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Effect of Temperature on Damage Identification of Laminated Composite by Means Numerical Methods

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Abstract

This study aims to examine the effect of temperature on damage detection in laminated composite materials. In this context, a carbon-reinforced composite plate with [0/90]s stacking sequence is modeled as intact and delaminated by the finite element method. The dimensions, thicknesses, materials used, and stacking sequences of the plates modeled as intact and delaminated are the same. The delamination in the delaminated plate is modeled as the gap in the middle of the plate. These modeled plates were analyzed at different temperature values between -50oC / +50oC. The natural frequencies, mode shapes, and modal curvatures of the plate were obtained by modal analysis. The variation of these data obtained with temperature was examined and the effect of temperature on these data was compared. According to the analysis results, it was observed that the effect of temperature on natural frequency values and modal curvature values was similar to the effect of delamination. The decrease in natural frequencies and the changes in modal curvatures due to delamination occurred with the increase in temperature even in the absence of delamination.

Keywords: Composites, Damage Identification, Numerical Methods, Temperature Effect.

1. Introduction

Damage detection in composite materials is crucial to maintaining structural integrity and safety. Modal analysis techniques are useful for identifying damage. The variations in modal curvatures are taken into account in this context as a signal for locating probable damage locations in composite materials [1, 2, 3, 4]. Natural frequencies and mode shapes of a material structure are used to identify the property known as modal curvature. Due to the presence or extent of damage, the modal curvatures of a damaged composite structure may alter [5]. Between modal curvatures, there is a noticeable variation in plate structure due to intrinsic degradation, particularly delamination [6]. For damage detection, modal curvatures in a predetermined intact reference state are compared with modal curvatures in a damaged structure[6]. The modal curvature difference serves as an indicator used to determine the location and extent of damage [7].

Composite materials are materials that are formed by combining different components and generally have superior mechanical properties. However, the different temperature environments to which composite structures are exposed can significantly affect material performance [8]. Temperature can also affect the mechanical properties of composite materials. Composite materials may show different mechanical properties at different temperature values [9,10]. While an increase in temperature causes a decrease in the stiffness and strength of the material, a decrease in temperature may cause the opposite effect [11].

Stiffness changes are very important in terms of vibration-based detection methods, which is one of the damage detection methods [12]. Vibration-based damage detection methods evaluate hardness changes to identify damaged areas using frequency changes in material or structure or changes in modal parameters. Therefore, changes in the mechanical structure of the material under the influence of temperature may affect damage detection.

However, the effect of temperature on damage detection in laminated composites is a complex and under-researched issue. In this context, this study aims to fill a critical gap in the existing literature by investigating the effect of temperature on the structural properties of laminated composite materials. The main contributions of this study include a comprehensive examination of the natural frequencies, mode shapes, and modal curvatures of composite materials. The most fundamental innovation provided by this study is to integrate the temperature effect into damage detection analysis and pave the way for the creation of more durable and reliable composite structures in dynamic environmental conditions. This study not only provides an understanding of the interaction between temperature and damage detection but also provides practical information that can be applied in various industries. Understanding the effect of temperature on the behavior of laminated composites also provides advantages in preserving the structural integrity, health monitoring, and extending the lifespan of composite materials used in fields such as aerospace, automotive, wind energy, and construction.

2. Analytical Theory

Any composite construction has internal stresses known as thermal residual stresses that develop during the composite's curing process. Composite plates that cure at temperatures other than the specified operating temperature experience thermal stresses and these stresses must be considered in the analysis. These stresses are inherent to the structure. The discrepancy between the matrix's and fiber's coefficients of thermal expansion is what causes them to form. Thermal residual stresses brought on by this shrinkage must be considered in any stress analysis of the composite structure and should not be disregarded. Residual stress limits the strength potential of composite materials.

