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Experimentally examining the mechanical behaviour of nap-core sandwich material – A novel type of structural composite

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Abstract

Experimental investigation of the nap-core sandwich is presented in detail, in which the nap-core is based on knitted fabric, being impregnated with a thermoset resin, formed to create cup-shaped naps, and stabilized to assume a permanent 3D contour. The material is a novel type of lightweight sandwich-structured composite which has good specific strengths and possesses various properties crucial for engineering applications, but its exploitation is still restricted due to insufficient research and understanding. The sample preparation is first described, being followed by the test implementation and outcomes. The results obtained from typical tests demonstrate high performance of the nap-core sandwich samples under different cases of loading. They also reveal the sandwich's essential behaviours which are similar to those of a common shell structure, giving it a great potential of being computationally modelled with finite element software.

Keywords

Sandwich structures, thermosetting resin, polymer fibres, structural composites, textile reinforcements, mechanical behaviour

Introduction

The nap-core sandwich composite

For decades, lightweight sandwich-structured composites (also called core materials) have been in an increasing demand in engineering applications on account of their high strengths and stiffness to the density, especially the compressive strength and the flexural strength.[1–4] Basically, the material is created by sandwiching a core between two stiff skins using some kind of bonding. In the industry of manufacturing aerospace and aircraft, non-metal sandwich material is used to fabricate most of lining elements in which the outer layers usually are impregnated phenolic resin – glass fibre laminates and the core is honeycomb or foam. When parameters of the core change, the behaviour of the sandwich changes as well. That results in a wide range of properties for numerous applications.[5–7] However, sandwiches with honeycomb or foam core have drawbacks which are limited drapability and closed inner structure. The former causes a difficult employment of the sandwich to curved surfaces, and the latter probably make accumulation of condensation water that increases weight and reduces the mechanical properties of the sandwich.[8–10] In that sense, the nap-core is derived from textiles to overcome the recent problems of the other cores. A typical nap-core has a 3D shape obtained from deep drawing, curing, and cooling a resin-impregnated 2D knitted fabric (see Figure 1).[11] The most successful fibre materials are thermoplastic polymers, aramid, glass, cellulose, basalt, and hybrid fibre. These fibres are non-toxic and strongly resistant against heat, solvents, hydrolysis,

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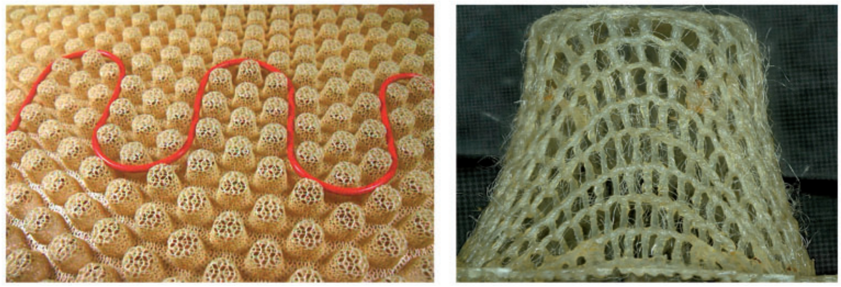

Figure 1. Photos of a typical nap-core (left) and one of its naps (right).

and oxidizing agents. Textiles made of them also prove to be highly durable and tough. Nevertheless, many of those materials have low elongation of break (around 4%) while the production of the nap-core necessitates the textile to stretch up to 250%. Therefore, fabrics fabricated by knitting technique are used as they are incredibly suitable for creating deep-drawn shapes without local fractures or crimps.[12]

The best materials for the matrix are thermoset resins Cyanate Ester, Epoxy and Phenol Formaldehyde for their working stability and health safety (good fire-smoke-toxicity standard). Beyond that, they are reasonable at price for commercial production and own a fast cross-linkage and low curing time. In practice, the selected resins have already shown good basic properties plus high compatibility with plasticizer and retardants as well as their excellent ability of wetting fibrous material.[12]

Geometrically, a nap-core is a combination of numerous periodic naps. To add bending stiffness, two hard skins are attached to the top face and bottom face of the nap-core to form a sandwich as shown in Figure 2. Although the nap-core sandwich has specific strengths not as high as those of the honeycomb at the same density, it offers many other desirable properties. In particular, the nap-core sandwich is rather flexible, so it can be bent over complex surfaces. The hollow fabric structure of the core allows good drainage and ventilation to fluid, and the slots between naps facilitate the integration of cables or tubes into the structure.[13] In addition, alterations of constituent materials and underlying geometries of the nap-core help to generate various types of the sandwich with adjustable properties to fit different requirements. Depending on the layout of naps, nap-cores are divided into two main types, single-sided nap-core and double-sided (symmetrical) nap-core. Of them, the former is more convenient for handcraft, and the latter is more suitable for automatic production.[14]

