Parametric Investigations of Mechanical Properties of Nap-core Sandwich Composites

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Abstract

The focus of this paper lies on the sensitivity of the nap-core sandwich – a novel kind of structural composite – to changes of its parameters. First, the fabrication, properties, and applications of the nap-core sandwich are briefly presented. This is followed by consideration of the sandwich composite's mechanical behavior. Finite element based simulation is applied to perform the parametric investigations. The height of the nap-core and the thickness of its knitted fabric as well as the face sheet of the sandwich are changed in order to investigate the dependence of the general mechanical properties of sandwich composites on those parameters. Experiments are used to validate the simulation results. The conducted investigation provides valuable information for the design of nap-core sandwich composites.

Keywords: A. Fabrics/textiles; A. Layered structures; B. Mechanical properties; C. Computational modeling.

1. Introduction

Composite materials, although rendering a relatively young group of modern engineering materials, have attracted a great deal of attention due to numerous benefits they offer. Modeling and simulation, as fundamental engineering activities, allow cost-effective investigation of their mechanical behavior and development of the structural design that fits some specific purpose. Even if limited to the work related to modeling, the scope of research in the field of composite materials is still rather broad. It ranges from providing basic modeling tools such as finite elements based on equivalent single-layer theories [1], layerwise theories [2, 3, 4], or their mixture [5, 6], via models that involve multi-functional [7, 8, 9] and functionally graded materials [10] and up to the models that deal with delaminated composites [11], damage detection and localization [12].

Sandwich-structured composites represent a special class of composite materials also known as core materials. They are created by laying a lightweight but thick core between two thin and stiff outer layers (also called skins or face sheets). The components are then bonded to one another using a strong adhesive to form a unique structure that possesses good out-of-plane compressive strength and high bending stiffness with a rather low density. Normally, the core has a hollow structure to reduce the weight [13]. Due to the notable performance-to-weight ratio and variety of the attached walls, the application of sandwich-structured composite materials continues to grow in automotive, aerospace, transportation and other industries. In particular, most lining elements are fabricated with non-metal sandwich materials of which the outer layers

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are usually laminated fabric composites and the core is honeycomb, foam, or nap-core. When the parameters of the sandwich's components change, the mechanical behavior changes as well. Hence, a wide range of properties may be produced for numerous applications.

Nap-core sandwich composite is a novel kind of cell-core material beside well recognized ones such as foam or honeycomb sandwich composites. Most sandwich structures with honeycomb or foam cores have a drawback originating from their closed inner structure. It causes difficulties in integration of supply lines (ducts and wires), and it may give rise to accumulation of condensation water that increases weight and reduces the mechanical properties of the structure. The nap-core has been developed not only to overcome the above problems but also to provide some important advantages in all physical, chemical as well as mechanical aspects [14]. Besides, nap-core sandwich is considered to be a type of textile composite as its nap-core and outer layers include fabric reinforcements. In other words, the nap-core sandwich is a textile composite fabricated with a sandwich structure [15].

The nap-core is made of 2D knitted fabric that is first pre-impregnated with a thermosetting resin and formed periodic cups with a pin mold by deep-drawing method. Afterwards, it is cured at high temperature for a few hours before cooled down at the room temperature to acquire a permanent 3-D form (see Fig. 1). The molding process gives the core crosswise periodic naps with cup-shaped profile, hence the name. To ensure the nap-core's desired properties (i.e., mechanical strength, deformability, wettability, and heat insulation), the constituent elements need to be properly selected, such as fiber material, resin material, knitting type of the fabric, etc.

Fig. 1. Photo of a nap-core

Since the nap-core resembles a fibrous structure, its resin plays the role of a coating layer rather than a monolithic matrix. Here, the resin – a thermoset – has a large number of significant functions, which is to

- Protect the fabric from harmful factors, and diminish the negative influence of small fractures in the fibers
- Keep a stable shape of the core, and reduce wrinkles and disorders to the fabric
- Keep the right position of the yarns, and minimize further fiber damage.

It is also worth mentioning that the resin possesses high reactivity and flexibility that are very important in continuous production of the nap-core, so its content in the entire nap-core is a matter of primary concern [16].

Beside numerous features shared with other sandwich-structured composites, nap-core and its sandwich own some unique ones. Due to the open structure, nap-core sandwich composites offer some rather important advantages for the design and installation including good drainage and ventilation and easy integration of ducts and wires. The knitted structure of the nap-core is already deformed non-uniformly after the forming process, so it is periodic at the macroscopic scale but non-periodic at the mesoscopic scale. Moreover, the nap-core is a composite rather than a single material, and its properties are changed significantly after the heating and curing stages. The nap-core may bear pre-stress at some level having undergone the described manufacturing procedure. Finally, the entire composite is anisotropic. Hence, it is difficult to forecast the properties of the nap-core sandwich.

Obviously, the unique structure and properties of nap-core sandwiches set them apart from other composite materials and render their testing and modeling a challenging task. Focusing on them, it has been found that not too much work has been reported and most of the published work so far is related to testing of nap-core sandwich structures. Gerber [17] tested and analyzed symmetrical nap-cores in terms of mechanical properties and compared them to single sided nap-cores and aviation-certified materials to evaluate their prospects for lightweight applications. Bernaschek et al. [18] compared nap-cores and honeycombs with respect to a number of mechanical properties such as flexural strength, modulus of elasticity, bonding of core material and facing. Gerber et al. [13] experimentally investigated symmetrical nap-core and honeycomb sandwich structures under impact load. Ha and Zehn [19] discussed the challenges of setting a suitable finite element (FE) model for nap-core sandwiched structures and reported in a further work [15] on approaches to FE modeling of nap-core composites, while the comparison with the experimental study proved the suitability of the built FE models. The present work extends the last mentioned one by using FE models to perform parametric investigations of geometric properties of nap-core sandwich composites, i.e. their influence onto their mechanical behavior. Namely, several geometric parameters, such as the overall height of the nap-core, the alignment pattern of the naps (triangular or rectangular), the upper and lower diameters of the naps, the distance between the nap centers, etc., determine predominantly the final properties of a nap-core sandwich.

2. Experimental investigation of nap-core sandwich

2.1. Samples and experiments

To obtain a nap-core sandwich, two thin face sheets of laminated composite are attached firmly to the top face and bottom face of a nap-core with a strong adhesive (Fig. 2). The resulting sandwich is open to both sides of its thickness, so it is classified as regional support composite - a kind of non-homogeneously supported sandwich structure [20]. The selection of knitted fabrics rather than other types of textile is crucial since knitting patterns permit larger elongation. There are a number of possible material choices for the core's fibers. Thermoplastic polymers (acrylic, polyester or polyamide), aramid, glass, cellulose, basalt, and hybrid fibers are the most successful ones (used alone or in combination) for they are non-toxic and strongly resistant against heat, solvents, hydrolysis and oxidizing agents. The fibers made of them also prove to be highly durable and tough. Nevertheless, many of those materials have low ultimate strain (around 4%) while production of the nap-core necessitates the textile to stretch even up to 250%. Thus, fabrics fabricated by knitting technique are used as they are very suitable for creating deep-drawn shapes without local fractures or creases [16].

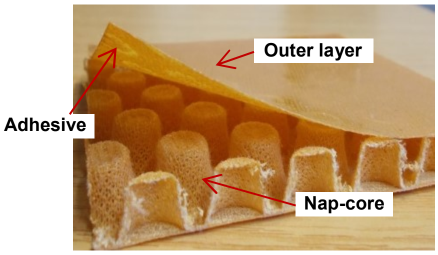


Fig. 2. Scheme of a typical nap-core sandwich

There are numerous types of nap-core available. However, it has been shown that their mechanical behavior exhibits a high degree of similarity, so this paper exemplifies only one of them, i.e. nap-core type P10-HN. Here, P means Phenolic resin, 10 denotes the height of the nap-cores in centimeter, and HN stands for Hybrid Nomex fiber. The appearance of the nap-core is shown in Fig. 3, while its parameters are given in Table 1. To ensure that the comparison between the samples is appropriate, a big panel of P10-HN nap-core sandwich was fabricated. Afterwards, all the samples were cut out from that panel.