According to classical laminate theory, thermal moments and resultant moments in composite materials are defined as follows, respectively.

$$\begin{bmatrix} M_x^T \\ M_y^T \\ M_{xy}^T \end{bmatrix} = \int \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix}_k \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{bmatrix}_k \Delta T z dz \quad (1)$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon^0{}_x \\ \varepsilon^0{}_y \\ \gamma^0{}_{xy} \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} k^0{}_x \\ k^0{}_y \\ k^0{}_{xy} \end{bmatrix} - \begin{bmatrix} M_x^T \\ M_y^T \\ M_{xy}^T \end{bmatrix} \quad (2)$$

Where M^T represents thermal moments, M represents resultant moments, $\bar{Q}_{ij}$ is the transformed reduced stiffnesses, α is the thermal coefficient, k is the layer number and ΔT is the temperature change, z is the directed distance, B_{ij} is bending-extension coupling stiffnesses and D_{ij} is bending stiffnesses, ε^0 is middle surface shear stress and k^0 is the middle-surface curvatures.

Equation (2) can be rearranged and written as:

$$\begin{bmatrix} \bar{M}_x \\ \bar{M}_y \\ \bar{M}_{xy} \end{bmatrix} = \begin{bmatrix} M_x + M_x^T \\ M_y + M_y^T \\ M_{xy} + M_{xy}^T \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon^0{}_x \\ \varepsilon^0{}_y \\ \gamma^0{}_{xy} \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} k^0{}_x \\ k^0{}_y \\ k^0{}_{xy} \end{bmatrix} \tag{3}$$

If the equation is rearranged to isolate curvatures on one side;

$$\begin{bmatrix} k^0{}_x \\ k^0{}_y \\ k^0{}_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}^{-1} \begin{bmatrix} \bar{M}_x \\ \bar{M}_y \\ \bar{M}_{xy} \end{bmatrix} - \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}^{-1} \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon^0{}_x \\ \varepsilon^0{}_y \\ \gamma^0{}_{xy} \end{bmatrix} \tag{4}$$

Modal curvature is calculated as second-order differentiation of mode shape. [1]

$$k = k_x + k_y = \frac{\partial^2 w(x,y)}{\partial x^2} + \frac{\partial^2 w(x,y)}{\partial y^2} \tag{5}$$

Where k_x and k_y are the modal curvatures along the X and Y-axis.

To find the damage factor, modal curvature differences of the delaminated composite plate and the reference composite plate are calculated. In regions where delamination occurs, modal curvatures increase due to a decrease in the stiffness of the composite lamina. Mode shapes obtained as a result of Finite Element Analysis (FEA) can be used to determine modal curvatures by central difference approximation. [1] Mathematically, X and Y axis-directed modal curvatures are [6];

$$k_x = \frac{w_{(i-1),j} - 2w_{i,j} + w_{(i+1),j}}{h^2} \tag{6}$$

$$k_y = \frac{w_{i,(j-1)} - 2w_{i,j} + w_{i,(j+1)}}{h^2} \tag{7}$$

Where w_{ij} is mode shape at i^{th} row and j^{th} column and h is the total thickness.

Absolute change in modal curvature is calculated as [6];

$$k = k_x + k_y = [D]^{-1}\left(\left[\bar{M}_x + \bar{M}_y\right] - [B]\left[\varepsilon^0{}_x + \varepsilon^0{}_y\right]\right) \tag{9}$$

It is known that the damage to the composite laminate causes alterations in the mechanical characteristics of the composite lamina. For this reason, in case of damage to the composite lamina, changes in the mechanical properties of the lamina will also cause changes in the modal curvature. However, changes in the temperature of the laminate will also cause changes in the thermal loads, as seen in the equation (9). Due to changing thermal loads, the modal curvature will change and differ from the reference value.

3. Finite Element Modal Curvature Analysis

In this study, to understand the dynamic structures of laminated composites under changing temperature conditions, thermal stresses were first applied to the plates, and then the plates were subjected to modal analysis. This method is called pre-stress analysis. ANSYS pre-stress analysis has been a good tool for extracting natural frequencies, mode shapes, and modal curvatures. The novelty of this approach lies in the careful application of thermal stresses and the relationship between the layers of the plate during pre-stress analysis. Thus, it is aimed to make a reliable simulation of the behavior of laminated composites under real conditions. The real conditions that composite structures are exposed to in practice are reflected by including thermal residual stresses and thermal moments in the analysis. With this application, the accuracy of the results has been increased.

Modal analysis was performed using a four-layered composite plate which has a 100 x 100 mm surface area and 1 mm thickness with a [0/90]s stacking sequence. Plates with temperature values of -50°C, -40°C, -30°C, -22°C, 0°C, 22°C, 30°C, 40°C, 50°C were analyzed in the analysis. In addition, a composite plate having the same dimensions with a delamination area of 20 mm x 20 mm with the same temperature values was evaluated. All of the composite plates are fixed at their edges, having the same fixed boundary conditions.