In comparison with common engineering textiles, the nap-core sandwich also possesses many advantages making it special. Firstly, the use of thermoset resin helps to repair small fractures and reduce wrinkles and disorders on the knitted fabric. Secondly, the forming and stabilizing steps keep an enduring shape of the core, giving it a necessary height without taking up more material. Thirdly, after cooling, the matrix will lock all fibre positions and prevent transposition of yarns so that eliminate the problem of inter-tow sliding.[8] Overall, the nap-core sandwich possesses high strength to density (specific strength), especially under compression and bending.

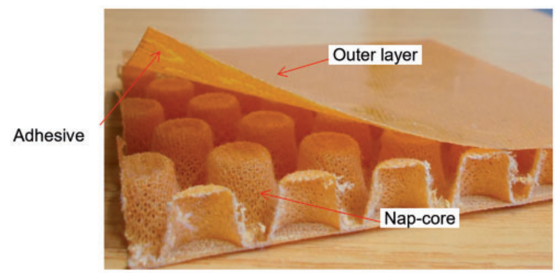

Figure 2. Scheme of a representative nap-core sandwich.

Although containing a large number of merits, the nap-core sandwich composite is currently not as reliable as honeycomb because it is still little understood. Its applications are almost interior decoration and cover in means of transportation whilst it is highly potential to be used as load bearing components. Thus, research of the material needs more attention as only that will bring it a deserved development. In this article, the authors will present an experimental investigation of the nap-core sandwich's mechanical behaviours. The other investigation – modelling based on finite element method – is likely to confront several difficulties due to the complicated underlying structures of the nap-core, and it will be present in a separate article.

Recent studies

Although being patented in 1977, the nap-core sandwich composite is relatively innovative with only a few years of mass production and development, so insight into it is limited. There have been a number of reports made by Monika et al. in 2006,[15] Bernaschek et al. in 2011,[14] and Gerber in 2017[11] describing its fabrication procedure, categories and properties in detail. However, there is only one article published by Gerber et al. in 2016 informing the result attained on inspecting dynamic behaviour of a symmetric nap-core sandwich under impact load.[8] This shortage explains inadequate employment of the nap-core sandwich in engineering applications despite its advantageous properties in all physical, chemical, and mechanical aspects.

On purpose of obtaining a more comprehensive understanding on the nap-core sandwich composite, the author has conducted a typical mechanical experiments on samples of two types of the material. The tests are compression, shear, three-point bending, and four-point bending. The samples, implementation, and results will be given in the next sections.

Comparison between nap-core sandwich and honeycomb sandwich

To have a deeper understanding of the nap-core sandwich, a comparison between it and a honeycomb sandwich with similar boundary dimensions has been carried out. For both kinds of sandwiches, the outer sheets are the same kinds of laminate composed of glass fabric and Phenol formaldehyde resin. The examined nap-core's knitted fabric is made of Aramid Hybrid for the yarns and Phenol formaldehyde for the matrix, of which the naps are triangularly arranged and have an average diameter of 6 mm. The mass-to-volume ratio of the nap-core sandwich sample is 55 kg/m^3. The comparative honeycomb is made of paper, having a cell width of 3.2 mm and a mass-to-volume ratio of 48 kg/m^3. The comparison is on compressive behaviours. The samples are illustrated in Figure 3, and the resulting behaviours of the two sandwich samples are presented in Figure 4.[15]

The experiments demonstrate that the honeycomb sandwich has better strengths and moduli in general, but the nap-core sandwich holds an outstanding advantage. When the damage happens, the strength of honeycomb sandwich descends abruptly and its force plunges, whereas the force of the nap-core sandwich goes down slowly with only a modest slope. This feature, in addition to great ventilation and an easy integration of wires, make the nap-core sandwich a good selection in numerous applications.[14,15]

Samples and experiments

Samples

Two types of nap-core and their sandwich composites are going to be introduced and examined in this article, which are P1-10 (single-sided nap-core) and P2-8 (double-sided

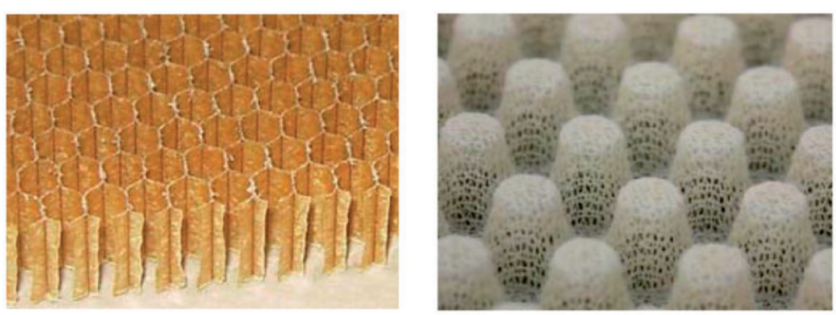

Figure 3. The honeycomb (left) and the nap-core (right) of the comparison. Source: Kunststoffe international GmbH.

