Identification of Delamination in Multilayered Composites

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Abstract. The paper presents the study of the vibrational behavior of laminated composites whose sheets are debonded but still in contact. The aim is to show that the delamination occurring in a given region of the structure produces different frequency shifts for the different bending vibration modes, dependent on the position and extent of the delamination. The vibrational response that comprises the frequency shifts of several modes constitute the delamination signature and can be therefore be used as a pattern in damage detection procedures. The paper presents a finite element analysis comprising composite structures with transversal cracks followed by different debondings which highlight the dynamic structural response individualized by damage position and severity.

1. Introduction

Damages influence the vibrational behavior of beam-like structures by diminishing the natural frequencies as a result of stiffness loss [1]. The stiffness loss, as well as the frequency decrease, directly depends on the damage shape and depth. Actual literature is rich in studies concerning detection of transverse cracks or delamination [2]-[6]. However, few studies deal with cracks of a more complex configuration as L or inverted T cracks that usually occur in composites [7] are, because of the difficulty in approaching such cases.

In our prior research we found a relation, applicable for isotropic or laminated beams, that permits to predict the frequency changes if the size and location of a transverse crack are known [8]-[11]. This relation leads to results similar to those obtained if a torsional massless spring is used to simulate the crack, but has the advantage of simplicity. In this paper, we compare the effect of transverse cracks with those of cracks having an L shape resulted as the longitudinal extension of a transversal crack.

2. Frequency shift due to transverse cracks

The mathematical relation predicting the frequency of the bending modes for a beam with a transverse crack, prior developed by the authors [12], imply the frequency of the healthy beam $f_{i,U}$, a term $\phi^2_i(x)$ representing the value of the normalized modal curvature that defines the crack location and a term $\gamma(0,a)$ representing the damage severity, which depends on the damage depth $a$. In a concentrated form, the relation of the damaged beam’s frequency $f_{i,D}(x,a)$ takes the form:

$$f_{i,D}(x,a) = f_{i,U} \left[ 1 - \gamma(0,a) \cdot (\phi^2_i(x))^2 \right]$$

(1)

The square of the normalized modal curvature (or bending moment) for a given crack position $x$ indicates the energy stored by the healthy beam in an infinitesimal slice $dx$ in which the crack is
located. The square of the normalized modal curvature is different for the different vibration modes, and, due to normalization, obviously takes values between 0 and 1 for all modes [13]. Distance \( x \) is taken from the fixed end. Figure 1 shows the energy distribution for the weak-axis bending vibration mode three. One can observe that there are locations where the crack produces no energy decrease and consequently it has no effect on the natural frequencies; this happens when it is located on inflection points. On the other hand, it produces main frequency alteration when it is positioned on local maxima of the modal curvature [14].

The damage severity \( \gamma(0,a) \) is the function representing the highest stiffness decrease due to a crack of depth \( a \), which for the cantilever beams occurs for the crack located at the fixed end (i.e. \( x = 0 \)). We demonstrated that for an isotropic beam the function representing the damage severity versus damage depth is continuous and can be derived using the beam deflection in healthy and damaged state [15]. A similar frequency evolution is found as using the fracture mechanics method, but the severity estimation using beam deflection is a simpler approach [16]. For multilayered beams, the function has disruptions, occurring when the crack totally separates the different layers [17]. An example of severity curves for a steel beam is presented in figure 2 with continuous line with square bullets, while the case of a composite beam of same thickness with five layers is plotted with simple continuous line.

