Numerical Study of the Effect of Temperature Changes on the Failure Behavior of Sandwich Panels with Honeycomb Core

Ismaeil Eynali[1], **Seyed Alireza Seyed Roknizadeh**[2*]

Abstract – In this paper, failure modes of sandwich panels are investigated numerically using finite element method. For this purpose, four sandwich beams of GFRP laminate skins and Nomex honeycomb core are considered. The models have been chosen so that they could cover all failure modes according to available experimental failure mode maps. Models are created and analyzed based on standard 3-points bending test, using ASTM standard C393-62. In order to investigate the effect of loading and sandwich panel parameters on failure behavior, finite element analysis has been utilized. The results are verified by comparing experimental and theoretical results. The constructed failure mode map shows dependence of failure mode on the ratio of skin thickness to span length, and honeycomb relative density. To Then, effect of temperature on the failure modes of sandwich panels, has been investigated. Results show that failure modes haven't depended on environment temperature and failure load decreases by increasing environmental temperature. The slope of reduction is a function of beam geometrical parameters. Depending on the parameters, the failure loads decrease between 10% to 40% by increasing environmental temperature.

Keywords: Sandwich panels, Honeycomb core, Failure mode map, Temperature effects.

1. Introduction

Sandwich panels are consisted of two stiff skins that are separated by a soft core as indicated in Figure 1. This type of separation would lead to an improvement in stiffness and structural strength of the structure along with a small increase of weight [1]. Therefore, sandwich panels are commonly applicable in the areas where high performance as well as low weight are required. Aerospace structures, high-speed submarines and racing cars are among the applications of these structures. The materials used in the skins are usually aluminum and steel with the advantage of low weight. While, polymers, aluminum, wood and composites are usually used in the core. To minimize the weight of these structures, the core can be used in foam or honeycomb forms. The Nomex material studied in this research is widely used in honeycomb cores. As stated, honeycomb composites have higher stiffness and strength; the stiffness of these materials can be predicted easily, however, estimation of their strength is very complex.

Modeling a sandwich plate in the form of a beam was carried out by Allen [2]considering the simplifying assumption of thinner skins compared to the core, as well as the homogeneous core with lower stiffness compared to the skin. Triantafillou and Gibson [3] developed the sandwich failure equations and obtained failure map of sandwich beam with foam core and metal skin under bending load by presenting the relation for computing the required load for different failures. Then, by performing experiments on these beams, they declared the dependency of the failure modes on the dimensions and properties of the beam.

In addition, they extended the optimization procedure of these structures to achieve the optimum values for the thickness of skin and core, so that the desired stiffness and strength are provided with the minimum weight. Birman et al. [4] examined the behavior of the sandwich structure by applying thermal flux to its surface and considering the linear variation for its properties. Additionally, they also studied the mechanical and thermal loadings on a sandwich beam with honeycomb core and multilayered skins.

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Some authors [5-7] have studied the failure modes of sandwich panels with flexible cores. However, their main focus was on panels with brittle cores such as foam, in which an appropriate approximation of the elastic and plastic behavior of these panels can be provided. Investigating the behavior of the skins is usually simpler compared to the foam or honeycomb cores due to the core response to shear loading resulted from the load applied to the skin and the panel surface. This behavior depends on the core material, relative density of core and the ratio of the core density to the density of the stiff materials constituting the core. Zhang and Ashby [8] modeled the elastic behavior of honeycomb material under shear and compressive loadings. Their obtained models were in good agreement with the results of the experiments that they had performed on Nomex honeycombs.

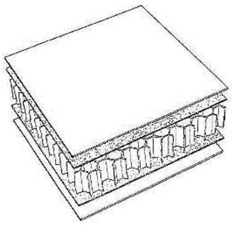

Fig 1. Sandwich panel with stiff skins and honeycomb core [9]

Wang et al. [10] investigated sandwich panels with honeycomb core and ceramic shell through three-point bending experiments. It was shown that a ceramic panel with different loading conditions can have different failure modes. In addition, the mechanical impact of the ceramic material as well as the geometrical dimensions of the honeycomb core was investigated in this study. Sun et al. [11] studied numerically and experimentally the dynamic response and failure modes of honeycomb sandwich panels subjected to high-velocity impact by a spherical steel projectile. Impact tests were performed at speeds of 70 to 170 m / s and its effect on the parameters of shell thickness, core height and cell size was evaluated.

By reviewing the conducted studies, it is found that no study has been performed on the effect of environmental temperature changes on the performance and failure modes of sandwich panels with honeycomb core; so, this paper aims to investigate this issue using numerical simulation. For this purpose, a sandwich panel consisting of a honeycomb core and a brittle skin under three-point loading is investigated.