Unidirectional carbon fiber material was used and the material properties were defined as follows.

Table 1. Natural Frequencies of the Delaminated Composite Plate

Mechanical Properties	
Density	1518 Kg/m^3
Young’s Modulus X Direction	1,2334E+11 Pa
Young’s Modulus Y Direction	7,78E+09 Pa
Young’s Modulus Z Direction	7,78E+09 Pa
Poisson’s Ratio XY	0,27
Poisson’s Ratio YZ	0,42
Poisson’s Ratio XZ	0,27
Shear Modulus XY	5E+09 Pa
Shear Modulus YZ	3,08E+09 Pa
Shear Modulus XZ	5E+09 Pa

Geometrically, the material is defined as a 2D square plate with dimensions of 100 mm x 100 mm, and this modeling process was also done using ANSYS.

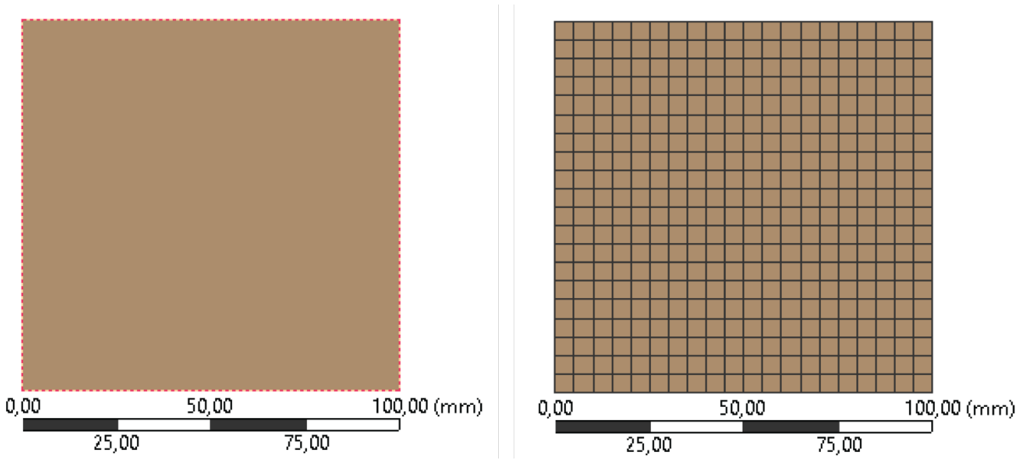

Fig. 1. Geometry and Mesh Model of Intact Composite Material

By using the same geometry, empty space was defined in the structure and the delamination was modeled as in Figure 2.

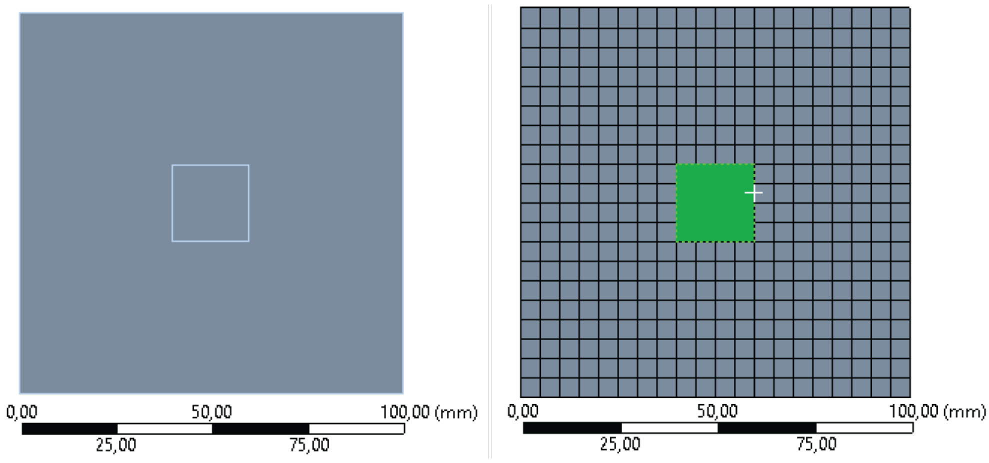

Fig. 2. Geometry and Mesh Model of Delaminated Composite Material

The natural frequencies of these structures were discovered by the modal analysis, and they are shown in Tables 2 and 3.

