Mechanical behavior of a sandwich with corrugated GRP core: numerical modeling and experimental validation

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ABSTRACT. In this work the mechanical behaviour of a core reinforced composite sandwich structure is studied. The sandwich employs a Glass Reinforced Polymer (GRP) orthotropic material for both the two external skins and the inner core web. In particular, the core is designed in order to cooperate with the GRP skins in membrane and flexural properties by means of the addition of a corrugated laminate into the foam core. An analytical model has been developed to replace a unit cell of this structure with an orthotropic equivalent thick plate that reproduces the in plane and out of plane behaviour of the original geometry. Different validation procedures have been implemented to verify the quality of the proposed method. At first a comparison has been performed between the analytical model and the original unit cell modelled with a Finite Element mesh. Elementary loading conditions are reproduced and results are compared. Once the reliability of the analytical model was assessed, this homogenised model was implemented within the formulation of a shell finite element. The goal of this step is to simplify the FE analysis of complex structures made of corrugated core sandwiches; in fact, by using the homogenised element, the global response of a real structure can be investigated only with the discretization of its mid-surface. Advantages are mainly in terms of time to solution saving and CAD modelling simplification. Last step is then the comparison between this FE model and experiments made on sandwich beams and panels whose skins and corrugated cores are made of orthotropic cross-ply GRP laminates. Good agreement between experimental and numerical results confirms the validity of the proposed model.

KEYWORDS. Sandwich Structures; Corrugated Core; Homogenisation; Finite Element.

INTRODUCTION

Composite sandwiches are a structural solution trying to integrate the advantages of the sandwich concept, high specific flexural rigidity, with those of Fibre Reinforced Polymer (FRP) composites, such as lightweight, complex shaping and flexible material assembling [1]. An optimised composite sandwich solution is a potential replacement of thick and heavy monolithic bidimensional structures, and hence an effective lightweight design strategy [2]. Therefore consideration for composite sandwich panels, both as primary and secondary structures, has been growing in particular in the transport sector [3,4]. This is for instance witnessed by the many recent EU funded projects that have somewhat involved the development of sandwich solutions, some of which comprise: ALCAS, APOLISS, CELPACT, DE-LIGHT, ENLIGHT, HYCOPROD, LITEBUS, MID-MOD, SANDWICH, SANDCORE, [3, 5].

A limitation to this high demand of sandwich solutions, and their more widespread adoption, is the lack of an adequate mechanical characterisation and specific design tools [3]. Furthermore, a composite sandwich is subjected to typical damaging of monolythic composites like delamination and debonding of laminated costituents [6-9].

The present study has considered a "structured core" sandwich concept, in which the traditional foam or honeycomb core is replaced or assisted by a corrugated laminate, in general made of the same material of the skin faces (see Fig. 1).

Corrugated-core sandwich concepts with various geometries (the most recurring being the trapezoidal and the sinusoidal shapes) have been proposed since the beginning of the last century [10]. Applications have been for many years limited to whole metallic or cardboard structures, and the extension to fully FRP solutions dates around the end of last century [11-13].

One reason for the special appeal of this class of sandwiches is the improved in-plane crashworthiness and out of plane impact resistance, mainly obtained by the more difficult skin-core debonding due to the generally stronger joining between the corrugated core and the skin faces [14-16]. The behaviour of corrugated sandwiches under transverse concentrated loading, typically poor for traditional foam cored sandwiches, is also significantly improved in many aspects: local indentation, local skin buckling, out-of-plane shear resistance [17,18]. Finally, the overall in plane stiffness and strength performances, especially in the corrugation direction, are also significantly improved. These advantages usually come at the expenses of a weight penalty (densities of corrugated cores are generally higher than foam cores), and a more complex manufacturing assembly.

Another difficulty intrinsic to the adoption of corrugated core sandwiches has been the lack of analytical/numerical tools for the effective prediction of their mechanical response at large scales, essential for designing complex structures (e.g. ships, aircrafts, heavy mass transport structures, etc..). In these cases, a detailed 3D FEM representation of the material is obviously far too computationally onerous and time consuming.