In the following sections, by reviewing the theory of beam for sandwich panels, the failure mechanisms and associated loads would be defined as a function of the skin thickness to beam span ratio for the sandwich panels of the honeycomb core. After that, four models of sandwich panels with different dimensions and core densities are determined and simulated by ANSYS software under three-point loading conditions. The models are chosen to cover all of the failure modes. Then, the results of simulation at ambient temperature are compared with the theoretical and experimental results of the literature and the validity of the simulation is evaluated. Finally, the effect of temperature change on the failure behavior of the sandwich panel with the honeycomb core is investigated. For this purpose, simulations are carried out at three temperatures of 50, 75, and 100 ° C, and the diagrams of failure load are presented in terms of temperature. The core and skin properties are assumed to be varied with the temperature and applied in the simulations.

2. Sandwich Panels Theory

In this section, the elastic analysis of sandwich beams under three points bending test is investigated. This analysis will be used in determining the stresses values in the skins and core, as well as estimating the failure load. First, a beam with simply supported boundary conditions as depicted in Figure 2, is considered. As it is obvious in this figure, the span of the beam is equal to L with the width of b; in addition, the central load of W is applied to it. The thickness of each skin is equal to t that are separated from each other by a honeycomb core of thickness c.

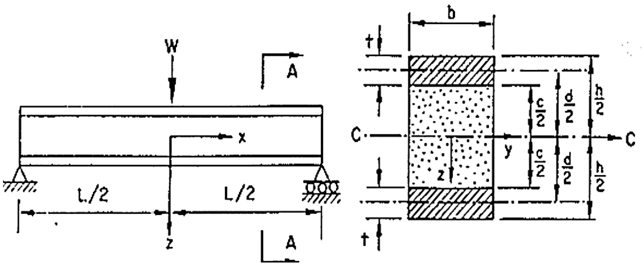

Fig 2. Beam with simply supported boundary condition along with its cross section [7]

The flexural stiffness of skins and core with respect to the central C-C line is calculated as [7]:

$$D = \frac{E_{fx} b t^3}{6} + \frac{E_{fx} b t d^2}{2} + \frac{E_{cx} b c^3}{12} \tag{1}$$

In which, E_{fx} and E_{cx}, are the Young's modulus of skin and core in the axial loading, respectively. Due to the three-point bending, the maximum bending moment occurs in the middle of the beam, which results in the maximum σ_{fx} stress in the skin:

$$\sigma_{fx} = \frac{ME_{fx}}{D}\frac{d}{2} = \frac{WL}{4dt} \quad \textbf{(2)}$$

In the theoretical model expressed in relation (2), the shear deflection of the core is neglected, which becomes important in low-density cores. By considering this effect, it is possible to predict the observed difference in the beam strength for different orientations of the honeycomb ribbon. Therefore, the equation(3) can be rewritten using the method proposed by Allen [2]:

$$\sigma_{fx} = \frac{WbL}{4}(\frac{c+2t}{2I} + \frac{WL}{4}\frac{t}{2I_f}\frac{1}{\theta}) \quad \textbf{(3)}$$

In equation (3), θ and I are expressed as equations (4) and (5), respectively:

$$\theta = \frac{L}{c}[\frac{G_{cxz}}{2E_{fx}}\frac{c}{t}\left(1+\frac{3d^2}{t^2}\right)]^{1/2} \quad \textbf{(4)}$$

$$I = \frac{bt^3}{6} + \frac{btd^2}{2} I_f = \frac{bt^3}{6} \quad \textbf{(5)}$$

In equation (4), G_{cxz} is the out-of-plane shear modulus of the core, I is the second moment of the area for sandwich beam with respect to its neutral axis, and I_f is the second moment of the area for the skins with respect to their censorial neutral axis. Equation (5) shows the dependency of θ to the relative stiffness of the skin to the core. Finally, with respect to the stated equations, the final load can be expressed as (6):

$$W = 4\sigma_{fx}\xi\frac{t}{L} \quad \textbf{(6)}$$

ξ in equation (6) can be obtained from equation (7):

$$\xi = \theta\frac{t^5/9 + t^3\,d^2/3}{ht^3(\theta-1)/3 + t^4/3 + t^2d^2} \quad \textbf{(7)}$$

2.1. Failure Modes of Sandwich Beam with Honeycomb Core

At least five failure modes are likely to occur in sandwich beams under bending load. These failure modes include: a) Face Yielding; b) Face wrinkling; c) Core shear under shear stress; d) Local indentation between core and face; e) Intra-cell dimpling. Face yielding occurs when the maximum normal stress of the face reaches the yielding strength. Similarly, if the maximum normal stress of the face reaches the critical wrinkling stress of face, wrinkling would be observed. Moreover, if the shear stress of the core reaches the core shear strength, the core shear would be occurred [9]. These failure modes are depicted in Figure 3.

