Numerical and Experimental Analysis of Sandwich Structures

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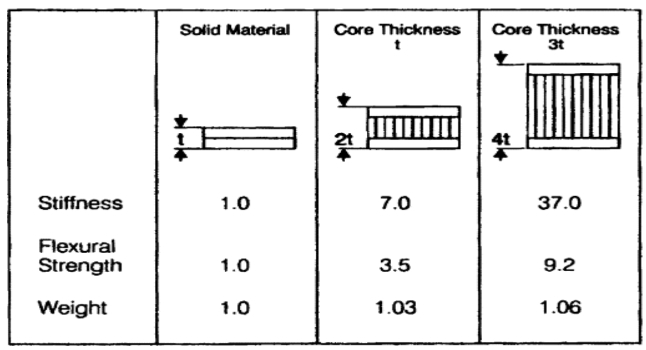
***Abstract** The unique characteristics and properties offered by the sandwich structures system provide a huge potential in various fields. Such uniqueness can be comprised in the relatively low weight to stiffness ratio compared with different kind of structures. Such superiority have increased its application within several industries including aerospace and naval industries, however, its application is still limited within the context of structural engineering. This paper aims to explore the performance of polyethylene terephthalate (PET) foam core sandwich panels and assess its applicability within the structural applications as structural beams and slabs. This paper experimentally and numerically investigate the performance of PET sandwich panels and propose a failure map for the PET sandwich panels to be used later to predict the failure mode of a given PET sandwich panel. The presented research lays the foundation for further implementation of PET sandwich panels in the field of structural applications such as cladding panels.*

I. INTRODUCTION

Sandwich panel structures are currently used within various many industrial fields. However, the applications of sandwich panels in the civil engineering field are limited. Sandwich panels consists of two fibers or sheets called the sandwich's top face and bottom face, characterized by high stiffness, separated by the core, which is the other component of the sandwich panel, as the core is characterized by its's lightweight and larger thickness [1]. The faces of the sandwich are typically formed of metals such as the aluminum or a fiber composite material, and the sandwich's core it typically formed of cellular material such as the honeycomb core or foam material (as the foam material could be formed from various types of materials such as the aluminum foam) [2]. The sandwich panel structures are similar to I-beams, as the flanges are the faces and the foam resembles the web). By increasing the foam thickness, the moment of inertia of the panel increases, however, the core is characterized by its light density which consequently does not increase the weight of the whole panels. As such, sandwich panels are generally characterized by stiffness to weight ratio compared to solid structures as demonstrated in Fig. 1. On the side, the core, which resembles the web of I-section is one of most influencing factors in the sandwich shear resistance.

Due to the mentioned features of the sandwich panels, they are a perfect choice to resist the bending stresses which can be evident in flexural members such as beams and slabs. Moreover, the different types of cores provide different characteristics to the sandwich panels such as the honeycomb core which is lighter in weight and provide a higher stiffness than the foam core types, and the foam cores types are preferred when thermal insulation is required along with a decent stiffness. Furthermore, the whole sandwich panel's mechanical properties count on several factors such as each of the component's material, stiffness, and geometry (the face, the core) as well as the panel's geometry. The ultimate goal in using sandwich panels is to provide the required stiffness with the least weight (highest stiffness-to-weight ratio).



	Solid Material	Core Thickness t	Core Thickness 3t
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Fig. 1: stiffness to weight ratio [4]

II. LITERATURE REVIEW

One of the most pioneering work on the investigation of the sandwich panel performance was that presented by T.C. Triantafillou and L. J. Gibson [5]. They concluded that, for the face yielding – face wrinkling, and core shear, the equations of the failure adequately reflect the load at failure, as for the sandwich composite structures built of a plastically yielding face as well as the core materials. Furthermore, based on the assumption that the normal stresses in the core are minor and could be neglected in comparison to the shearing stresses in the core, due to a simpler procedure for illustrating the failure mode map has been proposed. Moreover, they tested several sandwich beams, where they observed a debonding failure. On the other hand, the other shapes of sandwich beam failures appear in fractured materials. Furthermore, a failure map was proposed to predict mode of failure for each potential beam using its geometry, physical, and mechanical properties along with the loading configuration. Furthermore, in the case of

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determining the proper failure mode, the failure mode maps can be critical for the sandwich panels with a strength limitation.