By considering the periodic nature of the corrugation pattern, a number of works have tackled the problem by trying to homogenise the sandwich material into an equivalent two-dimensional orthotropic continuum material [10]. A structural sub-element of material is first identified as the repeating unit. The mechanical response of this elementary cell, subject to some kinematic conditions, is then reproduced by finding the elastic constants of a continuum plate element able to determine an equivalent response in terms of forces or energies. In general a simplified Kirchoff-Love plate behaviour is assumed (classical sandwich laminate theory), modified to allow for transverse shear deformation (Reisner-Midlin plate model). In fact the intrinsic out-of-plane low shear rigidity in sandwiches requires this further modelling effort [19,20].

One of the first homogenisation models, for a corrugated trapezoidal core shape, was proposed by Libove et al [21,22]. In these seminal works, some simplifying assumptions are made on the strain behaviour of the corrugated sandwich, such as infinite out-of-plane rigidity (no local indentation and skin face buckling can then be modelled), and transverse sections remaining straight in the deformed configuration, although allowed to rotate with respect to the middle plane (accounting for first order transverse shear deformation). It is noticed that the method outlined in [21,22] considers isotropic material constituents, although the final homogenised element is orthotropic due to the unidirectional orientation of the corrugation (structural ortotropy).

Following the above-described general approach, several other more or less refined homogeneisation methods have been proposed [10]. A number of works have extended the Libove's approach to different corrugations, obtaining some closed-form analytical solutions for specific geometries [23-28]. Some other works have proposed a characterisation of the homogenised element by FEM simulation of the behaviour of the corrugated sandwich elementary cell [29,30]. A number of works have proposed a plate formulation based on the Classical Lamination Theory [27,31,32], in some cases considering the corrugation as a separate layer from the faces [33]. A few authors have dedicated special effort to improve the modelling of the transverse shear deformation behaviour [34-36]. Another more sophisticated analytical approach, still based on the possibility to identify an elementary repeating element of material, is also the "asymptotic expansion homogenisation", successfully extended to corrugated sandwiches by a number of authors [10,37].

In the present work the classic approach presented by Libove et al [21,22] is revised in order to extend it to the use of orthotropic constituent materials. This in order to obtain an homogenisation model for a fully composite corrugated sandwich, where both skin faces and corrugated sheets are made of an orthotropic Glass Reinforce Polymer (GRP) material. The core laminate is in particular corrugated along one direction, and presents a trapezoidal shape type geometry with wide crests and troughs that provide the sites for the attachment to the skin faces, realised by a chemical bonding

continuity of the matrix resin. The space between the corrugate and skin laminates is filled by PVC foam, whose main contribution is to strengthen the core GRP webs against buckling.
The work provides an analytical formulation of the equivalent elastic constants of the homogenised model, which are also compared with those derived by a 3D FEM simulation of the elementary sandwich cell. The homogenised model has then been implemented in a typical shell element in ANSYS. Experimental tests have been performed on both beams and panels manufactured in-house by hand lay-up lamination. The beams have been tested in three point bending, along and perpendicular to the corrugation, in order to uncouple the relative bending stiffness. Specific loading conditions for the panels have also been implemented in order to reproduce pure torsional and coupled torsional-bending conditions. Results from all the experimental evaluations have matched very well the numerical predictions based on the homogenised model.