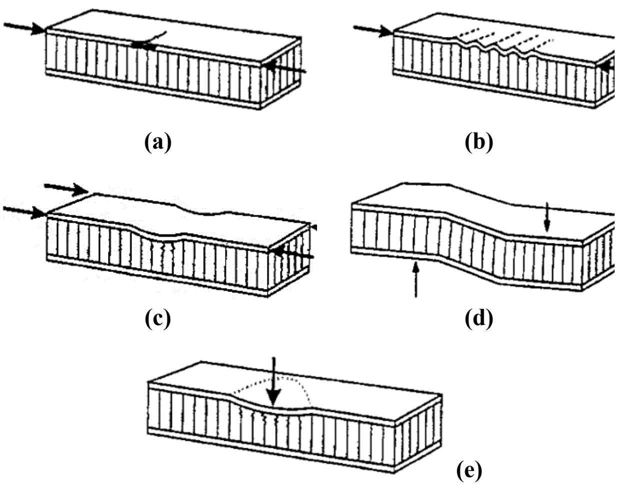

Fig 3. The failure modes of sandwich beam with honeycomb core: a) Face Yielding b) Intra-cell dimpling c) Face wrinkling d) Core shear e) Local indentation [9]

Table 1, describes the determination of the failure modes briefly. In the following sections, these equations are used for theoretical calculations.

Furthermore, in Table 2,the corresponding failure loads in a sandwich beam with a honeycomb core are listed. Based on the mechanic of the honeycomb core[9], if the applied load on the center of the sandwich beam reaches the prescribed limit, the failure mode is occurred.

Table 1: Determination of the failure modes in sandwich beam with honeycomb core [1]

Failure mode	*Face Yielding*	*Intra-cell dimpling*	*Face wrinkling*	*Core shear*	*Local indentation*
Failure stress	$\sigma_{fx} = \sigma_f$	$\sigma_{fy} = \frac{2E_{fx}}{1-\upsilon_{fxy}^2}(\frac{2t}{\alpha})^2$	$\sigma_{fw} = \frac{3}{(12(3-\nu_{cxz})^2(1+\nu_{cxz})^2)^{-1/3}} E_{fx}^{1/3} E_z^{2/3}$	$\tau_{cxz} = \tau$	$\sigma_z = \sigma_{cc}$

Table 2: Failure loads for sandwich beam with honeycomb core [9]

Failure mode	***Face Yielding***	***Intra-cell dimpling***	***Face wrinkling***	***Core shear***	***Local indentation***
Failure Load	$W_0 = 4\sigma_{fy}$	$W_0 = \frac{8}{1-\nu_f^2}(\frac{t}{\alpha})^2 E_f \frac{t}{L}$	$W_0 = 4B_1E_f^{1/3}E_s^{2/3}(\frac{t}{L})(\frac{\rho_c}{\rho_s})^{2/3}$	$W_0 = 2AE_sd(\frac{\rho_c}{\rho_s})$	$W_0 = 3.25\sigma_{fy}^{5/3}$

Table 1: Dimensions and characteristics of the investigated sandwich beams with honeycomb core

Beam index	***Honeycomb cell size***	***Beam width***	***Core thickness***	***Face thickness***	***Beam span***	***density***
A	**3 mm**	**40 mm**	**9.4 mm**	**0.38 mm**	**340 mm**	**128kg/m^3**
B	**3 mm**	**40 mm**	**9.4 mm**	**0.38 mm**	**380 mm**	**48kg/m^3**
C	**3 mm**	**40 mm**	**9.4 mm**	**0.38 mm**	**60 mm**	**128kg/m^3**
D	**3 mm**	**40 mm**	**9.4 mm**	**0.38 mm**	**50 mm**	**29 kg/m^3**

Table 2: Properties of the core and shell of the sandwich panels with honeycomb core [9]

Material	*Nomex*	*Laminated Skin GFRP*
Young's Modulus(GPa)	$E_s = 0.9$	$E_f = 20.5$
Shear Modulus(GPa)	$G_s = 0.32$	$G_f = 4.2$
Strength (MPa)	$\sigma_{sc} = 80$	$\sigma_{fy} = 300$
Poisson's ratio	$\nu_s = 0.4$	$\nu_f = 0.17$
density (mg/m^3)	$\rho_s = 0.724$	

3. Simulation and evaluation of failure modes

3.1. Properties and Geometry of the Model

In the preceding sections, the occurrence conditions of each failure modes in sandwich beam with honeycomb core are described. This section is dedicated to the simulations of these modes and validation of the conducted solution. For this purpose, four beams with the same characteristics except for the length and density of the core are utilized. The models are chosen so that they show different failure modes at 25 ° C. In Table 3, the geometric characteristics along with the associated density of each beam are listed.