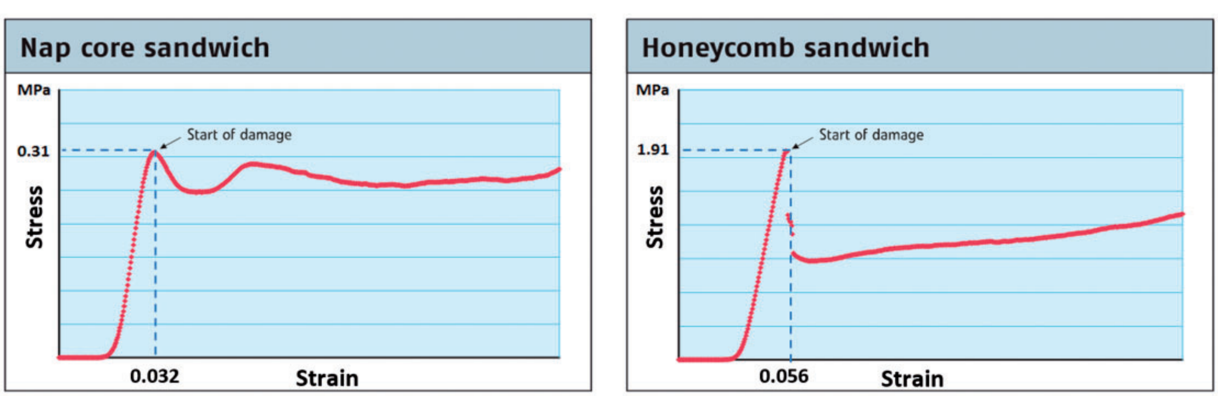

Figure 4. Compression to a sandwich with nap-core (left) and honeycomb (right). Source: Kunststoffe international GmbH.

nap-core). For the names of the nap-core types, "P" stands for Phenolic resin; "1" denotes single-sided; "2" denoted double-sided; "10" means 10 cm height; and "8" means 8 cm height. They are among the most common categories and different at all major elements: constituent materials, knitting patterns, and geometries. In other words, they are to some extent offer an initial overview on the nap-core sandwich-structured composite. Details are presented in Figure 5 and Table 1.

Sandwich samples are prepared following a standardized production procedure. At first, a 2D sheet of knitted fabric is pre-impregnated with a thermosetting phenolic resin to form a mixture in which the resin embeds the fabric inside to create a wet mixture of fabric and resin. The mixture is then laid between two halves of a pin mould to give the knitted sheet a 3D shape (with a height of 5–10 mm) as a combination of periodic-distributed identical cone-shaped naps. Afterwards, the mould with the sample inside is cured at 140°C for 4–6 h and cooled down at room temperature in a similar time. Henceforth, the nap-core takes up a stable shape, and the yarns no longer slide to each other. In the next step, the sandwich is completed by bonding the stabilized nap-core with two outer face sheets. Finally, the samples are cut from the big sandwich panel to desired dimensions.

As stated in the introduction, three usual experiments (e.g., compression, shear, and four-point bending) are going to be implemented for the inquiry of the sandwiches' mechanical behaviours. The experimental standards are D3410M – 03 for compression, DIN 53 294 for shear, and DIN 53 293 for four-point bending. The sample dimensions (length × width) are 5 × 5 cm for compression test, 20 × 5 cm for shear test, and 40 × 5 cm for four-point bending test (refer to Figure 6). The samples used for the current research comprise of materials as displayed in Table 1. For every kind of test, the number of the samples of each nap-core sandwich type is always equal to 5.

Sample fixations

Samples are sized and installed as in the standards. The schemes of fixtures are shown in Figures 7 and 8 in

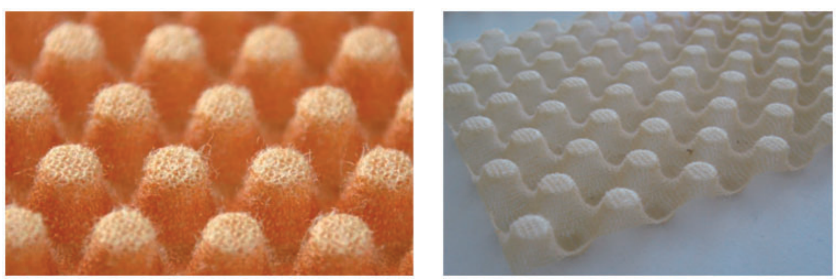

Figure 5. Nap-core types and P1-10 (left) and P2-8 (right).

