDENTIFICATION USING MODAL STRAIN ENERGY IN A STRUCTURE WITH ORTHOTROPIC PROPERTIES

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Abstract. *The modal strain energy method is numerically employed in order to identify the damage in a sandwich panel with honeycomb core. The damages were artificially imposed by decreasing the young's modulus value in a small area of the panel. The Finite Element Method was used for performing the modal analysis. According to the numerical results it was possible to detect the exact damage position on the structure by using the modal strain energy method.*

Keywords: *Modal Strain Energy, Damage Identification, Honeycomb Core*

1. INTRODUCTION

The development of techniques for detecting damage by non-destructive methods has been the object of studies since the 1980s (Kim and Stubbs, 1995). In engineering the monitoring of structures in order to identify damage is of great importance since it makes possible corrective interventions. There are methods that aim to analyze the whole common structure and other methods that enable the monitoring of small regions of the structure (Tufoi, *et. al*, 2015).

One of the available methodology used to detect the damage take into account the structural dynamic properties are the natural frequencies and the modes shapes monitoring. According to Kim and Stubbs (1995) most of studies devote efforts on monitoring the perturbation of the structural natural frequencies in order to check the damage presence. It's also important to highlight that those methods based on natural frequencies may present a limitation. The limitation relies on the fact that the structure may present severe damage resulting in a small frequency variation, in which can be classified as a measurement error (Kim, et. al., 2003).

In order to overcome this limitation an alternative method based on modes shape monitoring was introduced. Kim and Stubbs (1995) emphasized that the main advantage of this method is that it is more sensitivity to the damage than to the frequencies. Alternatively to the previous methods introduced is the Modal Strain Energy (MSE) which is based on modes shapes. The MSE consists of analyzing the strain energy variation in the structure when it presents damage. The reduction in stiffness of a structure can be characterized as damage and this causes an increase in the modal strain energy of the structure (Pereyra, *et. al.*, 1999).

The main goal of this work is to determine if MSE is accurate enough to monitor and identify damage in light orthotropic structures that are widely used in the aerospace industry. This kind of panels are usually manufactured as honeycomb structures having cells as hexagonal shape, Fig. 1. The cells geometry allow the reduction of weight and when associated with high resistance laminate plates allow a structure with good ratio weight-strength as well (Paik, *et. al.* 1999).

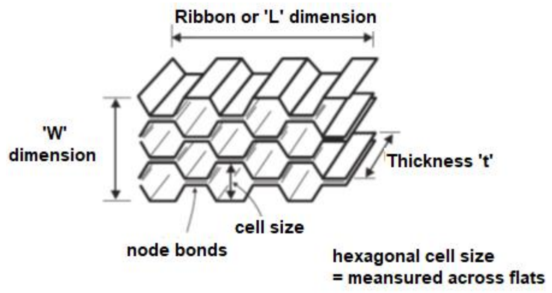

Figure 1. Geometry of core cell shape for sandwich honeycomb panels

A numerical analysis is performed by using the Finite Element Method (FEM) in an aluminum-aluminum sandwich panel with honeycomb core. The present numerical model has similar properties to a real panel used in the manufacturing of the Brazilian Geostationary satellite. This panel has already been characterized dynamically through the correlation of experimental and numerical modal analysis (Domingues, et al., 2017). Table 1 presents a comparison between the numerical natural frequency values and those obtained experimentally from Domingues (2017).

Table 1. Numerical and Experimental natural frequencies of the panel

Modes	Natural Frequencies for Modal Test (Hz)	Natural Frequencies Numerical (Hz)	Num x Exp (%)
1	159.2	159.5	0.19
2	201.6	204.9	1.63
3	430.4	426.7	-0.86
4	724.3	728.3	0.55
5	759.1	767.3	1.08

2. NUMERICAL METHODOLOGY

A 3D finite element model divided in 3 layers with dimensions of 670mm in the L direction, 300mm in the W direction and with 10mm of thickness was considered. The outer layers represent the faces with isotropic properties of aluminum alloy 2024 T3 with modulus of elasticity of 70GPa, Poisson coefficient of 0.3 and density of 2780Kg/m^3 with 0.3mm of thickness. The middle layer was simulated by taking into account the properties of the honeycomb. These properties were taken from the manufacturer's data sheet and represent the properties of 5056 aluminum alloy in hexagonal format. In the L dimension the modulus is 220MPa, in the W direction dimension is 103MPa and in the direction of thickness strength is 1.8MPa (HexWeb, 2000). The thickness of core was 9.4mm and the density of the structure was estimated based on the weight and approximate volume of the honeycomb structure of 77.64 kg /m^3. A convergence analysis was performed using the first natural frequency, see Fig. 2.

