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Numerical Analysis of The Microstructural and Geometrical Effects on The Flexural Behavior of Sandwich Structures with Skin/Core Delamination

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ABSTRACT

The effects of critical microstructural features on the mechanical behavior of sandwich structures under bending loading are investigated using the finite element method (FEM). The sandwich structures are made of a thick foam core and two thin skins consisting of laminated composites. The numerical results are extracted in the presence of the skin/core delamination which is one of the major failure modes of sandwich structures. The microstructural features include different types of woven fabric (E-glass, Kevlar and carbon), fiber volume fraction, number and arrangement type of layers in the composite skins, thickness and material properties of core, fracture toughness of adhesive face and the debonding length. Also, the effect of addition of carbon nanotubes (CNTs) into the foam core on the flexural properties of sandwich panels is studied. Comparisons are made between the predictions of the FEM and experimental measurements for the sandwich beams involving the skin/core delamination. A reasonable agreement is observed between two sets of results. It is found that the increase of fiber volume fraction and number of layers leads to an enhancement in flexural stiffness and increase in the delamination threshold load. The flexural properties of sandwich structures can be improved by increasing the thickness and elastic modulus of core. The results indicate that using carbon fibers into the composite skin is an efficient way to postpone the delamination of the skin from the core. Adding the CNTs can significantly enhance the delamination threshold load.

1. Introduction

Sandwich structures are made of two stiff and strong thin skins and a thick core with lower mechanical properties and weight. Because of great strength/stiffness to weight ratio, good acoustic and thermal insulation, high energy absorption capability and very good corrosion resistance, these structures are widely used in industrial products, such as aerospace, aircraft, high speed trains, ship hulls and turbine blades [1, 2]. Sandwich structures consisted of fiber-polymer laminated composite skins and lightweight foam core have been developed to meet the needs in boat hulls and submersible vehicles [3]. In general, these engineering structures are designed as panels that carry bending loads. However, the sudden variation in material properties across the interfaces between the skins and the core results in the large interlaminar stresses, frequently leading to skin/core delamination, which is a major failure mode in sandwich structures subjected to bending loads [4–6]. So, the flexural behavior of sandwich panels needs to be understood in order to obtain reliable design with high strength.

In this field, different methods have been developed mainly in order to precisely describe the bending response of sandwich structures. For example, Frostig et al. [7] established a theory based on variational principle for the bending behavior of sandwich beams with a flexible core, named high order sandwich panel theory. Skins were considered as metallic or laminated composites and core can be a foam or honeycomb. In this theory, the skins were simulated as two beams interconnecting with a core incorporated as a two-dimensional elastic medium. It was shown that the approach is applicable to any type of loading applied on the skins and to any type of boundary conditions of sandwich panels [7]. Also, a simple theory was proposed by Glenn and Hyer to predict the bending deflections of sandwich plates which defined the construction of a sandwich plate using low-cost materials (glass/PET skins and a nylon/PET core bonded together with a urethane adhesive) [8]. It was shown that the predicted bending values are about 10% higher than measured data. Imielińska et al. experimentally studied the effect of manufacturing on the mechanical behavior of E-glass fibre/polyester/PVC foam core sandwich panels [9]. They used the resin and adhesive for skin/core bonding. It has been reported that wet-lay-up skin/core bonding process is a superior option than bonding the skin to the core by an adhesive. Also, adhesive-bonded sandwich structures indicated a less extensive delamination area in the upper skin than the resin-bonded sandwich structures. Moreover, Jen and Chang [10] experimentally evaluated the four-point bending strengths of honeycomb sandwich beams with cores of various relative densities. It was stated that the delamination of the skin from the core is the major failure mode. The main effects of temperature changes contain a decrease in stiffness and development of residual stresses within the sandwich structures due to the mismatch in coefficients of thermal expansion of the core and skin [11]. For this reason, a closed form analytical solution based on the linear elasticity theory to study the bending response of sandwich panels was suggested in Ref. [11]. Then, Wang and Shen [12] studied the bending and post-buckling behaviors of a sandwich plate with functionally graded material (FGM) face sheets resting on an elastic foundation in thermal environments. The governing equation of the sandwich structure was solved by a two-step perturbation technique. Based on the numerical results, they stated that the foundation stiffness and temperature can play a critical role in the post-buckling and bending behaviors of sandwich plates. In another research, Cernescu and Romanoff [13] suggested a correction to the first and Reddy’s third order shear deformation theory to calculate the bending deflection of sandwich beams. Their model was based on the Timoshenko’s theory which was adapted for sandwich beams. They analytically and experimentally investigated the bending behavior of two sandwich configurations loaded in three-point bending tests. Also, Cao et al. [14] used the FEM and analyzed the effect of stiffness degeneration of adhesive layer on the flexural behavior of a sandwich beam with corrugated core under three-point bending. The numerical results showed that the possibility of debonding expansion in the adhesive layers near the upper and lower boundaries is visibly greater than that in adhesive layers near the neutral layer of beam structure. A numerical method based on the sublaminate generalized unified formulation (S-GUF) was proposed by D’Ottavio et al. [15] for the bending analysis of sandwich structures. They extracted the through-the-thickness distribution of the in-plane stress components for sandwich panel. In another research, the simple four-unknown shear and normal deformation theory was developed to study the static and dynamic responses of sandwich plates [16]. In regards to the first and higher order shear deformation theories, the number of independent unknowns of this theory preserves four degrees of freedom per node. The Galerkin weak form was used to derive the discrete system of equations which were solved via isogeometric analysis. Furthermore, Li et al. [17] numerically investigated the bending response of sandwich plates with different face sheet materials and a FGM core under transverse distributed loadings. The governing equations of sandwich panels were deduced based on the static equilibrium method and then solved by means of Navier approach. They analyzed the role of volume fraction distribution, the thickness to side ratio and the layer thickness ratio on the mechanical behavior of sandwich structures under bending loads. Groh and Tessler [18] presented a finite element analysis using efficient nine degree-of-freedom (DOF) and eight DOF shear locking-free beam elements combined with the refined zigzag theory to investigate the delamination failure in sandwich structures. Caglayan et al. [19] carried out some three-point bending tests to investigate the flexural strength and failure modes of neat and carbon nanotube (CNT)-reinforced polyurethane (PU) foam cored sandwich panels. Improvements of more than 30% in both core shear and facing strength of sandwich panels were observed due to the CNT-augmented PU foam and its tailored mechanical performance. Reinforcement of PU core with functionalized carbon nanotubes was reported to be an efficient way to postpone the debonding between face sheet and core. Also, several review papers on the bending behavior of sandwich structures exist in the literature [20–23].