ANALYTICAL MODEL OF HOMOGENISATION

In Fig. 1 left, the geometry of the sandwich considered for the homogenisation is sketched. It can be noted that the core has a trapezoidal shape in the transversal section of the corrugated laminate, symmetric with respect to mid-plane of the sandwich and constant along x. Because of its geometry, the corrugated laminate has an intrinsic orthotropy, in fact in-plane and out-of-plane behaviour changes between x and y direction. Homogenisation can be obtained once the unit cell is defined: in Fig. 1 middle its transversal section is depicted. It represents the repeated element of the periodic structure of the corrugated core, under the assumption of indefinite length in x. In Fig. 1 right the equivalent homogenised cell is depicted: we can consider it as a portion of a thin plate subjected to small deformation which elastic constant must be equal to those of the unit cell with the corrugated core. These constants are: in-plane stiffness (E_x, E_y, G_{xy}), flexural stiffness (D_x and D_y) and torsional stiffness (D_{xy}) and shear transversal stiffness (D_{Qx} and D_{Qy}).
The procedure exposed so far is the same as the one in [22] where some basic assumption were made:

- Small deflections,
- Elastic modulus of the equivalent plate in z is infinite,
- Linear segments normal to the mid-plane remain linear but not necessarily normal to the mid-plane because of the shear effect,
- Thickness of the skins small compared to the core,

Under these assumptions, in [22] expressions of the elastic properties of the equivalent cell were derived from the geometric parameters of the unit cell of the corrugated sandwich, for isotropic materials and symmetric transversal section of the core. In the present work, the limitation of an isotropic material has been removed for both skin and core. Two assumptions were added to the ones previously cited and are:

- Skins and core have the same layup,
- The layup is symmetric.

Procedure followed to obtain the expressions of the in-plane and out-of-plane stiffness is similar to the one in [22] but with the difference that, due to orthotropy of the laminate, the elastic constants of the material must be defined for the two directions x and y, in particular: E_x, E_y, ν_{xy} and G_{xy}. For purposes of the present work, only the out of plane equivalent properties are of interest. In-plane elastic stiffness were obtained too and are reported in Appendix for completeness but they don't play any role in the simulation and tests of the following paragraphs.
Flexural elastic stiffness are:

$$D_x = \frac{1}{2} E_x t_s h^2 + E_x I_c \tag{1}$$

$$D_y = \frac{\frac{1}{2}\left(t_s h^2 + 2I_c\right) E_x E_y t_s h^2}{E_x\left(t_s h^2 + 2I_c - \nu_{xy}\nu_{yx} t_s h^2 - 2\nu_{xy}\nu_{yx} I_c\right) + \nu_{xy}^2 E_y t_s h^2} \tag{2}$$

where I_c is the moment of inertia, per unit width, of the corrugation cross section with respect to its mid-plane, and ν_{ij} are flexural Poisson coefficients of the laminate.
And for the torsional stiffness:

$$D_{xy} = G_{mxy} t_s h^2 \tag{3}$$

At this stage, an analytical homogenized formulation of the transversal shear stiffness has not been obtained yet. For this reason, case studies here analyzed will concern applications where the shear deformation can be neglected (for example because of the presence of a PVC filler in the corrugation).

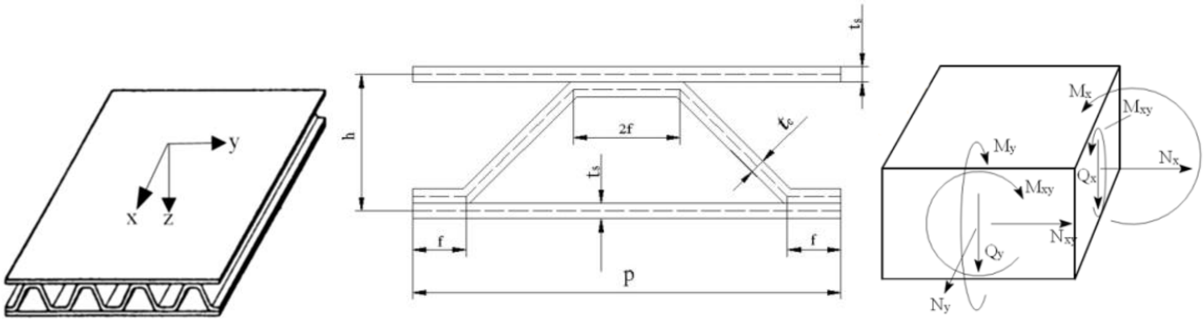

Figure 1: Axonometric view of the sandwich (left), definition of geometric parameters of the transversal section (middle), homogenised unit cell (right).