Table 1. Specifications of the nap-core sandwich types used for the experiment.

Nap-core type	Material	Boundary height (mm)	Fabric thickness (mm)	Volume weight (kg/m^3)
P1-10	55% fibre (90% Nomex + 10% Polyester) + 45% Phenolic resin	10	0.58	83
P2-8	50% fibre (80% Aramid + 20% Polyester) + 50% Phenolic resin	8	0.45	41

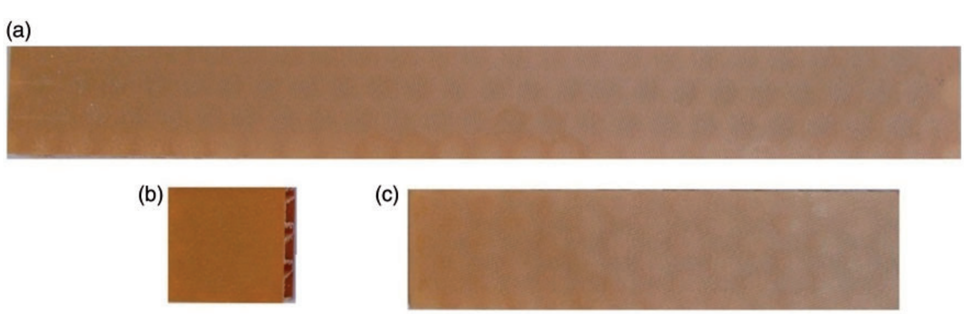

Figure 6. Samples of the experiments: (a) four-point bending, (b) compression, (c) shear.

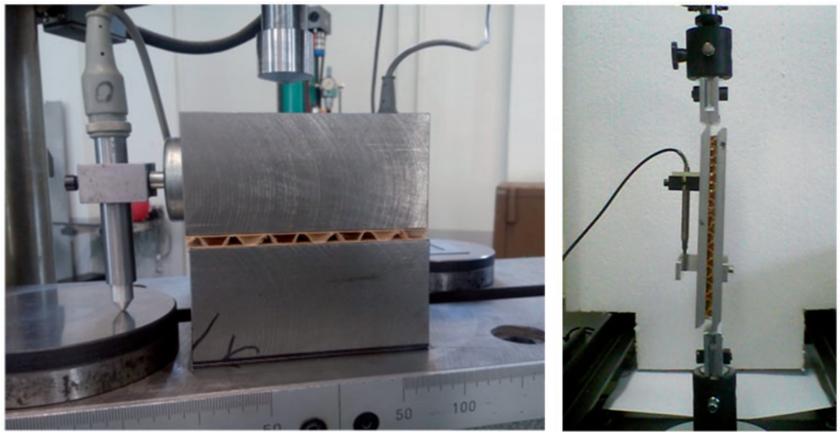

Figure 7. Fixture schemes for the tests: Compression (left) and Shear (right).

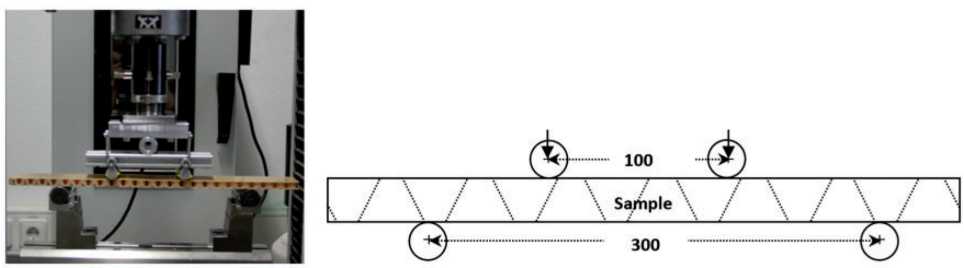

Figure 8. Fixture schemes for the four-point bending test.

which specific velocity of the load generator's head for each testing case is 10 mm/min for compression or four-point bending, and 1 mm/min for shear or three-point bending.

Results and discussions

Results

In this section, the results are shown and discussed. The relationship between the applied forces and displacements the sandwich's top sheet are illustrated in Figures 10 to 12. The plot of each sample will be created with a particular colour, and symbol ▲ marks the point with the maximal force in each test.