The beam is under three points loading with simply supported boundary condition and static load is applied at the center of the beam.

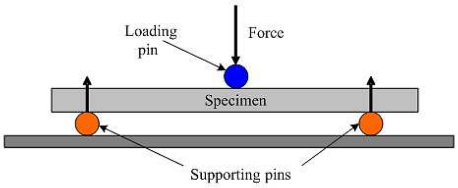

Fig 4 Three-point loading and applied boundary conditions on the studied sandwich panels

As previously stated, the material used in the skin and core are GFRP (Glass Fiber Reinforced Plastic) and Nomex, respectively. In Table 4, the mechanical properties of the face and honeycomb core are provided.

Temperature is an important factor in the design of mechanical structures due to the fact that these systems experience a variety of environmental conditions according to their extended applications. In order to investigate the effect of this important factor on the performance and failure modes of sandwich panels with honeycomb core, we first investigate the variation of material specifications according to the operating temperature. For this purpose, the strength of the two materials of the sandwich panel, GFRP for face and Nomex for the core, are evaluated at various temperatures. Previously, in Table 3, the mechanical properties of GFRP were determined at room temperature. In the following, the Young's modulus and the tensile strength of this material at various temperatures are studied based on existing references. In reference [12], Ou Yet al. examined the mentioned material at six different temperatures, experimentally.

In this study, for investigating the effects of temperature on the failure modes, the characteristics of the material in the four temperatures are evaluated. Accordingly, in Table 5, the Young's modulus of the glass fiber with its yield strength are extracted at four temperatures of 25, 50, 75 and 100 ° C.

In order to study the effects of temperature on the failure modes, the mechanical properties of Nomex® material are also evaluated at four temperatures. Table 6 specifies the Young's modulus of this material along with its yield strength at four temperatures of 25, 50, 75 and 100 degrees Celsius.

Table 3: Mechanical properties of the GFRP at different temperatures [12-13]

Temperature (°C)	*25*	*50*	*75*	*100*
Yield strength (MPa)	**300**	**280**	**255**	**205**
Young's modulus (GPa)	**30.5**	**29.4**	**27.5**	**26.2**

Table 4: Mechanical properties of the Nomex® at different temperatures [15-16]

Temperature (°C)	*25*	*50*	*75*	*100*
Yield strength (MPa)	**80**	**76.9**	**74**	**69.6**
Shear strength (MPa)	**0.96**	**0.91**	**0.89**	**0.84**
Young's modulus (GPa)	**0.9**	**0.81**	**0.72**	**0.65**

4. Modeling and Finite Elements Simulation

In order to model sandwich panels with honeycomb core, a well-known SOLIDWORKS software is utilized, which is a very powerful tool in mechanical science. In the following, the beam would be modeled using the dimensional data of the reference [9] as well as brochures by the honeycomb manufacturer. Figure 5 shows the used dimensions in honeycomb design. HEXEL company is the honeycomb manufacturer and the A1[1] honeycomb is the used for core.

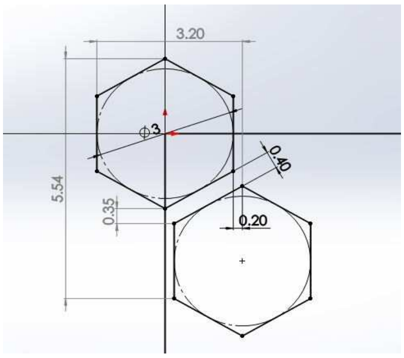

Fig 5. Two-dimensional design of the honey comb with the used dimensions in the modeling [9]

In the following, using the two-dimensional design, a three-dimensional model of honeycomb would be designed considering the panel dimensions used in this study; in addition, the prepared panel for analysis is designed as depicted in Figure 6. Then, simulation of composite beam in ANSYS software would be discussed.