NUMERICAL ANALYSES

Validation of the analytical model

The analytical model of homogenization has been validated with 3D Finite Element analyses on the unit cell subjected to simple load systems. In Fig. 2 loads and boundary constrains used to evaluate entities in eq (1-3) are shown. In particular, in each case a displacement field has been applied to the free section of the unit cell in order to reproduce the deformation occurring by applying a rotation in x or in y or in xy. Then, the total reaction force was calculated in correspondence of the constrained section and the stiffness obtained dividing the reaction by the imposed rotation.

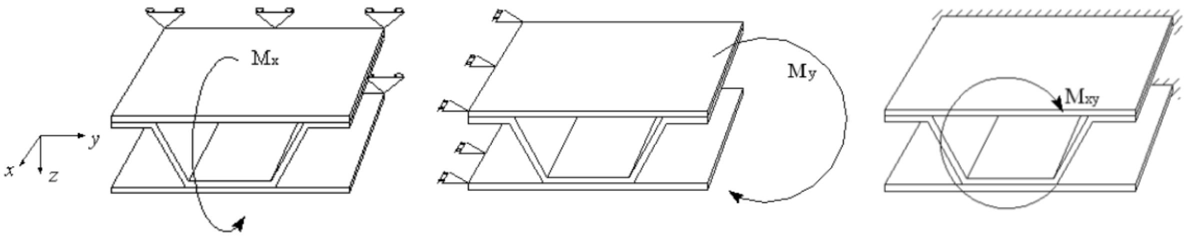

Figure 2: Load and constraint schemes to evaluate out of plane stiffness of the sandwich.

The model used for simulations is depicted in Fig. 3: a mapped mesh is obtained with Solid hexaedral elements in APDL Ansys [39]. The material model used is linear orthotropic and elastic constants of the material used are summarized in Tab. 1, together with main dimensions of the unit cell.

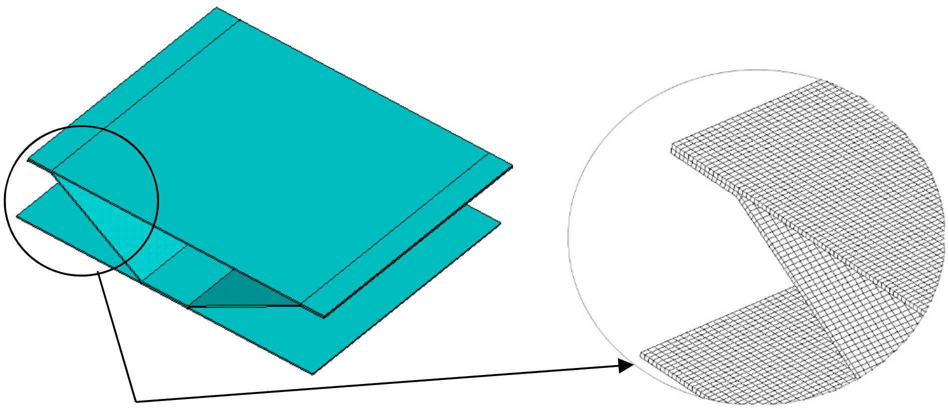

Figure 3: FEM model used to validate the analytical formulation.

E_x [GPa]	E_y [GPa]	G_{xy} [GPa]	ν_{xy}	p [mm]	f [mm]	h [mm]	t_s [mm]	t_c [mm]
10	17	1.85	0.1	80	14	24.2	1.11	0.96

Table 1: Elastic properties of the laminate and geometric parameters of the sandwich.

Results obtained from the three load and boundary configuration in Fig. 2 are given in terms of total reaction to an applied rotation (flexural or torsional). Each component of stiffness can be calculated by the ratio between the reaction calculated and the rotation. In Tab. 2, analytical results given by the proposed formulation in eq. (1,2,3) are compared with numerical results obtained with FEM with this procedure.

