Damage Assessment in Sandwich Panels using Modal Analysis

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Abstract

Composite sandwich panels are finding applications increasingly as primary load-carrying components in aircraft, marine, automotive, transportation and space structures. The sandwich panel increases the stiffness of the plate while the overall weight of a structure is reduced. ABAQUS is used to perform global damage identification in this paper. Size, location of the damage and the boundary conditions are the variables considered to study the effect of modal parameters on the sandwich structures. The sandwich panel in the present study comprises of Bi-woven Glass Fibre-reinforced polymer (GFRP) cloth for faceplates with Polyurethane Foam (PUFoam) as core.According to the numerical analysis, sandwich panels with one edge fully clamped (Cantilever – C-F-F-F) and largeoscillation modes are more delicate to the presence of simulated damage. The variations in natural frequencies are used to determine the size and location of the damage in a sandwich panel.

Keywords:*Composite sandwich panel, Damage revealing, Natural Frequencies,ABAQUS, PU foam*

1.0Introduction

Owing to their high bending stiffness & strength, sandwich composites are being used progressively in many engineering sectors. However, due to the presence of damage, the mechanical properties of sandwich composites are degraded severely. Failures of structures, particularly aircraft structures, often have catastrophic consequences. Damage detection, therefore, specifically on-line, becomes a very significant issue [1]. At present the available non-destructive evaluation (NDE) methods are mostly non-model methods, i.e., either visual or localized experimental methods, such as acoustic or ultrasonic methods, magnetic field methods, radiographs, eddy-current methods or thermal field methods [2]. It takes time and money to gain access to these procedures. In several circumstances, such as service aircraft testing and space structure [3] some of them are impracticable. Inadequacies of presently

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available NDE methods indicate a requirement of damage inspection techniques that can give global information on the structure and they do not require direct human accessibility of the structure [4]. This prerequisite has led to the advancement of model-based approaches that examine variations in the vibration characteristics of the structure. This vibration-based damage identification technique is non-destructive and relatively inexpensive for large structures [5, 6]. This method's underlying principle is to extract the modal factors of damaged structures, such as natural frequencies, deformed shapes, and damping ratios [7, 8]. In the field, measuring deformed shapes is cumbersome and is complicated.Fortunately, natural frequency use can be easily measured using a one accelerometer at multiple points and at the same time monitored in real-time with high accuracy [9, 10]. Although the use of natural frequencies appears to be encouraging, this method provides no data about the size and location of the damage [11]. As a result, more study is required to process the verified natural frequencies in order to quantify the size and location of damage in the sandwich plate.

As per different detection methods, the vibration analysis methods can be divided into the following major categories:changes in modal shape [12], modal shape curve methods[13, 14], sensitivity- based update methods, eigen structure assignment methods, optimal matrix update methods, changes in measured stiffness matrix methods, frequency response function method, and combined modal parameters method [15, 16]. From the above literature, it is evident that much of work addressed on damage detection in sandwich composites encompasses using experimental methods and there is no single source of literature on evaluating damage detection through numerical techniques. The power and speed of modern computers, and modelling methods have allowed remarkable developments in numerical techniques. Hence, the present work is emphasized on using vibration data to develop features that can be used to envisagethe magnitude as well as location of damages. More accurately the dynamic behaviour of the structure. Numerous damaged situations will be formed using finite element models. Then, linear modal analysis will be performedand modal parameters will be extracted. Lastly, the viability of this method in detecting and locating damages will be deliberated.

2.0 Method

2.1 Mechanical Properties of Composite Sandwich Panel

The facingsare Bi-woven GFRP and the core used is PU Foam. The thicknesses of the upper & lower facings aremaintainedat 1mm each, and the core thickness is 18mm.

