FAILURE MODE MAPS OF NATURAL AND SYNTHETIC FIBER REINFORCED COMPOSITE SANDWICH PANELS.

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Abstract
Based on theoretical approaches, a map predicting the failure mechanism of sandwich panels for a given material combination and beam geometry in three point bending can be constructed. In this work, failure maps for sandwich panels are presented for different face sheet / core combinations were studied. The cores used were a commercially available foam core(PVC foam) and a manufactured jute fiber reinforced honeycombs, while the skins were glass and jute fiber / polyester composites. Core and skin failure mechanisms as core shear, indentation, skin yield, debonding and skin wrinkling were included into the models.
The aim of this work was not only to develop alternatives to traditional cores. The investigation of the mechanical properties, manufacturing process and prediction of failure modes for flexural solicitations were also discussed.

1. Introduction

Sandwich panels are widely used as a means to build high-performance lightweight structures.
The weight reduction can be used to increase the payload, to increase the speed or just to reduce the energy consumption with maintained loading capability and top speed. [1]
The increasing requirement for bigger, faster and lighter vehicles has increased the importance of efficient structural arrangements, making sandwich constructions a well-established technique in lightweight component design. [2]
The separation of two thin skin layers by a lightweight core leads to an outstanding weight-specific bending stiffness compared to monolithic structures [3]. Therefore, this construction principle has increasingly been adopted in the last decades in numerous aircraft, train and space vehicles.
According to Allen [4] an efficient sandwich is obtained when the weight of the core is roughly equal to the combined weight of the faces.
Sandwich panels are used not only because of their advantages in terms of weight saving and structural performance, but also as an effective means to reduce costs [5]. Thus, design and development of new materials for low-cost high-performance cores have always been on the focus of manufacturers and applied industries as automotive, aerospace and transport.
At the same time, there is also an increasing interest to substitute glass and carbon fibers by natural ones [6] as well as replacing the traditional cores such as pvc foams, Nomex and aluminum honeycombs. Natural fibers present some advantages when compared to their synthetic counterparts: they are cheaper, they have lower mass per unit area, they are eco-friendly, recyclable and biodegradable by nature, they do not produce skin irritation, and they provide good acoustic-insulating properties.

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In a previous work novel honeycomb cores made of a natural-fiber reinforced composite were manufactured by lateral compression molding [7]. The composite consisted of a thermoset-polymer (vinylester) reinforced with jute fabrics.
This work has followed the research of Triantafillou [8] and Petras [9] for foam-core and honeycomb-core sandwich panels respectively. Failure maps were developed for sandwich panels comprising fiber reinforced composite skins and honeycombs, and commercial foam cores.
Also, the operating failure mechanisms were observed, discussed and correlated to the predictions given by the failure map. The aim of this work is not only to develop alternatives to traditional cores. The investigation of the mechanical properties, manufacturing process and prediction of failure modes for flexural solicitations will be also discussed.

2. Materials and methods

2.1. Theoretical background

Different failure modes of sandwich structures will be considered for the failure map construction. In this work the following failure modes will be considered:

Core Failure:

- Core shear

Shear loading in low stiffness cores is an important problem. If perfect contact between the skin and core is assumed, the weakest component of the structure will be the first to fail under shear [10]. Typically the skins are much stiffer and thinner than the core, so the shear failure stress can be as assumed to be the shear strength of the core.

- Indentation

Frequent cause of damage in sandwich panels involves the indentation of the core due to compressive local loading. It should be noted that such damages may cause a serious reduction in load-bearing capability even if they usually cannot be observed from outside the sandwich construction [11].

Face Failure:

- Skin Yield

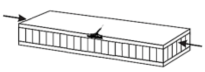
Skin yielding occurs when the tensile loaded side reaches the failure load of the composite skin.

- Face Wrinkling:

The wrinkling of the facesheet can be viewed as the buckling of a beam in axial compression (the face sheet) supported by the core [12]. This elastic instability involves wavelengths greater than the cell size. Depending on the relation of the bonding strength to the compressive strength of the core the wrinkling can occurs inwards or outwards.

Bonding Failure:
The debonding between the core and the skins was also considered. A very basic approach suggests that debonding occurs when the shear stress on the bonded surface of the core exceeds the bond adhesion strength. The shear stress multiplication at a face-sheet-to-core has a direct relation with the ratio of bonded area to the total cell area.
All the considered failure modes are resumed in Table 1

Table 1: Considered failure modes

Failure type	Stress formulation	Visual identification
Skin yield	$W_0 = 4\sigma_{fY}\frac{t}{L}\xi$	

