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Manufacturing and Flat-wise Compression Performance of Modified 3D Integrated Sandwich Fabric Composites

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Abstract
In this study, a novel manufacturing technique for three-dimensional integrated sandwich fabric with an '8'-shaped inside layer structure was developed. Furthermore a new integrated sandwich fabric with an '88'-shaped inside layer structure was designed in comparison with the '8'-shaped inside layer structure. The flatwise compression characteristics of the three-dimensional integrated sandwich fabric composites with different inside layer angles, inside layer heights and inside layer structures were investigated. The results showed that the inside layer structure of integrated sandwich fabric composites woven by the double rapier technique stand more uprightly than those woven by the traditional velvet weaving technique. What is more the corresponding flatwise compression performance was also greatly improved. Furthermore compared to '8'-shaped inside layer structure composites, '88'-shaped inside layer structure composites can not only retain the majority of pores but also greatly improve the flatwise compression performance of the composites.

Key words: *three-dimensional, inside layer structure, flatwise compression, integrated sandwich fabric composites.*

Introduction

Integrated sandwich fabrics with hollow inside layers are produced by weave technology, and the skins are strongly connected with each other by the link of inside layer materials, considered as interwoven with the skins. As a new type of 3D fibre reinforcement, its composite provides a sandwich structure with a high skin-inside layer de-bonding resistance and potential for cost-effective sandwich construction [1 - 3]. The integrated sandwich fabric composite is a special kind of structural material, by the virtue of its high strength weight ratio, damage tolerance, and low manufacturing cost. Nowadays 3D composites have been widely used in large areas of boats, aircraft wings, the sandwich of oil tanks as well as in various floors and partition walls. Some relevant studies have been carried out by some scholars who contrastively analysed the stretching, compression, bending and shearing performance of composites with different degrees of height . Meanwhile the low velocity impact [4, 5], dynamic compression [6], shock loading [7], and modelling [8 - 10] have also been studied. Earlier researches indicated that the mechanical property of integrated sandwich fabric composites was dependent on the inside layer structure, especially the flatwise compression performance. Thus some other methods were applied in order to improve the flatwise compression performance of integrated sandwich fabric composites. The method of filling foam into hollow parts was studied and the results suggested that this could not only improve the mechanical properties of the inside layer as designed but also eliminate the specific hollow structure and increase the additional self-weight considerably [11, 12]. Zhu CY designed some new inside layer structures (including the 'X' shape, 'V' shape, and honeycomb, etc) to improve its mechanical properties [13, 14]. But the results showed that this method, involving the complex weave technology, could increase the self-weight of the fabric significantly, though the flatwise compression performance of integrated sandwich fabric composites could be improved by the modification of the woven technique.

So far, studies on 3D composites have mainly focused on experimental tests such as the basic mechanical performance, low-velocity impact and other properties. However, other aspects of 3D composites such as the preparation, structural theory, and flatwise compression have not been properly studied. In this work, the manufacturing and flatwise compression performance of integrated sandwich fabric composites were studied on the basis of the observation and analysis of the structural character and woven procedure. Additionally a new type of inside layer structure - the '88' shape was also designed to improve the flatwise compression property of integrated sandwich fabric composites.

Manufacturing of integrated inside layer sandwich composites

Structural and procedure analysis

A rapier loom was used to weave the integrated sandwich fabric, with only one shedding forming every weaving cycle, and the wefts in the upper and lower skins were inserted and beat-up respectively, which resulted in the two skins being not in the same vertical plane and the inside layer material not being fully

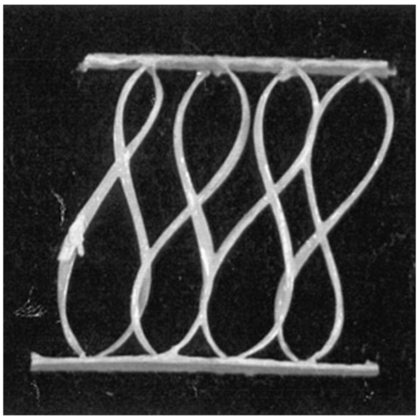

Figure 1. Integrated sandwich fabric composite.