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[1] A1 High Strength Nomex Aramid

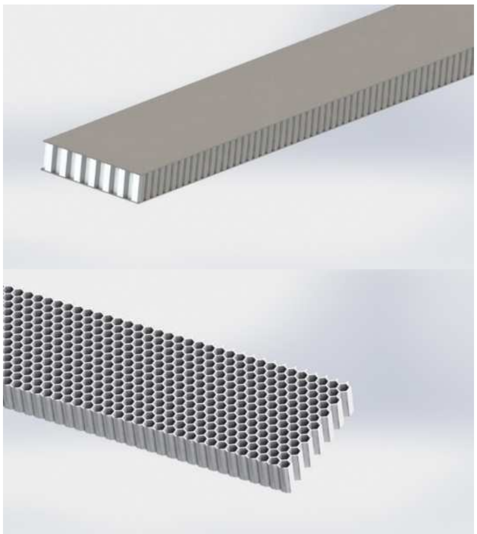

Fig 6. Three-dimensional design of the core and the modeled sandwich beam with honeycomb core

After designing in SOLIDWORKS, the beams were imported into the ANSYS software and the desired boundary conditions are applied. In Fig. 7, the boundary conditions and governing loading on the system were observed. The three-point loading method based on the ASTM C392 standard was used.

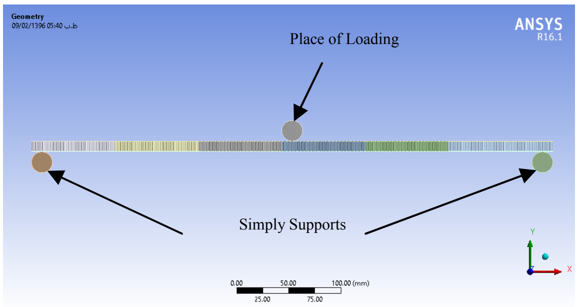

Fig 7. Imposed boundary conditions on sandwich beam with honeycomb core in ANSYS software

For meshing the model, the division technique was used to provide accurate meshing due to the complexity of the honeycomb geometry. Otherwise, the software would not be able to mesh the model due to the thin honeycomb walls, and the controllability of meshing would be reduced significantly. In general, it can be seen that the division of large geometries into several small geometries, in addition to enhance mesh quality, also increases its controllability. Figure 8 illustrates the geometry of the honeycomb core that was prepared for meshing in the ANSYS software and numerical solution.

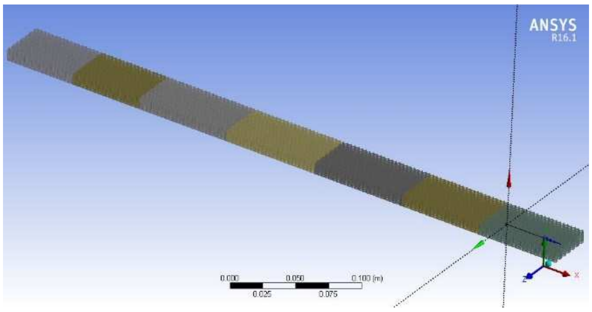

Fig 8. Honeycomb core of the sandwich panel that is divided into smaller volumes

In Figure 9, the created meshing for Finite element analysis of the sandwich panel is presented. The number of elements created in this meshing is equal to 442,000 elements, which can be varied due to the mesh independency for various models used in this research.

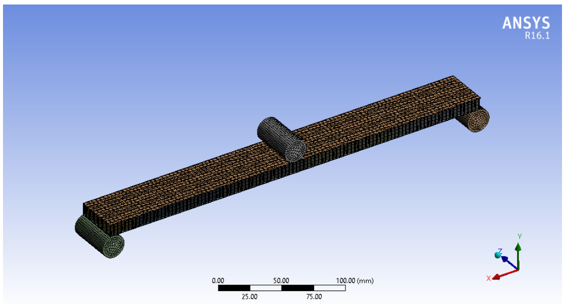

Fig 9. Designed meshing for investigating the failure modes in ANSYS software

The simulation of the sandwich panel behavior with a honeycomb core under a three-point loading is discussed below. The main objective in this section is to validate the simulation performed by ANSYS software. Regarding the above discussion, there are five general failure modes in sandwich panels. In other words, different loading conditions, support, geometry and materials used in composite construction would result in a dominant failure mode in the system.

In the first section, a specific failure mode is evaluated using the dimensions and specification of the panel tested in reference [9] under incremental loading conditions. The aim is to compare the behavior of the panel in a loading cycle. Afterwards, three other models are examined separately for checking the failure load and failure mode and validated for the next use in simulation phase, in which the behavior of the panels under different temperature conditions would be evaluated. Table 7 illustrates the dimensions of this panel for simulation.

Table 5: Dimensions of the first simulated specimen for validation and loading [9]

Honeycomb cell size	*Panel width*	*Core thickness*	*Face thickness*	*Panel span*
3 mm	40 mm	9.4 mm	0.34 mm	340 mm

After applying the boundary conditions and the desired loads, the simulation was performed. Figure 10 shows the deformation of the beam subjected to 36.3 kN/m loading. As seen in the figure, the maximum deflection in the beam is equal to 5.42 mm.