Table 2. Natural Frequencies of the Intact Composite Plate

	Temperature / Natural Frequencies								
Mode Number	-50°C	-40°C	-30°C	-22°C	0°C	22°C	30°C	40°C	50°C
1	542,97	532,68	522,07	513,35	488,12	470,81	450,28	436,6	422,29
2	878,14	865,12	851,57	840,33	807,37	770,98	756,78	738,2	718,62
3	1873	1863,7	1854,2	1846,5	1825	1802,9	1794,6	1784,2	1773,5
4	1949,6	1938,2	1926,4	1916,8	1889,3	1859,9	1848,7	1834,1	1819

Table 3. Natural Frequencies of the Delaminated Composite Plate

	Temperature / Natural Frequencies								
Mode Number	-50°C	-40°C	-30°C	-22°C	0°C	22°C	30°C	40°C	50°C
1	522,8	514,84	506,69	500,03	480,97	470,72	453,02	443,11	432,87
2	802,77	792,33	781,53	772,61	746,74	719	704,78	690,63	675,84
3	1751,2	1743,8	1736,3	1730,4	1713,8	1698,4	1689,2	1681,6	1129,3
4	1915,6	1908	1900,2	1893,7	1874,6	1853,4	1844,7	1833,1	1820,4

As can be seen from Tables 2 and 3, the natural frequencies of the intact plate decrease as the temperature increases, the same is true for the delaminated plate. When looking at the natural frequencies for intact and delaminated plates at the same temperatures, it is seen that the natural frequency of the delaminated plate is lower than that of the intact plate. This is a result consistent with previous studies.

3.1. Mode shape deformations

The first mode's natural frequency and the mode shape of the plates were assessed. Analysis results were extracted and the obtained mode shape deformations were compared. Mode shape deformations occurring at -50oC, 0oC, and 50oC are given in Figure 3, Figure 4, and Figure 5.