2.2 FEM Model of the Composite Sandwich Panel

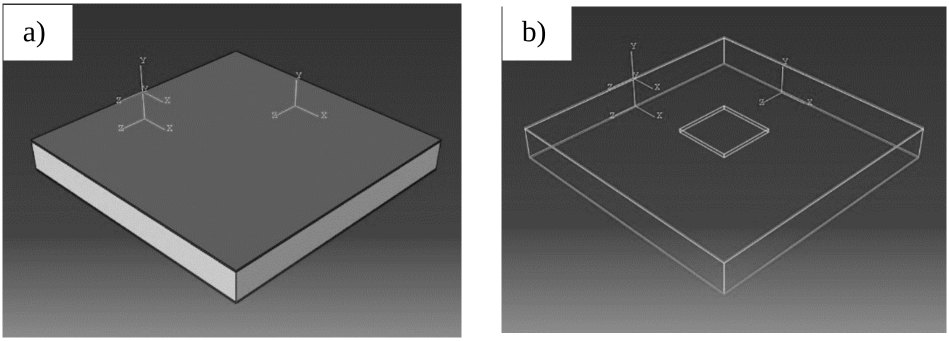


Fig.1. FEM models of composite sandwich panela) the pristine sandwich panel and b) the damaged sandwich panel where damage occurs inside the core

Fig. 1 represents the composite sandwich panel's 3D geometry model. The ABAQUS finite element package is used to generate the model. The sandwich plate measures 150 mm x 150 mm x 20 mm. The eight-noded linear brick element (C3D8) is used to mesh faceplates and core.Material properties for core and faceplates are shown in Table 1. As shown in Fig. 2, homogeneous assumptions are used with elastic and engineering constants, as well as composite layup with fibre orientation [0,90,0] for both top and bottom faceplates (a). The mesh is of standard size. The tie constraints with hard contact and frictionless interaction are used to establish the interaction between the faceplate and the core. The perfect intact model as well as the model with a defect are both modelled and examined. Grid-convergence analysis is performed to obtain accurate results while keeping computation time to a minimum.

Table 1. Mechanical Properties of Composite Sandwich Panel

Material	Properties	Values
GFRP (orthotropic)	Density	1610 Kg/m^3
	E_1 or E_x	16.84 GPa
	E_2 or E_y	16.84 GPa
	E_3 or E_z	7.78 GPa
	ν_{12} or ν_{xy}	0.15
	ν_{23} or ν_{yz}	0.49
	ν_{31} or ν_{zx}	0.49
	G_{12} or G_{xy}	2.46 GPa
	G_{23} or G_{yz}	2.38 GPa
	G_{31} or G_{zx}	2.33 GPa
PUF (isotropic)	Density	100 Kg/m^3
	E_x	26.7 GPa
	ν	0.32

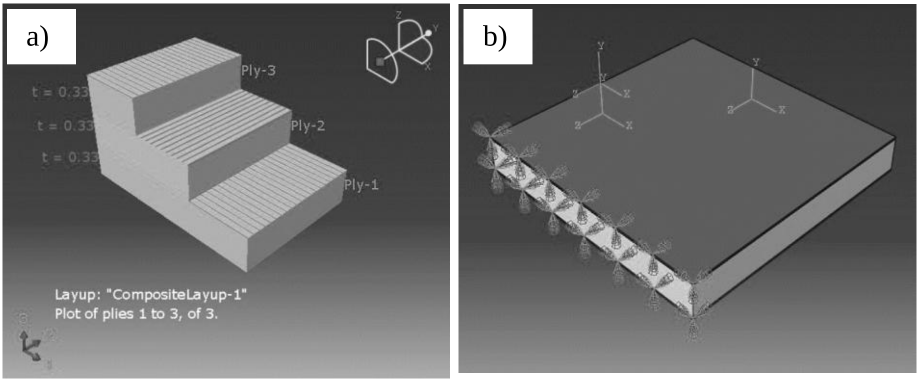


Fig. 2. a) Composite layup of faceplate and b) Boundary condition fixed at one edge (cantilever)

Six modes with one edge fixed (C-F-F-F: Clamped Free – Free- Free) conditions shown in fig 2(b) is investigated firstly for debonding damage which is observed between facings and the core. Damaged element is introduced along 2mm upper part of the core with ratios of 5%, 7% and 10% as shown in Fig 3. Secondly, single hole of size 10mm diameter and three holes of 10mm diameter is introduced shown in fig 4 are investigated to understand the influence of these damages on the modal parameters From [17], it is observed that for thedamage identification parameter the first six natural frequencies areadequate for the analysis.