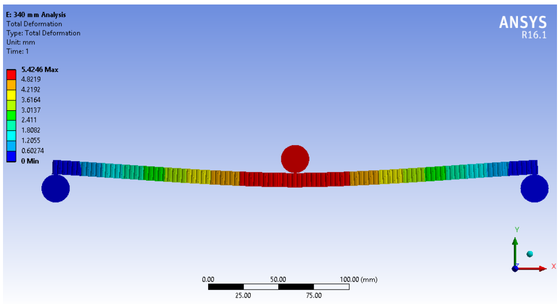

Fig 10. Transversal deformation of the composite beam subjected to the load of 3.36 kN/m

Moreover, in Figure 11, the Von Mises stress generated in the sandwich panels is depicted; as can be seen, the maximum value of 105 MPa is occurred in the face. This stress value would lead to face wrinkling that is in agreement with reference [9].

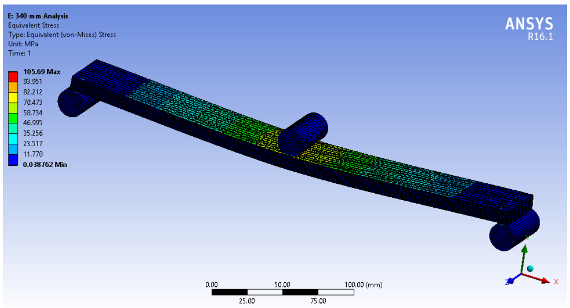

Fig 11. Von Mises stress in the panel with the maximum value in the face

In order to verify the validity of the performed modeling in ANSYS software, simulations were conducted for different loads and a comparison is provided between simulation and experimental results. Figure 12 illustrates this comparison; as shown in this figure, there is a good match between experimental results and performed simulations, which indicates the accuracy of the simulation. The insignificant error can be attributed to the lack of accurate information on the attachment of core to the face as well as the cutting procedure of Nomex. However, despite the mentioned issues, the error is negligible and can be ignored.

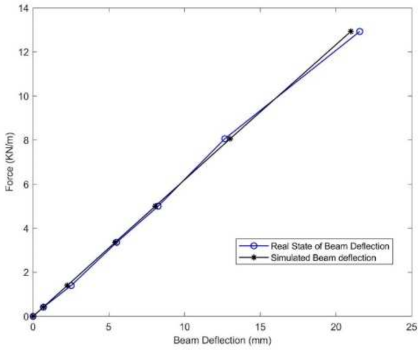

Fig 12. Comparison of the theoretical and experimental results of a sandwich panel with honeycomb core

The simulation in ANSYS software were performed after applying boundary conditions and existing loadings. In order to investigate the failure modes in the modeled sandwich beams, a certain limit was determined for load and the load was increased from minimum to maximum and the failure results were compared.

5. Results

5.1. Results Validation

In order to verify the accuracy of the simulation results discussed in this study, the obtained results for the ambient temperature, including the failure mode and the associated load were compared with the theoretical results of Table 2 and experimental results of reference [9] and the results are provided in Table 8.

This comparison is performed for failure mode and failure load. As can be seen in the table, simulation has been able to predict the failure mode and failure load, and a very good fit between these results and theoretical and laboratory results are seen.

Table 6: Comparison of the obtained results from the simulation in ANSYS software with the theoretical and experimental results

Beam index	***Failure mode comparison***			***Failure load comparison***		
	Simulation failure mode	**Theoretical failure mode [9]**	**Experimental failure mode [9]**	**Simulation failure load**	**Theoretical failure load [9]**	**Experimental failure load [9]**
A	**Face Yielding**	**Face Yielding**	**Face Yielding**	**13.9 kN/m**	**13.6kN/m**	**14.7 kN/m**
B	**Face Wrinkling**	**Face Wrinkling**	**Face Wrinkling**	**6.52kN/m**	**6.21kN/m**	**6.1kN/m**
C	**Core Crushing**	**Core Crushing**	**Core Crushing**	**48.5kN/m**	**42.3kN/m**	**44.4kN/m**
D	**Core Crushing**	**Core Crushing**	**Core Crushing**	**6.87kN/m**	**6.87kN/m**	**6.87kN/m**

5.2. Investigation of the Effect of Temperature Changes

After validating the results and simulations at ambient temperature, this section examines the effects of changes in ambient temperature on the failure load and failure modes of the sandwich panel with the honeycomb core. Four temperatures of 25, 50, 75 and 100 ° C was considered for ambient temperature. In order to investigate these effects in the ANSYS software, the specifications of the material were changed and the simulation was performed again. After each loading, the failure criteria were examined and compared. If any of these five failure modes were observed, the failure load was recorded for comparison.