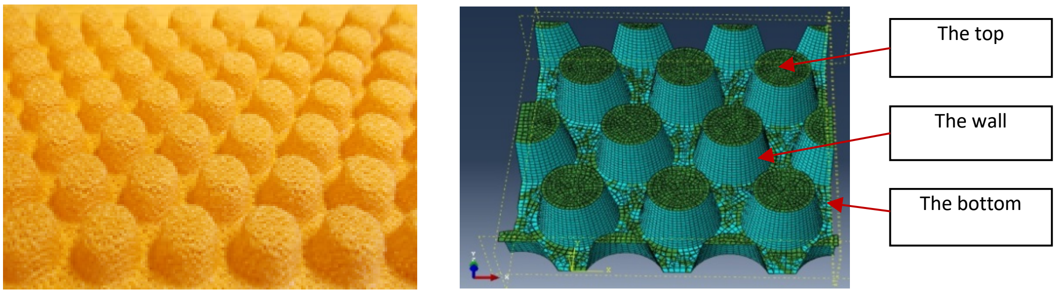


Fig. 3. Nap-core type P10-HN: Actual sample (left) and simulation model (right)

Table 1

The parameters of P10-HN nap-core

Material	Boundary height (mm)	Fabric thickness (mm)	Volume weight (kg/m^3)
60% fiber(5%Elasthane + 86%Nomex + 9%Polyamide) + 40% Phenolic resin	10	0.49	39

Three typical experiments were conducted on the samples of P0-HN nap-core sandwich: compression, shear, and four-point bending. Table 2 gives the standards, sample sizes and test speeds.

Table 2

Specifications for the mechanical tests on P10-NH nap-core sandwich

Test	Standard	Sample size length(mm) x width (mm)	Test speed (mm/minute)
Compression	D 3410/D 3410M – 03	50 x 50	10
Shear	DIN 53 294	200 x 50	1
Four-point bending	DIN 53 293	400 x 50	10

2.2. Experimental results

As already mentioned, the performed experiments contain three types of tests: compression, shear and bending. Whereas the experimental result of the four-point bending test was already reported by Ha and Zehn [15], this paper includes the results of all the experimental tests. The resulting relation between the force applied onto the sandwich and the displacements of the sandwich's top layer is presented and analyzed. The result of particular interest is the maximum force when buckling occurs, which might also be accompanied by debonding of the top skin.

Due to the structure of the nap-core sandwich, in the compression test (Fig. 4, left) the sample first undergoes a nonlinear interim period during which the nap-cores are gradually loaded until each of them provides the full resistance. Subsequently, the sample deforms linearly almost till the point at which the buckling occurs, followed by a fast decrease of the force (Fig. 4, right).

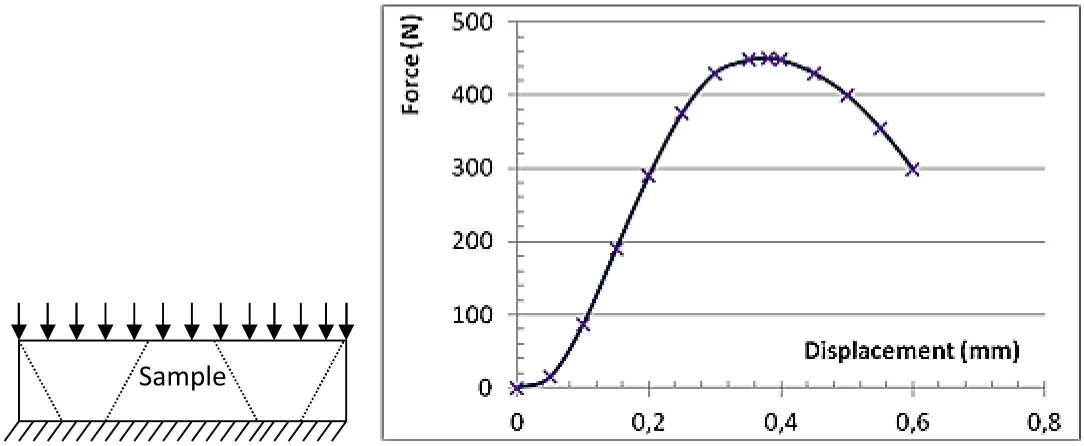


Fig. 4. Experimental scheme and data of the compression test on P10-HN nap-core sandwich

In the shear test (Fig. 5, left), a clear establishment period is not observed (Fig. 5, right). The sandwich sample performs almost linearly from the very beginning of the test until the point of shear buckling. Interestingly, the force does not descend but remains nearly unchanged beyond the point of shear buckling. The same phenomenon was observed in the shear test of sandwiches with aluminum honeycomb, reviewed by Francois Cote et al. in 2006 [21], but the reasons are different. While hardening of the metal honeycomb core is what characterized the test by Francois Cote et al., the yarn jamming within the knitted fabric nap-core is the cause of the effect in the test reported here. Normally, yarn jamming happens when the fabric is extended in one direction (either weft or warp). Thus, the spacing between the adjacent yarns in the other direction is gradually narrowed. The yarns finally get in contact and hold each other better. In the shear test 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 collapse. In the end of the shear test, a further damage, namely the entire debonding of the top layer, might also occur.

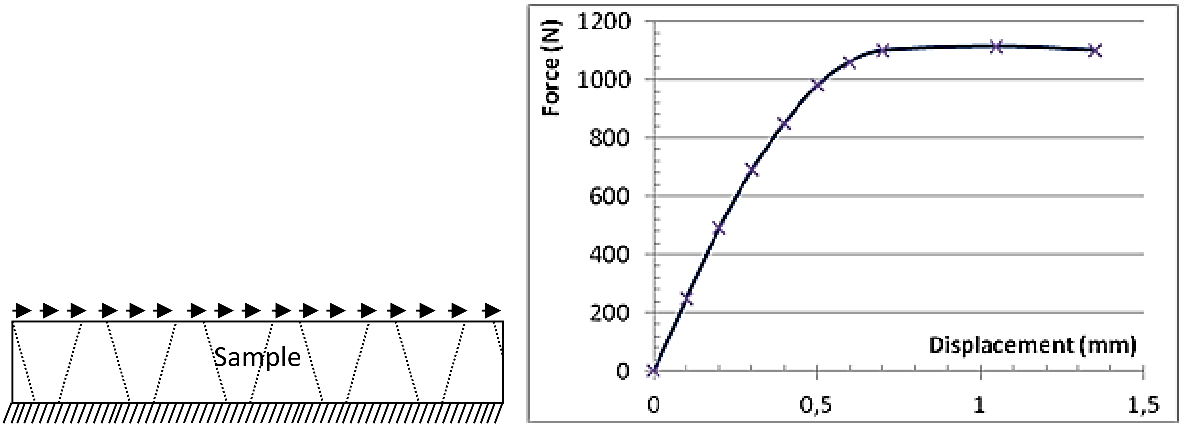


Fig. 5. Experimental scheme and data of the shear test on P10-HN nap-core sandwich

In the bending tests (Fig. 6, up), the establishment period can be observed (Fig. 6, bottom) but it is significantly shorter than that of the compression case. The damage is either local buckling of the nap-core or local debonding of the upper (compressed) sheet. In the four-point bending test, the damage occurs when the upper sheet delaminates locally around the positions of the maximum stress (due to local shear generated when the sample deforms under the bending load), which leads to abrupt force reduction.