The damage ratio [17] is defined as:$DR = \left(\frac{A_d}{A_{total}}\right) \times 100\%$(1)

where, *DR* is the damage ratio (%), A_d is the damaged area(mm^2), and A_{total} is the total area of the sandwich plate model (mm^2).

The natural frequency deviation [17] is defined as:

$$\Delta\,\omega = \left(\frac{|\omega_D - \omega_I\,|}{\omega_I}\right)\times 100\% \quad (2)$$

in the above, $\Delta\,\omega$ (%) is the change in the natural frequency that becomes the damage parameter in this study, ω_D is the natural frequency of damaged sandwich plate (Hz), and ω_I is the natural frequency of the pristine sandwich plate (Hz).

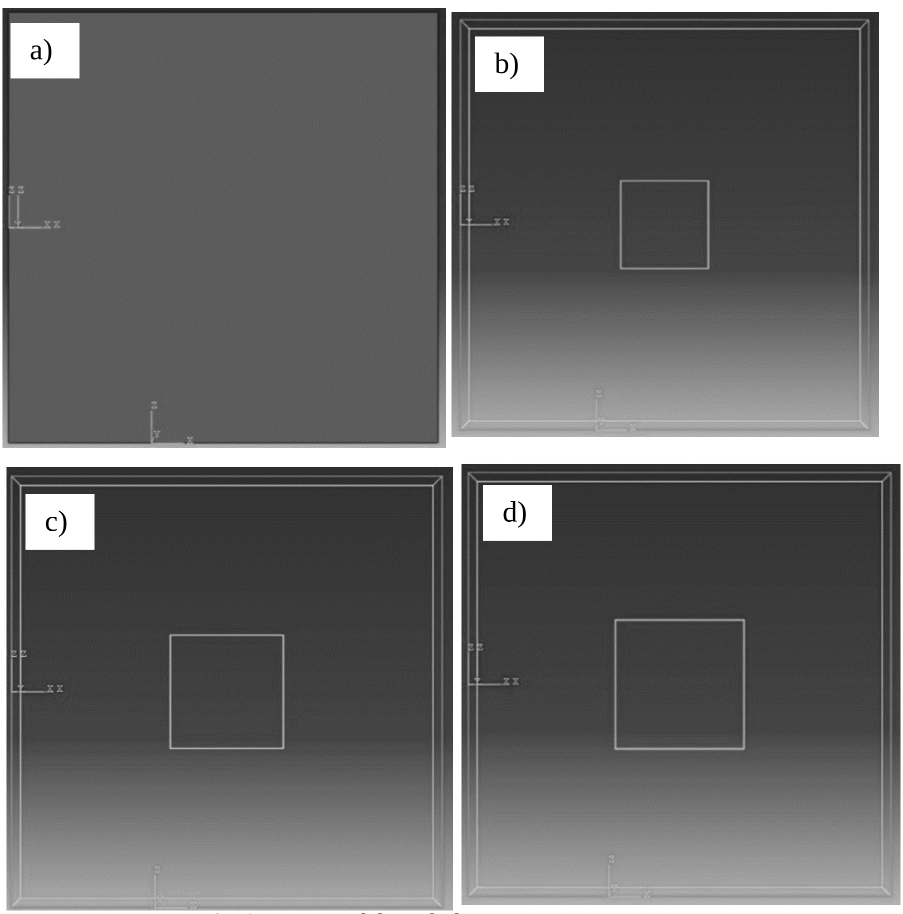


Fig. 3. FEM models with damage ratios variations
a) Pristine sandwich panel b) Damaged panel with 5% damage ratio
c) Damaged panel with 7.5% damage ratio and d) Damaged panel with 10% damage ratio.

