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Research Article

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Article Info	Abstract
	In this study, a stress analysis and free vibration analysis were carried out for a curved sandwich composite beam. The curved composite beam was manufactured using glass fibers and vinylester resin. The polyvinylchloride (PVC) foam was preferred in the manufacturing of the sandwich composite beam for obtaining desired structure. The effect of the root and vertical cracks on the stress distribution and critical buckling loads for a curved composite sandwich beam were investigated numerically. The vibration analysis was performed experimentally and numerically. Experimental and numerical results were in a good agreement for the in-plane vibrations. It was seen that, the critical buckling forces changed not uniformly for the transverse crack and also, buckling loads decreased with increasing root crack length.

1. Introduction

Composite materials are recently the most preferred materials in aircraft, marine automotive structures. Most of the structural components in aircraft and marine structures may contain curved beam regions or may be in the form of curved panels. And the laminate stress versus bending moment is an important characteristic in the curved laminated beam. However, structural sandwich is a special form of laminated composite bonded together, although the properties of thick, light and weak of core material. Moreover, these materials are good candidates for automotive, aerospace, civil engineering's and navy industries because of their light, stiff and strong structures. They are especially used in automotive, aerospace, civil engineering's and navy industries. These materials possess high specific strengths, high ensuing the absorption, high bending stiffness, high load carrying capacity, thermal insulation and good sound reduction. However, they have low density, low cost, high stability and buckling.

Many references have studied the vibrations of curved beams made of the isotropic materials [1-3]. Just a few papers have been allocated for the composite ones. Ahmed [4, 5] has studied the in-plane vibration of sandwich beams by the finite element method. Di Taranto [6], Lu [7] and Nelson [8] have investigated the free and forced vibrations of a three-layer damped ring. Qatu et al. [9], [10] and [11] solved the free vibration of shallow and deep arches by the Ritz method and the energy method.

A fixture for testing curved sandwich beams in flexure was designed and evaluated by Andrew and Carlsson [12]. The test specimen is a continuous sandwich beam consisting of a central circular 90° region connected by two straight legs. The fixture was designed

according to the four-point flexure principle to produce a pure bending moment in the curved region.

Finite Element Method (FEM) with nonlinear geometrical analysis as well as curved beam theory and an approximate 2D elasticity solution have been carried out by Guedes and Sa [13] and they tested the curved panels under three-point bend (3PB) load by experimental methodology. In order to get the mechanical and strength characterizations of the pipe material systems, the test specimens cut out from pipe samples oriented in the tangential direction and then hoop modulus and strength were measured using the specimens. Flat and curved sandwich beams have been studied by Okutan Baba B. [14], and Srinivasa Thoppul. An experimental study has been carried out to determine the effect of curvatures and debond on the flexural stiffness and strength of composite sandwich structures with 15°, 30°, 45° and 60° open angle) with debond located at the top (upper) and bottom (lower) face/core interface were made from fiber-glass/epoxy laminate skins and polyurethane foam core. Four-point test results indicated a reduction in stiffness due the presence of debonds and curvature, but more predominantly, the results showed that the peak load reduces sharply with the presence of upper debond. To measure the interlaminar tensile strength, a novel specimen of a four-point curved beam is evaluated by Cui et al [15]. Detailed finite element analysis was carried out to investigate the appropriateness of the data interpretation formula. From the failure modes of the specimens, it has been concluded that the test specimen recommended for measuring the interlaminar tensile strength. The experimental results on stress-strain behavior of a curved sandwich beam under a uniform loading were obtained by Bozhevolnaya and Kildegaard [16]. Natural frequencies for cantilevered doubly-curved laminated composite shallow shells were studied by Qatu and Leissa [17] using Ritz method with algebraic polynomial displacement. The effect of various parameters (material, number of layers, fiber orientation, and curvature) upon the frequencies were studied by them. Experimental results were compared with the results obtained using finite element methods. The in-plane vibrations of a circular curved beam with a Mode I open transverse crack was investigated by Öz and Das [18]. Extension of neutral axis, bending, and rotary inertia effects were included. FEM was used to calculate natural frequencies for different crack depths and locations and for different boundary conditions. Birman and Byrd presented the effect of the matrix crack on the stiffness and natural frequencies of a composite beam [19]. They reported that change in the natural frequency is more considerable if the crack propagates into longitudinal layers.