Furthermore, numerical, theoretical, and experimental studies have been conducted on sandwich beams with Polyurethane (PU) foam core and glass fiber faces in a joint effort of Ahmed Mostafa, Krishna Shankar, and E. V. Morozov [6]. As they concluded that the load-deformation curve resulting from the experimental tests exhibited initially linear elastic behavior of the sandwich beam besides a reduction in the slope before the breakage. Moreover, the core shear failure was the failure mode of the sandwich structure accompanied by the skin debonding from the core within the shear zone. Furthermore, the anticipated failure load using the theoretical model of analysis was quite well, but the correlation of the nonlinear behavior was not achieved decently. Moreover, their finite element (FE) predictions showed reliable results compared with their experimental program as well. It worth nothing to mention that their developed FE model accounted for the bonding material between the core and the faces.

Furthermore, an experimental and numerical study has been done on sandwich beams with E-glass/Epoxy faces and Polyvinyl chloride (PVC) foam core as a joint effort by Tae Seong Lim, Change Sup Lee, and Dai Gil Lee [7], the efforts of the study concluded that the mechanisms of the foam's statically failure of the sandwich beams were explored using a numerical analysis and experimental as well, as the analysis approach of the study., moreover, their numerical investigation showed a good agreement with the experimental observations specially in predicting the ultimate capacity of the tested beams.

Furthermore, Azmi and Abdullah conducted a study to investigate the effect of using coconut coir fiber to reinforce the PU foam core on the performance of sandwich panels [8]. The study showed an enhanced performance for the tested panels. The reinforced panels showed superior performance in terms of resisting and preventing the buckling of the sandwich beam.

III. EXPERIMENTAL

A. SPECIMENS DATA AND TESTING

The experimental phase of this study was performed on six foam core sandwich beam samples tested under a quasi-static through a three-point bending mechanism. The sandwich panels composed of PET foam core sandwich beams with E-glass/epoxy faces. The experimental tests were performed at room temperature with a constant loading rate of 2 mm/min. The tested specimens were named "T20" as in that the thickness of the sandwich's face is 4 mm and the core thickness is 20 mm. Vertical stiffeners are placed in equal spacing of 31mm, where the thickness of the stiffeners was 1 mm as shown in Fig (2). Furthermore, Fig. 3 incorporated with Table 1 the dimensions tested specimens, whereas Table 2 summarizes the material properties of the tested specimens.

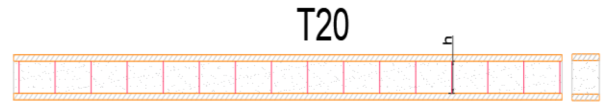

Fig. 2: Specimen (T20) geometry

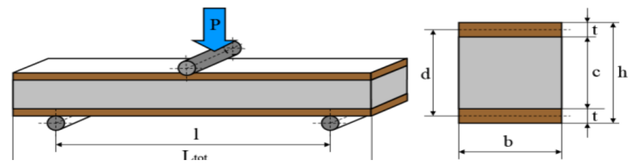

Fig. 3: 3PB samples placing [9]

Table 1: Specimens properties 1

No.	Geometrical parameters				Vl Stiffeners		
	l (mm)	t (mm)	b (mm)	c (mm)	No.	h(mm)	b(mm)
T20	420	4	25	20	16	20	25

Table 2: Specimens properties 2

No.	Sandwich beam		Density (kg/m^3)		Young's modulus (Mpa)		Yield strength (Mpa)	Weight (g)
	Face	Core	ρf	ρc	Ef	Es	σyf	
T20-1	E-glass/epoxy	PET Foam	1848	134	42000	2700	867	198
T20-2								193
T20-3								195
T20-4								196
T20-5								198.8
T20-6								197.3

B. EXPERIMENTAL RESULTS

All the specimens were failed in shear (core shear failure) as shown in Fig. 4. Also all the specimens showed a linear performance till failure. Table 3 summarizes the ultimate load and deflection for the tested beams. It worth mentioning that the difference at the ultimate load is backed to the uncertainties associated with the specimen's construction as it was noticed that T20-1 had some minor flaws at the core and at the interface between the core and the faces. Moreover, Fig (5) shows the load-displacement curve of the tested beams acquired from the performed experimental testing.