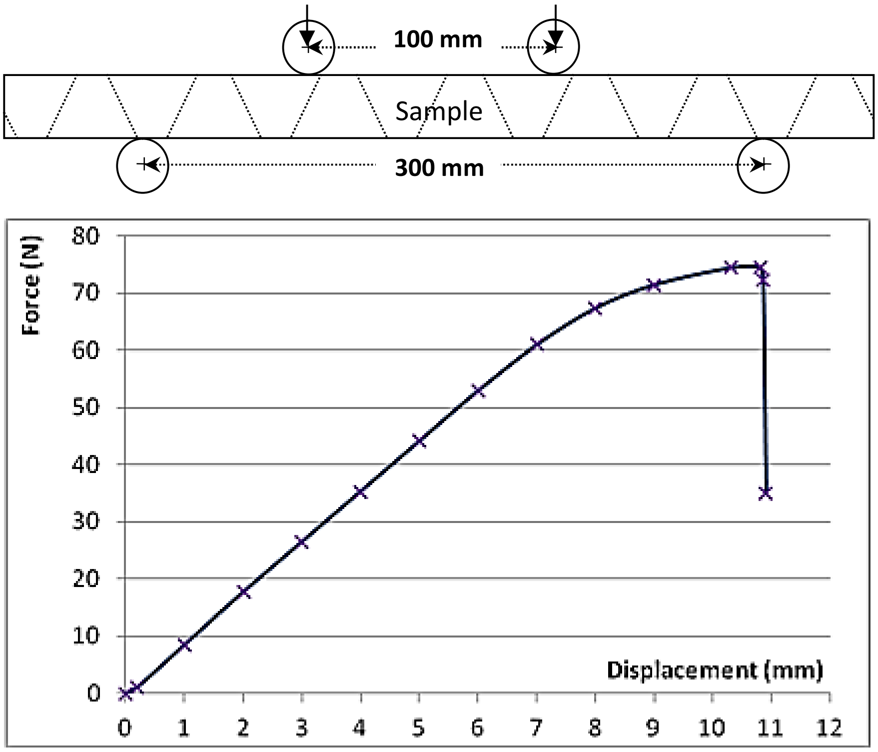


Fig. 6. Experimental scheme and data of the four-point bending test on P10-HN nap-core sandwich

3. Determination of nap-core elastic properties for the purpose of simulation

A textile structure can be viewed at three hierarchical levels. Coming bottom up, a polymer matrix and tiny fibers (also called mono-filaments) compose the yarns at the microscopic scale. In turn, the yarns are arranged to form the fabric at the mesoscopic scale. Finally, the fabric becomes the whole reinforcement of the composite at the macroscopic scale [22].

Finite element based simulation of nap-core sandwiches demands their elastic properties. Focusing on global, i.e. macroscopic behavior of the structure, certain assumptions are introduced into the FE modeling, as explained in the following. The outer layers are treated as thin shells because their thickness is typically less than 1/15 of their span, while the transverse shear effect is negligible [23]. The adhesive between the parts of the sandwich is always modeled as a very thin bonding layer. The nap-core is also modeled as a 3D-shaped thin shell. This implies that the macroscopic structure of the nap-core is unchanged, but its mesoscopic structure is converted from a knitted fabric into a thin shell. The actual nap-core is non-continuous and heterogeneous, while the modeled nap-core is continuous and homogeneous. Observed in this manner, the nap-core is equivalent to an anisotropic material, which generally has 21 independent elastic constants in the stiffness tensor. However, a further assumption is adopted in this work that the nap-core can be modeled as an orthotropic material – having nine independent elastic constants in the stiffness tensor. Already at this point, it should be emphasized that the agreement between the experimental and simulation results proved the assumption was justified. The nine elastic constants of an orthotropic material can be given in terms of three elastic moduli, three Poisson's ratios, and three shear moduli associated with the material's principal directions. With the above introduced assumptions, all the material parameters related to the thickness direction can be neglected, thus reducing the number of required engineering constants to four. These are the elasticity moduli, the shear modulus and Poisson’s ratio with respect to the in-plane directions, denoted by E_1, E_2, G_{12}, and ν_{12}, respectively. The in-plane axes are typically selected so that the first axis represents the wale direction, while the second axis represents the course direction of the nap-core's knitted fabric.

There are two approaches to obtaining the material parameters for FE simulations of a thin shell nap-core. The first approach is based on experimental investigation done on a designated knitted flat sheet. The second approach is computational homogenization implemented on the carefully selected Representative Volume Element (RVE) of the nap-core’s knitted fabric. The implementation of the two approaches has been detailed in references [15] and [19]. Hereafter, they are briefly reviewed.

The experiment-based approach:

In this approach, a knitted flat sheet is made of the same material as the actual nap-core’s fabric, a special procedure is applied to produce a rather similar pre-stressed state in the sheet to the one in the nap-core’s wall after molding and, finally, the engineering constants of the sheet are determined by experiments. The following steps are performed:

i) Determine the elongation of the nap-core’s wall assuming that the knitted fabric extends uniformly on its slopes and top faces (Fig. 3, right).
ii) Prepare a sheet of the same knitted fabric and pre-impregnated with the same resin and content;
iii) Stretch the pre-impregnated fabric, so that the elongation determined in the first step is obtained. Hence, the usual molding step is herewith replaced by a stretching step;

iv) Cure the stretched fabric at the same temperature and in the same time interval as already done with the nap-core to get a rather similar material state in the flat sheet.

v) Perform the experiments with the flat sheet and determine the engineering constants.

Another important aspect should be highlighted here. Namely, the obtained results confirm that the material parameters of the nap-core's wall are substantial. In other words, they play the major role in the determination of force and displacement of the nap-core sandwich, while those of the remaining nap-core's partitions, i.e. the top and the bottom faces (Fig. 3, right), are of minor influence (contribute less than 1.5% to the results). This is the critical understanding about the nap-core sandwich mechanical behavior as it permits a simplification by setting the determined engineering constants of the nap-core's wall to its whole structure (i.e. to all the nap-core's partitions: the top, the wall, and the bottom) without affecting the result significantly. This simplification is used in the present work.

The simulation-based approach:

In this method, the cured nap-core's knitted fabric is assumed to be periodic at the mesoscopic scale, which allows for simulation-based homogenization of its elastic properties. There are several homogenization techniques of which the asymptotic homogenization (AH) method [24, 25] and the Representative Volume Element (RVE) method [26] are the most suitable ones for materials of complex structure such as knitted fabrics. The RVE homogenization is quite often the method of choice due to its relative simplicity when applied to anisotropic fabric structures. This approach demands a careful selection of the RVE's geometry. Subsequently, a FE simulation is performed with suitable boundary conditions applied in order to determine the effective, i.e. homogenized properties. The homogenization approach may appear at the first glance more complicated than the experiment-based approach previously described. The input material data require the parameters of the constituents, i.e. fiber and resin, after curing. However, that is compensated by not having to do numerous tests and, additionally, by the applicability of the approach to various nap-core categories.

<u>Homogenization scheme</u>

The homogenization proceeds as follows:

i) *Determine the RVE of the nap-core's knitted fabric:* There are numerous ways of choosing it, but in practice, an optimal RVE should be as small and simple as possible while keeping all the material parameters of the nap-core wall irresponsive to boundary conditions.

ii) *Model the RVE in a FE program:* A finite element model of the selected RVE is created with all the material properties assigned.

iii) *Apply the constraints to the RVE and do the computation:* The periodic boundary conditions are applied to constrain the nodes on the RVE's opposite pair of faces. Ultimately, using the results of such a numerical analysis, the homogenized engineering constants of the RVE are determined.

The homogenized engineering constants of P10-HN nap-core's thin shell obtained by means of the two above described approaches are given in Table 3.

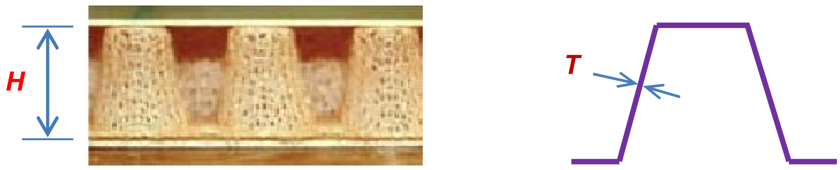
Table 3

The homogenized engineering constants of P10-HN nap-core's thin shell

Engineering constants	E_1	E_2	G_{12}	ν_{12}
Experiment-based approach	1.17E7	4.75E7	7.58E7	0.28
Simulation-based approach	1.08E7	4.67E7	7.26E7	0.28

4. Parametric investigation

With the material parameters available, the FE simulation models are prepared and used to investigate the effect of parametric changes of the nap-core sandwich structure. For each of the considered loading cases, a convergence analysis has been first done to determine the FE mesh that produces the converged results. The performed analyses are geometrically nonlinear and displacement-controlled in order to cover the post-buckling behavior as well. Such an investigation is expected to be of particular interest for the design specification and optimization of engineering applications. Beside the nap-core sandwich's geometrical parameters (e.g., the total height and the fabric thickness, Fig. 7), the variation of the material of the outer layers of the nap-core sandwich is also considered in the investigation. The results are presented below.