The effects of crack ratios and positions on the fundamental frequencies and buckling loads of slender cantilever Euler beams with a single-edge crack were investigated by Karaagaç et al. [20]. A finite element algorithm based on energy method and the results obtained from the proposed numerical method were verified by doing experiments. Ozturk and Sabuncu [21] investigated the effect of the ply orientation on the natural frequencies and dynamic stability characteristics of a composite beam resting on the elastic supports. They reported that the stacking sequence has considerable effects on the dynamic properties of the composite beam. Shu and Della [22] studied the free vibration characteristics of beams with multiple delaminations. They reported that the delamination has considerable effects on the natural frequencies and mode shapes for relatively larger delamination sizes due to the decreasing structural stiffness. Cam and et al. [23] studied the effect of the crack on vibration of cracked beam, experimentally and theoretically. They used echo method for predication the size and location of the crack for cracked beam. They found that the theoretical results (ANSYS) agreed with experimental results. Toygar et al. [24] studied the effect of the interface crack, which was located at the beam free end, on the lateral buckling and free vibration frequencies of a sandwich composite beam both experimentally and numerically. They reported that the buckling load and natural frequencies of the beam

decrease as the crack length increases, and the decrement of these parameters is more prominent for the bottom crack case.

In this study, a stress analysis and free vibration analysis were done for curved sandwich composite beam. The buckling loads for the root crack were calculated by using the finite element method. The free vibration response of the sandwich composite curved beam was measured by experimentally. The in-plane vibration modes are obtained after the numerical vibration analysis was performed for the damped case using FEM. As a conclusion, a specific curved composite beam was modelled in Ansys software and the numerical results were compared with that of the experiments.

2. Materials and Method

In this study, a stress analysis and free vibration analysis were carried out in a curved sandwich composite beam. The curved composite beam was manufactured by the firm, GCG Marine Inc., Izmir, Turkey. In the manufacturing, glass fibers and vinylester resin were used. The PVC foam was preferred in the manufacturing of the sandwich composite beam for obtaining desired structure (Fig. 1). As seen in Fig.1, the thickness of the laminate at the bottom side is thicker than that of the top one due to the enduring outside forces. The width of the curved beam was maintained as 10 mm.

Fig. 1 Curved composite sandwich beam

The upper laminate with the thickness of 5 mm was manufactured by a randomly distributed glass-fiber layer and four woven layers. The lower laminate was manufactured using by three woven layers and a randomly distributed layer. The upper laminate was stronger than the lower laminate in terms of the mechanical and physical properties of the layers which are given in the Table 1. The specimen was modelled using Ansys 14 software. The specimen used in the experiments was scanned and the data were taken on the coordinate systems of the specimen's projection. These data were used as keypoints in the Ansys 14 software. In the data; 116 nodes and 87 elements were generated.

Table 1 Physical and mechanical properties of upper and lower laminates

Order of lamina	Distribution of fibers	Unit mass (Kg/m²)	Poisson ratio	Modulus of elastisity (GPa)
Upper laminate				
1	Randomly	0.45	0.28	12.50
2	Woven	0.80	0.14	23.20
3	Woven	0.85	0.13	25.40
4	Woven	0.85	0.13	25.40
5	Woven	0.85	0.13	25.40
Lower laminate				
1	Woven	0.85	0.13	25.40
2	Woven	0.85	0.13	25.40
3	Woven	0.80	0.14	23.20
4	Randomly	0.45	0.28	12.50