	D_x [Nmm]	D_y [Nmm]	D_{xy} [Nmm]
Analytical eq. (1,2,3)	4.26E6	5.61E6	1.20E6
Numerical FEM	4.39E6	5.88E6	1.15E6

Table 2: Comparison between the analytical model and FEM method

Numerical implementation of the analytical model

The behavior of a sandwich structure with a corrugate core can be effectively numerically simulated by using suitable finite shell elements that implement the homogenized analytical model. In this way, an equivalent model of the real structure is obtained where only the mid-surface of the sandwich is considered. Advantages of this technique with respect to a full 3D model mainly consist in remarkable time saving in modeling and numerical computation.

In the present work, the SHELL99 element of the ANSYS library has been used [39]. This element has eight nodes with six degrees of freedom each (three displacements and three rotations) and can be customized via the direct definition of its stiffness matrix **D** that relates the vector of moments **M** with the vector of curvatures **k**. This relation is expressed with the following expression:

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{12} & D_{22} & D_{23} \\ D_{13} & D_{23} & D_{33} \end{bmatrix} \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} = \begin{bmatrix} \dfrac{D_x}{1-\mu_{xy}\mu_{yx}} & \dfrac{\mu_{yx} D_x}{1-\mu_{xy}\mu_{yx}} & 0 \\ \dfrac{\mu_{yx} D_x}{1-\mu_{xy}\mu_{yx}} & \dfrac{D_y}{1-\mu_{xy}\mu_{yx}} & 0 \\ 0 & 0 & -\dfrac{D_{xy}}{2} \end{bmatrix} \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} \tag{4}$$

where coupling terms between flexural and torsional behaviour (D_{13} and D_{23}) are null in a cross-ply layup [38] and where μ_{ij} are Poisson flexural coefficients of the whole sandwich, coming from Poisson coefficients of the laminate skins via these expressions [21]:

$$\mu_{xy} = \nu_{xy} \quad \text{and} \quad \mu_{yx} = \frac{D_y}{D_x} \mu_{xy} \tag{5}$$

Submatrices **A** and **B** of the complete formulation of the stiffness matrix of a laminate are not considered in this work because only out-of-plane behaviour are simulated and symmetrical layups are assumed.

EXPERIMENTAL TESTS

Preparation of samples

Corrugated core sandwich panels have been prepared using unidirectional glass fiber fabric (with 220 g/m² unit weight) and polyester resin. From a PVC panel (Klegecell® R45 by DIAB) several prismatic bars with trapezoidal section have been cut off. The presence of the PVC was due both for the manufacturing process and to reduce the possibility of local indentation of the sandwich. Sandwich has been assembled following this procedure (see also Fig. 4 left for a detailed view): stacking of glass fiber fabrics by hand layup to obtain the bottom skin, positioning of the PVC

bars to create the open mould for the corrugate, hand lay up of the corrugate onto the mould, positioning of the remaining PVC bars to create the planar surface for the final skin, hand lay up of the upper skin. Layup and assembling of the whole sandwich have been finalized within pot-life time of the resin; in this way, all components of the sandwich have been bonded with co-cured joints. It must be remarked that the presence of the PVC filler in the corrugate does not affect the validity of the homogenized analytical model, because its contribution to the flexural and torsional stiffness is negligible. Transversal shear stiffness of the sandwich is strongly influenced by the foam but, for the cases studied in the next sections where no shear is present, formulas (1,2,3) and the shell finite element described in sec. 2.2. can be applied.
Both for skins and for the core the layup used is [90/0/90] where the 0° direction is coincident to the longitudinal direction of the corrugate, defined as x. Elastic properties of laminates have been calculated by means of standard characterization tests on unidirectional samples of the type $[0_n]$ and $[90_n]$. Resulting constants are summarized in Tab. 1.
From the sandwich panels, beams have been cut off with axes parallel to the x and to the y direction (named as x-type and y-type in the following). In particular, the width of the x-type beams is equal to the width of the unit cell of the corrugated core, see Fig. 4 right. Both beams and panels have been tested in quasi-static conditions with universal testing machines.

