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Effects of Structural Damage on Dynamic Behavior at Sandwich Composite Beams - Part I-Theoretical Approach

This paper series presents an analysis regarding the dynamics of sandwich composite beams, embedded at one end*, in order to highlight the effect of geometrical and material discontinuities upon the natural frequencies. In first part (Part I), analysis was performed with Euler-Bernoulli analytical method for determining the vibration modes and in second part (Part II), analysis was performed with numerical simulation in SolidWorks software for a five-layer composite. In the last section of the paper, an example is shown regarding how to interpret the obtained results.*

Keywords*: beam, finite element, frequency, simulation, structure*

1. Introduction

Periodic inspection and control of the engineering structures are imperatively needed in terms of the real-time fault detection and thus ensure safety use of the structure.

The early identification of structural damage during the mechanical structure operation, allows well planned maintenance with important impact on reducing operating costs, or can justify replacing the structure, in order to avoid accidents that can have tragic consequences for individuals and failures, which can cause significant financial and material losses [4], [5].

In this work is presented the studies on beam-type composite structures, undertaken to establish the relevance of cross faults influence on the dynamic behavior of the beam.

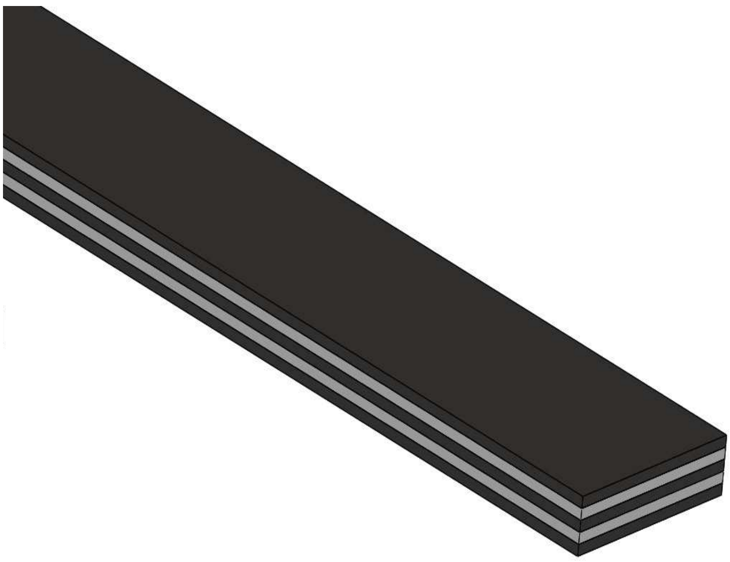
2. The damage effects of isotropic materials beams

The structural damage influences the dynamic behavior of structures by changing the mechanical and the dynamical characteristics, such as modal shapes, natural frequencies and the degree of damping, flexibility or stiffness. On these principles are based the global methods of fault detection.

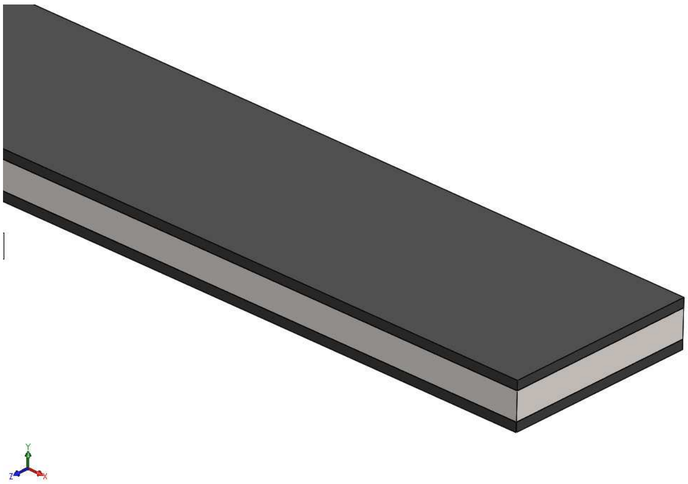
Into the literature, the methods most commonly presented and considered in industrial applications, and they are those based on the change in frequency [1], [2] and [3].

They can be divided in their turn into two categories: methods that allow only fault detection, and advanced methods for localization and quantification of the faults. Composite materials are composed of two or more structure distinct identified constituents, with physical and / or mechanical different properties. In contrast to the natural materials with properties well known, the composites are developed to meet specific needs, enabling a new approach of the structural design.