It is well-known that delamination between the skin and core has a detrimental effect on the sandwich structures because the load transfer between face and core is compromised. Debonding may be created during manufacturing and it might grow under both static and dynamic loadings during the service lifetime of the structures [24–26]. To the authors’ knowledge, there is not any work on the investigation of the effects of microstructural features on the bending response of sandwich structures in the presence of skin/core delamination. Also, the effects of adding CNTs which may play an important role in the mechanical behavior of CNT-reinforced foam cored sandwich panels are rarely explored and considered in the material modeling. It is noticed that CNT-reinforced polymer foams have the opportunity to tailor mechanical properties as well as to add multi-functionality to the sandwich structures making them attractive for aerospace, shipbuilding and other industries. Hence, it is very essential to develop reliable and efficient methods which enable accurate predictions of the advanced structure mechanical response. The experimental methods to evaluate the mechanical behavior of hybrid systems are time-consuming and costly. In this frame, the use of theoretical approaches sounds promising.

The objective of this paper is to establish a numerical model based on the FEM for studying the effects of microstructural features including volume fraction and different types of woven fabric, number and arrangement type of layers in the laminated composite skin, thickness and material properties of core, fracture toughness of adhesive face and the debond length on the flexural behavior of sandwich panels in the presence of skin/core delamination. Also, the bending response of sandwich structures with CNT-reinforced polymer foam is investigated. The paper is organized as follows. Section 0 describes the numerical simulation based on the FEM in details. Also, the geometrical and material properties of sandwich panels are presented in Section 0. Section 0 represents the numerical results for the flexural behavior of sandwich beams. Also, the accuracy of the proposed method is assessed by comparing the numerical predictions and experimental managements. Finally, concluding remarks are introduced in Section 0.

2. Numerical simulation of the sandwich panels

In this section, first, a brief description of cohesive zone law is presented. Then, the details of the numerical simulation of sandwich panels provided by ABAQUS 6.14 finite element package are introduced.

2.1. Cohesive law

The cohesive zone model is a suitable model in evaluating the initiation and propagation of delamination. In this study the cohesive zone model has been utilized to predict and analyze the delamination of the skin from the core in sandwich structures. Among two methods of cohesive elements and cohesive surfaces, due to the very small thickness of the adhesive layer, the cohesive surfaces are used for numerical modeling. The first step to accurately evaluate the growth of delamination is to select the appropriate structural relations for interlayer elements and determine a structural relationship for them. This relationship in elements with no thickness relates the interlayer traction to the relative separation between the adjacent nodes of the element and, for thick elements, relates interlayer traction to the interlayer strain of the element. According to Figure 1, the traction-separation relationship in the interlayer element is initially linearly elastic and when the stress reaches a maximum value which corresponds to the interlayer strength, a gradual decrease in the stiffness of the interlayer element starts. Finally, when the stiffness of the interlayer element reaches zero, the interlayer element will be completely degraded [27].

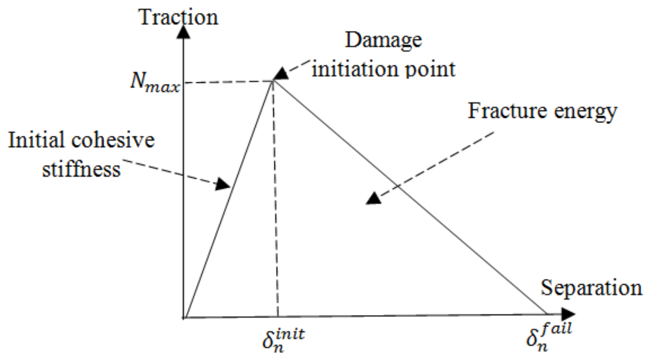

Figure 1. Bilinear traction-separation law

In this study, the maximum stress criterion has been used to predict the beginning of degradation. In this criterion, it is assumed that the failure begins when the stress at the point of attachment and the maximum stress become equal, as follows:

$$max\left\{\frac{\langle t_n\rangle}{t_n^0},\frac{t_s}{t_s^0},\frac{t_t}{t_t^0}\right\}=1 \tag{2}$$

where symbol ⟨ ⟩ represents the expression that compressive stress has no effect on the debonding and is considered to be zero. Also, $\boldsymbol{t_n^0}$, $\boldsymbol{t_s^0}$ **and** $\boldsymbol{t_t^0}$ express the contact stresses when either the maximum stress is purely vertical or shear in the secondary and tertiary shear directions. In this work, to predict the propagation of delamination, the relationship introduced by Bezeggah and Kenane known as the B-K criterion is utilized which more details are available in Ref. [28]. Note that this criterion has been adopted in ABAQUS finite element package.