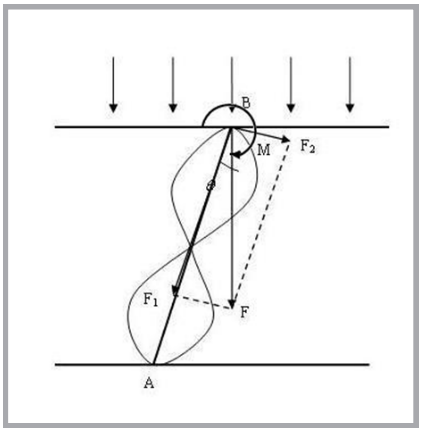

Figure 2. Loading situation of flatwise compression on core structure.

upright [15, 16]. As shown in ***Figure 1***, the '8' shaped inside layer material was tilted right, and the tilt angle seriously affected the mechanical properties of the composites, especially the flatwise compression performance. ***Figure 2*** shows a schematic drawing illustrating the loading situation in conditions of flatwise compression. As shown in ***Figure 2***, line AB, F and θ represented the '8' shaped inside layer material, the flatwise compression on the upper panel and the tilt angle, respectively.

It is clear that the flatwise compression (F) imposed on the panel can be analysed as a pair of forces F1 and F2. F1 is along the direction of line AB, while F2 is perpendicular to line AB. According to mechanics, F2 will generate a moment of force (M), a major factor of structural instability. When increasing the tilt angle of the inside layer materials, the moment of force (M) will rise in magnitude sufficiently, resulting in a change in the destroyed form of the inside layer material, from crushed to rotating damage at points A and B. When the moment of force (M) generated by F2 is beyond the fixed moment at points A and B, the composite will be damaged. Moreover ***Figure 2*** also clearly shows that the arm of F2 was much longer than the fixed force at points A and B, hence the rotating damage of the composite caused by F2 was much easier than the crush damage caused by F1. Therefore ensuring the inside layer material keeps upright is an effective method to improve the flatwise compression performance of integrated sandwich fabric composites.

In order to make the inside layer materials straight, integrated sandwich fabric was woven by a rapier loom with a pair of rapiers, composed of three sets of harnesses, double rapiers, two let-off systems and an indirect take-up device. A schematic drawing of the woven process is shown in ***Figure 3***. The warp was divided into two parts: the skin warp and inside layer warp, which were separately fed by constant-tension and a fixed-length let-off device [17, 18]. Different from the traditional warp let-off motion, the skin warp used constant tension let-off, while for the inside layer warp it was constant length let-off motion. For the skin warp, while two sheds were formed by the harnesses, the weft of upper and lower panels were inserted at low speed at the same time by the rapiers. As with the constant length let-off motion for the inside layer warp, the connection length could be changed by the speed. Because of the thickness of 3D integrated sandwich fabric, traditional take-up technology could not meet the requirements. Thus a parallel manner of traction was used to lead the fabric in flat way by controlling the warp tension and accuracy of traction. Additionally the translational beating-up mechanism was adopted to ensure that the weft in the upper and lower skins can be on the same vertical plane. Furthermore the tension of single yarn must keep consistency to ensure the absence of uneven stitches during the weave process.