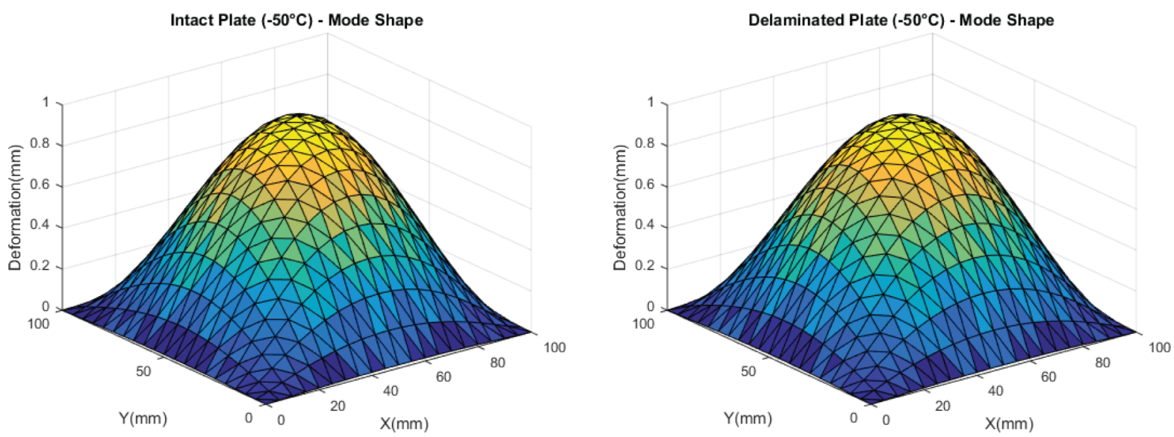

Fig. 3. Intact and Delaminated Plates Mode Shapes at -50ºC

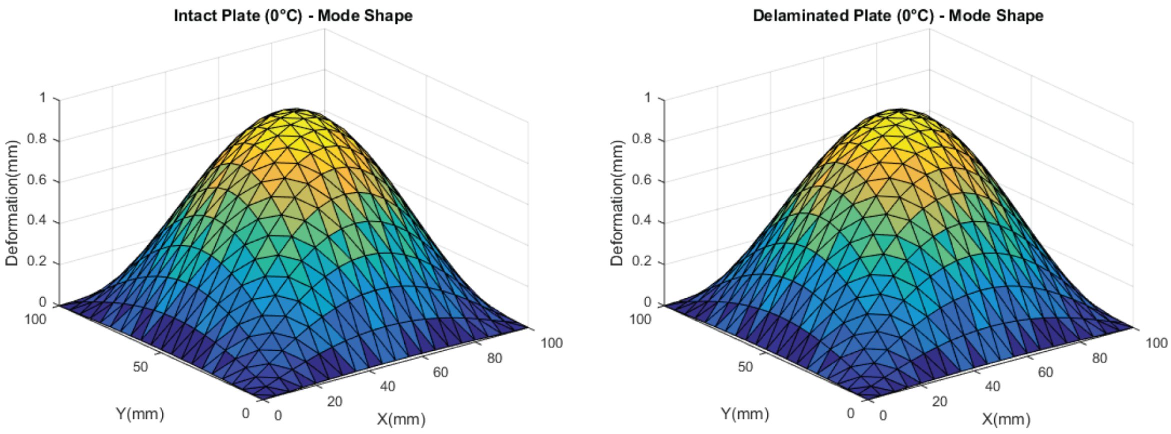

Fig. 4. Intact and Delaminated Plates Mode Shapes at 0°C

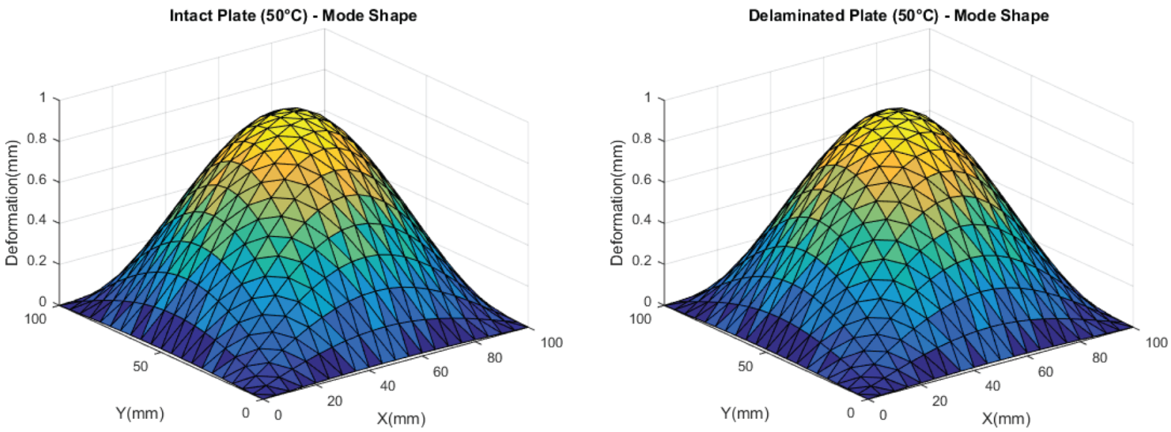

Fig. 5. Intact and Delaminated Plates Mode Shapes at 50°C

It is shown in the figures above that the results of the mode shapes are quite similar and there is no clear distinguishing difference between intact and delaminated plates. For this reason, it is very difficult to comment on the temperature effect on the detection of the damage or whether there is any damage according to the mode shapes in the plate.

3.2. Normalized modal curvatures

The modal curvatures for intact and delaminated plates were calculated at different temperatures using the equations (5), (6), (7) and (8). Modal curvature changes occurring at -50°C, 0°C, and 50°C are given in Figure 6, Figure 7, and Figure 8.