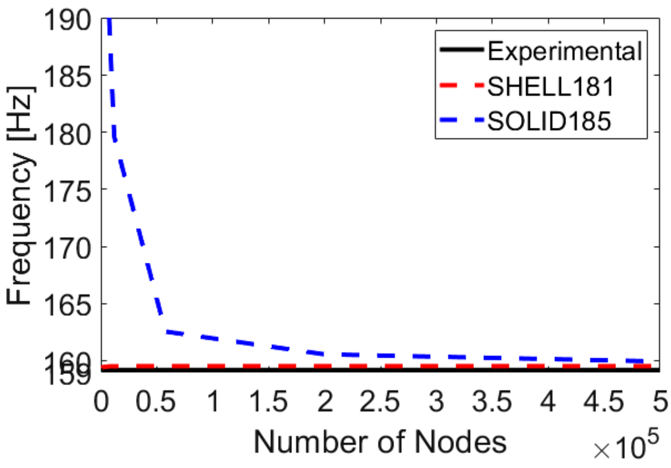

Figure 2. Mesh convergence

After performing a convergence analysis the finite numerical model was discretized with the element SHEL181 resulting a mesh with 2070 elements and 2170 nodes. In order to implement the MSE it is mandatory to determine the dynamic properties of the undamaged panel. These results obtained are stored and used as reference for subsequent damage analyzes. The MSE is calculated using the vector shape and stiffness matrix according to eq. (1).

$$U_i = [\,\Phi_i\,]^T\,[\,K\,]\,[\,\Phi_i\,] \tag{1}$$

U_i represents the MSE in absence of damage for the mode shape "i", Φ_i is mode shape vector "i" and K is stiffness matrix. After analysis of the undamaged structure, the next analyzes will be identified with a dash above eq. (2).

$$\overline{U_i} = [\,\overline{\Phi_i}\,]^T\,[\,\overline{K}\,]\,[\,\overline{\Phi_i}\,] \tag{2}$$

If the structure is undamaged the ΔU results equal to zero, where:

$$\Delta U = \overline{U_i} - U_i \tag{3}$$

When the structure has a presence of any damage the ΔU is expected be greater than zero. Once the presence of damage is detected, (i.e. $\Delta U>0$), the next step relies on identify the damage position. Thus the structure is divided into a predefined number of regions where the MSE is applied for each one of them by using simultaneously eq. (4) in absence of damage and eq. (5) for the panel with damage.

$$U_{ij} = [\,\Phi_{ij}\,]^T\,[\,K_j\,]\,[\,\Phi_{ij}\,] \tag{4}$$

$$\overline{U_{ij}} = [\,\overline{\Phi_{ij}}\,]^T\,[\,\overline{K_j}\,]\,[\,\overline{\Phi_{ij}}\,] \tag{5}$$

U_{ij} is the MSE of mode shape "i" for region "j", Φ_{ij} is mode shape vector "i" for region "j" and K_j is the stiffness matrix of the region "j". The sum of the energy of each mode shape was performed for each region to define the amount of MSE associated with that region.

In this case, the panel was divided into 9 regions with approximate dimensions of 223mm in the L direction and 100mm in the W direction and numbered 1 to 9 as shown in Fig. 3. The damage was artificially inserted as a reduction of the young module in one of the 9 regions of one face. This damage is similar to some structure failure such as a lack of contact between the face and the honeycomb core.

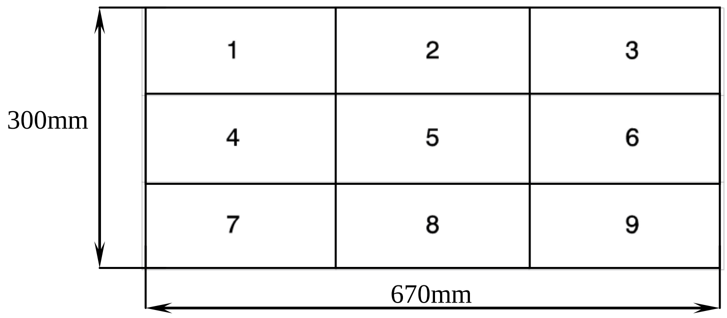

Figure 3. Division of the panel in 9 regions

3. NUMERICAL RESULTS

The numerical results were analyzed by considering the natural frequencies variation when there is a reduction of the stiffness in one region of the face and by the identification of damage when a region of the face is reduced by 25% and 10% of Young's modulus.

After the calculation of the modal strain energy for each region of the panel without damage, 8 analyzes were performed considering a reduction of 25% and 10% of the young's modulus of face in regions 1, 2, 4 and 5. Only 4 regions were analyzed due to symmetry. Region 1 is similar to regions 3, 7 and 9. Region 2 is similar to region 8 and region 4 is similar to region 6. Tables 3 and 4 present the natural frequencies for each case.