Table 3: Experimental Failure loads

No.	Failure Load (N) F(exp)	Deflection (mm)	Failure mode
T20-1	1475	12.15	Core shear
T20-2	1210	10.86	
T20-3	1335	10.5	
T20-4	1635	13.6	
T20-5	1635	16	
T20-6	1385	10.3	

Fig. 4: the core shear failure on T20

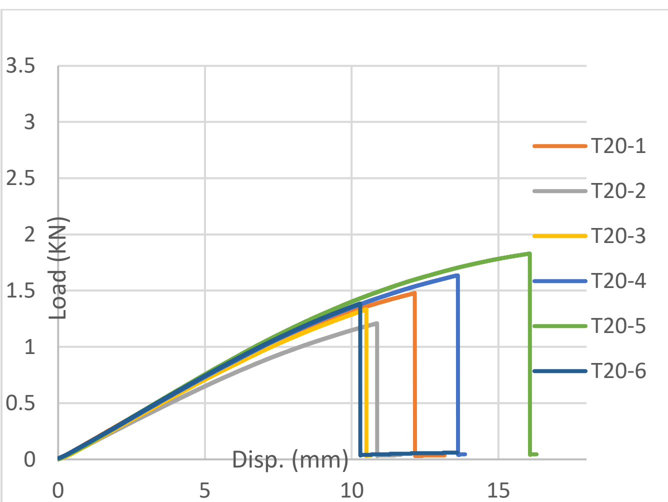

Fig. 5: Load- Disp. graphs of T20

IV. Numerical Analysis

A. Failure Modes

The failure of the sandwich beams could take several shapes, as each shape or mode of failure imposes a limit on the capacity of the beam compositions. Moreover, the different failure modes become crucial depending on the sandwich beam's loading configurations and the physical geometry, adding also the determination of the sandwich structure's limitations. Furthermore, the essential failure shapes which could take place on sandwich beams have already been addressed previously but their impact cannot be overstated. Moreover, the real question is the method or the procedure undertaken to determine the impact or the effect of choosing a specific material for the sandwich beam with a specific geometry, and the failure mode of the sandwich beams could vary depending on that combination [9]. As the general idea is by equating two of the failure shapes equations as two different types of failure could happen in the same load, as the result of that establishing a transition between two different failure shapes, the equations for the main failure modes in the sandwich beams are [5]:

Failure mode: face yielding

$$P = C1 * b * c(\tfrac{t}{l})\sigma yf \qquad \text{(EQN.1)}$$

Failure mode: face wrinkling

$$P = 0.57C1 * C3^{\frac{2}{3}} * b * c\left(\frac{t}{l}\right)Ef^{\frac{1}{3}} * Es^{\frac{2}{3}} * \left(\frac{\rho c}{\rho s}\right)^{\frac{2A}{3}} \qquad \text{(EQN.2)}$$

Failure mode: core shear

$$P = C2 * C4 * b * c * \sigma ys\left(\frac{\rho c}{\rho s}\right)^{B} \qquad \text{(EQN.3)}$$

B. Failure Modes Map

By equating the face wrinkling (EQN.2) and face yielding (EQN.1) failure mode equations we get the first line of the transitional equations as a function of the relative density of the core of the sandwich:

$$\left(\frac{\rho c}{\rho s}\right) = \left(\frac{\sigma yf}{0.57C3^{\frac{2}{3}} * Ef^{\frac{1}{3}} * Es^{\frac{2}{3}}}\right)^{\frac{3}{2A}} \qquad \text{(TEQN.1)}$$

Moreover, the second transitional equation is formed by equating the face yield failure mode (EQN.1) and the core shear failure mode (EQN.3) to get the second transitional equation:

$$\frac{t}{l} = \frac{C2 * C4}{C1}\left(\frac{\rho c}{\rho s}\right)^{B} * \left(\frac{\sigma ys}{\sigma yf}\right) \qquad \text{(TEQN.2)}$$

Finally, the third transitional equation is formed by equating the face wrinkling failure mode (EQN.2) with core shear failure mode (EQN.3) to get the last equation [5]:

$$\frac{t}{l} = \frac{C2 * C4}{0.57 * C1 * C3^{\frac{2}{3}}}\left(\frac{\rho c}{\rho s}\right)^{B-2A/3} * \left(\frac{\sigma ys}{Ef^{\frac{1}{3}} * Es^{\frac{2}{3}}}\right) \qquad \text{(TEQN.3)}$$

Furthermore, for a three-point bending sandwich beams the ratio of the sandwich beam's face thickness to the loading span usually ranges from $1 * 10^{-4}$ to 0.1, and the ratio of the relative density of the core of the sandwich usually ranges from $1 * 10^{-3}$

to 1. Moreover, many failure modes could take place on the sandwich beam, but the dominant failure modes are (face yielding, face wrinkling, and core shear). Moreover, the relative density of the core represents the vertical axis and t/l *represents* the horizontal axis, hence for the low values of the thickness per span the face of the sandwich beam fail by wrinkling as the buckling is high and can't be resisted by the face. On the other hand, when that value is high the face can resist the buckling, and the failure transfer to the core as a core shear failure [10]. Moreover, when the chosen foam core material has w high density, and the relative density value is high, the failure occurs in the face as face yielding failure [11].