Table 2 Physical and mechanical properties of foam and vinylester

Material	Unit mass (Kg/m³)	Modulus of elastisity E (GPa)
PVC 100 Foam	100	0.11
Vinylester	880	3.6

The schematic representation of the curved beam is shown in Fig. 2.
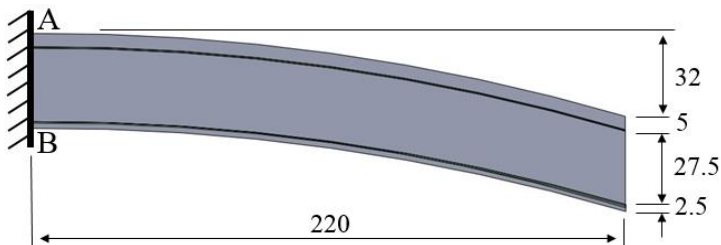

Fig. 2 The modeling of curved composite sandwich beam

In the FEM analysis modeling, upper root cracks were considered as 40, 60, 80, 100 and 120 mm, as shown in Fig. 3. The σ_x stress component was chosen in the stress analysis of the beam since σ_x stress component was higher than the other components. The thickness of the upper root crack was chosen as 0.05 mm. It is observed in the FEM modeling that, when the crack increases, the intensity of the stress component of σ_x reaches higher stress values; especially at the point A. The magnitude of the stress component of σ_x increases gradually at the point B for compressive stress component of stress component of σ_x.

Beside the root crack, it was also considered a vertical crack through the upper composite layers as shown in the Fig. 4. The cracks with the gap of 0.05 mm were formed at distances of 40, 60, 80, 100 and 120 mm from the cantilever beam. It is observed that in the FEM analysis that the distance between vertical crack and the point A increases while the intensity of the stress component of σ_x increases gradually at the point A, whereas the

intensity of stress component of σ_x increases rapidly at the point B. It was also performed a vibration analysis for the solid curved beam and a buckling analysis.
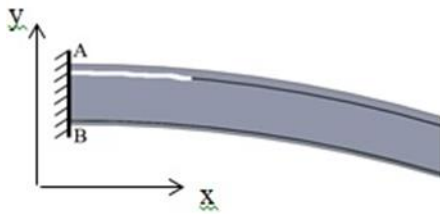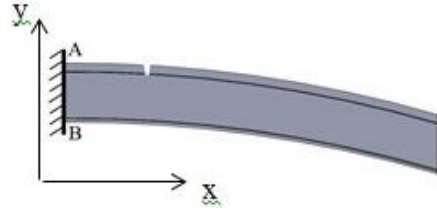

| Fig. 3 Upper root crack | Fig. 4 Vertical root crack |

3. Buckling Load

The buckling loads for the root crack were calculated by using the FEM. In all cases, the buckling loads were calculated numerically as shown in Fig. 5. The analysis was performed for different three buckling loads on the curved composite beam model as seen in the Fig. 5.
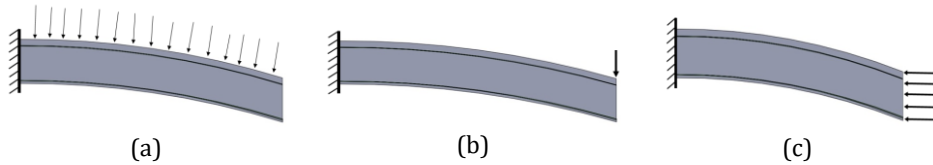

(a)   (b)   (c)

Fig. 5 Buckling loads (a) distributed force, (b) vertical single force, and (c) distributed horizontal force