(a) (c)

Fig. 7. Geometrical parameters of the nap-core: (a) height *H*; (b) fabric thickness *T*.

4.1. Nap-core height (*H*)

In this case, the performance of the nap-core sandwich will be examined with an alteration of the nap-core's height (Fig. 7, left). The nap-core's height, *H*, is varied from 7mm to 12mm with an increment of 1mm. The change of *H* affects the stretch of the nap-core's fabric wall, which furthermore affects the resulting effective material properties.

Compression

The experimental results presented in Fig. 8 show that the nap-core's compressive strength decreases with the increase of its height. This is the consequence of several effects. With the increasing height, the slenderness of the single nap-cores as sub-domains increases as well. Furthermore, the nap-core's knitted walls become thinner as its knitted fabric is more stretched in production for higher values of height. And, finally, due to the same stretching effect, the resulting effective material constants have somewhat lower values. All these effects render the nap-core sandwich structure more susceptible to buckling under compression. Fig. 9 reveals that the simulation results reflect the experimental results as the compressive behavior and maximum force are similar. The inevitable differences between the experimental and simulation diagrams can be reasonably explained by idealizations implemented in the FE models. Those idealizations exclude the interim period at the very beginning (due to the perfect geometry of the model) and small local fractures that occur when the maximum force is reached and which is the cause of the relatively fast force decrease in the experiment. Additionally, one of the idealizations is the fact that the simulation models are prepared with the same geometry at the boundary, which is not the case with the experimental samples. As already explained, the actual samples are characterized by significant differences in the boundary geometry.

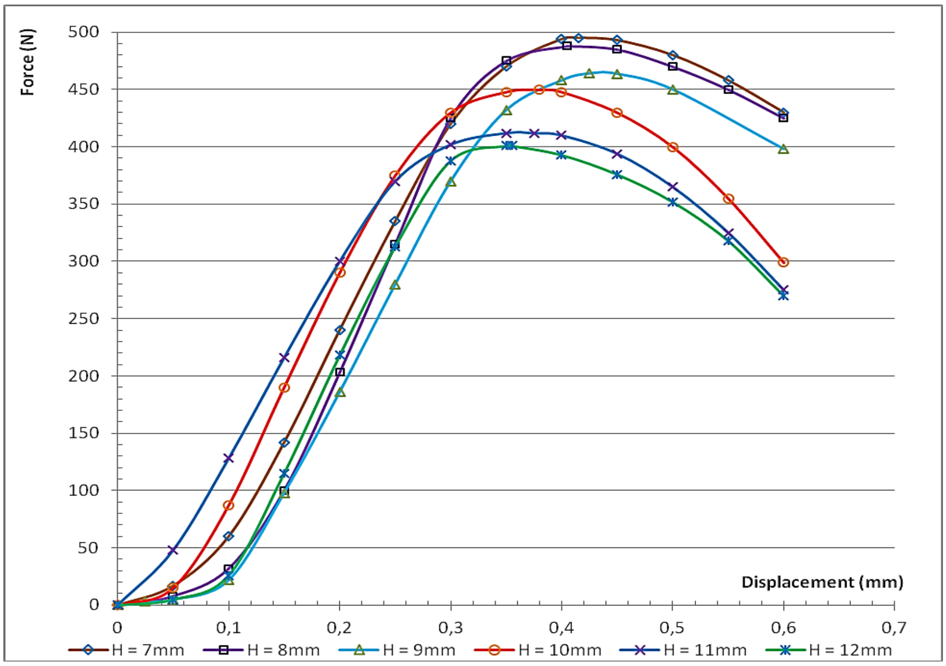


Fig. 8. Compression force versus displacement of the nap-core sandwich with varying *H* – experimental results

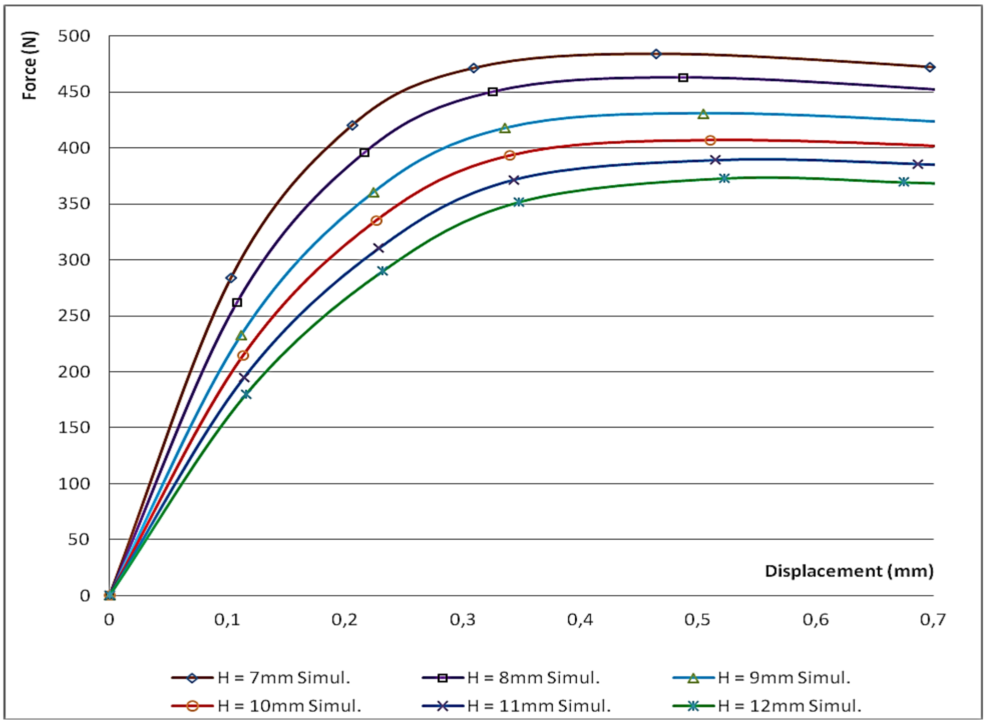


Fig. 9. Compression force versus displacement of the nap-core sandwich with varying *H* – simulation results

Fig. 10 depicts the development of the buckling force for the considered values of *H*. Again, bearing in mind the idealizations of the numerical models, the experimental and numerical results are in a good agreement in both the obtained values and trend of change of the buckling force with the increasing height.

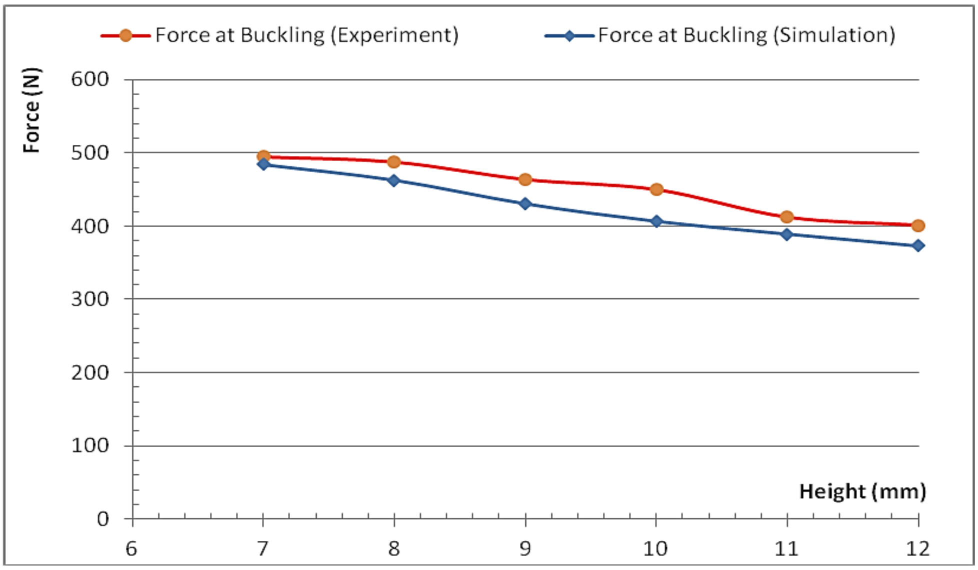


Fig. 10. Buckling force in compression versus the nap-core's height

<u>**Shear**</u>

In the shear test, the load carrying capacity of the nap-core sandwich samples behaves similarly as in the compression test: the higher the nap-core, the lower the maximum force (Fig. 11). The reasons are practically the same as in the compression test. The basic difference in the behavior is after reaching the point of maximum force. Namely, in this case the structure keeps its load carrying capacity in a relatively wide range.