![Figure 1. Stored energy distribution for the bending vibration mode three.](image1)

![Figure 2. Damage severity for a steel beam and a 5-layered composite beam, respectively.](image2)

The frequency decrease is found from the mathematical relation (1) as:

\[
\Delta f_i = f_{i,U} - f_{i,D}(x,a) = f_{i,U} \cdot \gamma(0,a) \cdot (\varphi_i^2(x))^2
\]

As a consequence, the relative frequency shift for any bending vibration mode \( i = 1...n \), denoted \( \Delta f_i(x,a) \), is the ratio between the frequency shift of that mode and the corresponding frequency of the undamaged beam [18]-[19]:

\[
\Delta \tilde{f_i}(x,a) = \frac{f_{i,U} - f_{i,D}(x,a)}{f_{i,U}} = \gamma(0,a) \cdot (\varphi_i^2(x))^2
\]

From relations (2) and (3) clearly results that the frequency shift curves, i.e. the evolution curves of the cracked beam’s frequency for different locations along the beam for a given mode, are similar for the isotropic and laminated beams, respectively. The single difference consists in the amplitude of the shift \( \gamma(0,a) \). From figure 2 one can observe that a crack with depth 2 mm has the severity 0.005 for the layered beam, while the severity for the steel beam is obviously lower (approximately 0.0015). On the other hand, one can observe that the severity 0.05 is achieved in the isotropic beam for the crack depth 3.1 mm; this crack will provide the same effect as the 2 mm crack in the composite beam.
Figure 3 illustrates the frequency shift curves belonging to bending vibration mode three for a steel beam for cracks reducing the cross-section area with 17%, 33% and 50% respectively. Here one can observe that, by increasing the damage depth iteratively with a step of 17%, the curves maintain their shape but the frequency drop increases exponentially. For a multilayered beam as that studied in [17], consisting of five layers with 1 mm thickness (three of steel and two of foam), the severity increases faster with the crack depth, without altering the frequency shift curves in any mode.

3. The effect of transverse crack extension by delamination on the natural frequencies

This section is dedicated to the study of a crack with complex shape, consisting in a transverse extension followed by a delamination. It was shown in previous section that multilayered beams with transverse cracks behave as isotropic beams, the only difference consisting in the frequency decrease rule. Based on this observation and for reason of simplicity, without altering the achieved results, we employ in the study presented herein a beam having all layers of steel. Actually, the specimen is a steel beam with an L-shaped crack.

It is expected to attain significantly bigger frequency decreases in if the crack spreads also in longitudinal direction [20]. Thus, to compare the effect of a transverse crack with an L-shaped crack, normalization of results is necessary.

3.1. Materials and method

The modal analysis was performed by means of the finite element method (FEM) by involving the ANSYS simulation software. The specimen was a prismatic beam of steel, having the dimensions and material properties presented in Table 1. Boundary conditions corresponding to a cantilever beam were taken into consideration, meaning that the left beam end was constrained and the right beam end free. The model was meshed by using hexahedral elements having the maximum edge size 2 mm, resulting in a total of 37500 elements.

| Table 1. Beam dimensions and material’s physical-mechanical properties |
|-------------------|-----------------|-----------------|-----------------|-----------------|-------------------|-----------------|
| Length $L$ [mm]   | Width $B$ [mm]  | Thickness $H$ [mm] | Mass density $\rho$ [kg/mm$^3$] | Young modulus $E$ [N/m$^2$] | Poisson ratio $\nu$ [-] |
| 1000              | 50              | 5               | 7850            | $2 \cdot 10^{11}$          | 0.3               |

First, the natural frequencies for the first six weak-axis bending vibration modes of the healthy beam were targeted. The attained results are presented in Table 2.

In the second stage, the modal analysis comprised damaged beams of the same dimensions and material as the healthy one. The damage consists of a transverse crack with depth 2.5 mm, which is extended to the right in the longitudinal direction with a 50 mm “delamination”, as shown in Figure 4.
The damage is positioned with its left end at 20 mm from the fixed beam end, and is iteratively removed to the right with a step of 20 mm; last simulated damage has the left end at 940 mm from the fixed end, thus 47 damage cases being simulated.

The aim of this paper is to compare the dynamic behavior of beams with a transverse crack with those of the damaged beam an L-shaped crack. Therefore, the relative frequency shift curves for both cracks are plotted. For the transverse crack this is made by involving relation (1), while for the L-shaped crack the results obtained from the FEM supported analysis are taken. For better comparing the results, the severity $\gamma(a)$ is artificially increased by a scaling factor. This factor is individually chosen for each mode, in order to achieve in both curves the same value for the biggest shift, as indicated by point A for vibration mode 2 in Figure 5.