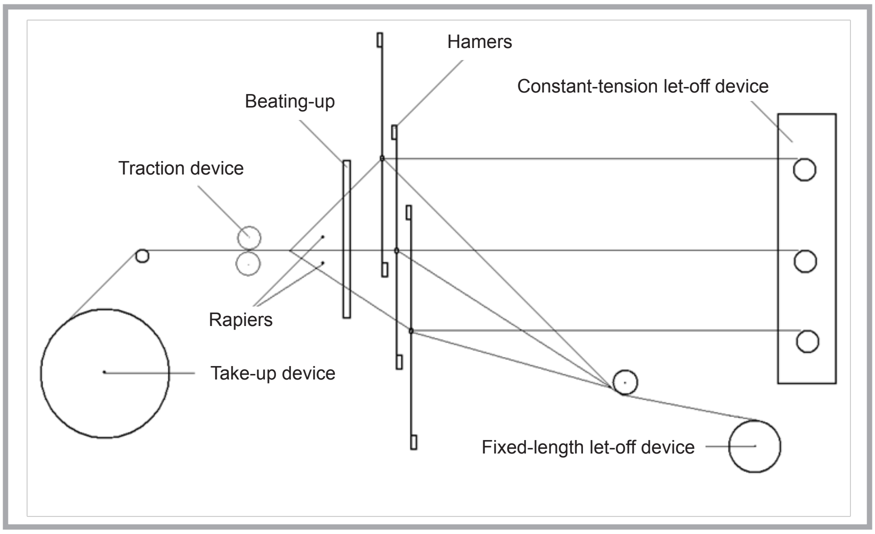

Figure 3. *Schematic drawing of the woven process.*

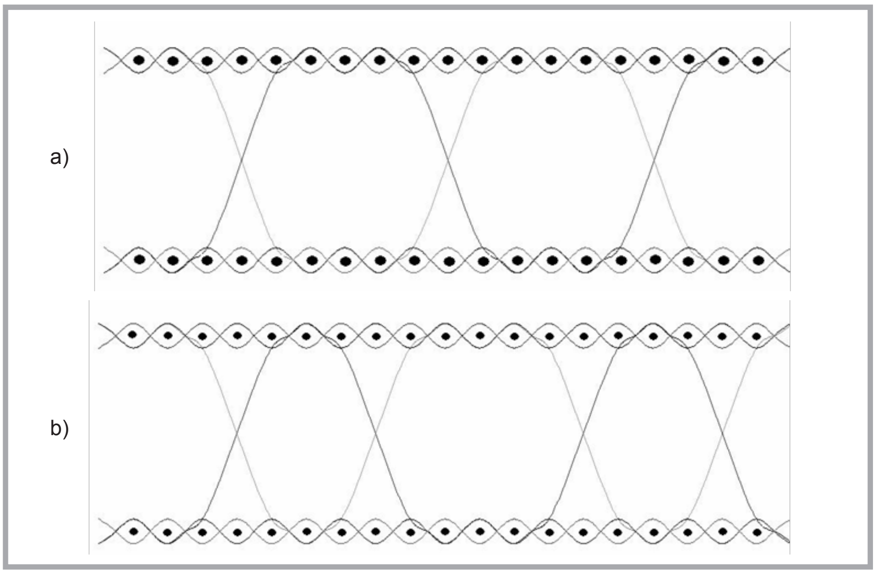

Figure 4. *Schematic of integrated sandwich fabric structure: a) "X"shape core structure, b) "XX" shape core structure.*

Fabrication

Structural design

The integrated sandwich fabric consisted of two identical parallel skins linked together by means of inside layer fibres, whose structure can be seen from ***Figure 4***. The weave structure of the skins was designed as plain. It is well known that the dense texture can provide enough slippage resistance for the inside layer fibres interwoven in the skins. As shown in ***Figure 4***, the inside layer fibre was designed for two patterns: 'X' shape and 'XX' shape. When forming a 'X' or 'XX' shape, the inside layer fibre must be interwoven in the skins in a 'W' or 'M' shape in order to ensure the position and height of inside layer materials.

VARIM process

There are several molding technologies to prepare fibre reinforced composites, such as hand lay-up, vacuum-assisted molding, dipping, injection molding and

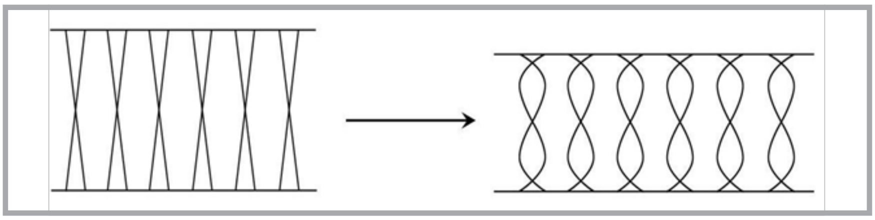

Figure 5. Formation of ‘8’ shape from ‘X’ shape.