4. Vibration Analysis

The free vibration response of the sandwich composite curved beam was measured by using experimental set-up shown in Fig. 6. The vibration signals were generated by a PCB 086C01 type impact hammer and these signals were detected using four PCB 352A24 type accelerometers as shown in Fig. 7. Each of the accelerometers has a sensitivity of 100 mV/g, weight of 0.8 gm and is suitable for vibration measurements within a range of 0.4-12000 Hz. All the vibration signals acquired from accelerometers were sampled at 8000 Hz and recorded on a computer using a NI PXI 4496 (which is a trade mark of National Instrument) data acquisition system and LabVIEW software, as seen in Fig. 6.
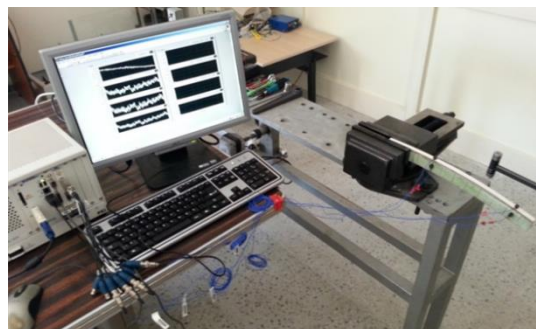

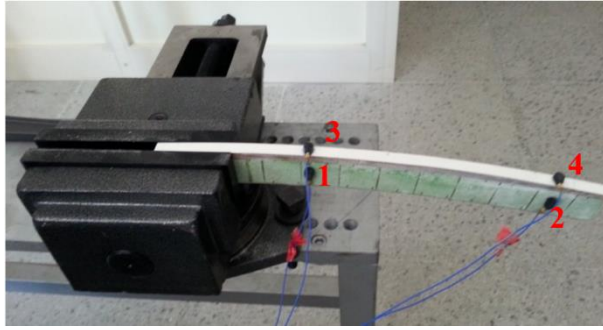Fig. 6 Experimental set-up for free vibration measurement

Fig. 7 Accelerometers and their locations on the sandwich composite curved beam

5. Results and Discussion

The Buckling loads were obtained using the FEM for the root cracks as given in Table 3. As seen in the table, buckling load decreased with the increasing the length of the crack. The large root crack caused a decrement in the buckling loads for all cases, since the inertia moment of the cross section of the beam decreased. The buckling loads reached high values, due to the short length of the beam and the higher thickness of the beam.

Table 3 Buckling loads in root cracks

The length of the crack (mm)	Distributed force (N/mm) [Fig. 5a]	Vertical single force (N) [Fig. 5b]	Distributed horizontal force (N/mm) [Fig. 5c]
Solid	3.02	2794	49.39
40	2.68	2685	32.77
60	2.12	1917	34.30
80	1.44	1414	27.67
100	1.12	920	21.89
120	0.91	718	19.35

The critical buckling loads for the vertical cracks are given at the Table 4. As seen in this table, the critical buckling forces decreased from solid beam to the beams which have 40 mm and 60 mm vertical cracks. However, the buckling loads did not change uniformly for the cracks at the distances of 80, 100 and 120 mm. It has a peak for the crack at 80 mm for all the typical critical buckling forces.

Table 4 The critical buckling loads for the vertical cracks

The length of the crack (mm)	Distributed force (N/mm) [Fig. 5a]	Vertical single force (N) [Fig. 5b]	Distributed horizontal force (N/mm) [Fig. 5c]
Solid	3.02	2794	26.30
40	2.80	1365	13.42
60	2.49	1535	29.61
80	2.98	1709	33.96
100	2.98	2133	36.12
120	2.98	2359	38.08