Generally, fracture toughness, initial elastic stiffness, and the yield stresses are the effective parameters in the cohesive zone. In order to obtain the properties of the adhesive layer in the modeling of cohesive surfaces, three steps must be carried out, as follows:

1- First, a sandwich panel sample with available experimental flexural behavior data is simulated in the FEM software.
2- In the first analysis, the guessed adhesive properties for the foam-skin surfaces are implemented in the FEM software.
3- The results of numerical method and experimental data are compared. By changing the effective parameters of the cohesive zone, it is tried to fit the numerical results to the experimental measurements.

2.2. Geometrical and material characteristics of sandwich panels

In this section, all geometrical and material properties of the sandwich structure used in FEM, presented which are similar to those of standard test method in Ref. [29]. A schematic sketch of dimensions and cross section of sandwich beam is shown in the Figure 2 which $\mathrm{L = 370mm}$, $\mathrm{b = 60mm}$, $\mathrm{d = 18.5mm}$, $\mathrm{t_c} =$

15mm, $t_s = 1.75$mm. So, in ABAQUS finite element package, sandwich beam is defined in two parts, which part 1 consists of a composite sheet as upper skin and part 2 consists of lower skin and foam core. The part 2 is partitioned in two subsections to easily define the material specifications. For the three-point bending test fixture, two solid cylinders ($\emptyset = 25mm$) are modeled, and a similar cylinder is used to apply the bending load. Figure 3 shows the simulated sandwich beam in ABAQUS finite element package. The schematic sketch of simply supported sandwich beam with geometrical characteristics is shown in Figure 4. Span length is 320mm. Both loading (L.C) and boundary conditions (B.C) are displayed in this figure. The sandwich beam consists of a homogeneous polyvinyl chloride (PVC) foam core with two stiff and strong skins. The skins are bonded to the PVC core by an adhesive layer to permit the load transfer between the components. Both upper and lower skins are made of E-glass fabric-reinforced epoxy laminated composites with 8 layers. The volume fraction of glass fiber within the skins is equal to 50%.

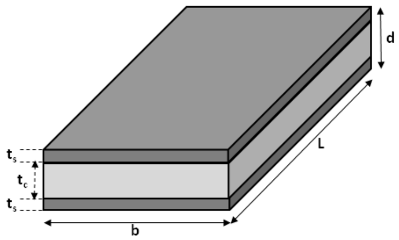

Figure 1. A schematic sketch of dimensions and cross section of sandwich beam

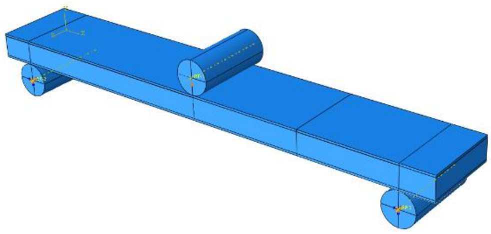

Figure 2. Simulated sandwich panel in FEM

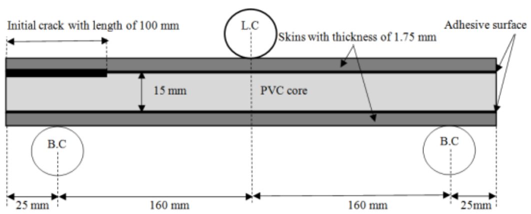

Figure 3. A schematic sketch of simply supported sandwich beam

The material properties of glass fiber-epoxy composite and PVC core are tabulated in Table 1.

Table 1. Material properties of glass fiber-epoxy composite and PVC core

$E_{11} = E_{22}$ (GPa)	E_{33} (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	$\upsilon_{12} = \upsilon_{13}$	υ_{23}
13.7	6	1.49	1.86	0.3	0.21
0.0848	0.0848	0.0385	0.0385	0.1	0.1

2.3. Analysis type, contacts and boundary conditions

Nonlinear static analysis has been used to investigate the debonding of the skin and core due to the low loading rate and high deformation. The connection between the upper skin and the core is modeled by defining the contact and using the adhesive surfaces method. Similar to other studies, it is necessary that a part of upper skin, called the initial debonding (pre-existing debond), is not attached to the core (Figure 5). The reason for this is to facilitate the occurrence of the debonding phenomenon, before occurance the other fatigue modes such as fiber fracture, matrix cracking, etc. As shown in Figure 4, pre-existing debond length is 100 mm. It should be noted that in all samples, the common contact surface of the core and the skin are considered the same.

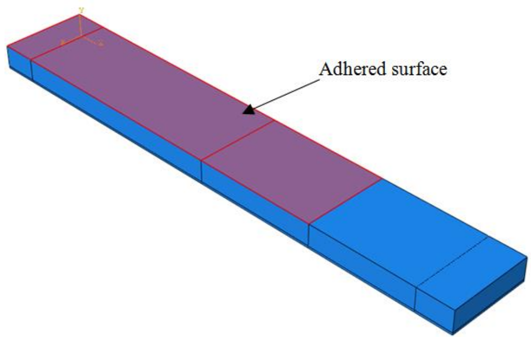

Figure 4. Adhered surface and initial debonding

Defined coordinate system is shown in Figure 3. For loading fixture (L.C), there are no degrees of freedom in X and Y directions. By defining a reference point and an equation of motion, the load can be applied to the reference point, so that the loading fixture moves exactly the same amount. All degrees of freedom for lower cylinders are closed. Also, In order to prevent the samples from sliding in the transverse direction, the core and the lower surface are tied in the Y-direction. The initial loading on the sandwich beam is in displacement control type, in which a load equivalent to 15 mm of displacement is applied to the loading fixture in the three-point bending model.