so on [19]. Vacuum Assisted Resin Infusion molding (VARIM) is an economical molding technology for large scale workpieces [20]. Here, according to the reference, the molding process of integrated sandwich fabric composites was prepared by VARIM technology [21]. Epoxy resin (E-51), polyamide curing agent (651) and epoxy reactive diluent (660), supplied by the Wuxi Resin Factory of Blue Star New Chemical Materials Co., Ltd. were used. Because of the fibre stiffness and fabric structure, the inside layer material does not fully stand up to form an X shape, but buckles between the two skins to form an ‘8’ shape, forming a continuous inside layer structure between the upper and lower skins. The forming process is shown in ***Figure 5***.

Flatwise compression test

The flatwise compression strength of integrated sandwich fabric was tested by the INSTRON 3385H universal material tester according to the standard of GB/T1453-2005 [22]. Test samples for flatwise compression were of the size of 60 × 60 mm. The ambient temperature was about 25 °C and the relative humidity about 50 - 60%, with a 2 mm/min load speed. The flatwise compression test process is shown in ***Figure 6***.

To study the effect of the tilt angle on the flatwise compression property of integrated sandwich fabric composite, ‘8’ shaped inside layer structure samples with different tilt angles (0°, 15°, 30°, 45°) were prepared, controlling the angle error within 2°. Moreover samples with three height degrees (6 mm, 8 mm, and 10 mm) were designed for experimental analysis. Contrast experiments for ‘8’ and ‘88’ shape samples with four different degrees of height (6 mm, 8 mm, 10 mm, and 12 mm) in the flatwise compression test were also carried out in this study.

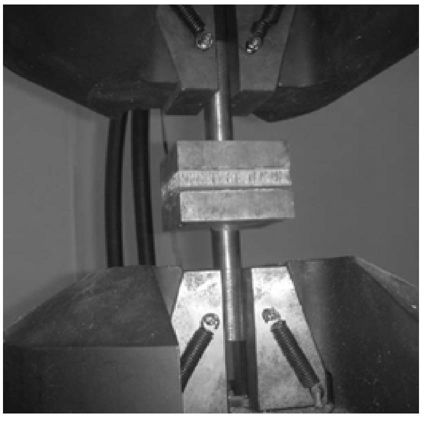

Figure 6. Flatwise compression test.

Results and discussions

Effect of inside layer material tilt angle

It is said that the inside layer material of the integrated sandwich fabric composite plays an important role in the flatwise compression test and the main damage form of the integrated sandwich fabric composite was attributed to its inside layer material. Therefore the bearing capacity of the inside layer material determined the strength and stability of the composite in the flatwise compression test. Thus the tilt angle of the inside layer material became a significant factor for the stability of the integrated sandwich fabric composite.

Samples with different tilt angles were tested, the results of which are shown in ***Figure 7*** (see page 100). It can be clearly observed from ***Figure 7.A*** that the flatwise compression strength was reduced along with the increasing tilt angle of the inside layer materials. An obvious discrepancy in the breakage process between the small angle (0° and 15°) and high angle (30° and 45°) emerged: The stress of both the small and high angle samples increased linearly with the displacement, but the difference occurred at the yield point. The stress of the samples with a small angle gradually decreased after arriving at the yield point. Meanwhile the samples with a high angle still kept a constant stress along with an increase in displacement after arriving at the yield point. When the peak point was reached, the inside layer materials of samples with a high angle began to collapse, in other words, the composite became dilapidated. Therefore the damage of the integrated sandwich fabric composite was mainly reflected as inside layer material damage in the flatwise compression test. The tilt angle was a key factor in effecting the flatwise compression performance of the integrated sandwich fabric composite.