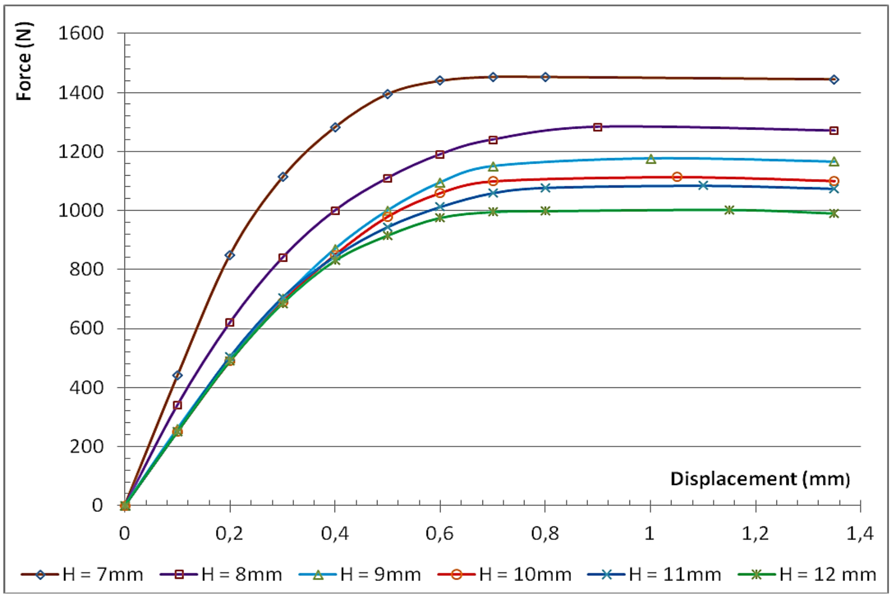


Fig. 11. Shear force versus displacement of the nap-core sandwich with varying *H* – experimental results

The results of the shear simulation are presented in Fig. 12. One may notice that the agreement between the simulation and experimental results is slightly better compared to the compression test. It may be reasonably assumed that this fact can be explained by lower sensitivity of the experimental results to the geometry of the sample edges for this load case.

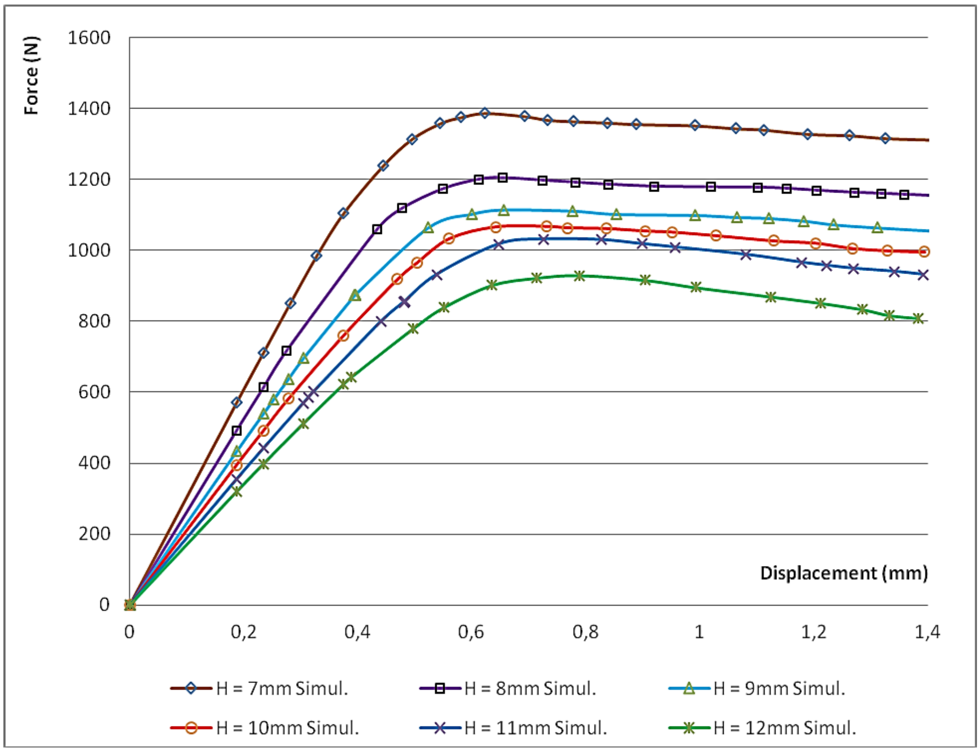


Fig. 12. Shear force versus displacement of the nap-core sandwich with varying *H* – simulation results

The diagram in Fig. 13 shows that the experimentally determined and numerically predicted maximum forces are in this case also in a rather good agreement.

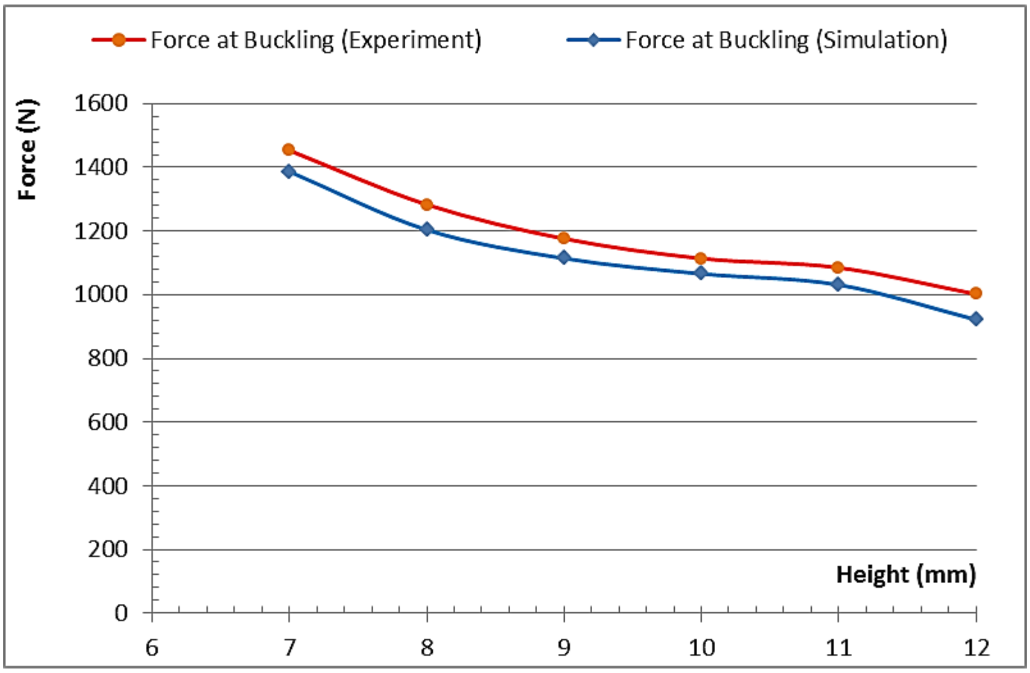


Fig. 13. Maximum force in shear versus the nap-core's height

Four-point Bending

The varying nap-core height has divergent influences onto the bending behavior. Larger values of the height increase the inertial moments of the sample as the stiffness and carrying capacity of the outer layers come more to the fore. But at the same time, as already elaborated, the nap-core wall becomes thinner and the effective material constants have lower values, and both of those effects decrease the stiffness in bending. The diagram in Fig. 14 reveals that the buckling force in bending continuously increases with the increasing values of height, thus suggesting that the first mentioned effect prevails with the considered samples. This case is also characterized by the abrupt reduction of load carrying capacity after the maximum force is reached, which is the consequence of delamination of the outer layers.

