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COMPRESSIVE BEHAVIOR OF A NOVEL CORE MATERIAL FOR SANDWICH COMPOSITES

SANDVİÇ KOMPOZİTLER İÇİN ÖZGÜN BİR ÇEKİRDEK MALZEMESİNİN BASMA DAVRANIŞI

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ÖZET

Sandviç kompozitlerin mekanik özellikleri daha çok çekirdek malzeme yapısına bağlıdır. Ticari bal peteği çekirdek malzemelerde mekanik veya darbe yükü altında meydana gelen hasar genellikle, çekirdek birim hücrelerinin delaminasyonu ve ezilmesi olarak gerçekleşmektedir. Ayrıca, ticari çekirdek malzemelerin ortak özelliği, yüksek maliyetleridir. Güncel araştırmaların ekonomik yaklaşımı, sıradan malzemelerin ileri malzemelere dönüştürülmesi ilkesine dayalı çalışmalara yön vermektedir. Günümüzde çevresel etkiyi azaltmaya yönelik düşük maliyetli/yüksek performanslı ürünlerin geliştirilmesi önemli bir gereksinimdir. Bu çalışmada, özel bir dikiş tasarımı kullanılarak sandviç kompozitler için yeni bir çekirdek malzeme geliştirilmiştir. Geliştirilen çekirdek yapı, 'rombus (eşkenar dörtgen) çekirdek' olarak tanımlanmakta ve ticari çekirdek malzemelerine kıyasla daha düşük maliyet/daha yüksek performans sunmaktadır. Rombus ve ticari çekirdek yapıların basma davranışı karşılaştırılmıştır. Rombus çekirdek yapılar en yüksek basma dayanımını göstermiş ve hücre duvarlarını oluşturan dikiş bölgelerinde herhangi bir delaminasyon/ezilme olmaksızın basma yüküne maruz kaldıktan sonra yapısal bütünlüklerini korumuşlardır.

Anahtar Kelimeler: Sandviç kompozitler, çekirdek yapı, rombus çekirdek, dikiş, basma davranışı

ABSTRACT

The mechanical properties of sandwich composites are more depended on the core material structure. Damage of the commercial honeycomb core materials are generally occurred as delamination the unit-cells of core material under mechanical or impact loads. In addition, the common feature of commercial core materials is their high-cost. Economic approach of the current researches are led the studies based on the principle of converting ordinary materials into advanced materials. Nowadays, the development of low-cost/high-performance products that serve to reduce environmental impact is an important requirement. In present study, a novel core material is developed for sandwich composites by using a special stitching design. The developed core structure is defined as 'rhombus core' which offers a lower cost/higher performance compared to commercial core materials. The compressive behavior of rhombus and commercial core structures are compared. Rhombus cores showed the highest compressive strength and retained their structural integrity after compressive load without any delamination/crushing at stitching regions.

Keywords: Sandwich composites, core structure, rhombus core, stitching, compressive behavior

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INTRODUCTION

As a lightweight material with high mechanical performance and energy absorption, the sandwich composites with a light cores between two strong face sheets have a great attention in many usage areas as energy and automotive (Ratwani, 2010; Kopp et al., 2004). It is possible to produce faster and more efficient solutions that save energy for many application areas by combining core and face materials. For example, the ability to reach wind energy at competitive prices per megawatt, or the design of lightweight containers or trolleys that can carry more loads and save fuel. In addition to some other material characteristics, the selection of strategic core materials in accordance with the field of use, sandwich composites can gain thermal insulation, low water absorption, sound and dielectric properties (DIAB Knowledge Series, 2017).

Damage resistance of the sandwich composites crucially depends on the core architectures (Zhou et al., 2014; Shengqing and Boay, 2013). The common commercial core materials are honeycomb or foam-based. There are many studies about the mechanical and impact properties of sandwich composites that are produced by using commercial core materials (Wei, 2022; Wu, 2019; He and Hu, 2008; Hazizan and Cantwell, 2003). A limited number of studies are performed by using novel sandwich designs to improve the both mechanical and impact damage resistances of sandwich composites. Neje and Behera (2019) produced sandwich composite structures with different cell geometrical shapes using 3D spacer fabrics combined with woven cross-links. It was revealed that the rectangular core sandwich composites with double-layered wall structure had the highest compressive strength among all structures, followed by the pile-bonded composite structure. It has been stated that the compression and bending behavior of core materials depend on the thickness of the load-bearing walls in the structure, the angle between the wall and the loading axis, and the configuration in which the walls integrate with the surface layers. Zhao et al. (2014) investigated the compression properties of 3D spacer woven composites with pile heights ranging from 5 mm to 30 mm. It was stated that as the pile heights increase, the out-of-plane compression properties decrease, while the in-plane compression properties increase substantially. Mountasir et al. (2013) developed an innovative weaving technology for the production of 3D rectangular void double-walled woven fabrics from high-performance hybrid yarns (glass/carbon/polypropylene). They stated that woven multilayer structures with load-oriented crimped fiber arrangement are suitable for high preform rigidity and a repeatable production. George et al. (2014) designed a prismatic shape braiding core material for sandwich composites. The core part of sandwich is fixed to 3D woven carbon fabric by stitching. The performance of sandwich composites under load is evaluated experimentally and numerically.