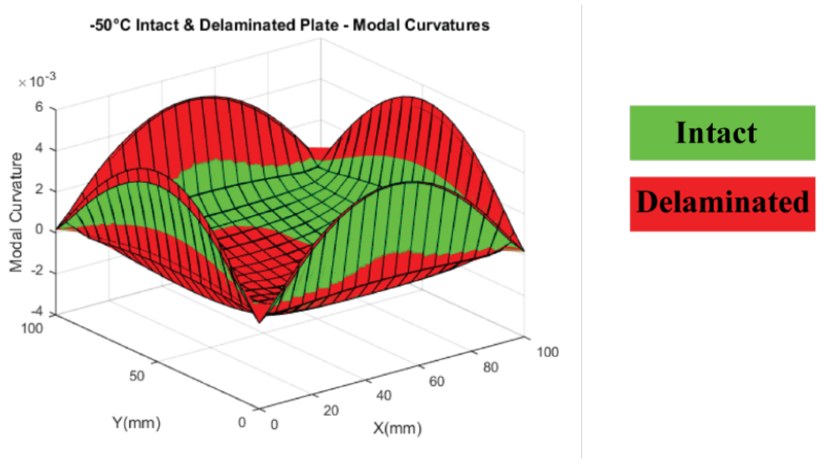

Fig. 6. Intact and Delaminated Plates Modal Curvatures at -50ºC

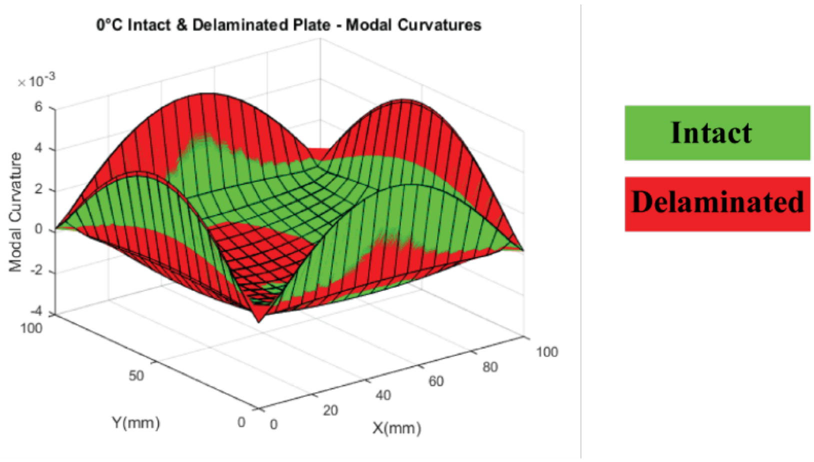

Fig. 7. Intact and Delaminated Plates Modal Curvatures at 0ºC

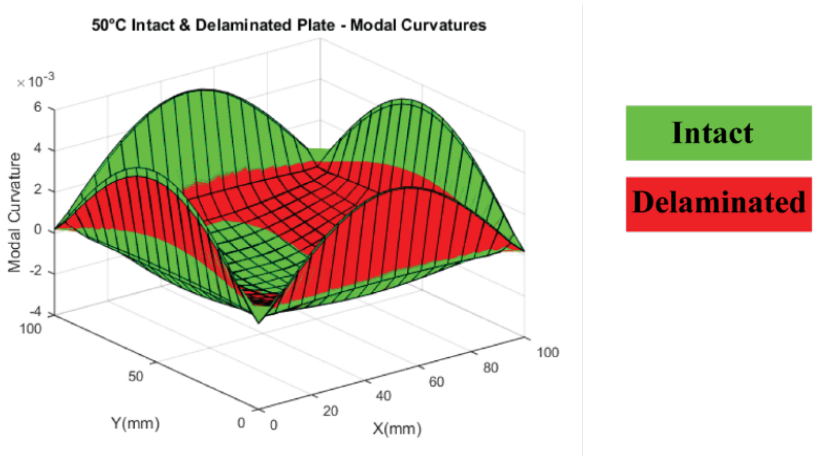

Fig. 8. Intact and Delaminated Plates Modal Curvatures at 50ºC

The modal curvature change by the effect of the temperature and delamination at the middle of the plates and the left edge of the plates are shown in Figure 10 and Figure 11.