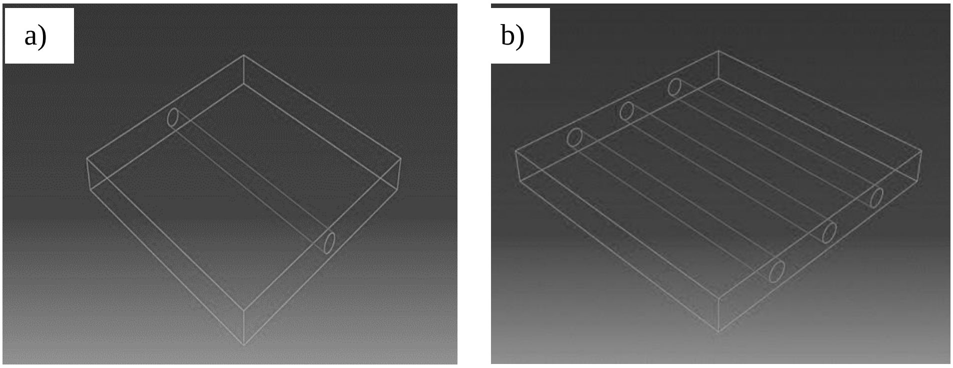


Fig. 4. FEM models of composite sandwich panel with through hole core damage
a) 10mm diameter single hole at the centre of the core
b) Three holes inside the core of 10mm diameter

The research examines not only the influence of the damaged ratio on natural frequencies, but also the damage detection procedure. Variations of damage are situated at 25% of the model lengths (near the fixed edge, location A), 50% of the model lengths (middle of the sandwich plate model, location B), and 75% of the model lengths (edge of the sandwich plate model, location C) (centre of the sandwich plate model, location C). Fig-5demonstratesthe composite sandwich panel with 10% damage in 3locations with Clamped Free Free edge (cantilever) boundary conditions.

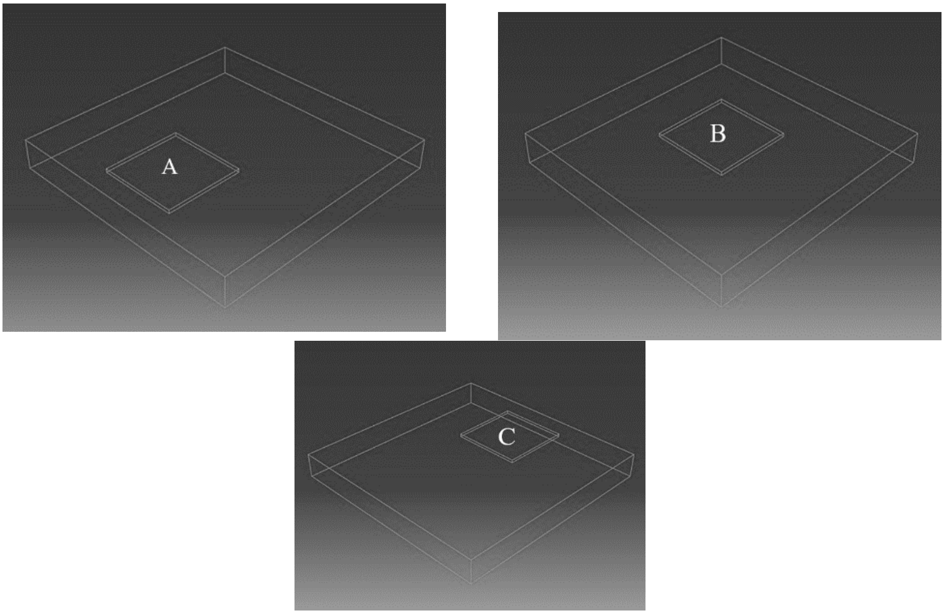


Fig. 5. Sandwich panel FEM models with varying damage locations
a) 10% damaged sandwich plate at 25% of the plate length b) 10% damaged sandwich plate at 50% of the plate length c) 10% damaged sandwich plate at 75% of the plate length