The crush response of honeycomb core sandwich composites consists of elastic buckling of the cell walls followed by a plastic buckling, separation of bonds at the cell interfaces and breaking of the resin layer (Aktay et al., 2008). The cells collapse enough that they begin to touch the opposing cell walls and the broken pieces clump together and further deformation compresses the cell wall itself (Zhang and Ashby, 1992). Sun et al. (2016) stated that the critical crushing load increased sharply with the increase of the honeycomb wall thickness and adhesive bond between cells. Paik et al. (1999) also stated that the increase in wall thickness of a honeycomb core cell delayed the onset of plastic deformation and resulted in a significant increase in ultimate and crush strengths. While the adhesive bond between neighboring cells affects the core crushing behavior of sandwich composites, it is important for sandwich composite design to consider the effects of other parameters such as overall size, cell size, foil thickness, honeycomb thickness, whole cell number, and material properties (Chawla et al., 2003).

The main damage of sandwich composites is commonly core crushing and buckling caused by the weakness of core cell-walls. The crushing and buckling parameters are more affected by the core parameters as the resistance of core cell-walls. Stitching is an effective method to improve the strength of core cell-walls which also influences the damage resistance of sandwich composites. In this study, a novel core structure is developed for sandwich composites by using a special stitching design of polypropylene (PP) fabric and compressive properties of this core material are compared with commercial core materials. In the literature, there are not any core structure manufacture based on the combining the layered woven fabric with stitching. Stitching of layered fabrics and molding the unit-cells in desired shape provide design flexibility. The developed core structures have a high potential to use in various areas such as wind blades, automotive, marine and aerospace since they can be used in both in-plane and out-of-plane directions.

MATERIALS AND METHODS

Core Structure Design and Manufacturing

In this study, a rhombus core material is manufactured for out-of-plane usage. Six layers polypropylene (PP) woven fabric (Ritas, Turkey) are stitched in the designed stitching lines. The specifications and the microscopically view of PP woven fabric are presented in Table 1 and Figure 1, respectively.

Table 1. Specifications of PP Woven Fabric

Weave type	Density (per cm)		Yarn linear density (tex)		Crimp (%)		Thickness (mm)	Weight (g/m^2)
	warp	weft	warp	weft	warp	weft		
Plain	9	5	143	238	5	5	0.85	236

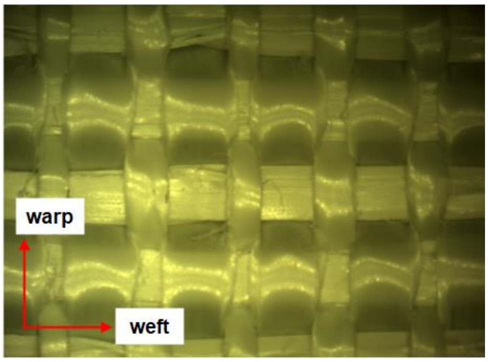

Figure 1. Microscopically View of PP Woven Fabric (×10 magnification)

Stitching is performed on a Siruba L818F-M1A (Japan) stitching machine in 6 step/cm stitching density with 100%-PP stitching yarn (Coats, Turkey) and using lock stitching type. Two different stitching widths as 36 mm (CL, unit-cell dimension: 18 mm) and 18 mm (CS, unit-cell dimension: 9 mm) are used which provide different sizes of unit-cells. Six layers PP fabric are stitched in parallel to warp direction. PP fabric dimension is 40 × 40 cm. Spaces between the layers are moulded in a frame by using the metal rods to obtain corrugated forms. These rods are positioned at perpendicular to the spaces in the layered structure for rhombus unit-cell structure (Figure 2). XPS foams are used to keep the right distance and position of unit-cells. The epoxy resin and the hardener (Hexion MGS L285 resin and Hexion H285 hardener) are mixed (100/34) and applied to stitched fabrics by hand lay-up. Then, the structure placed in the frame is held at room temperature for 24 hours to cure. Post-curing is carried out at 80°C for 1 hour in an oven. Figure 2 shows the schematic views of in-plane and out-of-plane forms of rhombus core structures. The CL and CS cores are cut in 20 mm dimensions for out-of-plane samples.