2.4. Meshing

Eight node brick elements (Solid C3D8R) are used to mesh all the top and bottom skins and the foam core. The size of the elements, as shown in

Figure 5, is smaller near the debond tip and the critical points where the most stress distributions occur in order to better represent the separation. According to the descriptions of the Abacus Software Guide and the theory of using adhesive surfaces, the elements that are in contact with each other on two adhesive surfaces must match point by point (Figure 7).

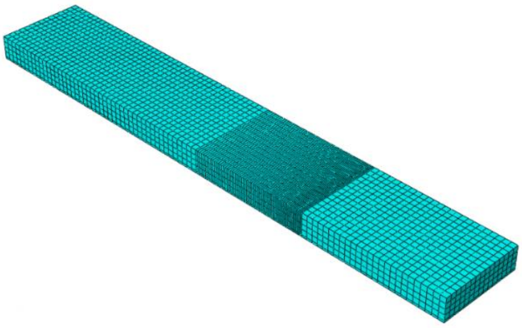

Figure 5. Increasing the mesh density in the debond tip

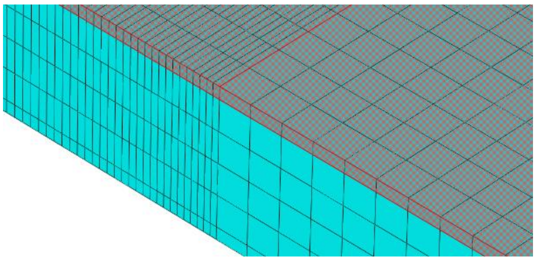

Figure 6. Matching elements of adhesive surfaces

3. Results and discussion

In this section, first, the results of the present model compared with other numerical simulations and experiments. Then, several parametric studies are done to investigate the effects of critical microstructural features, including variation in material and geometrical properties of beam constituents on the mechanical behavior of the sandwich panel under bending loading.

3.1. Verification of the numerical model

The predictions by the FEM utilized herein are first compared against those from the numerical results by Xie et al. [30] which analyzed an end-notch flexure (ENF) configuration. The ENF configuration and the related dimensions are displayed in Figure 8. The width of specimen is 10 mm. Also, similar properties are considered for both upper and lower beams which are bonded to each other. The elastic modulus and Poisson's ration of the isotropic beam are 70 GPa and 0.3, respectively. According to Ref. [30], the fracture toughness and shear strength of cohesive zone are 1.45 N/mm and 2.85 MPa, respectively. Also, plane stress elements "CPS4" are used in FEM meshing. Figure 9 displays the comparison between the present FEM solution and numerical prediction of Ref. [30] for load-deflection curve. The results of the present FEM are found to be in good agreement against the predictions from the numerical approach of Ref. [30]. The difference between the two sets of results may be primarily caused by the use of different theories and number of elements used in analysis to evaluate the beam flexural behavior. Figure 10 shows the debonded geometry in ENF specimen.

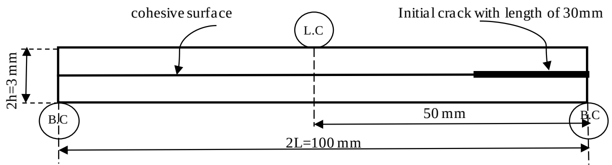

Figure 7. Configuration of ENF specimen for pure bending according to Ref. [30]

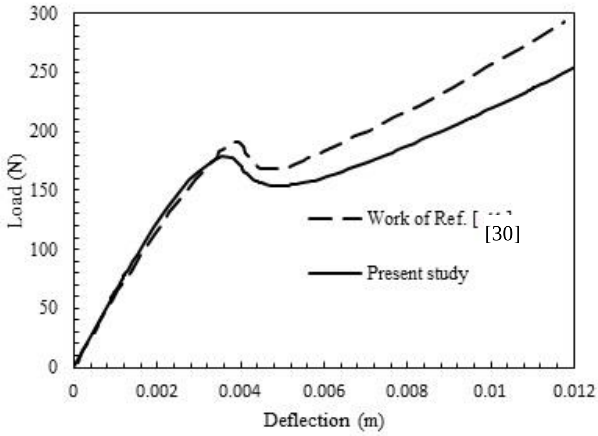

Figure 8. Comparison between the results of the present FEM and numerical simulation of Ref. [30]

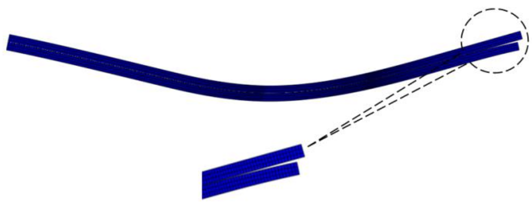

Figure 9. Debonded beam geometry in ENF specimen

In order to further prove the validity of the present simulation framework, the predictions of the FEM approach are compared with the experimental data [31] for bending behavior of sandwich beams. Figure 11 shows the comparison between the results of the present FEM and experiment for a sandwich beam with of a 30 mm thick H100 PVC foam core and 2 mm E-glass/polyester face sheets. The face and core moduli are 16.4 GPa and 135 MPa respectively. The specimens were 35 mm wide and the span length was 150 mm. The initial debond length, measured from the loading line to the crack tip was 25 mm. The lever arm distance is 40 mm. In this figure, the variation of the applied load with the deflection of sandwich beam is plotted. It should be noted that the number of elements in finite element analysis is considered to be 1820. It is observed from Figure 11 that good agreement exists between the FEM prediction and experimental measurement. Also, this comparison shows the correctness of the cohesive zone properties adopted in the FEM software. Thus, it can be inferred from the comparison shown in Figure 9 and Figure 11 that the present modeling approach can be reliably applied to predict the mechanical behavior of the sandwich structures under bending loads. Figure 12 illustrates the delamination of the upper laminated composite skin from the PVC foam core.