The face yielding – face wrinkling transitional equations are plotted as a horizontal contour on the failure map, the face yielding – core shear is plotted as an inclined contour on the failure map, and the last contour on the failure map is constructed on the failure map using face wrinkling – core shear transitional equation as it plotted as an inclined contour as well. The slopes of the inclined contours as determined on the typical sandwich beams by experiments, and the angle of the face yielding – core shear contour is almost equal to 33 degrees, and the angle of the face wrinkling – core shear contour is almost equal to 70 degrees. Moreover, the values are determined using an experimental methods as the angles of both contour lines are depending on the relation between the core properties and the core density, as shown in Fig (6) [5].

Using the typical method and the transitional equations mentioned previously, we can construct the failure map for our sandwich beams.

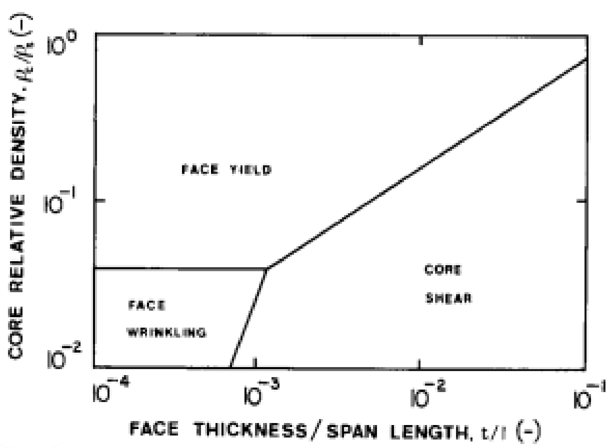

Fig. 6: typical failure map [5]

Furthermore, if the relationship between the core properties and the core density is assumed to be a linear relation the angel of the transitional contours will have new values, the face yield - core shear contour will have an angel equal to 45 degrees, and the face wrinkling – core shear contour line will have an angel equal to 72 degrees, as the two methods give close values but different, and as the contour lines will be used in designing it would be critical to avoid the uncertainty, due to that a modification on the failure map is proposed to avoid such uncertainty, by constructing an envelope as a limit for the face yield – core shear contour and for the face wrinkling – core shear contour, the range or the envelope will be limited to the typical practical failure map and the map constructed under the assumption that the relation between the core properties and core density is linear relation, as shown in Fig (7) [12].

Furthermore, using both methods to illustrate a new map with a larger range between the failure modes could be useful in the designing phase to choose the required failure mode with higher certainty by avoiding the envelope between the transitions of the modes, as shown in Fig (8).

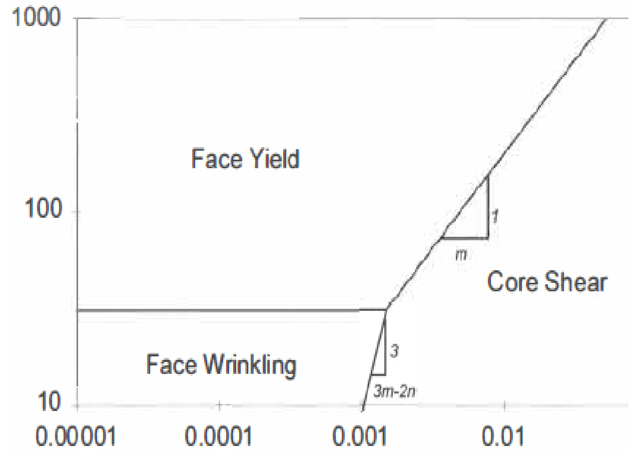

Fig. 7: Dan Zenkret's failure map [12]