As shown in ***Figure 7***, it can be concluded that the effect of the tilt angle on the flatwise compression strength had great dependence on the height of the inside layer materials. It was mainly attributed to the torque of F2 (***Figure 2***), which increased along with the height of the inside layer materials. The bearing capacity of the inside layer material could reach a peak as the inside layer materials became fully upright. Moreover the upright position of the inside layer material depends largely on the weaving process, while ordinary velvet weaving technology could not guarantee the uprightness and stability of inside layer materials.

Compression performance contrast between ‘8’ and ‘88’ inside layer structural materials

The flatwise compression performance of ‘8’ and ‘88’ shaped samples with 4 different degrees of height (6 mm, 8 mm, 10 mm, and 12 mm) were tested, the results of which are shown in ***Figure 8*** (see page 102).

It can be seen from ***Figure 8*** (see page 102) that the ‘88’ inside layer structure can improve the flatwise compression strength drastically, especially at the height of 12 mm, whose increment speed could reach 70%. As shown in the figure, the thicker the sample is, the higher the increasing rate is of the flatwise compression strength of the ‘88’ integrated sandwich fabric composite. Thus it can be stated that the ‘88’ inside layer structure can provide a method to resolve the stable problem. Although the flatwise compression strength would be obviously reduced with an increase in height, it can also have a positive effect on settling the limit of the thickness.

Conclusions

In the present study, a new integrated sandwich fabric with an ‘88’ shape inside layer structure was designed, as well as a new weave technique using a rapier loom with a pair of rapiers, which included