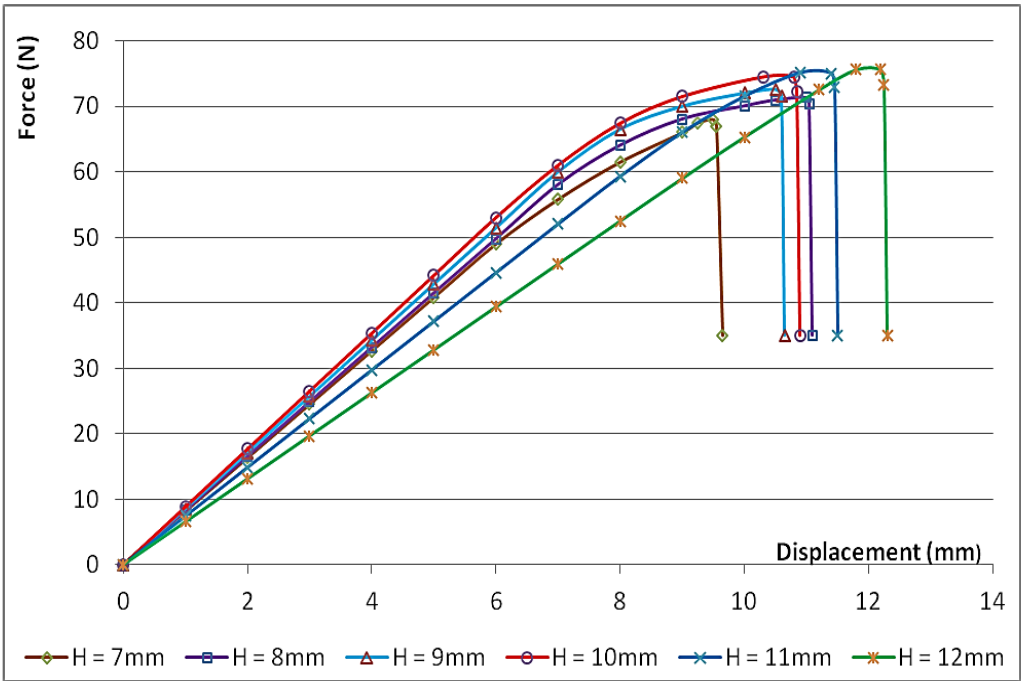


Fig. 14. Four-point bending force versus displacement of the nap-core sandwich with varying *H* – experimental results

Fig. 15 depicts the simulation results. The major difference between the simulation and experimental results is in the post-buckling behavior and this is the consequence of the fact that the debonding is not considered in the simulation.

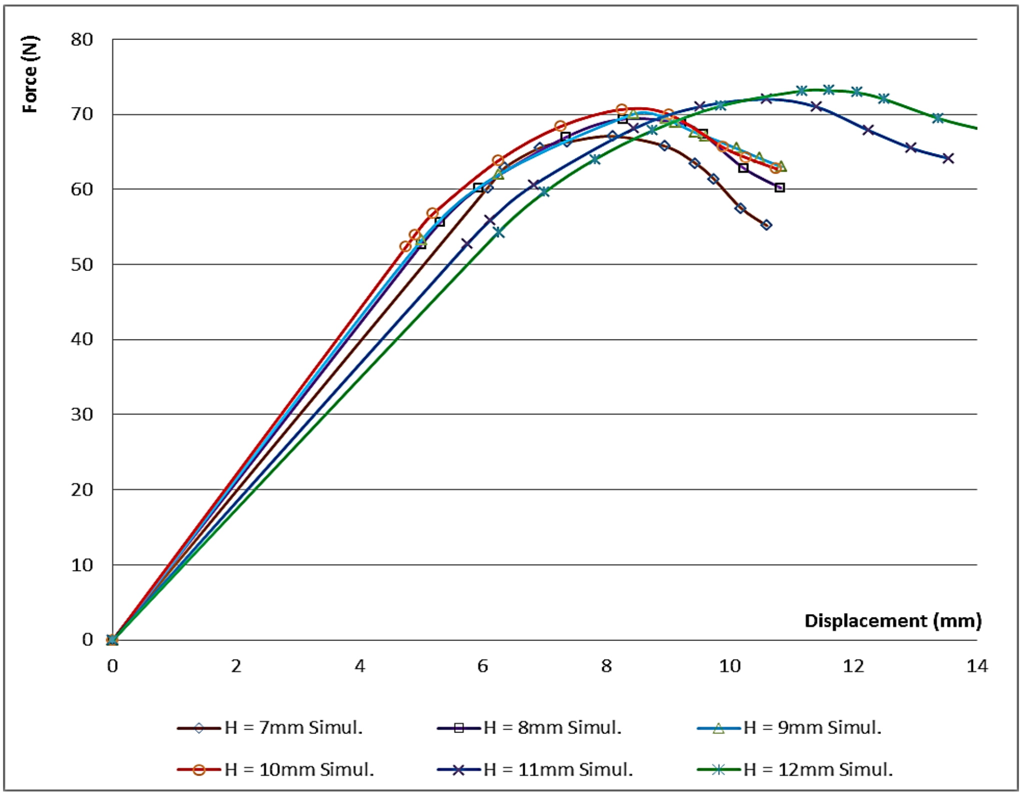


Fig. 15. Four-point bending force versus displacement of the nap-core sandwich with varying *H* – simulation results

Finally, regarding the maximum bending force before buckling occurs, Fig. 16 shows a similar level of agreement between the experiment and simulation as in the previous cases.

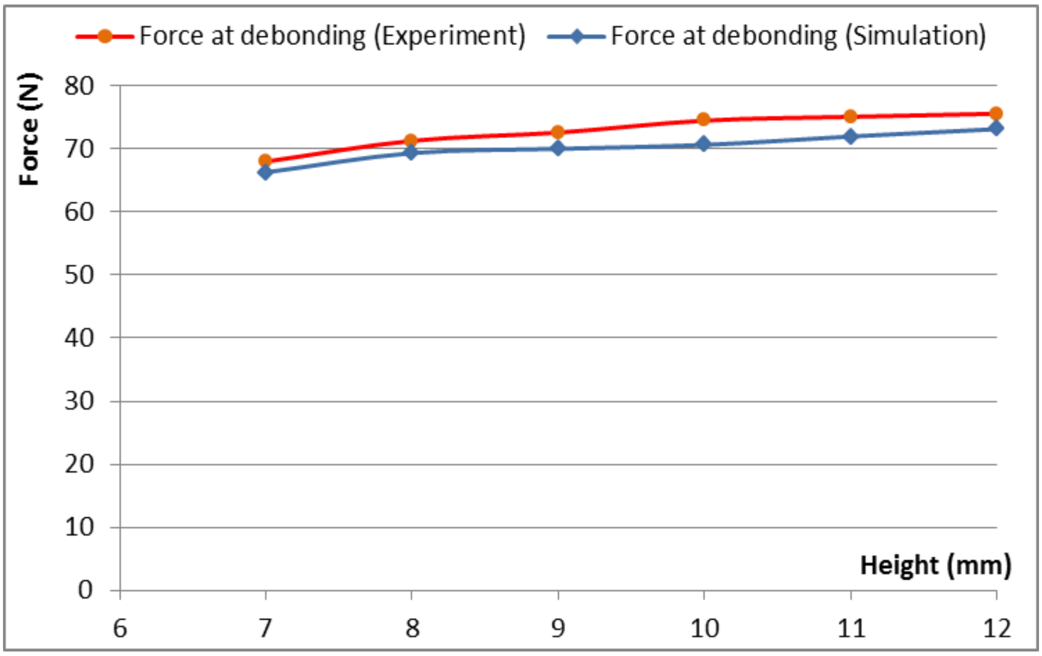


Fig. 16. Maximum force in bending versus the nap-core's height

Hence, it has been seen that with the increasing thickness *H*, the maximal force of P10-HN nap-core sandwich decreases in the compression and shear, but increases in bending. Obviously, a proper choice of *H* will be decided based on specific application of the nap-core sandwich structure and associated loads. Table 4 summarizes the obtained results.

Table 4
Results of the tests and simulations on P10-HN nap-core sandwich with variable *H*.