3.0 Results and Discussion

3.1 Numerical Simulation

Finite element method was adopted to evaluate the vibration parameters of pristine and damaged sandwich composite panels.

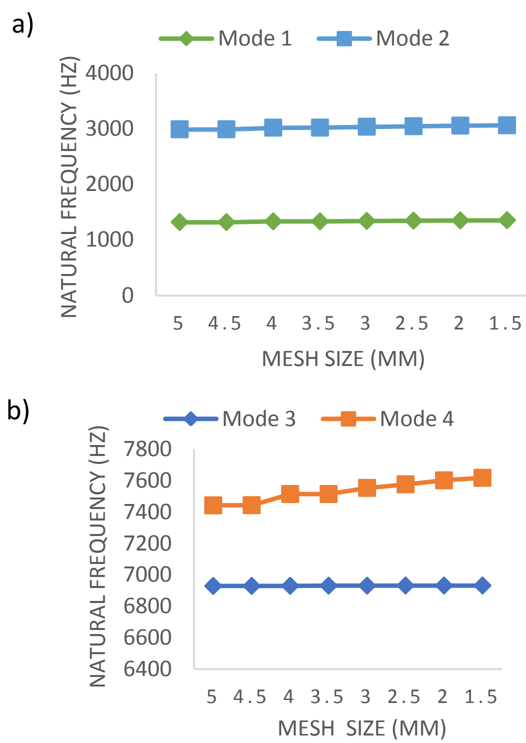
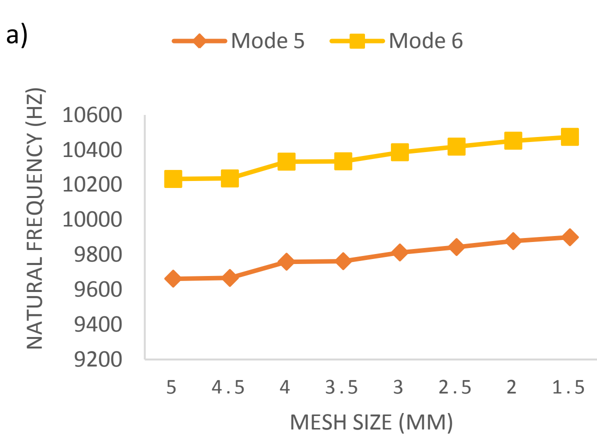


Fig. 6. Convergence studies for pristine sandwich panel a) 1st and 2ndsecond mode and b) 3rd and 4thmode



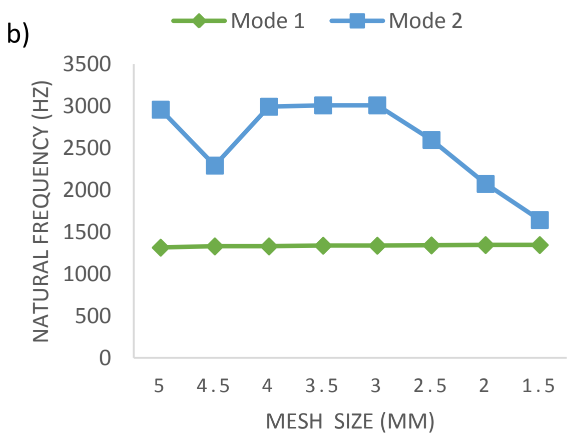
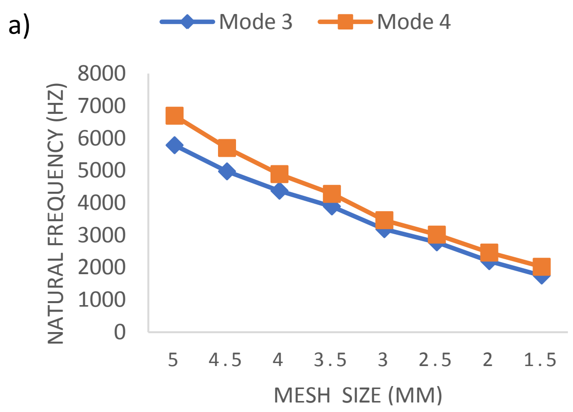