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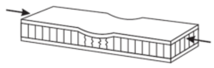
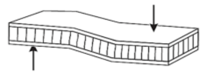
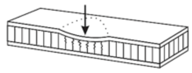
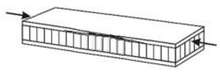
Face Wrinkling	$W_0 = 4B_1 E_f^{1/3} E_s^{2/3} \left(\frac{t}{L}\right)\left(\frac{\rho_c}{\rho_s}\right)^{2/3}\xi$	
Core Shear	$W_0 = 2AE_s d \left(\frac{\rho_c}{\rho_s}\right)^3$	
Indentation	$W_0 = 3.25\sigma_{sc}\left(\frac{\rho_c}{\rho_s}\right)^{5/3}\delta$	
Bonding Failure	$W_0 = \tau_{int}\frac{\rho_c}{\rho_s}\frac{h^3}{3t(h-t)}$	

2.2. Skins and sandwich panel manufacture.

Fiber reinforced honeycomb cores were obtained by Vacuum Assisted Resin Transfer Infusion (VARI). The mold dimensions were 300 mm in length (ribbon direction), 300 mm in width and 12 mm in height, and it contained a 21×16 array of 12-mm (cell size) hexagonal inserts. The clearance between the inserts, and thus the honeycomb wall thickness, was t= 1 ± 0.10 mm.
To prepare the fiber-reinforced honeycombs, strips of bidirectional jute woven fabric were cut and placed between the inserts following a zigzag pattern in the ribbon direction as shown in Figure 2. In order to facilitate the placement of the reinforcement and its uniform distribution along the walls, the fabrics were put in place at the same time the inserts were fixed to the bottom plate. The walls and the inserts with the shape of the cells were kept in place by screwing them to the bottom plate.
A general purpose polyester resin was infused into the mold at 20°C. The wall thickness resulted in t=1.06 ± 0.198 mm. Skins of bidirectional glass fiber and jute fabrics were obtained by VARI with an average thickness of 1.94 ± 0.056 mm. The same polimeric matrix was used
In addition, a commercial pvc foam core (Divinycell™ H130) was used for comparison purposes.
The cores and the skins were bonded together using the same polyester resin and a heated hydraulic press that allowed applying pressure during the bonding stage. In addition, since the skins and cores were not fully cured, the heated press was used for a post curing stage of all the components comprising the panels altogether with the resin used as a glue. This method enhanced the bonding characteristics since polymerization occurred between skins and cores.

2.3 Failure map construction

Several factors affect the failure load and failure mechanisms of the sandwich panels as shown in Section 2.1. The type of failure depends on properties of the skin and core solid material such as the relative density of the core, the thicknesses of the skin and the core, and the beam span L. Following the work of Petras et al [9], predictive failure maps for the manufactured panels based on analytical parameters are provided.
These maps were developed as a function of the non-dimensional geometrical parameters of density of core and density of monolithic material (ρc/ρs) and thickness and span of sandwich beam (t/L) the boundaries of failure modes were obtained by equating the critical loads for different failure modes.
It is important to note that the failure map mode does not give information about the failure load of the component. It shows the most possible failure mode, which is the mode that reaches its critical load first.
The failure map of natural fiber cores with natural fiber reinforced skins is shown in **Figure 1**, where five zones corresponding to each failure mode proposed can be observed. For lower densities, (low ρc/ρs ratio) the possible failure modes are core shear and face wrinkling, depending on the test span. For longer support spans, the failure mode will be associated to wrinkling of the skins. It can be taken as the buckling of the face sheet in axial compression supported by the lower density and more elastic core. For smaller spans, the shear stress becomes dominant and the sandwich panel fails by core shear

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even for more compact cores. For cores in the range of ρc/ρs = 0.01 and over, failure by face yielding is the dominant mechanism for a wide range of spans.

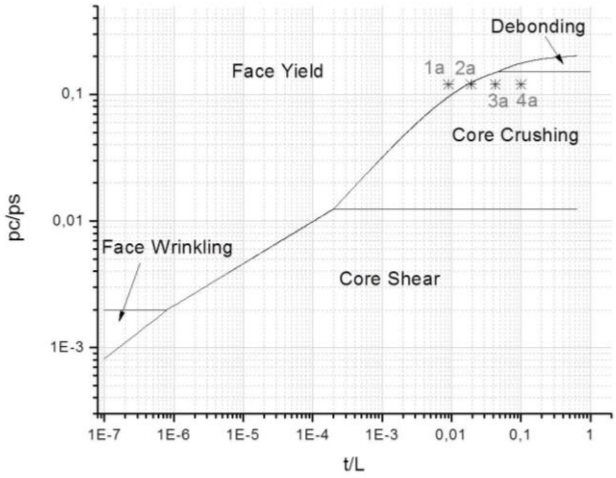

Figure 1. Failure map of Natural fiber core with natural fiber reinforced skins

A debonding failure area for a narrow range of high-span and high relative density core can also be found. Over that relative density value, the face yield mechanism is the only possible failure mode. For high t/L ratios, the core crushing is the dominant mechanism since the facesheets can withstand the load that causes the compressive failure of the core.