The stress component σ_x was selected in the analysis, since it was the highest stress component in the beam for the given solution. The distribution of σ_x for the root crack was shown in the Fig. 8. According to the figure, the length of the crack was increased, the intensity of the stress component of σ_x at the point A increased rapidly, due to the smaller inertia moment of the beam and crack effects. However, it is seen that the crack length was increased, the intensity of the σ_x increased slowly when compared to the stress component at A, because of the inertia moment of the cross section of the beam decreased, slowly as seen in Fig. 8. The stress component of σ_x was also investigated for the vertical cracks, at the points A and B, as shown in Fig. 9. This figure shows that σ_x component gradually increased at long distances of the vertical crack on the curved composite beam. The magnitude of σ_x at point B was higher than that of point A. When it reached 120 mm, the stress intensity of σ_x was 45.06 and -80.70 MPa at point A and B, respectively. It was also observed that the intensity of σ_x reached the high values at the lower point B.
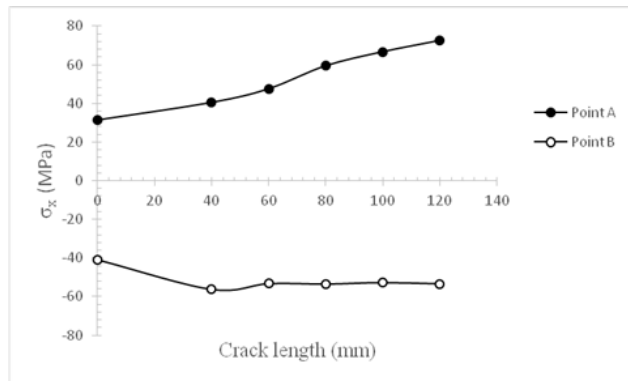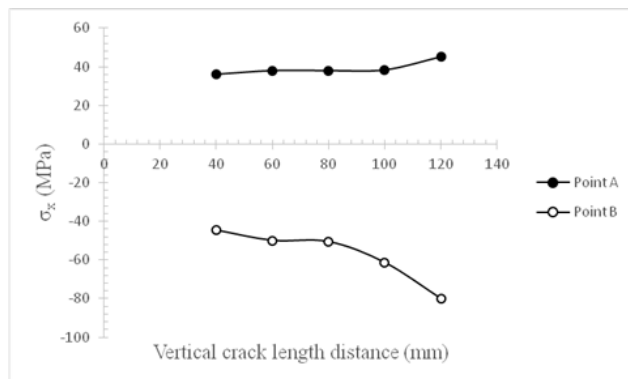

Fig. 8 σ_x versus the crack length

Fig. 9 σ_x versus the vertical crack length distance

The impact response of the composite curved beam was measured by the accelerometer 3 is shown in Fig. 10. The natural vibration frequencies were extracted from the impact responses obtained from four accelerometers by the application of the fast Fourier transform.
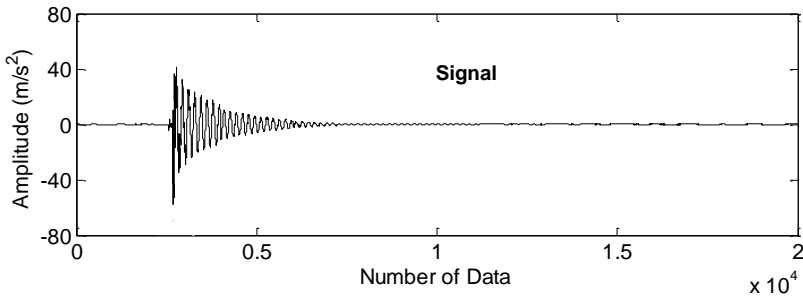
Fig. 10 The impact response of the sandwich composite curved beam measured by accelerometer-3