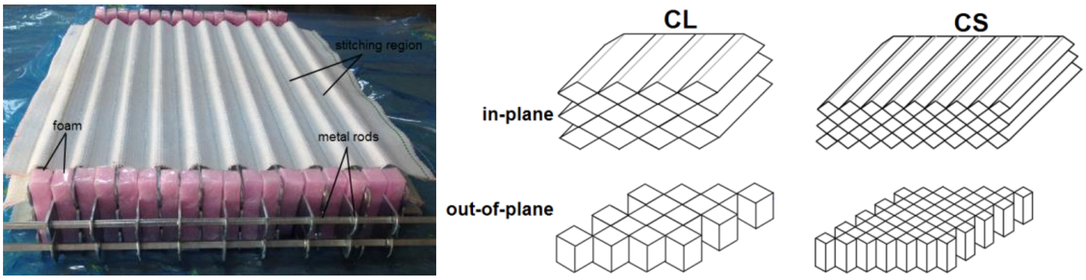

Figure 2. Schematic Views of In-Plane and Out-Of-Plane Forms of Rhombus Core Structures

Compressive Tests

Compressive tests of core structures are performed on a Zwick-Roell universal tester according to ASTM C365-16 (2016) at 0.5 mm/min testing speed. Compressive tests are performed on commercial cores of aluminium and PP honeycombs and XPS (extruded polystyrene) rigid foam for comparing purposes. Three samples were tested for each specimen. Figure 3 shows the compressive tests of core structures. The compressive strength and modulus were calculated according to formulations (1) and (2) in ASTM C365-16.

$$\sigma = \frac{P}{A} \tag{1}$$

$$E = \frac{S \times t}{A} \tag{2}$$

where; σ: compressive strength (MPa), P: maximum load (N), A: cross-sectional area (mm^2), E: compressive modulus (MPa), S: force-elongation ratio in the linear region of the curve (N/mm), t: core thickness (mm).

Figure 3. Compressive Tests of Core Structures

RESULTS AND DISCUSSIONS

Table 2 defines the testes core structures. Besides CL and CS rhombus core structures, two types of aluminium honeycomb, a PP honeycomb and a XPS rigid foam are tested. XPS has the lowest density while CS core has the highest density. Thicknesses of structures are almost same except PP core.

Table 2. Definitions of Tested Core Materials

Core materials	Definition	Unit-cell shape	Unit-cell dimension (mm)	Thickness (mm)	Density (kg/m^3)
CL	Rhombus core	Rhombus	18	20	75
CS	Rhombus core	Rhombus	9	20	120
XPS	Rigid foam	-	-	19	35
PP	PP honeycomb	Honeycomb	12	10	90
AL-12	Aluminium honeycomb	Honeycomb	12	20	40
AL-8	Aluminium honeycomb	Honeycomb	8	19	60

Table 3 and Figure 4 present the compressive test results of core structures. Compressive strength-deformation curves of the structures are given in Figure 5. The compressive loads of core structures are varied from 309.40 N to 4963.36 N. AL-8 core showed the highest compressive load and followed by AL-12, CS and CL core structures. Deformations of core structures are varied from 1.22% to 6.70% in which AL-12 showed the lowest deformation. XPS core had the lower load, strength and modulus values compared to other core structures as expected.

Table 3. Compressive Test Results of Core Structures

Core materials	Load (N)	Deformation (%)	Compressive strength (MPa)	Compressive modulus (MPa)
CL	2707.98	4.09	0.79	21.71
CS	3893.01	5.26	1.96	53.71
XPS	309.40	4.03	0.12	5.57
PP	2691.47	6.70	1.08	26.04
AL-12	4713.18	1.22	0.91	100.27
AL-8	4963.36	2.63	1.11	51.21