In the same kind of test, the resulting force and displacement are not exactly the same between the samples. Beside common measurement errors, the most important factor is the change at the samples' boundaries. Because the naps are diagonally distributed whilst the cutting lines are horizontal or vertical to the panels' borders, many naps are cut apart. Coming from sample to sample, the cutting lines are not at the same place, so the shapes of incomplete naps along every boundary change as well (see Figure 9). That makes the result fluctuate in the end. In the preparation of the samples for each test, the differences of the boundary geometry between the samples are intended to examine how it will affect the result.

Figure 10–left reveals the results of P1-10 nap-core sandwich samples in the compression test. They all showed a typical behaviour under compression, but the values of their force and displacement scattered a bit. The maximum force changed between 1100 N to around 1250 N, and the displacement at the buckling altered between 0.44 mm and 0.51 mm. There are several explanations for these differences. Firstly, the differences in the boundary geometry make the results altered. Secondly, the resin content of the samples is not perfectly the same from sample to sample. Thirdly, the curing process could not make a strictly uniform effect on the entire big panel of the nap-core sandwich – which would be divided into many separated samples.

Figure 10–right demonstrates the behaviour of P2-8 nap-core sandwich samples in compression was like that of P1-10 nap-core sandwich samples. However, the establishment period was much shorter, only occurred when the displacement was smaller than 0.075 mm and the force was less than 100 N. Although the displacement at the buckling is not so

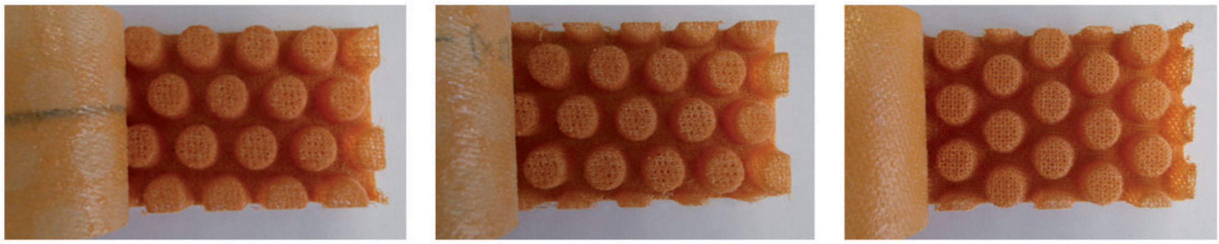

Figure 9. Nap-core samples having the same dimensions but different boundaries.

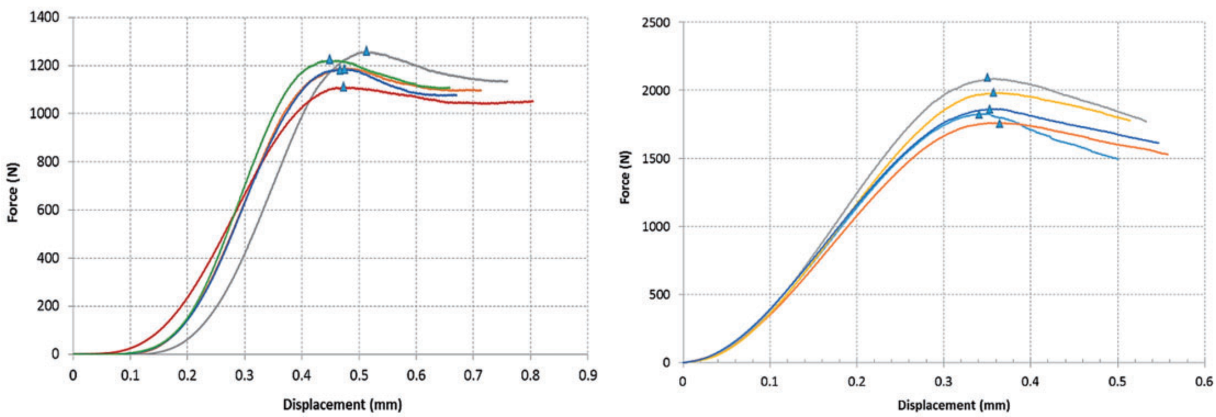

Figure 10. Experimental results of the compression tests: P1-10 sandwich (left) and P2-8 sandwich (right).

different (0.34–0.36 mm for P2-8 nap-core sandwich, and 0.44–0.51 mm for P1-10 nap-core sandwich), the maximum force of P2-8 nap-core sandwich samples is markedly higher (1750–2100 N for P2-8 nap-core sandwich, and 1100–1250 N for P1-10 nap-core sandwich). Among the samples, the maximum force and the displacement at buckling are pretty different, and the reasons are very similar to those of P1-10 nap-core sandwich.