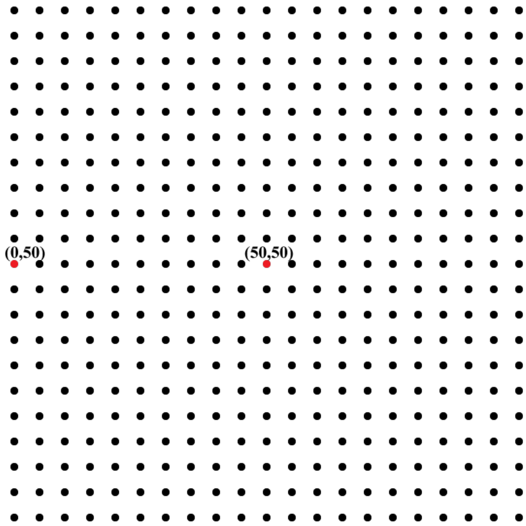

Fig. 9. Nodes On The Plate

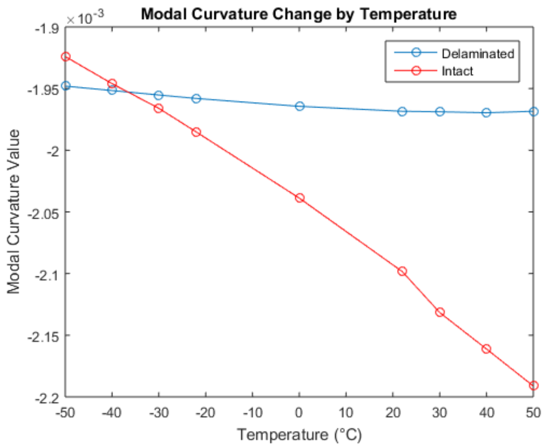

Fig. 10. Modal Curvature Differences at Node (50,50)

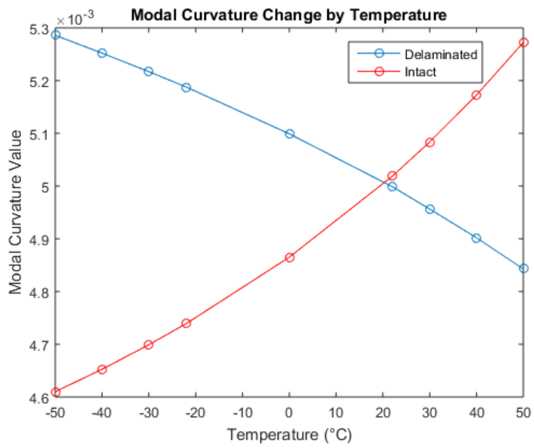

Fig. 11. Modal Curvature Differences at Node (0,50)

The graphs show that the temperature change causes a change in the modal curvatures of the intact plate. Additionally, at the same temperatures, variations are seen between the intact and delaminated plate modal curvatures.

4. Conclusion

In this study, ANSYS Pre-stress analysis was employed to assess the modal curvatures, mode shapes, and natural frequencies of intact and delaminated plates at various temperature levels. The acquired results support previous research and demonstrate that the natural frequencies of the plates decrease as temperature rises [13, 14, 15]. Additionally, it was found that the delaminated plates' natural frequencies were significantly impacted by the temperature increase. Loss of stiffness and a drop in frequency are results of delamination. Delamination results in a truncated region in the plate structure, which reduces frequency and causes a loss of stiffness. [16] The temperature states of the plates play a significant influence on the natural frequencies and dynamic behavior of plates, which are better understood as a result of these findings.

Based on these findings, it has been observed that the decrease in natural frequencies and the change in modal curvatures with the increase in temperature in composite materials are very similar to the results of delamination occurring in the composite material. Therefore, observing these changes in material properties and making an inference that there is delamination in the material is insufficient to reach a definitive conclusion. This demonstrates the need to understand the effect of temperature on composite materials and include it in health monitoring analyses. In this way, by eliminating the temperature effect, the material can be monitored more accurately and a more accurate result can be reached as to whether there is delamination on the material.

In summary, with this study, the effect of temperature on the dynamic behavior of the plates and the importance of considering temperature factors in structural integrity assessment and damage detection are emphasized. Additionally, temperature-dependent effects on damage detection have been brought to light by comparing modal curvatures between intact and delaminated plates. These findings contribute significantly to the understanding of composite material behavior under various environmental conditions. Advanced simulation tools such as the ANSYS Pre-Stress Analysis methodology are used to pave the way for future developments in the application of composite materials. The vital role of temperature considerations in structural analysis is recognized, deepening this understanding of laminated composites and paving the way for more accurate and reliable evaluations in practical applications. In addition, the proposed solution methodology stands out with its ability to distinguish temperature-dependent effects in damage detection, an aspect often overlooked in traditional studies.

Author Contributions

Mehmet Ali Akın: Collected the data, Contributed data or analysis tools, Wrote the paper.
Bülent Ekici: Conceived and designed the analysis.

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