Fig. 7. a) Convergence studies for pristine sandwich panel: 5th and 6th modesand b) Convergence analysis for 5% damaged sandwich panel: 1st and the 2nd modes



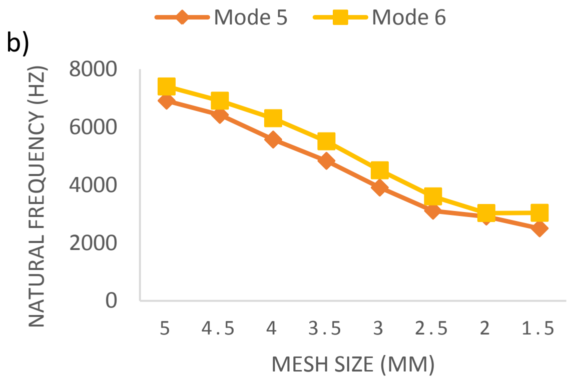


Fig. 8. Convergence analysis for 5% damaged sandwich panel a) the 3rd and the 4th mode b) 5th and the 6th mode

A mesh convergence analysis is carried out to ensure the accuracy of the numerical analysis results. Fig. 6 - 8 depict the convergence analysis of a complete sandwich panel and a 5% damaged sandwich panel for the first six modes. The natural frequency value is steady at a meshing size of 4 mm, as perFig. 6 and 7(a), specifically in the 4th, 5th, and 6th modes.However, according to Fig. 7(b) and 8, the first six natural frequencies are more steady at a grid size of 3.0 mm, implying that a 5% damaged composite sandwich panel requires a finergrid size to achieve a more steady natural frequency value. As a result, it was determined that the grid size employed in this study should not exceed 3.0 mm in order to allow both the pristine sandwich plate and the damaged sandwich plate convergence analyses.

A grid size of 3.0 mm was also used in study on the estimation of damage to the polyurethane elastomer core sandwich structure [17].To examine the influence of number of holes, damage ratios, holes and the location of on natural frequency deviation, size of the mesh was altered to bothpristine sandwich and damaged sandwich panels.

3.2 Influence of Damage Ratio

This section explains the influence of damage ratio on the deviation of natural frequency fordifferent modes on a sandwich plate for fully clamped at one edge. Table 2 depicts the natural frequency of the pristine and damaged sandwich panels with various damage ratios in different modes. Table3 summarizes the influence of the damage ratios on the natural frequency deviation.Table 4 also depicts the natural frequency of the pristine sandwich panel and damaged sandwich panel with one and three circular holes in various modes. Table 5 summarizes the effect of the number of circular holes on the natural frequency parameter.

Natural frequency deviation is the damage pointer proposed in this study. Seguel [18] uses a similar definition of the natural frequency deviation. It can be observed form Table 2 that there is a reduction in natural frequency due to the presence of damage. Greater the size of damage, greater the deviation in natural frequency which is depicted in Table 3. The most significant natural frequency deviations occurred in the 5th mode, at 151.14 percent, 233.17 percent, and 336.28 percent, respectively. In the case of Table 4, the decrease in frequency is due to an increase in the number of circular holes. Table 5 also shows that the deviation in natural frequency surges with the increase in number of circular holes. When the average deviation in each mode is taken into consideration, the maximum natural frequency deviation was noticed for the third mode. The most significant natural frequency deviation occurred in the third mode at 2.85 percent and 9.7 percent for single circular holes and three circular holes, respectively. Natural frequency changes occur as a result of local deformation around damaged zones, particularly in complex modes. Damage detection in complex modes is more sensitive and as a result, complex modes must be considered for the damage pointer in order to estimate the size of the damage in sandwich panels.