Figure 2 shows simultaneously the divinycell - glass fiber and divinycell -natural fiber reinforced skins failure maps. The natural fiber reinforced skin has a Young modulus in the range of 3,9 GPa and a tensile strength of 30 MPa while the glass fiber composite skin has a Young modulus of 15,5 GPa and a tensile strength of 450 MPa. In **Figure 2** the effect of changing the skin properties while maintaining the thickness constant, can be observed. A stiffer and stronger skin makes less probable the face yielding failure, and enlarges the core crushing area of the map. This can be a desirable effect in applications involving energy absorption [13-14]. Stronger skins also produces of a boundary between face wrinkling and core crushing areas, which is not present for natural fiber skins.

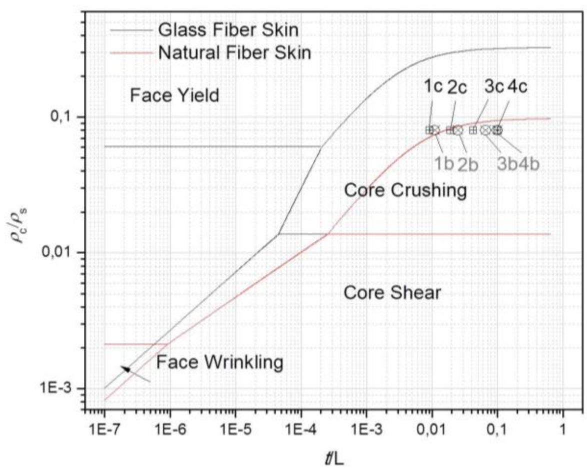

Figure 2. Divinycell- glass fiber and natural fiber reinforced skins failure maps.

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Figure 3 compares the failure map of the sandwich panel made with natural fiber honeycomb core and natural fiber composite skins with that of and the sandwich panel made with Divinycell core and the same skins. It can be seen that the combination of natural fiber skin and natural fiber core results on a larger core crushing area with a wider ρc/ρs possible ratio. It is important to note that changing the core material had less notorious effect than changing the skins for the studied materials.

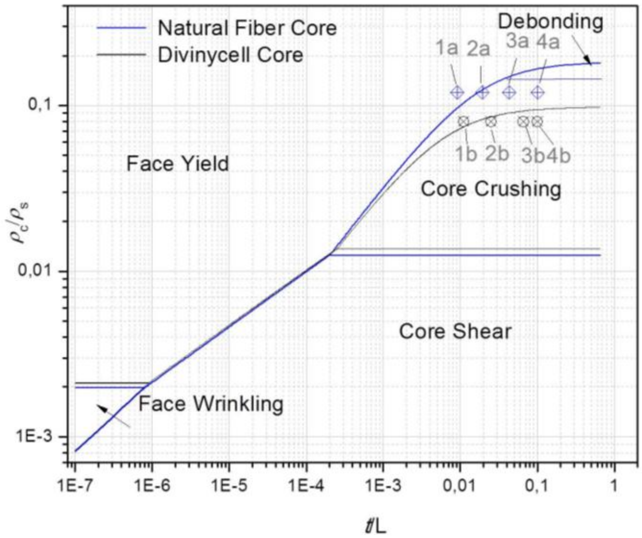

Figure 3. Natural fiber skin failure map comparison with natural fiber and Divinycell core.

2.4 Model Validation

Three point bending tests were conducted using the different core/skins combination and changing the span of the testing beam, and the failure modes were identified. Sets of 3 samples for each material and span were tested.

The failure maps developed were compared with experimental results. In all cases, good accordance with the predicted and the observed mechanisms was found. The experimental points are marked as “x” in Figures 1,2 and 3.

3. Conclusions

In this work the flexural behavior of sandwich panels was investigated. Fiber reinforced honeycomb cores were obtained by Vacuum Assisted Resin Transfer Infusion (VARI) in a special mold. Sandwich panels with combinations of natural fiber cores/ pvc foam core and jute reinforced/ glass fiber reinforced skins were manufactured. Analytical models were studied in order to predict the mechanical response of all the specimens with different face sheet / core combinations. A complete mechanical characterization of the base materials (jute/polyester composite, glass fiber/polyester composite, jute reinforced honeycomb core and divynicell core) was done in order to apply the models.

Different failure modes of sandwich structures such as, core shear, core crushing, face wrinkling and face yielding, and for the all natural fiber panel, the facesheet debonding was included were considered for the predictive failure map construction.

In order to validate the maps, three point bending tests were carried out to study the mechanical behaviors of the composite sandwich beams. Most of the specimens showed a core crushing failure type in accordance with the map prediction. Only the jute reinforced polyester core with jute reinforced skins showed a switch in the mode from core crushing to face yielding with the change on the loading condition. A good agreement between the predicted and observed modes was found in all cases.

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