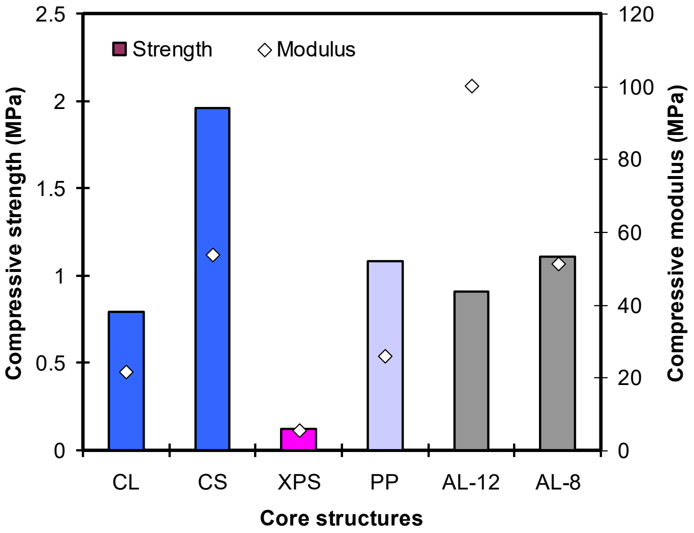

Figure 4. Compressive Strengths and Modulus of Core Structures

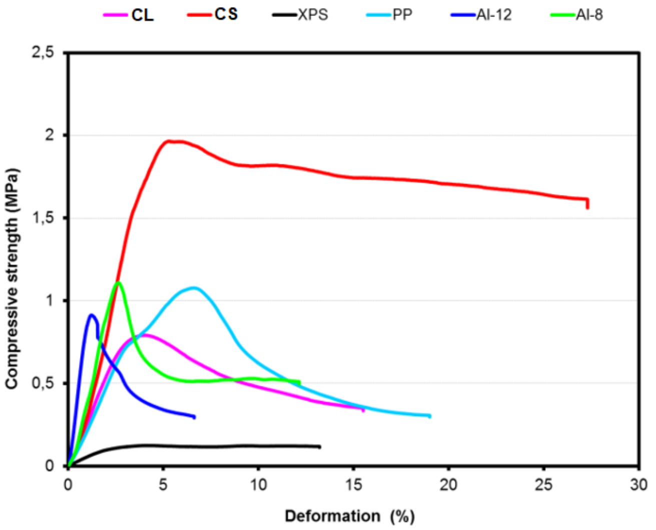

Figure 5. Compressive Strength-Deformation Curves of the Core Structures

CS rhombus core showed the highest compressive strength. Stitching was strengthened the joint regions of unit-cells. This structure was followed by Al-8 and PP structures. Compressive strength and modulus of rhombus cores were increased by the decrease in unit-cell dimensions. AL-12 showed the highest compression modulus and followed by the CS rhombus core. It was determined that the compressive strength and modulus of the CS structure developed within this study were almost 2 times higher than the commercial PP core structure and showed similar deformation. In addition, when the strength-deformation curves (Figure 5) of the core structures are examined, it is possible to conclude that the CS core structure could absorb more energy than those of the CL rhombus core and commercial cores. As seen in Figure 6, the core crushing was severely occurred in Al-12 and AL-8 structures since the adhesive bond between neighbouring cells affects the core crushing behaviour of sandwich composites. However, the CL and CS rhombus cores maintained their core cell-walls and minimized the core crushing with their strengthened cell-walls by stitching. The results of the test showed that the rhombus core structures could be an alternative to the commercially used core structures.

Also, rhombus core structures offer a considerable low cost. The cost of commercial aluminium honeycomb core is about 600 $/m^2 while the cost of PP honeycomb core is almost 65 $/m^2 (Kompozitnet, 2022). The estimated cost of rhombus core is about 6 $/m^2. The cost analyse of core materials showed that the developed rhombus core has about 100 times lower cost than aluminium honeycomb cores and about 10 times lower cost than PP honeycomb cores.

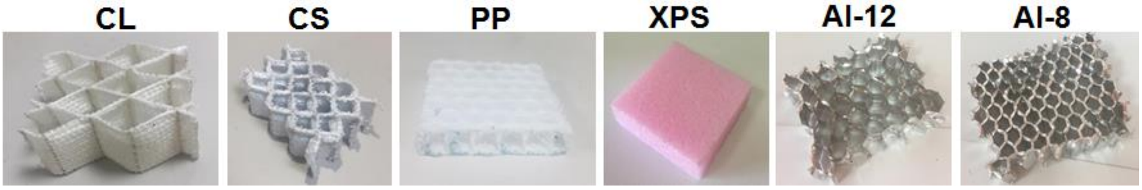

Figure 6. The Views of Core Structures after Compressive Test

CONCLUSIONS

A novel core material is developed for sandwich composites by using a special stitching design. The developed core structure is defined as rhombus core which offers a lower cost/higher performance compared to commercial core materials. The compressive behaviour of rhombus and commercial core structures are compared. The conclusions are:

- CS rhombus core showed the highest compressive strength and followed by Al-8 and PP structures.
- AL-12 showed the highest compression modulus and followed by the CS rhombus core.
- Stitching was strengthened the joint regions of unit-cells.
- The compressive strength and modulus of the CS structure developed within this study were almost 2 times higher than the commercial PP core structure and showed similar deformation.
- The core crushing was severely occurred in Al-12 and AL-8 structures since the adhesive bond between neighbouring cells affects the core crushing behaviour of sandwich composites. However, the CL and CS rhombus cores maintained their core cell-walls and minimized the core crushing with their strengthened cell-walls by stitching.
- The compressive test results showed usage areas as with their low-cost/high-performance properties.

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