Table 2. Natural frequency (Hz) of the sandwich panel in the 1st six modes

	Natural Frequency (Hz)			
	Pristine Sandwich	5% Damage	7.5% Damage	10% Damage
Mode 1	1341	1336	1330	1315
Mode 2	3038	3008	2065	1570
Mode 3	6931	3185	2248	1700
Mode 4	7553	3464	2548	1937
Mode 5	9812	3907	2945	2249
Mode 6	10386	4505	2994	2637

Table 3. Natural frequency deviation (%) of the sandwich panel in the first six modes

	Natural Frequency Deviation (%)			
	5% Damage	7.5% Damage	10% Damage	Average
Mode 1	0.37	0.82	1.97	1.05
Mode 2	0.99	32.02	48.32	27.11
Mode 3	117.61	208.31	307.71	211.21
Mode 4	118.04	196.43	289.93	201.46
Mode 5	151.14	233.17	336.28	240.19
Mode 6	130.54	246.89	293.86	223.76

Table 4. Natural frequency (Hz) of the sandwich panel in the first six modes

	Natural Frequency (Hz)		
	Pristine Sandwich	Single hole of 10mm dia	Three holes of 10mm dia
Mode 1	1341	1338	1331
Mode 2	3038	3015	2972
Mode 3	6931	6739	6318
Mode 4	7553	7567	7295
Mode 5	9812	9779	9661
Mode 6	10386	10217	10023

Table 5. Natural frequency deviation (%) of the sandwich panel in the first six modes

	Natural Frequency Deviation (%)		
	Single hole of 10mm dia	Three holes of 10mm dia	Average
Mode 1	0.22	0.75	0.49
Mode 2	0.76	2.22	1.49
Mode 3	2.85	9.7	6.28
Mode 4	0.19	3.54	1.87
Mode 5	0.33	1.54	0.94
Mode 6	1.65	3.62	2.63

3.3 Influence of Damage Locations

The examined sandwich panels with varied damage places can produce differences in natural frequency even for the identical damage ratios. The effect of damage sites on the natural frequency deviation of a 10% damaged sandwich panel with one edge fixed constraint is shown in Table 6.

FromTable-6, the damage atposition A (near the fixedend) incurs the maximum natural frequency deviance of 95.12% while the damage at location C (far from the fixed edge) results in the lowest natural frequency deviance of 86.61%. It can be established that the lower the natural frequency deviation, the farther the location of the damage from the clamped edge. Other studies have confirmed the findings, which show that the influence of damage on natural frequency decreases as one move away from the fixed edge. As a result, the natural frequency deviancevariable can be used to identify the position of damage in the sandwich panel.

Table 6. Effect of the damage locations on the natural frequency deviation

	Intact Sandwich	Damage at Location A	Damage at Location B	Damage at Location C
Natural Frequency (Hz)	3038	1557	1570	1628
Natural Frequency Deviation (%)	-	95.12	93.5	86.61

4.0 Conclusion

In this paper, Finite Element analysisis utilized to investigate the damage in composite sandwich panels with the aid of vibration data. The natural frequency deviation parameter was used to help develop vibration-based damage identification.The influence of the damage ratio on the natural frequency deviance is examined, and it is discovered that the maximum the size of the damage, the larger the natural frequency deviation. The size of the damage can be anticipated if there is a specific natural frequency deviance on the composite sandwich panel.