3.1. Case 1- Reduction of 25% of the Young's modulus

The analysis of the variation of natural frequencies shows that for a reduction of 25% of Young's Modulus the presented differences were smaller than 5% Tab 3. As it is a numerical model it is possible to verify this variation. However in a real measurement case this difference would be considered within the experimental tolerance.

Table 2. Natural frequencies for 25% Young's Modulus reduction

Damage in	Mode 1[Hz]	Mode 2[Hz]	Mode 3[Hz]
Undamaged	159.57	204.90	426.77
1st region	158.92	203.84	423.36
2nd region	156.83	202.65	423.77
4th region	158.94	203.50	423.79
5th region	157.09	201.93	424.36

By applying the identification method proposed by Kim and Stubbs (1995), it was possible to identify and localize the damage more accurately. When a region presents some change in its mechanical properties which would characterize damage, its strain energy changes. The region with the greatest energy variation indicates the presence of damage, as can be followed in Fig. 4.

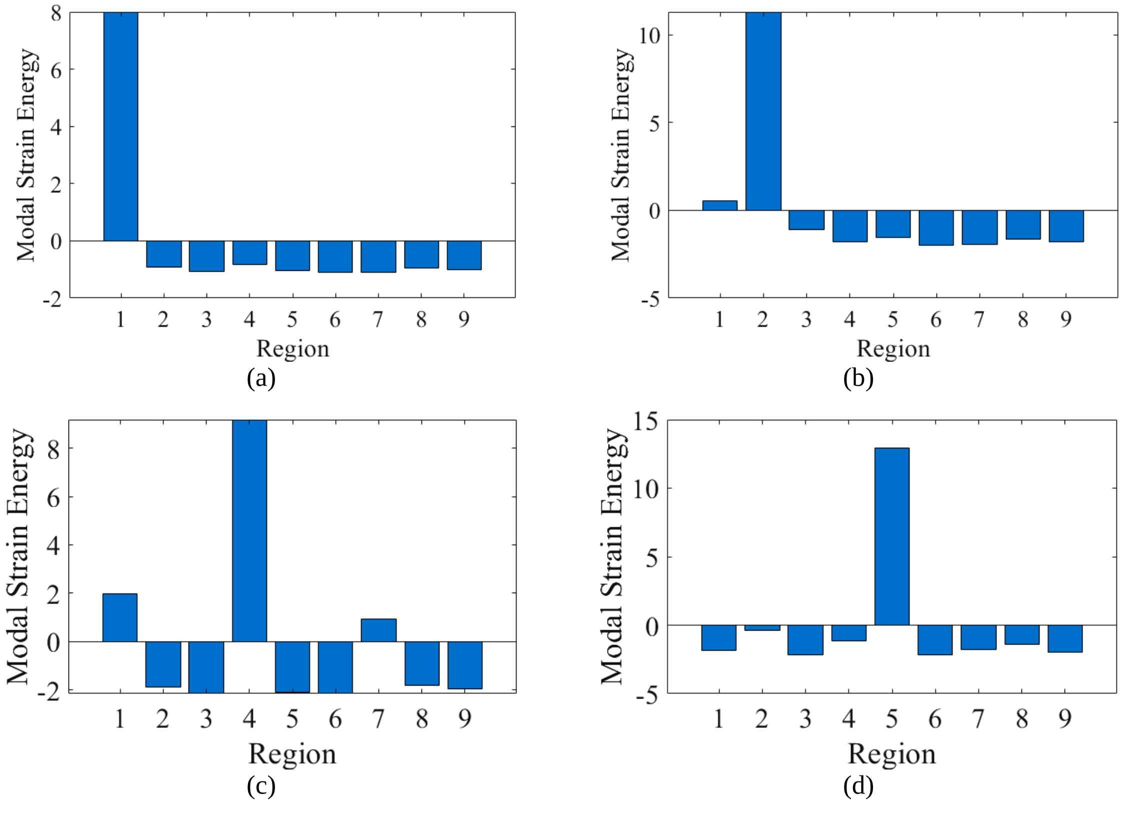

Figure 4. MSE variation considering the damage of 25% Young's Modulus reduction in the region: (a) 1, (b) 2, (c) 4 and (d) 5

For the case of 25% reduction of the young's modulus it was possible to identify and locate the region that the damage was deliberately imposed.

3.2. Case 2- Reduction of 10% of the Young's modulus

The second case has as main objective to analyze the sensitivity of the present method. It consists of an analysis of a reduction of Young's Modulus less severe than those imposed to case 1. The variation in frequency values is less noticeable than presented in Tab 4 for the first case. In this second case the differences were less than 1%.