In the following diagrams, the variations of the failure load and the deflection in terms of temperature are plotted for A to D beams. The failure mode of beam A is face yielding, which is not changed with the temperature variation and the temperature has not changed. The variations of the failure load and deflection at different temperatures are presented in Figures 13 and 14, respectively. As shown in Fig. 13, the failure load is decreased with increasing temperature, which may be attributed to the reduction of material strength in high temperatures. About 18% increase in beam deflection is also observed in Figure 14 with increasing temperature.

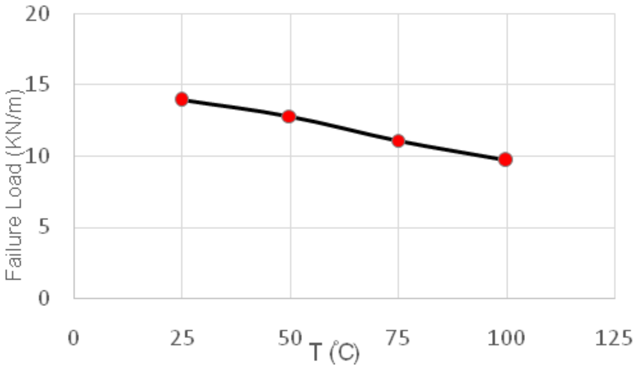

Fig 13. Variation of failure load in different temperatures for sandwich Panel A

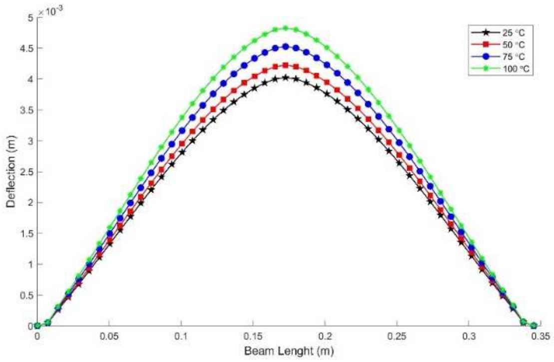

Fig 14. Beam deflection for different temperatures for sandwich Panel A

The failure mode of the second model sandwich panel at ambient temperature was, face wrinkling. This mode is actually a buckling mode in which the buckling wavelength is larger than the width of the honeycomb cells.

Similar to the previous case, simulations were carried out for different loads at different temperatures. The results indicate that at all temperatures used in this study, the failure mode of second panel is not changed. The failure load and deflection of the second beam at different temperatures are plotted in Figures 15 and 16, respectively. According to this figure, decreasing trend of failure load can be observed with increasing temperature. Figure 16 shows the beam deflection, which increases about 35% with increasing temperature.

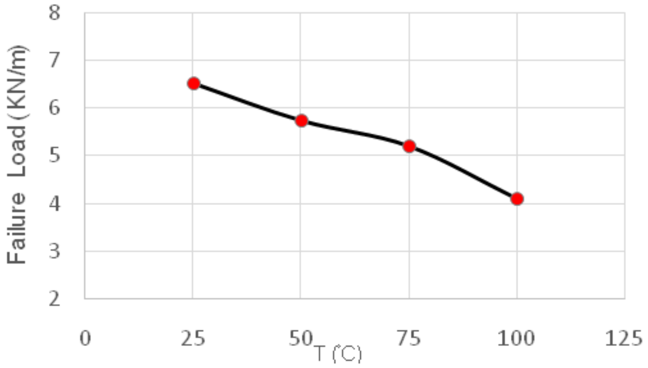

Fig 15. Variation of the failure load at different temperatures for the sandwich panel B

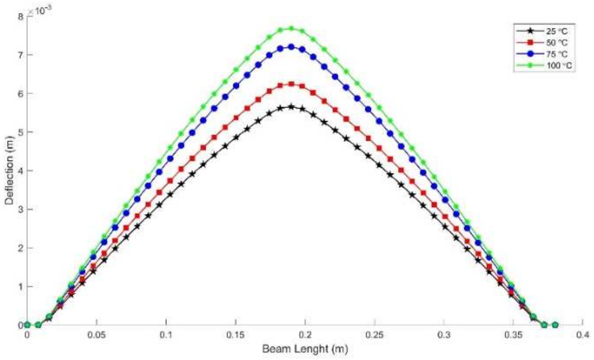

Fig 16. Variation of beam deflection at different temperatures for the sandwich Panel B

Local indentation failure mode was observed for the third panel examined in this study. This failure mode occurs due to the crush and tear of the composite core.