Fig. 11 shows the frequency content of the impact response of the curved beam measured by accelerometers 1 and 2 for in-plane vibration. As seen in the figure, the natural frequencies obtained from the FFT analysis were 143.9, 631.4, 1038, 1379, 1888, 2985 and 3445 Hz, respectively.
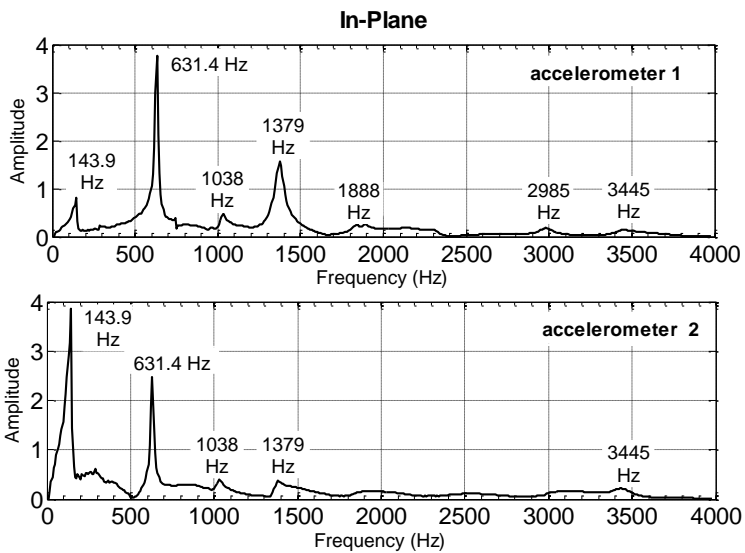

Fig. 11 Frequency content of the impact response recorded by accelerometers 1 and 2 for in-plane vibration

For out of plane vibration, the FFT results were calculated from the impact responses and the results were recorded by the accelerometers 3 and 4 are given in Fig. 12. The five natural frequencies of the composite curved beam were obtained in the frequency spectrum as a result of the location of the accelerometers. The natural frequencies of the out of plane vibration were 47.99, 363.1, 955, 1888 and 2985 Hz, respectively.
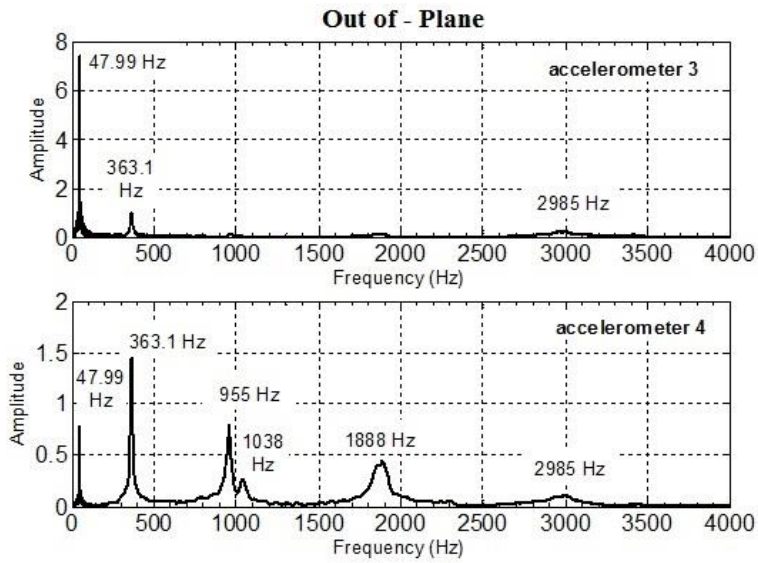
Fig. 12 Frequency content of the impact response recorded by accelerometers 3 and 4
for out of plane vibration

The numerical vibration analysis was performed for the damped case using FEM. The in-plane vibration modes are given in Table 5.

Table 5 The comparison of experimental and numerical vibration values

Experimental vibration modes (Hz)	Numerical vibration modes (Hz)
144	154
631	526
1038	1047
1379	1537
1888	1778

As seen from Table 5 agreements between the experimental and numerical methods are good.

6. Conclusion

In this study, the effect of the root and vertical cracks on the stress distribution and critical buckling loads were investigated for a curved composite sandwich beam, numerically. The vibration analysis was performed experimentally and numerically, following conclusions are drawn:

- Buckling loads decreased with increasing root crack length.
- The stress intensity of σ_x component increased at the cantilever beam with increasing the root crack length.

- The stress intensity of σ_x component at the cantilever beam, changes not uniformly for the transverse crack.
- There was no uniform change in the critical buckling forces of the transverse crack.
- Experimental and numerical results were in a good agreement for the in-plane vibrations.

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