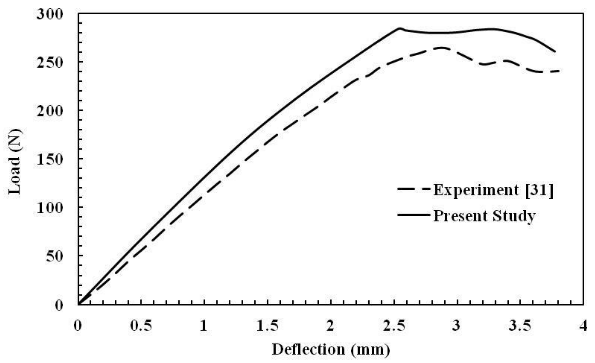

Figure 10. Comparison between the results of the present FEM and experimental data [31] for bending behavior of sandwich beam with glass/polyester face composite in skins

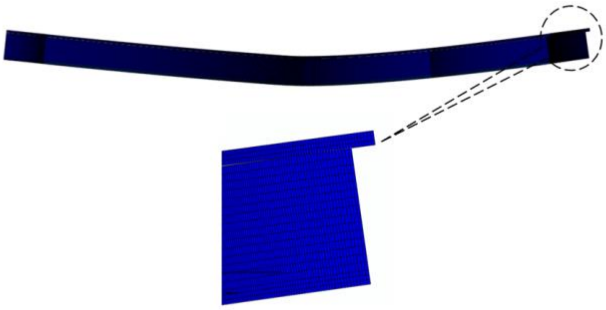

Figure 11. Delamination of the upper skin from the core in sandwich beam

3.2. Parametric studies

After verifying the validity of the proposed model, the parametric studies are carried out for the sandwich beams with 8 layers of E-glass fiber-reinforced epoxy composite in upper and lower skins. Unless otherwise stated, all geometrical and material properties for generating numerical results are similar to those the properties mentioned in Section 02.2.

3.2.1. Mesh sensitivity analysis

First, a mesh sensitivity analysis is performed to verify the convergence of the present approach for the bending analysis of sandwich structures in the presence of skin/core delamination. The variation of bending load with deflection for various numbers of elements used in FEM is indicated in Figure 13. For this analysis, five different numbers of elements, including 1820, 5540, 11780, 14700 and 16800 are selected. The results show that all predictions of the FEM with the selected numbers of elements are very close to each other. By increasing the number of elements over 1820 leads to more computational cost without improving the results. For example, the run time of FEM solution with 1820 elements and 16800 elements is about 240 s and 7840 s, respectively, corresponding to a 3166% increment. One can conclude from Figure 13 that a mesh size of 1820 elements is quite sufficient to obtain the results and hence, this mesh size is chosen for the rest of solved examples. Although the results of the numerical simulation with 1540 elements are not presented herein, however, it is only possible to obtain the mechanical response of the sandwich panel in linear elastic regime using the FEM with these numbers of elements.

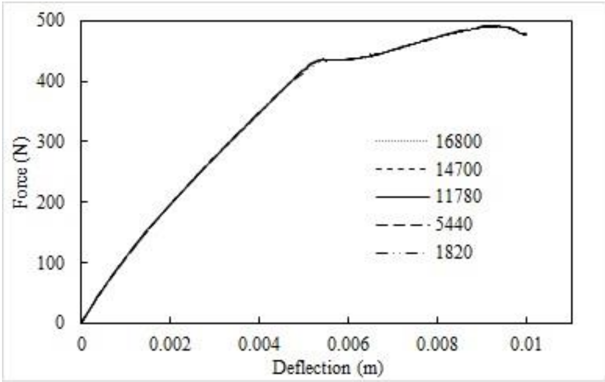

Figure 12. Effect of number of elements in numerical simulation of FEM on the flexural behavior of sandwich panel

3.2.2. Study on the thickness of foam core

Figure 14 illustrates the effect of variation in thickness of foam core on the mechanical behavior of sandwich beams under bending loading. For this analysis, three different values, including 15 mm, 16 mm and 17 mm are selected for the core thickness. It is seen that the flexural behavior of sandwich structures is sensitive to the core thickness. With the increase of core thickness, both the flexural stiffness and skin/core delamination threshold load can be increased. Based on the standard test method for flexural properties of sandwich beams i.e., ASTM-C393, following relation is used to determine flexural stiffness EI [29]:

$$EI = \frac{FL^3}{48\Delta} \tag{3}$$

where F is the maximum value of load in linear elastic regime, and Δ is the deflection corresponding to F. Also, L is the length of sandwich structure. Table 2 provides the values of flexural stiffness and delamination threshold load for three values of core thickness. The rise of core thickness from 15 mm to 17 mm leads to a 27.13% enhancement of flexural stiffness and a 10.34% enhancement of delamination threshold load. So, the mechanical performance of sandwich structures under bending loads can be improved by the increase of core thickness.