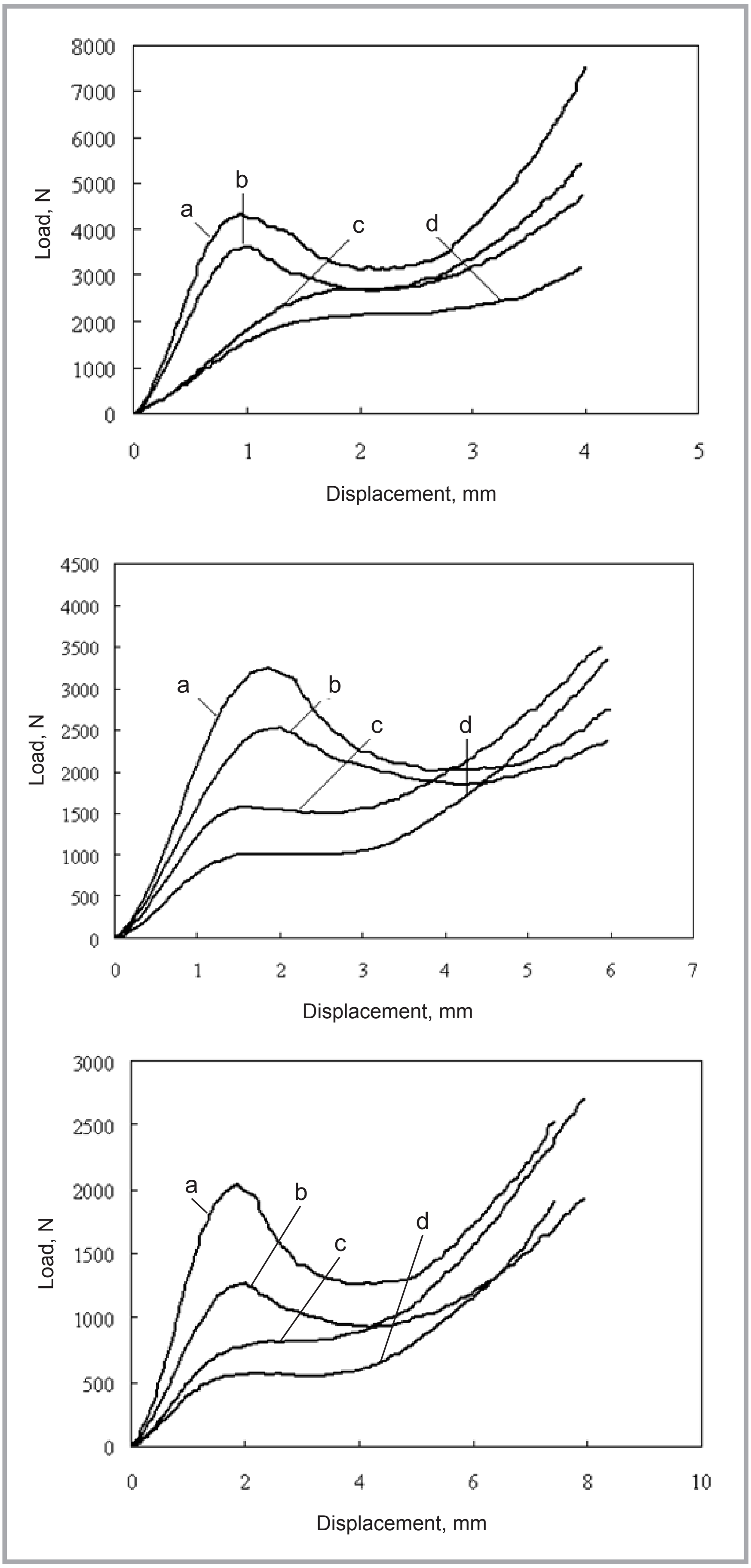

***Figure 7.** Flatwise compression performance of integrated sandwich fabric composite with different pile angles (Height = 6 mm (A), 8 mm (B) and 10 mm (C): a - tilt angle 0°, b - tilt angle 15°, c - tilt angle 30° and d) tilt angle 45°).*

three sets of harnesses, double rapiers, two let-off systems and an indirect take-up device, playing an important role in the weave techniques invented. The flatwise compression strength was reduced along with the increasing tilt angle of the inside layer materials, and the flatwise compression strength clearly decreased with an increase in the height. Additionally it was found that the integrated sandwich fabric composite with '88' shaped inside layer material was superior to that with an '8' shaped inside layer material.

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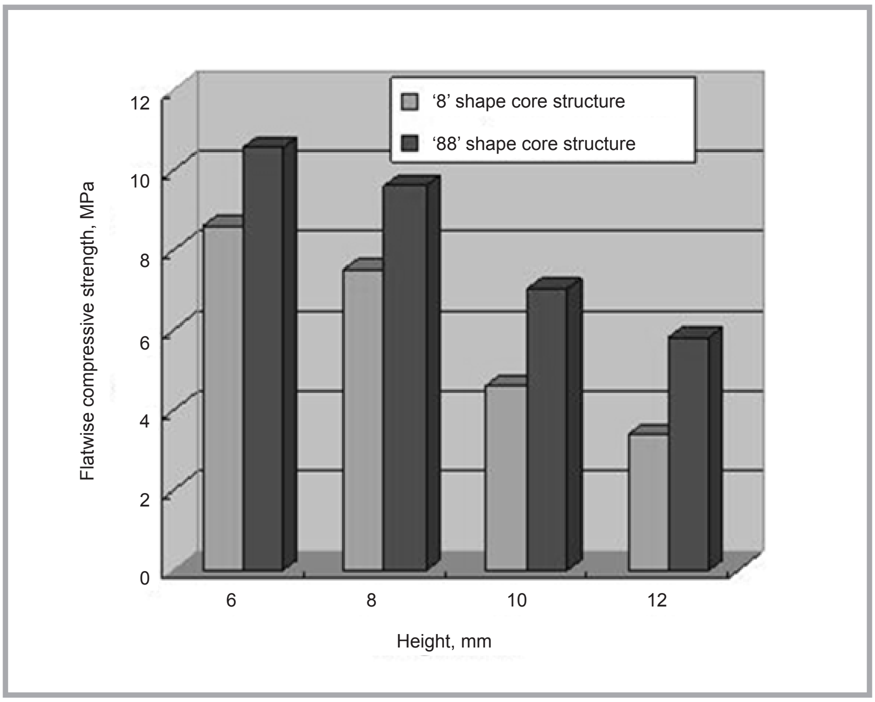

Figure 8. Flatwise compression strength contrast.

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