As shown in Figure 11–left, the force and displacement of the samples were not much scattered, and the deformation did not contain a clear establishment period. All of the samples deformed linearly as the test started until the force went up to 1500 N and the displacement was equal to 0.22 mm. Later, the samples deformed nonlinearly. The force kept increasing to more than 3000 N. When the displacement was over 0.85 mm, the shear buckling would happen suddenly before the displacement reached 1.2 mm. Of five samples, two had the force reducing very slightly after the shear buckling, and three had the force declining steeply after the shear buckling. That was resulted from the difference of the cohesion strength of the sandwich samples. The phenomenon that the force plunged is an indication of the delamination of the entire upper sheet. Mostly, the weaker the cohesion strength is, the sooner the delamination of the upper sheet happens. In general, the delamination happens abruptly and there is difficulty predicting its commencement precisely, but it can be delayed by improving the quality of the adhesive.

In Figure 11–right, the samples show the same behaviour but much higher range of force. When the displacement was less than 0.2 mm, the samples' deformations were nearly linear, and the forces increased fast from 0 to 2600 N at least and 3400 N at most. Afterwards, the samples behaved nonlinearly. The force still went upward fast until the shear buckling happened at a displacement between 0.6 mm and 0.8 mm. The maximum force (at the shear buckling) changed somewhat from sample to sample. It ranged from around 4750 N to around 5250 N.

As shown in Figure 12–left, the samples underwent a quick nonlinear establishment period when the displacement was less than 0.75 mm. Subsequently, they behaved almost linearly until the initiation of the damage (i.e., the local debonding of the upper sheet). Based on the charts, it is viewed that five samples acted not identically. Two samples buckled when the force was around 75 N and the displacement increased over 6 mm for the one and 7.5 mm for the other. The third sample worked linearly until the force got more than 90 N, and its damage occurred when the displacement was about 6.5 mm (the blue chart). The remaining two samples continued to work as the force went up above 105 N, and they only buckled when the displacement

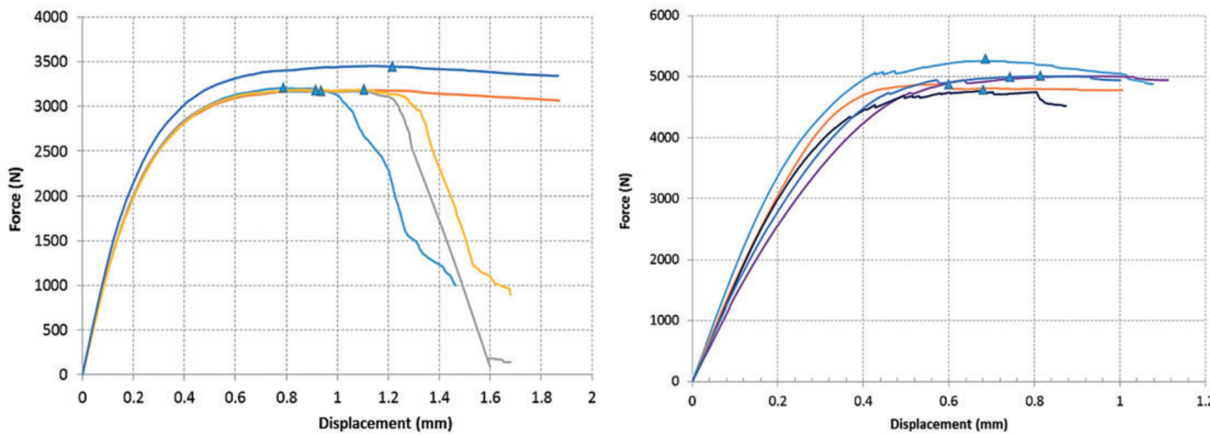

Figure 11. Experimental results of the shear tests: P1-10 sandwich (left) and P2-8 sandwich (right).