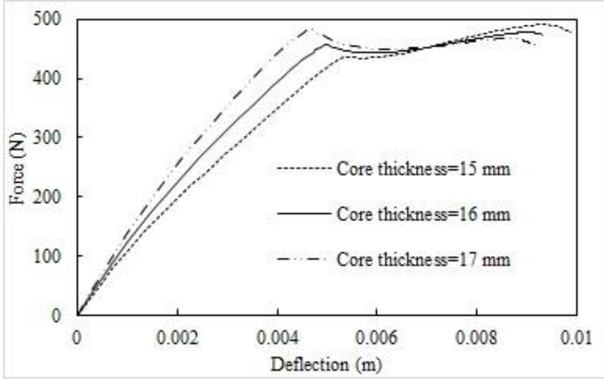

Figure 13. Effect of thickness of foam core on the flexural behavior of sandwich panel

Table 2. Flexural stiffness and delamination threshold load for different core thicknesses

Delamination threshold load (N)	Flexural stiffness ($N.m^2$)	Core thickness (mm)
435	56.03	15
460	62.8	16
480	71.23	17

3.2.3. Study on the elastic modulus of foam core

Figure 15 presents the load-deflection curves for three core elastic moduli, including 56.46 MPa, 84.77 MPa and 127.16 MPa. It is observed that the flexural behavior of sandwich panels exhibits strong dependency on the core mechanical properties. Higher core elastic modulus enhances the flexural stiffness, and thus reduces the compliance. For example, the flexural stiffness of the sandwich beam with core elastic modulus of 84.77 MPa is 56.03 $N.m^2$, whereas this value for the sandwich beam with core elastic modulus of 127.16 MPa is about 67.6 $N.m^2$, corresponding to a 20.06% improvement. Also, it is shown from Figure 15 that the delamination threshold load can be increased by increasing the core elastic modulus. For example, when the core elastic modulus increases from 84.77 MPa to 127.16 MPa, a 9.19% improvement has been obtained for the delamination threshold load.

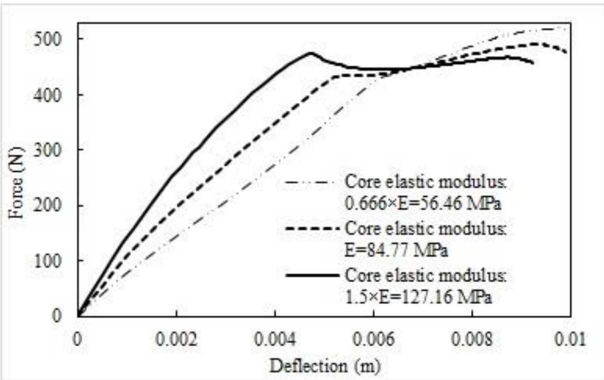

Figure 14. Effect of elastic modulus of foam core on the flexural behavior of sandwich panel

3.2.4. Study on the number of layers in skins

One the most important recognized features of the sandwich structures is the number of layers in laminated composite skins. In this frame, the variation trend of applied load with deflection of the sandwich specimen for different numbers of layers in laminated composite skins is determined and the numerical results are presented in Figure 16. It is found that the influence of the number of layers in composite skins on the mechanical behavior is very significant. It can be observed from the figure that the flexural stiffness and delamination threshold load increase with the increase in number of composite layers of skins. It is due to the fact that the mechanical properties of lower and upper skins improve with the increase of layers leading to a more contribution to the load bearing. Table 3 provides the values of flexural stiffness and delamination threshold load for four different numbers of layers. It can be determined that the increase in number of layers from 6 to 16, the flexural stiffness and delamination threshold load can be improved by 135.1%, and 26.2%, respectively.

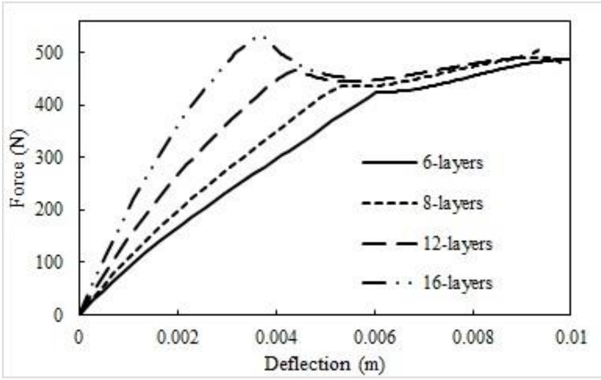

Figure 15. Effect of number of layers of E-glass fiber-epoxy composite in skins on the flexural behavior of sandwich panel

Table 1. Flexural stiffness and delamination threshold load for different numbers of layers

Delamination threshold load (N)	Flexural stiffness ($N.m^2$)	Number of layers
420	47	6
435	56.03	8
462	71.68	12
530	100.5	16

3.2.5. Study on the fiber volume fraction

The fiber volume fraction used in the composite skins is an important parameter in the design of sandwich structures. Hence, a parametric study of E-glass fiber volume fraction in the mechanical behavior of sandwich beams under bending loading seems to be essential. Figure 17 shows the effect of variation in fiber volume fraction on flexural behavior of sandwich beams. The numerical results are obtained for different values of fiber volume fraction, including 40%, 50% and 55%. It is observed a strong dependency of the sandwich beam bending response on the fiber volume fraction. Based on the Figure 17, with increasing the fiber volume fraction, the flexural stiffness will be increased. For example, for the volume fractions of

40% and 50%, the calculated flexural stiffness of sandwich beam is 43.6 N.m^2 and 56.03 N.m^2, respectively. Moreover, one way to postpone the delamination of upper skin from the core can be increase of the fiber volume fraction in composite skins as shown in Figure 17. It is related to the fact that the skins mechanical properties of laminated composites can be enhanced as the fiber volume fraction increased.