Table 3. Natural frequencies for 10% Young's Modulus reduction

Damage in	Mode 1[Hz]	Mode 2[Hz]	Mode 3[Hz]
Undamaged	159.57	204.90	426.77
1st region	159.27	204.45	425.53
2nd region	158.48	204.01	425.71
4th region	159.27	204.32	425.65
5th region	158.55	203.73	425.89

When applying the MSE to perform the damage identification it was possible to identify and locate the damage as in the previous case Fig. 5.

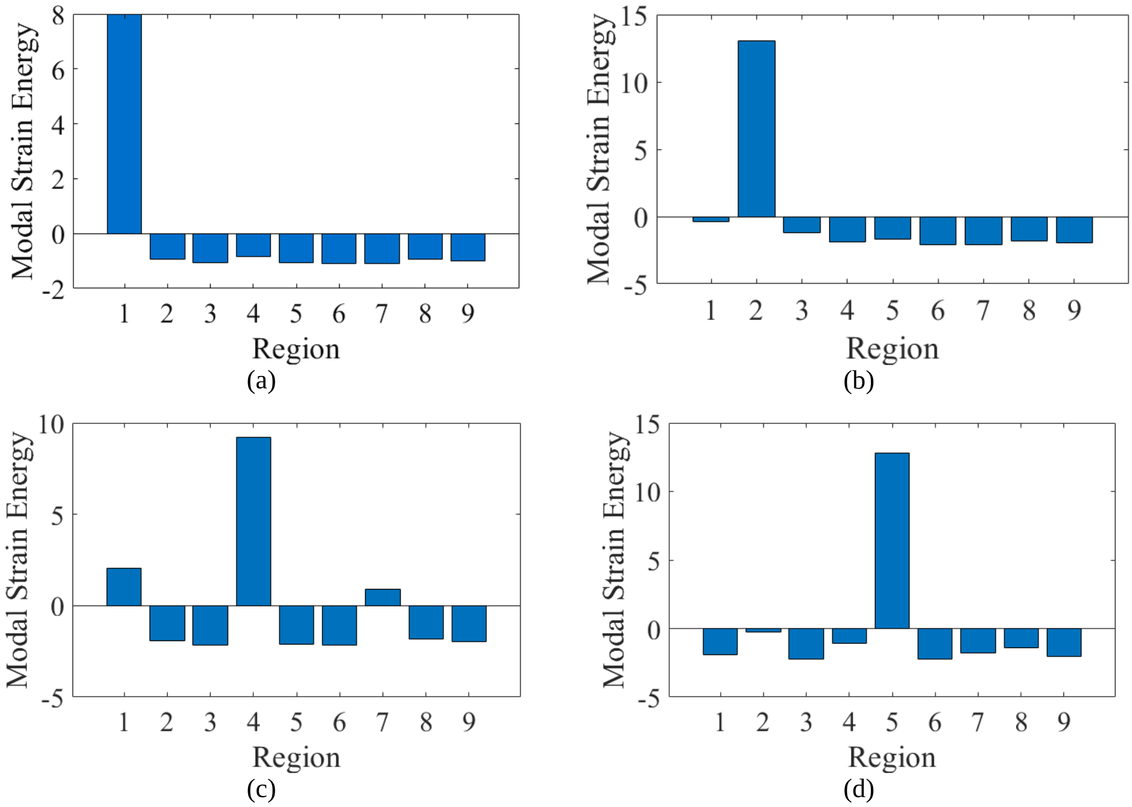

Figure 5. MSE variation considering the damage of 10% Young's Modulus reduction in the region: (a) 1, (b) 2, (c) 4 and (d) 5

In the outermost region, region 1, the modal strain energy variation was larger than the other regions. It is also possible to observe that the regions around the damaged region were also affected by small variation of strain energy. In addition to locating the damage in all regions in both cases it is possible to notice a decrease in the scale of reduction from 25%, fig. 4, to a reduction of 10%, fig. 5.

4. FINAL CONCLUSIONS

In this work the results of an analysis of damage identification were presented using the MSE. This analysis was applied in a finite element model of a lightweight aluminum-aluminum structural panel with honeycomb core. The SHELL181 element was used for the numerical model whose values of frequencies and modes shapes are closed to the real structure characterized dynamically by Domingues (2017). The MSE calculation by using the vibration mode vector and the stiffness matrix it was possible to identify and locate the damage as well as measure depending on the variation in the young's modulus value. According to the present results it was concluded that the MSE based on the strain energy is more accurate in determining the structural damage than when performed by natural frequency variation. As a future work the authors are devoting efforts into perform the present methodology experimentally.

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6. RESPONSIBILITY NOTICE

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