3.2. Results and discussion
Modal analysis was first performed for the healthy beam. The results, in terms of the frequencies for the first six bending vibration modes, are presented in Table 2. These fit the values obtained with the analytical method, the errors being less than 0.5%. Afterwards, the frequencies for the beam with an L-shaped crack were extracted. Examples of values obtained for the crack position at 240 mm, 500 mm and 760 mm from the fixed beam end are presented in Table 2, along with the values obtained for the transverse crack by calculus by employing relation (1). One can easily observe that, as expected, the effect of the L-shaped crack effect is much greater than that of the transverse crack.

Table 2. Frequencies obtained by simulation for the healthy beam, the beam with a transverse crack and the beam with an L-shaped crack placed at different locations on the beam.

| Mode | Healthy beam | $x = 240$ mm | $x = 500$ mm | $x = 760$ mm |
|------|--------------|--------------|--------------|--------------|
|      | Transverse crack | L-shaped crack | Transverse crack | L-shaped crack | Transverse crack | L-shaped crack |
| 1    | 4.090        | 3.997        | 3.265        | 4.066        | 3.835        | 4.088        | 4.074        |
| 2    | 25.627       | 25.614       | 25.147       | 24.973       | 19.973       | 25.427       | 23.629       |
| 3    | 71.757       | 70.659       | 61.452       | 71.753       | 70.728       | 69.961       | 56.824       |
| 4    | 140.631      | 137.715      | 127.344      | 137.111      | 119.671      | 137.037      | 117.195      |
| 5    | 232.533      | 231.150      | 228.712      | 232.521      | 224.884      | 230.871      | 213.681      |
| 6    | 347.462      | 346.995      | 314.755      | 338.762      | 306.723      | 347.077      | 337.822      |

To deeply understand the phenomena of frequency shift due to different type of damage, we plotted the frequency shift curves for both types of crack. For comparison reasons, the severity of the transverse crack is artificially increased, as explained in previous sub-section.
Figure 5. Frequency versus crack location for both types of damages for six vibration modes.

The way how an L-shaped crack diminishes the natural frequencies of the beam is shown by the evolution of the relative frequency shift with the crack position. One can observe that, in comparison with the transverse crack, the shifts due to an L-shaped crack are significantly greater in amplitude.

4. Conclusion
The frequency shift curves for a beam with an L-shaped crack were determined by simulation and compared with the values deduced for the transverse crack with an original mathematical relation. It was found that the two crack types produce different shifts, but the curves representing these shifts are somehow similar.

The key finding of the study refers to the largest frequency shift of the particular modes, which for the L-shaped crack does not longer manifest at the fixed end. An exception is the vibration mode one, which has a single maximum, right at the fixed end. This shows that achieving a unique severity for all modes is no longer possible.

Analyzing the frequency shift curves plotted for the L-shaped crack, it has been observed that the points of extrema do not match those found for the transverse crack. It was also noticed that the frequency of the beam with an L-shaped crack never reaches the frequency of the healthy beam. The phenomenon is increasingly pronounced for higher-order modes and the cracks closer to the fixed end. This happens differently to the beam with a transverse crack. In this case, no frequency drop is
remarked if the transverse crack is located at a point of inflection because here bending does not manifest and thus stress and strain are null. In the case of L-shaped cracks, a larger beam segment loses its rigidity due to the crack configuration. Thus, along with the damage on the beam slice located at the inflection point, which does not affect the frequency, also the neighbor slices are affected. This further damage produces a frequency drop that is visible in the frequency shift curves of the beams with L-shaped cracks.

In fact, in the case of L-shaped cracks, the beam manifests as having multiple transverse cracks of various types along the segment that includes the delamination, or as a beam with a segment of lower rigidity but without loss of mass. It is the challenge that faces the authors to find the mathematical relation expressing the frequency shift curves for the L-shaped crack starting from this conclusion. However, for damage detection purpose, the damage patterns can be contrived using the FEM simulation results.

5. References

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