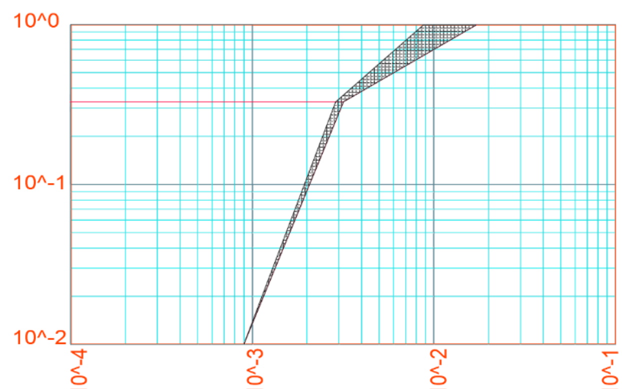

Fig. 8: proposed developed failure map

V. VERIFICATION OF NUMERICAL MODEL

A. THE LOAD-DISP. CURVES

Fig. 9 demonstrates the measured load-displacement curves of the experimental program as well as the numerical one. The analytical model had an average deviation of 12% from the experimental program. Fig. 1 shows a good agreement between the observed and calculated stiffness and capacity. Furthermore, the comparison between the failure loads from the experimental results and numerical results was as shown in Table 4:

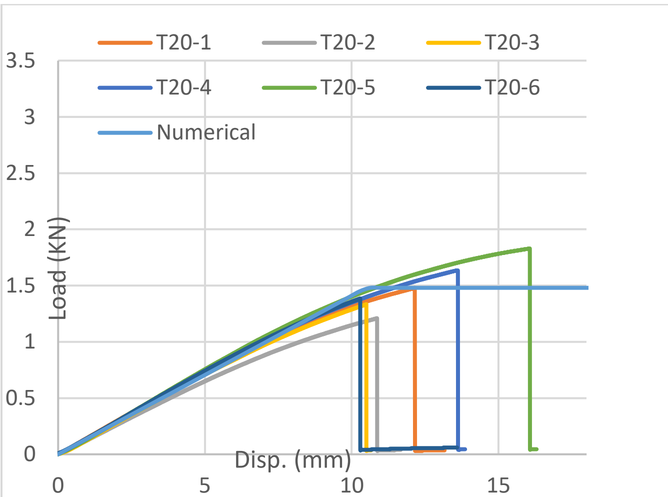

Fig. 9: Verification for the numerical model

Table 4: Comparison between Experimental. & Numerical

No.	Failure Load (N)		%error
	F(exp)	F(numerical)	
T20-1	1475	1480.243	0.35
T20-2	1210	1480.243	18.26
T20-3	1335	1480.243	9.81
T20-4	1635	1480.243	-10.45
T20-5	1830	1480.243	-23.63
T20-6	1385	1480.243	6.43

Likewise, a failure map was developed to graphically represent the predicted failure mode of the sandwich beam by illustrating the boundaries between the various failure modes. Furthermore, the failure maps show the relative density of the sandwich's foam core (ρc/ρs) on the vertical axis and the face thickness of the sandwich / the span of the sandwich beam (t/l). Moreover, the corresponding values for the tested sandwich beam specimens were represented as distinct points, taking into account the span of the sandwich beam and the geometry of each sandwich beam. The failure map for the tested sandwich beams with the variable geometry and characteristics subjected to the three points bending loading is illustrated previously and applied to the tested sandwich beam in Fig (10).

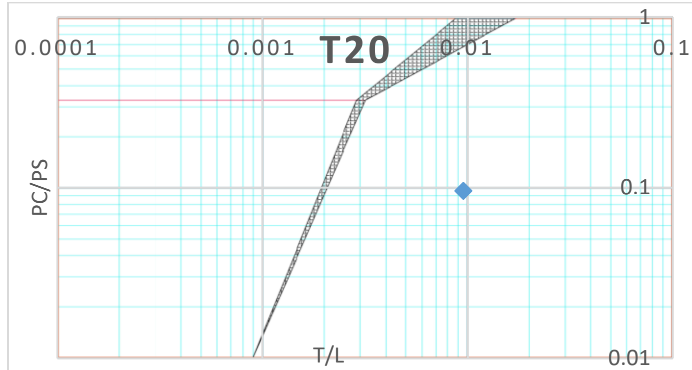

Fig. 10: Failure mode map for the tested sandwich

CONCLUSION

This study presented an experimental and numerical investigation for PET foam core sandwich beams tested under quasi-static loading in a three-point bending scheme. Several conclusions were inferred out of this study such as:

- The tested PET foam core sandwich beams with E-glass/epoxy faces showed a linear performance till failure.
- A new failure map has been proposed accounting for different failure modes. The proposed failure map was based on failure spectrums rather than explicit failure boundary.
- The numerical and experimental model was in quite good agreement, with an average deviation of 12%. However, to increase the reliability of the numerical model, the interference bond between the core and the faces should be considered.

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