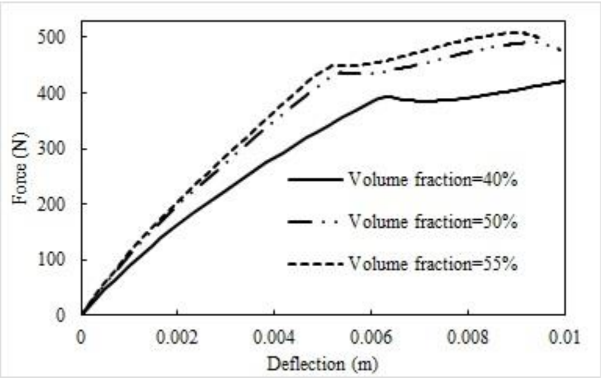

Figure 16. Effect of E-glass fiber volume fraction in skins on the flexural behavior of sandwich panel

3.2.6. Study on the types of woven fabric

It is well accepted that different types of woven fabric such as glass, Kevlar and carbon can be used to produce the laminated composite skins. Figure 18 shows the effect of change in woven fabric type on the bending behavior of sandwich beams. The numerical results of the FEM are provided for glass, Kevlar and carbon fibers used as reinforcement in composite skins. It is seen that the use of composite skins reinforced with carbon fibers is an efficient way to improve the flexural stiffness and to postpone the delamination of the skin from the core. This is due to the fact that the mechanical properties of carbon fiber are higher than those of glass and Kevlar fibers. The values of flexural stiffness and delamination threshold load of carbon fiber-epoxy skin/PVC foam sandwich beam are determined to be equal to 79.8 N.m^2 and 526 N which are significantly higher than those of glass fiber-epoxy skin/PVC foam sandwich beam.

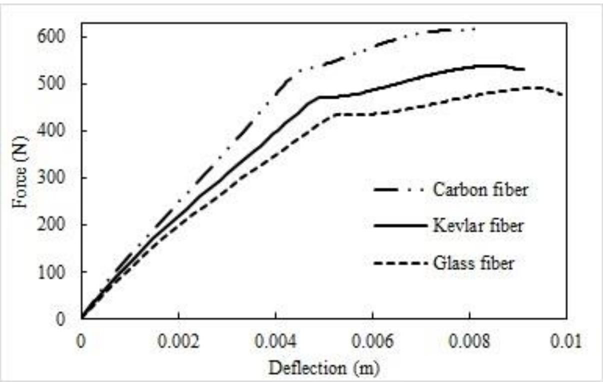

Figure 17. Effect of different types of fibers on the flexural behavior of sandwich panel

3.2.7. Study on the arrangement types of woven fabric

In this section, the effect of different arrangement types of woven fabric in the skins of laminated composite on the flexural behavior of sandwich beams is examined. Four types of woven fabric arrangements, including 8 layers of glass fiber (8G), 4 layers of carbon fiber/4 layers of glass fiber (4C,4G), 2 layers of glass fiber/4 layers of carbon fiber/2 layers of glass fiber (2G,4C,2G) and 1 layer of carbon fiber/6 layers of glass fiber/1 layer of carbon fiber (1C,6G,1C) are selected. The load-deflection curves for these types of fiber arrangements are illustrated in Figure 19. It is found that the type of fiber arrangement can significantly contribute to the mechanical behavior of sandwich structures under bending loading. Among them, the sandwich beam containing 4 layers of carbon fiber and 4 layers of glass fiber has the maximum level of flexural properties.

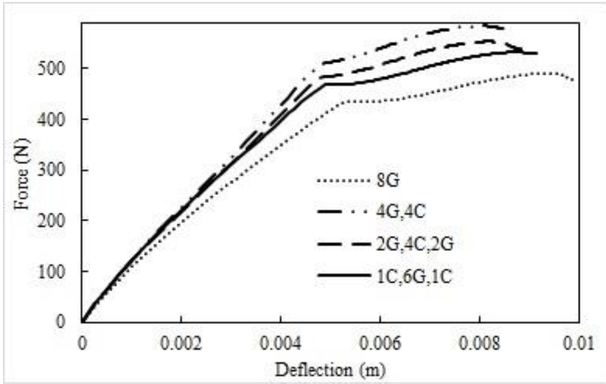

Figure 18. Effect of different types of fiber arrangements on the flexural behavior of sandwich panel

3.2.8. Study on the debonding length

In order to investigate the role of debonding length on the mechanical behavior of sandwich panels under bending loading, three specimens with debonding length of 75 mm, 100 mm and 125 mm are simulated. The load-deflection curves of these sandwich specimens are indicated in Figure 20. As expected, with decreasing the debonding length in sandwich beams, both flexural stiffness and delamination threshold load increase significantly.

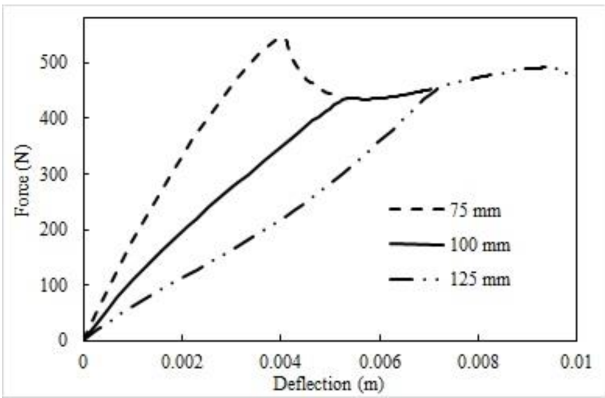

Figure 19. Effect of debond length on the flexural behavior of sandwich panel

3.2.9. Study on the fracture toughness of adhesive surface

A sensitivity study is performed in order to examine the role of fracture toughness of adhesive surface in the bending response of sandwich panels. For this purpose, three different values, including 0.35 N/mm, 0.4 N/mm and 0.45 N/mm are selected for the fracture toughness of adhesive surface between the upper composite skin and PVC core. The numerical results of the FEM are presented in Figure 21. It is clearly observed that the change of fracture toughness does not contribute to the flexural stiffness of the sandwich beams. However, the value of delamination threshold load is dependent on the fracture toughness. Generally, it is possible to postpone the delamination of upper skin from the core by increasing the values of fracture toughness of the adhesive surface. For example, the delamination threshold load for the considered sandwich structure has been predicted to be about 397 N and 472 N when the fracture toughness of adhesive surface is equal to 0.35 N/mm and 0.45 N/mm, respectively.