Additionally, when we record complex modes, the damage identification in the sandwich panel becomes increasingly important. The influence of damage positions on natural frequency shows the beyond the damage sites are from the fixed edge, the lower the natural frequency deviance. As a result, the damage position can be estimated as a function of the distance from the sandwich panel's fixed edge.

References

1. T G Gerardi, Healthy Monitory Aircraft, *Journal of Intelligent Material System and Structure* 1, 375- 385, 1990.
2. S W Debling, C R Farrar, M B Prime, D W Shevitz, Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review, *Report A*-13070- MS ¸L*os Alamos*, 1995
3. Z Chaudhry, C A Rogers, Smart structures: on-line health monitoring concepts and challenges, *Proceedings of the* 48*th Meeting of the Mechanical Failures Prevention Group*, W*akefield, MA*, U.S.A. 13 - 19, 1994
4. P M Tappet, T D Snyder, H HRobertshaw, Attacking the damage identification problem, *Proceedings of SPIE* 2 T*he International Society for Optical Engineering Smart Structures and Materials*: *Smart Sensing, Processing, and Instrumentation*, 2443, 286 -294, 1995
5. K J Vamvoudakis-Stefanou, J S Sakellariou, S D Fassois, Vibration based damage detection for a population of nominally identical structures: Unsupervised Multiple Model (MM) statistical time series type methods, *Mechanical Systems & Signal Proceedings*, 111, 149 – 171, 2018
6. P J S Cruz, R Salgado, Performance of vibration-based damage detection methods in bridges. *Computer-Aided Civil Inf.*, 24, 62–79, 2009
7. M Frizzarin, M Q Feng, P Franchetti, S Soyoz, Modena C. Damage detection based on damping analysis of ambient vibration data,*Struct Control Hlth.*,; 17, 368-385, 2010
8. M S Cao, G GSha, Y F Gao, W Ostachowicz, Structural damage identification using damping: a compendium of uses and features,*Smart Mater Struct.*,; 26:043001, 2017
9. Z Zhang, K Shankar, T Ray, E V Morozov, M Tahtali, Vibration based inverse algorithms for detection of delamination in composites, *Composite Structures*,102, 226–236, 2013
10. M Radzienski, M Krawczuk, M Palacz, Improvement of damage detection methods based on experimental modal parameters,*MechSyst Signal Pr.*,25, 2169–2190, 2011
11. Z Zhang, K Shankar, E V Morozov, M Tahtali, Vibration-based delamination detection in composite beams through frequency changes,*Journal of Vibration Control*, 22, 496–512, 2014

12. R D Adams, P C Cawley, J Pye, B J Stone, A vibrational technique for non-destructively assessing the integrity of structures, *Journal of Mechanical Engineering Science*, 20, 93 -100, 1996
13. O S Salawu, C Williams, Damage location using vibration mode shape,*Proceedings of the 12th International Modal Analysis Conference*, 933 – 939, 1994
14. J Chance, GR Tomlinson, K Worden, A simplified approach to the numerical and experimental modelling of the dynamics of a cracked beam, *Proceedings of the 12th International Modal Analysis Conference*, 778 -785, 1994
15. O S Salawu, C, Williams, Structural damage detection using experimental modal Analysis - A comparison of some methods, *Proceedings of the 11th International Modal Analysis Conference*, 254- 260, 1993
16. K Waldron, A Ghoshal, M J Schulz, M J Sundaresan, F Ferguson, P F Pai, Damage detection using finite element and laser operational deflection shapes,*Finite Element Analysis & Design*, 38, 193–226,2002
17. A Ismail, A Zubaydi, B Piscesa, R Chandra Ariesta, Tuswan, Vibration-based damage identification for ship sandwich plate using finite element method,*De Gruyter. Open Eng.*, 10, 744–752, 2020
18. F Seguel, V Meruane, Damage assessment in a sandwich panel based on full-field vibration measurements, *Journal of Sound and Vibration*, 417, 1–18, 2018