According to the performed simulation, it is found that similar to the previous cases, the failure mode remains unchanged for different loads at different temperatures. Figures 17 and 18 show the variations of failure load and deflection at various temperatures. Regarding figure 17, as depicted in previous figures, the decreasing trend of the failure load with temperature increase can be concluded; however, the variation slope is much higher in this case. Figure 18 emphasizes the insignificant effect of temperature variation on the beam deflection.

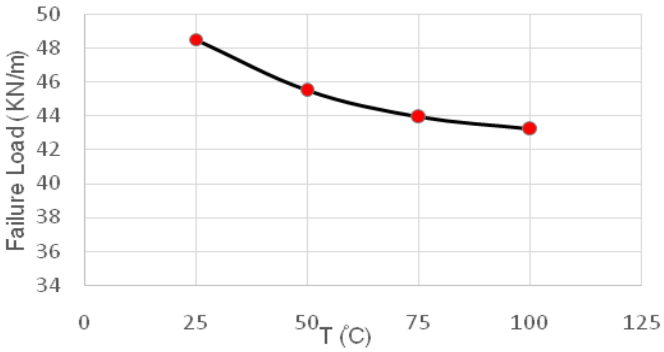

Fig 17. Variation of the failure load at different temperatures for the sandwich panel C

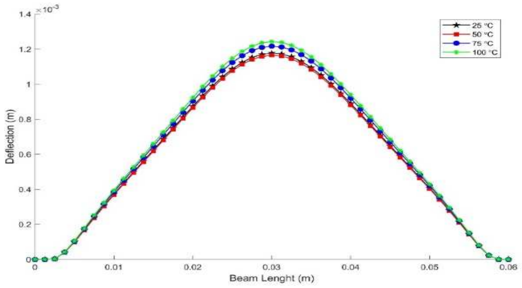

Fig 18. variation of beam deflection at different temperatures for the sandwich panel C

Finally, the failure mode of the fourth sandwich panel, which was Local indentation, similar to the third case was investigated. As stated, this failure mode occurs on the honeycomb core due to crunching and tearing.

According to the performed simulation for different loads and different temperatures, core shear was observed as the failure mode of fourth panel. Figures 19 and 20 show variations of failure load at various temperatures. Just like previous diagrams, the failure load is reduced by increasing temperature. In Figure 18, again the insignificant increasing effect of temperature on the deflection is observed.

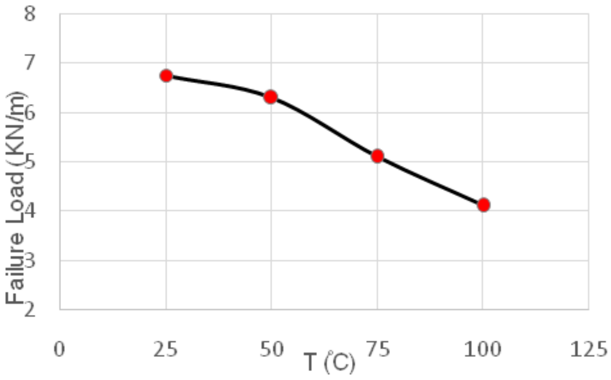

Fig 19. Variation of the failure load at different temperatures for the sandwich panel D

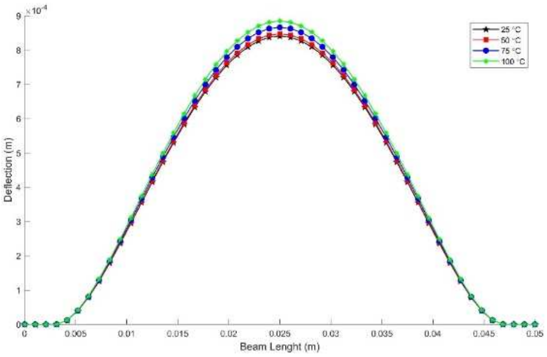

Fig 20.Variation of beam deflection at different temperatures for the sandwich panel D

6. Conclusion

In this paper, failure load and failure mode of four sandwich panels with honeycomb core were studied at three temperatures higher than room temperature in order to investigate the effect of temperature change on the failure behavior of these structures. The core and face of the sandwich panels were made of Nomex and GFRP, respectively. The investigations were conducted by the help of ANSYS software. The effect of temperature change on the failure behavior and deflection of simulated sandwich panels was evaluated.

According to the obtained results of the failure modes at different temperatures, the independency of these modes on environmental temperature changes was concluded. In addition, it was observed that the beam deflection is directly related to the beam length and increases by increasing the beam length. Moreover, it was found that the failure load is decreased with increasing temperature as a function of beam aspect ratio. Increasing the temperature in general, reduces the ultimate strength as well as the modulus of elasticity in the shell and core, which greatly reduces the failure load of all particular failure modes.

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