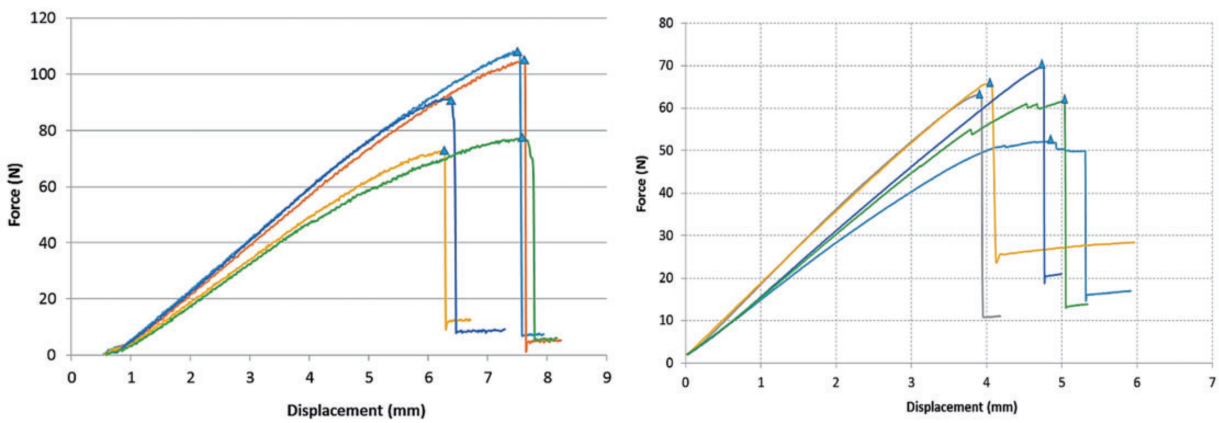

Figure 12. Experimental results of the four-point bending tests: P1-10 sandwich (left) and P2-8 sandwich (right).

was more than 7.5 mm. The differences in the four-point bending tests of the samples demonstrate an obvious influence of the nap-core sandwich's boundary geometry.

Figure 12–right indicates that the samples of P2-8 nap-core sandwich performed very similarly as the samples of P1-10 nap-core sandwich. The results, consisting of the force and the displacement, also scatter to some degree, but they are lower than those of P1-10 nap-core sandwich samples. Namely, the maximum force is between 50 N and 70 N, and the displacement at the debonding of the upper sheet is between 3.9 mm and 5.5 mm. Once again, the influence of the sandwich's boundary geometry is observed.

Through the experiments, buckling of the nap-core and debonding of the upper skin can also be viewed clearly. They are displayed by Figures 13 to 15.

Discussions

It can be noted that the sandwich acts almost like a typical linear elastic material before the damages.

Figure 13. Buckling of the nap-core sandwich samples in the compression test.

Figure 14. Shear buckling of the nap-core sandwich samples in the shear test.

Moreover, all samples show good average material strengths and moduli on density, which are shown in Table 2.

There are a number of factors of the nap-core that affect the obtained results of the tests on the sandwich samples, i.e. the boundary geometry, the resin content, and the curing condition. Of them, the boundary geometry is the major one, and its influence is most considerable in the four-point bending tests. To have a clearer insight into the role of the nap-core in the sandwich's strength, the amount and aspect ratio of the nap-core per area are taken and displayed in Tables 3 and 4, of which R1 is the ratio of the mass of the nap-core to the mass of the whole nap-core sandwich, and R2 is the ratio of the top area of the nap-core to the base area of the whole nap-core sandwich. It is noted that for each sandwich sample, there is a trend that the bigger the amount and the aspect ratio of the nap-core per area, the higher the value of the maximal force. This is not absolutely correct in every case but it can be seen an appropriate ground to compare the maximum forces of the nap-core sandwich samples in the same loading status.

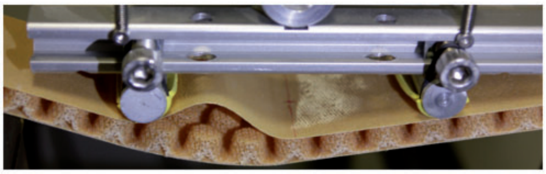

Figure 15. Local debonding of the nap-core sandwich's upper layer in the four-point bending.

In the compression, the samples first underwent a nonlinear interim period in which new contacts were established since the nap-core is made with knitted fabric. Subsequently, each nap of the nap-core provided the full resistance and the sandwich deformed

Table 2. Average densities and outcome values of the sandwich samples used for the experiment.

Nap-core sandwich type		P1-10		P2-8	
Test	Parameters	Value	Standard deviation	Value	Standard deviation
Compression	Elasticity modulus (MPa)	26.6	5.26	24.57	0.72
	Compressive strength (MPa)	0.51	0.06	0.74	0.02
	Sample density (kg/m^3)	183.2	2.63	175.06	2.13
	Specific strength (kN.m/kg)	2.78		4.23	
Shear	Shear modulus (MPa)	12.25	0.48	11.26	2.88
	Shear strength (MPa)	0.32	0.01	0.43	0.11
	Sample density (kg/m^3)	182.3	1.30	174.10	2.50
	Specific strength (kN.m/kg)	1.76		2.47	
Four-point bending	Flexural modulus (MPa)	1890.58	165.33	3241.82	273.59
	Flexural strength (MPa)	7.32	0.94	6.06	0.53
	Sample density (kg/m^3)	181.9	4.04	174.68	1.24
	Specific strength (kN.m/kg)	40.24		34.69	

Table 3. The mass ratio and the aspect ratio of the nap-core per area for P1-10 nap-core sandwich.