P10-HN Nap-core Sandwich		**Compression**	**Shear**	**Four-point Bending**
Sample size (cm x cm)		**5 x 5**	**20 x 5**	**50 x 5**
H (mm)	Critical force	F_{max}(N)	F_{max}(N)	F_{max}(N)
7	**Experiment**	495.00	1453.00	68.00
	Simulation	484.00	1386.52	66.30
	Difference	*-2.22%*	*-4.58%*	*-2.50%*
8	**Experiment**	488.00	1283.00	71.30
	Simulation	462.85	1203.82	69.35
	Difference	*-5.15%*	*-6.17%*	*-2.74%*
9	**Experiment**	464.00	1176.00	72.60
	Simulation	430.75	1114.22	70.03
	Difference	*-7.17%*	*-5.25%*	*-3.55%*
10	**Experiment**	450.00	1114.00	74.50
	Simulation	406.78	1065.89	70.64
	Difference	*-9.60%*	*-4.32%*	*-5.18%*
11	**Experiment**	412.00	1085.00	75.10
	Simulation	389.31	1031.16	71.99
	Difference	*-5.51%*	*-4.96%*	*-4.14%*
12	**Experiment**	401.00	1002.00	75.60
	Simulation	373.08	921.68	73.16
	Difference	*-6.96%*	*-8.02%*	*-3.23%*

4.2. Thickness and layout of the nap-core's knitted fabric (*T*)

Tests and simulations prove the importance of the thickness and layout of the nap-core's knitted fabric layer (Fig. 7, right) for the overall mechanical properties of the nap-core sandwich. To demonstrate this influence, a nap-core sandwich structure is considered, whereby the nap-core type P10-HN is: a) a single layer of knitted fabric with the thickness of 0.49 mm, and b) double layer with the overall thickness of 0.7 mm.

<u>Compression</u>

The diagram in Fig. 17 reveals the remarkable differences in the load carrying capacity of the sandwich structure in compression when its nap-core is changed from option a) to option b). In both the experiment and simulation, the maximal force increases almost 4 times. The values of buckling force determined by the experiment and the simulation agree well, while the post-buckling behavior predicted by the simulation is obviously different from the experimentally determined one due to local debonding that is not a part of the simulation.

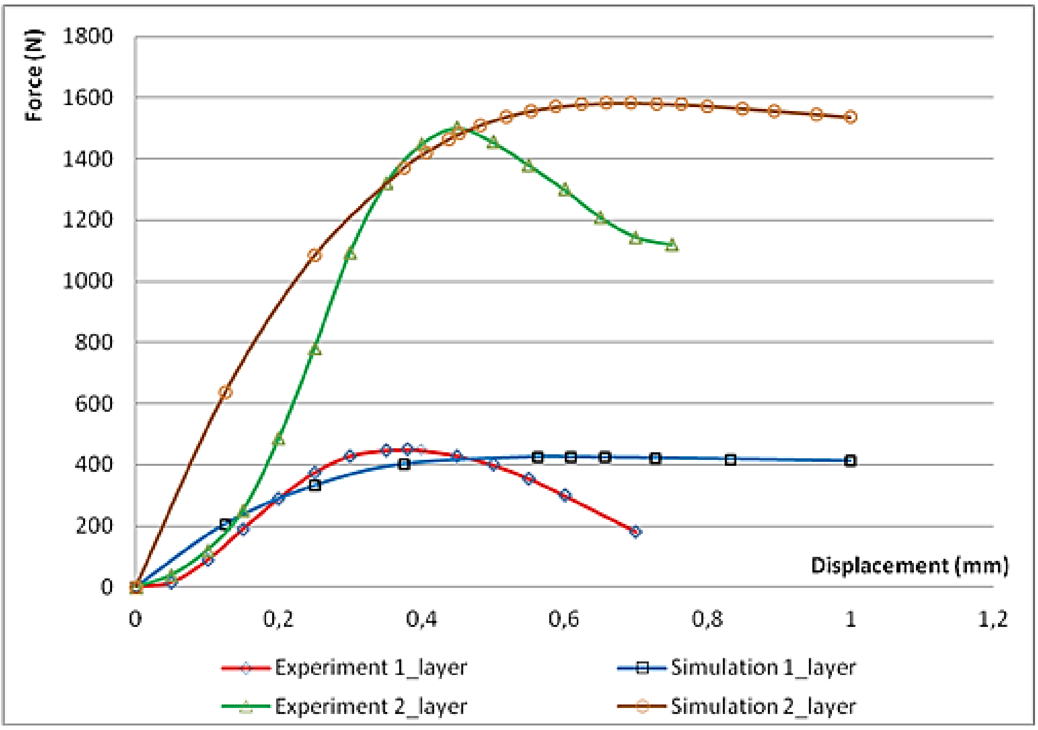


Fig. 17. Compression results of the nap-core sandwich with different fabric thicknesses: simulation vs. experiment

Shear

The comments from the compression test extend to the shear test with the major difference that the critical force increases approximately 2.5 times from option a) to option b). Additionally, the force decreases only slightly after the maximum is reached, as no debonding occurs (Fig. 18).

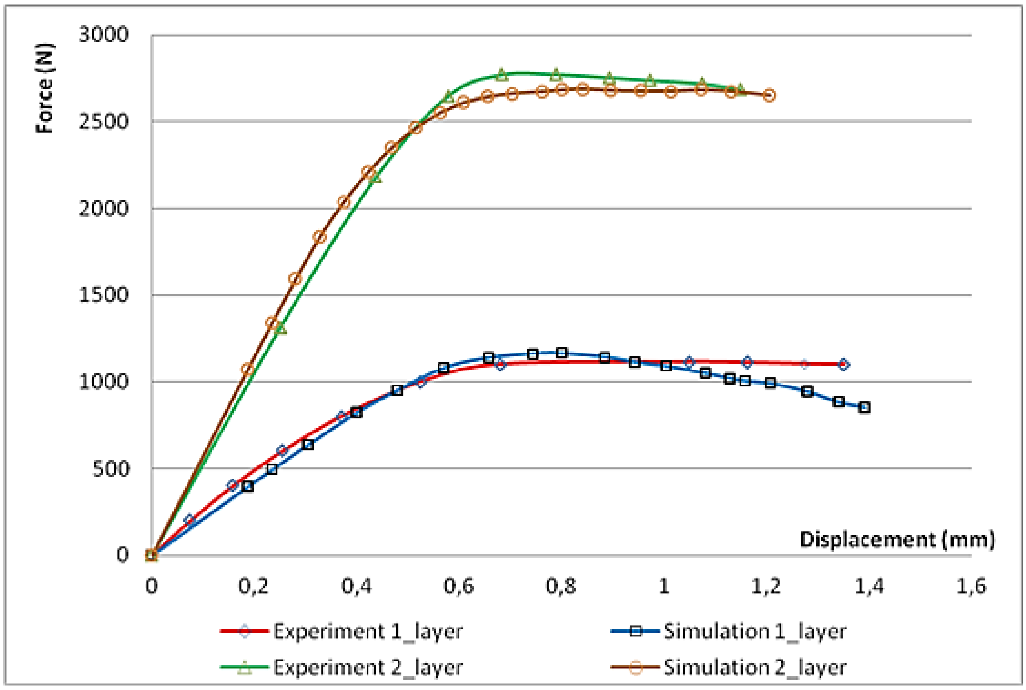


Fig. 18. Shear results of the nap-core sandwich with different fabric thicknesses: simulation vs. experiment

Four-point Bending

In the four-point bending, the maximal force increases approximately 2 times with the considered increase in the thickness. Debonding of outer layers explains the significant difference between the experimentally determined and simulated post-buckling behavior, as emphasized earlier (see Fig. 19).