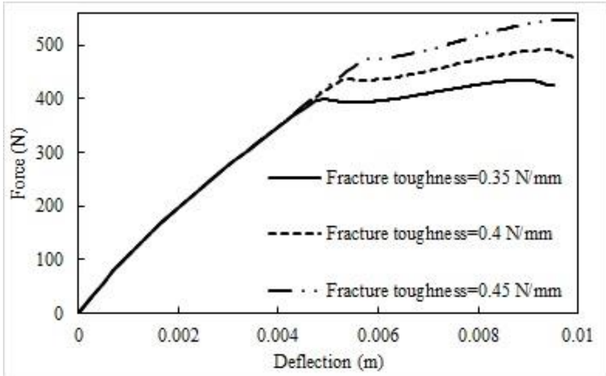

Figure 20. Effect of fracture toughness of adhesive surface on the flexural behavior of sandwich panel

3.2.10. Study on the CNTs within the foam core

The mechanical properties of core material may determine the flexural properties of sandwich panels [19]. Todays, development of polymeric foam cores with higher mechanical characteristics and multi-functionality has greatly attracted the possibility of adding nanoscale fillers to the existing foams to adopt the properties for the industrial needs. The carbon nanotubes (CNTs) have been usually investigated by many researchers to produce the CNT-reinforced polymer foams [19]. Thus, as the final case study by the FEM, the role of adding CNTs into the foam core in the bending response of sandwich structures is analyzed. To deal with CNT-reinforced polymer core, its mechanical properties must be predicted. Details for material properties of carbon nanotube-reinforced composites can be found in Ref. [32].

The performance of polymer system filled with CNTs is considerably controlled by the interfacial bonding between a CNT and the polymer material [33]. In these composite materials, the non-bonded van der Waals (vdW) interactions between the CNT and polymer play a key role in the mechanical properties. In the micromechanical modeling of this type of composite system, the non-bonded vdW interaction has been considered as an equivalent solid continuum interphase.

Figure 22 shows the mechanical behavior of sandwich beams with CNT-reinforced foam core under bending loading. The material properties of CNT and interphase characteristics have been given from Ref. [34]. The load-deflection curves are extracted for different values of CNT volume fractions, including 0, 0.05%, 0.1% and 0.12%. Based on the numerical results of the FEM, the flexural behavior of sandwich panels can be significantly improved by the addition of CNTs into the foam core. It is found that the flexural stiffness and delamination threshold load increase by increasing CNT volume fraction. Table 4 provides the values of flexural stiffness and delamination threshold load for different volume fractions of CNTs within the foam core. As compared to base sandwich panel (i.e., without CNT), the flexural stiffness and delamination threshold load of sandwich beam with 0.1 vol% CNT-reinforced foam core indicate an enhancement of 82% and 37.5%, respectively.

Table 2. Flexural stiffness and delamination threshold load for different volume fractions of CNTs

Delamination threshold load (N)	Flexural stiffness ($N.m^2$)	CNT volume fraction (%)
435	56.03	0
500	77.6	0.05
598	102.06	0.1
623	107.7	0.12

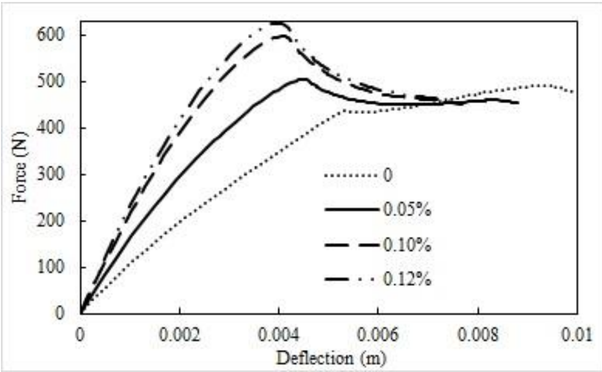

Figure 21. Effect of adding CNTs within the foam core on the flexural behavior of sandwich panel

4. Conclusions

In this work, a comprehensive analysis based on the FEM was done to investigate the effects of critical microstructural features on the mechanical behavior of sandwich panels under bending loading. The sandwich structure was made of E-glass fiber-reinforced epoxy laminated composite skins and PVC foam core. A specific attention was paid to the delamination of upper composite skin from the core. Two comparisons with experimental data of the flexural behavior of sandwich beam revealed the accuracy and efficiency of the proposed numerical approach. It was found that the flexural stiffness and delamination threshold load can be improved by increasing (1) fiber volume fraction, (2) number of layers within the skins, (3) core elastic modulus, and (4) core thickness. Also, the results indicated that increasing fracture toughness of adhesive surfaces can postpone the upper skin/core delamination. It was observed that different types of fibers and their arrangement significantly contribute to the mechanical behavior of sandwich panels subjected to bending loading. Generally, addition of nano-sized reinforcements such as CNTs can improve the flexural stiffness and postpone the delamination between the skin and core. The proposed numerical approach with obtained results could be useful to guide design of sandwich panels with superior mechanical properties.

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