P1-10 nap-core sandwich	Compression					Shear					Four-point bending				
Sample no.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R_1	0.492	0.494	0.498	0.500	0.503	0.440	0.441	0.443	0.445	0.451	0.413	0.434	0.437	0.438	0.442
R_2	0.284	0.288	0.290	0.293	0.295	0.289	0.290	0.293	0.294	0.298	0.281	0.286	0.292	0.295	0.299
Max force (N)	1109	1189	1197	1222	1252	3174	3187	3190	3206	3456	73.2	77.1	91.6	105.1	108.1

Table 4. The mass ratio and the aspect ratio of the nap-core per area for P2-8 nap-core sandwich.

P2-8 nap-core sandwich	Compression					Shear					Four-point bending				
Sample no.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
R_1	0.264	0.269	0.271	0.272	0.274	0.217	0.219	0.220	0.222	0.223	0.208	0.211	0.214	0.216	0.219
R_2	0.344	0.348	0.352	0.359	0.365	0.344	0.348	0.352	0.359	0.367	0.340	0.344	0.352	0.359	0.367
Max force (N)	1762	1829	1865	1983	2088	4766	4854	4892	5013	5261	52.6	61.9	63.4	65.6	69.9

linearly until the buckling happened, which caused a quick downgrade of the force.

In the shear, there was not a clear period of establishment as that in the compression case, and the sandwich also performed linearly before that happened the shear bucking. Interestingly, the force did not descended responsively but kept unchanged for a time. This phenomenon also occurred in shear test of sandwiches with aluminium honeycomb, reviewed by François et al. in 2006,[16] and the reasons are not similar. There was hardening character of the metal material within the honeycomb core while there was yarn jamming within the knitted fabric nap-core. Normally, yarn jamming occurs when the fabric is extended to one direction (either weft or warp); thus, the spacing between the adjacent yarns in the other direction is gradually minified; the yarns then get in contact and hold one another better. In a shear case of the nap-core sandwich, the extension of the nap-core's knitted fabric is not uniform, so there is also a local accruement of the yarns in the fabric, which keeps the nap-core from a collapse. In the end of the shear tests, the second damage (i.e., the entire debonding of the top layer) might happen.

In the four-point bending, the sandwich worked similarly as itself in the shear test at first. The upper sheet delaminated locally around the places where the stresses are applied and that led to the plunge of the force.

When compare the experimental samples of the two nap-core types to one another, it is noticeable that the sandwich of P2-8 symmetric nap-core has the higher strength in the compression and shear tests while the sandwich of P1-10 nap-core has the higher strength in the four-point bending test.

One marked reason making P2-8 nap-core sandwich has very good mechanical properties is its geometry. Namely, the top diameter of its naps is rather small, which is only 5.5 mm compared to 9.5 mm of the other nap-core types. Therefore, the density of naps within P2-8 nap-core is very thick, giving its sandwich high strength. On the other hand, P1-10 nap-core possesses good mechanical properties since it has a greater thickness, heavier volume weight, and stronger fibre compared to P2-8 nap-core.

Conclusion

The experimental results have demonstrated the essential attribute of the nap-core sandwich, which implies a great possibility for numerical simulation of at least the linear stage and initiation of the damage if not the whole progression. Its linear elasticity is really different to normal dry knitted fabric (without resin), which is usually non-linear. Although the two nap-core types have knitting patterns and they are different at many other elements, the sandwich samples of both of them behave mechanically in an identical way. If not count the interim period in the compression tests, the nap-core can be considered as a shell structure which is much easier to be modelled with finite element software.

In actual applications, the differences in the boundary geometry of the nap-core sandwich samples are inevitable, and their effect to the performance of the samples may be considerable, especially in the bending condition. Therefore, variety of boundary geometries needs to be taken into account, and every design for the use of nap-core sandwich should be computed on the weakest case.

With fast development of the nap-core sandwich, finding simulation methods for it are so necessary because they will permit more cost-effective investigations on a wide range of the nap-core sandwiches, particularly when their parameters alter a great deal. Furthermore, different applications may require different parameters and specifications of the nap-core sandwich, and computational modelling is the most efficient and quickest way to optimize designs of the sandwich structures and predict their mechanical performances in advance. This has been developed by the authors and will be presented in a different paper.

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