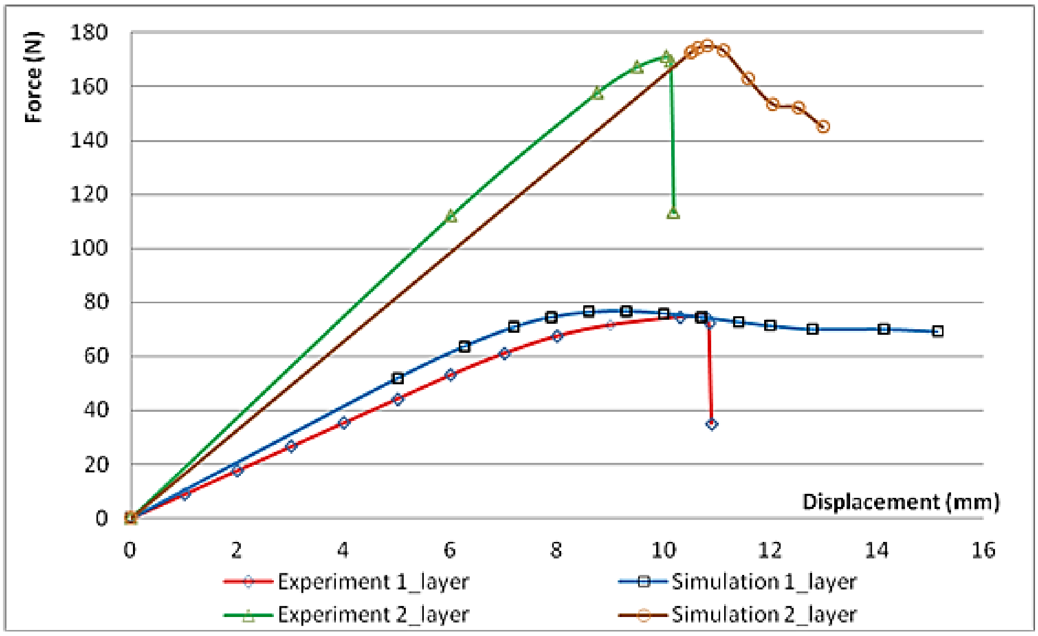


Fig. 19. Four-point bending results of the sandwich with different fabric thicknesses: simulation vs. experiment

As expected, the increase of the nap-core's thickness improves the strength of the structure with respect to all the considered types of loads but, obviously, the degree of improvement is different for different types of loads. Hence, the sensitivity of structural resistance to the change of the nap-core's thickness depends on the type of load. Obviously, the type of load the structure is exposed to determines whether a change of this structural parameter should be used as a measure for structural improvement. Table 5 overviews the attained results.

Table 5

Result of the tests and simulations on P10-HN nap-core sandwich when T changes

P10-HN Nap-core Sandwich		**Compression**	**Shear**	**Four-point Bending**
Sample size (cm x cm)		**5 x 5**	**20 x 5**	**50 x 5**
Nap-core's fabric thickness		F_{max}(N)	F_{max}(N)	F_{max}(N)
One-layer fabric	Experiment	450.00	1114.00	74.50
	Simulation	426.29	1164.27	76.78
	Difference	*-5.27%*	*4.51%*	*3.06%*
Two-layer fabric	Experiment	1500.77	2772.85	171.21
	Simulation	1583.54	2687.92	175.13
	Difference	*5.52%*	*-3.06%*	*2.29%*

4.3. Material of the face sheets

Beside the nap-core, the face sheets are also important for the sandwich's overall strength, particularly in bending. Therefore, the influence of face sheets' material is also explored here. In doing that, the nap-core material is kept unchanged (type P10-HN). In all previously reported cases material Airpreg PC8242 is used for the outer layers. Here, a new material, Gurit PHG600, which is significantly less stiff than Airpreg PC8242, is additionally employed. Three different samples are prepared, with the only difference related to the face sheets: 1) single layer Airpreg sheets; 2) double-layer Airpreg sheets and 3) single-layer Gurit sheets. As the outer layers of the sandwich are fixed to the testing machine in the compression and shear tests, the change of the material of the outer layers plays no role in those tests. Hence, the influence is tested in bending only. The experimental results of the four-point bending are presented in Fig. 20.

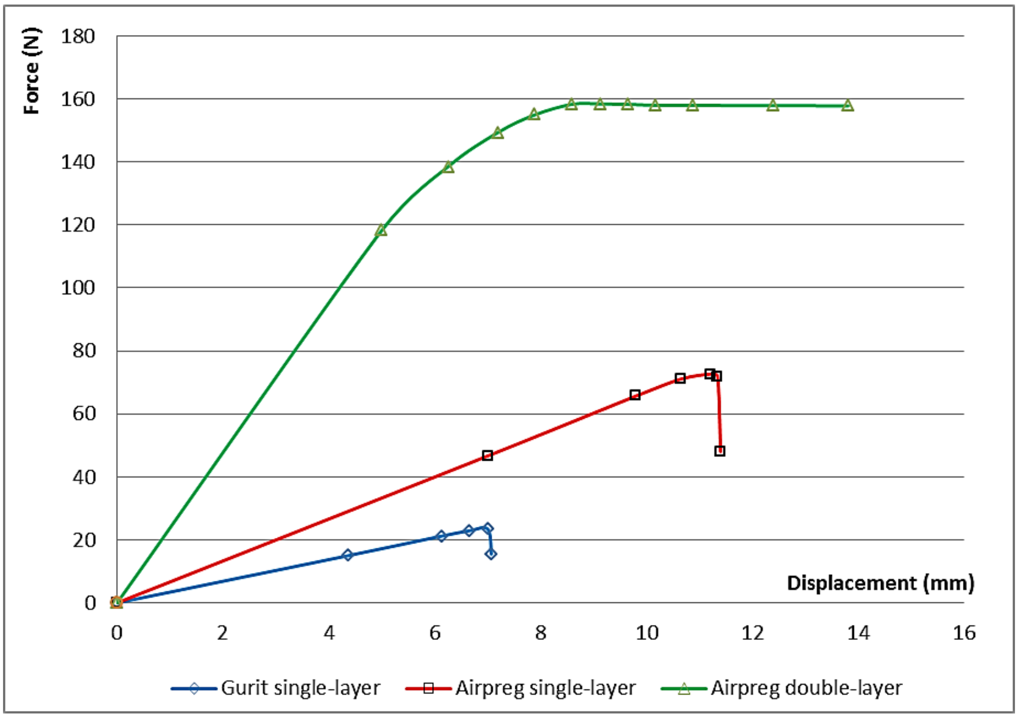


Fig. 20. Four-point bending results of the sandwich with different outer layers: Experiment

Four-point bending

The results display significant differences in the performance of the sandwich in the four-point bending with different material and layout of its skins' material. Compared to the sample with one-layer Airpreg skins, the sample with one-layer Gurit skins has much lower maximal force (only one third). On the other hand, the sample with two-layer Airpreg skins has a much higher maximal force (more than two times). Of even greater importance is the behavior of the sandwich structure after the maximal force has been reached. In the case of double-layer, the force remains almost constant, while the other cases are characterized by abrupt drop of the force. This is due to the much larger resistance of the outer layers in the double-layer solution against bending and the resistance is maintained to a certain degree even after debonding occurs. Hence, this solution is more robust in buckling.

5. Conclusion

Successful modeling and simulation of the nap-core sandwich structures is a prerequisite for answering the question: which parameters of the nap-core sandwich need to be changed and how in order to improve certain performance? The parametric studies have confirmed theories on the nap-core sandwiches claiming that:

- when the nap-core's height is decreased, the sandwich's load-carrying capacity increases in compression and shear, but decreases in bending;
- when the fabric thickness increases, the load-carrying capacity increases in each type of test;
- increasing the stiffness of the outer layer and changing their layout (single- or double-layer) results not only in a stronger but also in a significantly more robust sandwich structure.

The parametric investigations met two objectives: confirmed the suitability of the approaches to obtaining the effective material properties and effectiveness of the simulation FE models and, additionally, provided valuable knowledge on how the nap-core sandwich structures behave and perform with variable geometric parameters under various loading conditions. This knowledge will certainly facilitate the design optimization of the nap-core structures. However, it is obvious that a number of parameters of the nap-core sandwich composites need to be considered simultaneously to reach a high-performance solution in cases of complex loading conditions. On the other hand, almost any change brings certain drawbacks beside the benefits, and hence, reaching a solution that is close to the optimal one may be rather difficult and demanding. Surely, engineers will rely on computer programs and suitable modeling tools to assist the design optimization of the nap-core sandwich structures.

Beside the optimization problems, the future work may include the simulation of the whole production process of the nap-core sandwich structures. This could introduce many additional aspects into the analysis, such as the post-buckling behavior, fatigue limit, resilience, effect of the local damages, and dynamic behavior. This work will require a great deal of effort, but it will also harvest many benefits such as more accurate results, better control of the relation between the input parameters and the output behavior, and easier movement from one to another type of nap-core.

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