Laminated structures are a special class among the composites, which are manufactured by attaching the thin sides on the lightweight core, with high enough thickness and rigidity (Figure 1.a. three-layer beam and Figure 1.b. five-layer beam).



a)



b)

Figure 1. Laminated structures: a) three-layer beam and b) five-layer beam

The faces of laminated structure are usually made of steel or aluminum having a core of low density material, such as foam, PVC, PTFE. The spatial distribution of the constituents gives the desired mechanical and physical properties (sometimes chemical properties). This construction provides to the composite layers a high bending stiffness, in relation to weight [7], [8].

The natural frequency of the isotropic materials beams can be determined by the relation (1):

$$f_n = \frac{(\alpha_n L)^2}{2\pi}\sqrt{\frac{EI_z}{mL^3}} \tag{1}$$

where f_n is the proper frequency of module n (n = 1, 2, 3, ...), $\alpha_n L$ is the wave number of the module *n*, which depends on the shape conditions, *E* is the longitudinal elastic modulus, *Iz* is the moment of inertia regarding the weak axis, ρ is the density of material by which is made the beam, *A* is the cross-sectional area and *L* is the length of the beam.

For rectangular sections of beam, can obviously have:

$$A = B \cdot H \tag{2}$$

$$I_z = \frac{B \cdot H^3}{12} \tag{3}$$

if the sides of the cross-sectional are width *B* and height *H*.

For composites, the relation (1) may be applied with the condition of use an appropriate form of rigidity *EI*. This can be determined for each one, and then can be composed for the whole section, using Steiner's formula for parallel axes. In that, the interest is to have high rigidity and low weight, the outer faces have to be by metal and the core / cores by lightweight material; therefore, it is suggested an odd number of layers.

Thus, in this study the two types of materials (of beams) are considered, a 5-layers one and another of 3 layers, both with the overall height of 5 mm, defined as follows:

- the 5 layer composite has three layers of steel placed outside and in the middle (the thickness of the $s_{OL}=s_{1,3,5}$=1 mm) and two layers of PVC (S_{PVC} with the same thickness $s_{PVC}=s_{2,4}$=1 mm) sandwiched between steel layers;

- the composition of the three layers is similar to that with 5-layers one, but the central layer of the steel is replaced with the PVC. This makes the metallic core thickness $S_{PVC}=S_3$=3 mm, as shown in Figure 2.

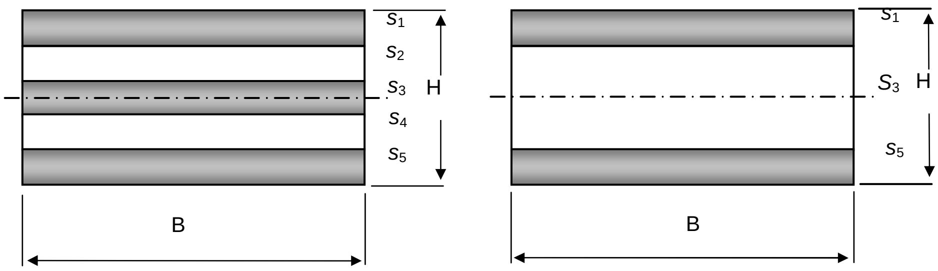


Figure 2. Section of the two analyzed composites

For the five-layer composite, the rigidity *EI* is computed as follows:

- for layer 1:

$$EI_1 = E_{OL}\left[\frac{Bs_1^3}{12} + d_1^2(Bs_1)\right] = E_{OL}\left[\frac{Bs^3}{12} + 4Bs^3\right] \quad (3)$$

- for layer 2:

$$EI_2 = E_{PVC}\left[\frac{Bs_2^3}{12} + d_2^2(Bs_2)\right] = E_{PVC}\left[\frac{Bs^3}{12} + Bs^3\right] \quad (4)$$

- for layer 3:

$$EI_3 = \frac{EBs_3^3}{12} = \frac{EBs^3}{12} \tag{5}$$

where, d_1 is the distance from the gravity center of layer 1 to the neutral axis and the distance d_2 takes from the gravity center of layer 2 to the neutral axis.

Since, all layers have the thickness s, and the distance $d_1=d_2=2s$, and the structure is symmetric about the Oz-axis ($EI_1=EI_5$ şi $EI_2=EI_4$), it can be write:

$$EI_{comp} = 2EI_1 + 2EI_2 + EI_3 = E_{OL}\left[3\frac{Bs^3}{12} + 9Bs^3\right] + E_{PVC}\left[2\frac{Bs^3}{12} + 2Bs^3\right] \tag{6}$$

or:

$$EI_{comp}^{(5)} = \frac{37E_{OL}Bs^3}{4} + \frac{13E_{PVC}Bs^3}{6} = \left(9{,}25E_{OL} + 2{,}167E_{PVC}\right)\cdot Bs^3 \tag{7}$$

Similarly, the stiffness of the three layers composite can be determinate, as:

$$EI_{comp}^{(3)} = \left(8{,}167E_{OL} + 2{,}25E_{PVC}\right)\cdot Bs^3 \tag{8}$$

On the other hand, into the frequency relation appears the composite structure weight, which can be determined by the relationship:

$$m_{comp} = \rho_{OL}\sum_{j=1}^{p} A_j L + \rho_{PVC}\sum_{k=1}^{q} A_k L \tag{6}$$

where, p is the number of steel layers and q is the number of PVC layers. For the five layer composite, the beam mass will be:

$$m_{comp}^{(5)} = 3\rho_{OL}BsL + 2\rho_{PVC}BsL = (3\rho_{OL} + 2\rho_{PVC})BsL \tag{7}$$

and for the three layers composite:

$$m_{comp}^{(3)} = 2\rho_{OL}BsL + \rho_{PVC}BSL = (2\rho_{OL} + 3\rho_{PVC})BsL \tag{8}$$

By introducing the expressions (4) and (7), respective (5) and (8) into the equation (1), the frequency of the considered composite beam may be determined.

The following formula determines the frequency for the 5-layers composite:

$$f_n^{(5)} = \frac{(\alpha_n L)^2}{2\pi}\sqrt{\frac{(9{,}25E_{OL} + 2{,}167E_{PVC})\cdot Bs^3}{(3\rho_{OL} + 2\rho_{PVC})BsL^4}} \tag{9}$$

It should be note that the modal shapes are similar with those determined for isotropic materials, as long as the ratio stiffness-mass does not exceed a critical value. At the exceeding of this value, the Euler-Bernoulli model is no longer adequate, and it is necessary to use a more complex model, such as Shear and Timoshenko [4-5].

In order to illustrate the calculation of frequencies, two beams as described above, in which the steel is elastic modulus E_{OL}=2,06·10^{11} N/m^2 and density ρ_{OL}=7850 kg/m^3, and the rigid PVC has longitudinal modulus E_{PVC}=2,41·10^9 N/m^2 and density ρ_{PVC}=1300 kg/m^3.

Each layer has a length L=1000 mm, and the rectangular cross-section implies the dimensions: B=20 mm, height H=5 mm.

The results related to the stiffness and the mass, are shown in Table 1 together with the results achieved for the same beam geometry, made entirely of steel.

Table 1. Values for the stiffness and the mass

Features / Beam type	EI_{OL}	EI_{PVC}	EI_{total}	m_{OL}	m_{PVC}	m_{total}
	[N/m^2]	[N/m^2]	[N/m^2]	[kg]	[kg]	[kg]
Whole steel	42,7	-	42,7	0,785	-	0,785
5 layers composite	33,8	10,4	33,9	0,471	0,052	0,523
3 layers composite	33,5	10,7	33,6	0,314	0,078	0,392

Analyzing the data from Table 1, it is noted that the stiffness of composite structures is approach, as order of the magnitude, to the steel beam, but the mass decreases significantly when introducing the layers of PVC.

Also, it can be note that the central layer brings an insignificant contribution to the rigidity of the structure, which recommends the use of lightweight materials in the area. Table 2 shows the value of the ratio between the frequencies of the three types of structures analyzed.

Table 2. Values of the ratio between frequencies

	5 layers composite Whole steel	3 layers composite Whole steel	3 layers composite 5 layers composite
Frequency ratio	1,092	1,255	1,15

When designing structures, it has to bear in mind that the proper frequencies increase with the increasing of light weight material, which can be a disadvantage, in some cases.

4. Conclusion

The aim of this script was to analyze the relations performed to calculate the natural frequency of isotropic materials, and it determines that they can be expanded in the case of sandwich beams, if accurate determination of the structure stiffness and mass is provided. Therefore, Timoshenko and Shear models for the rigid structures are appropriate for the studied beams, as well.

Accomplished studies have also shown that, due to the defect, the frequency of sandwich beam is changing and becomes higher than the steel beam. Thus, the global methods for fault detection are also successfully applicable in the case of sandwich beams.

Acknowledgments

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