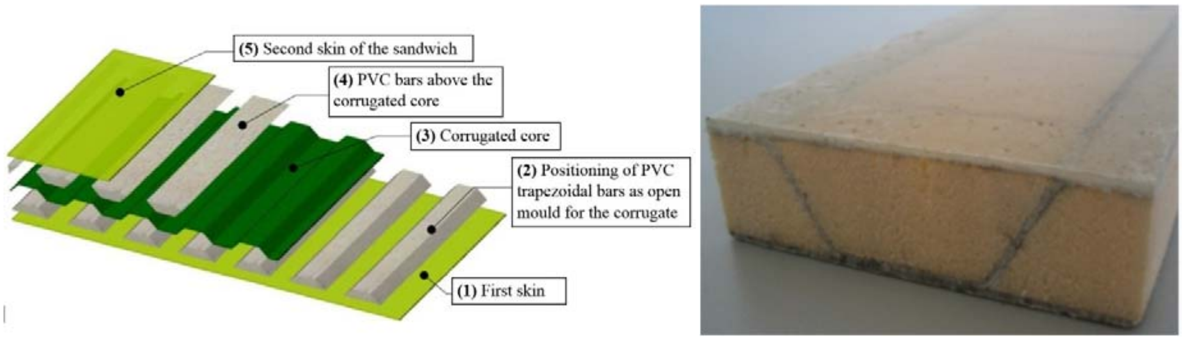

Figure 4: A sketch of the manufacturing process of the sandwich (left), a picture of a sandwich beam (right).

3.2. Experimental validation of the analytical-numerical model

At first, basic loading configurations have been chosen in order to maintain uncoupled flexural and torsional terms of the analytical model. In this way, it is easy to measure each component of stiffness of the sandwich and compare it with results previously obtained. For the flexural stiffness D_x and D_y, Three Point Bending (TPB) tests have been performed on the x-type and y-type beams. To correct the measured data from any spurious contribution of shear deformation, a variable span strategy [1,40] was followed where all the loading data collected are plotted for different span length. The interpolation line of these data can be expressed as:

$$y = mx + q \rightarrow \frac{w}{PL} = \frac{1}{48D_{x,y}}L^2 + \frac{1}{4D_{Qx,y}} \tag{6}$$

where w is the displacement at mid-span (measured at the surface opposite to the loading pin to avoid errors due to indentation [12]), P is the applied load per unit width, L is the span between the supports and D_Q is the shear stiffness.
Fig. 5 shows results obtained in the tests for the x-type and the y-type beam at different span length, and Fig. 6 shows the test setup. Apparent flexural stiffness, $D'_{x,y}$, is given in Tab. 3: this entity is calculated from eq. (6) neglecting the term related to shear. It can be noticed that, in this way, the apparent flexural stiffness of the beam varies with the span length and is underestimated with respect to the one obtained analytically and numerically in Tab. 2. The interpolation of data in Fig. 5 fixes this issue and the stiffness obtained from the slope of the lines ($D_{x,y} = 1/48m$) are very similar to the ones in Tab. 2.
Concerning torsional stiffness, it must be admitted that it is very difficult to setup such a test for a large sandwich. For this reason, the test we performed in laboratory (called scheme 1) is able to guarantee a torsional-dominant state, especially in the inner part of the sample, but some spurious effects still exist in proximity of supports. The panel is supported by the two opposite ends of one diagonal and is loaded by the two ends of the other diagonal. Loading scheme and test setup are shown in Fig. 7. From the test, a linear load vs. displacement curve was obtained and its slope was compared with the one obtained with the FEM model, using the homogenized shell element, shown in Fig. 7 right. Results are: 43 N/mm from experiments and 45 N/mm from numerical analysis, confirming the validity of the proposed method.

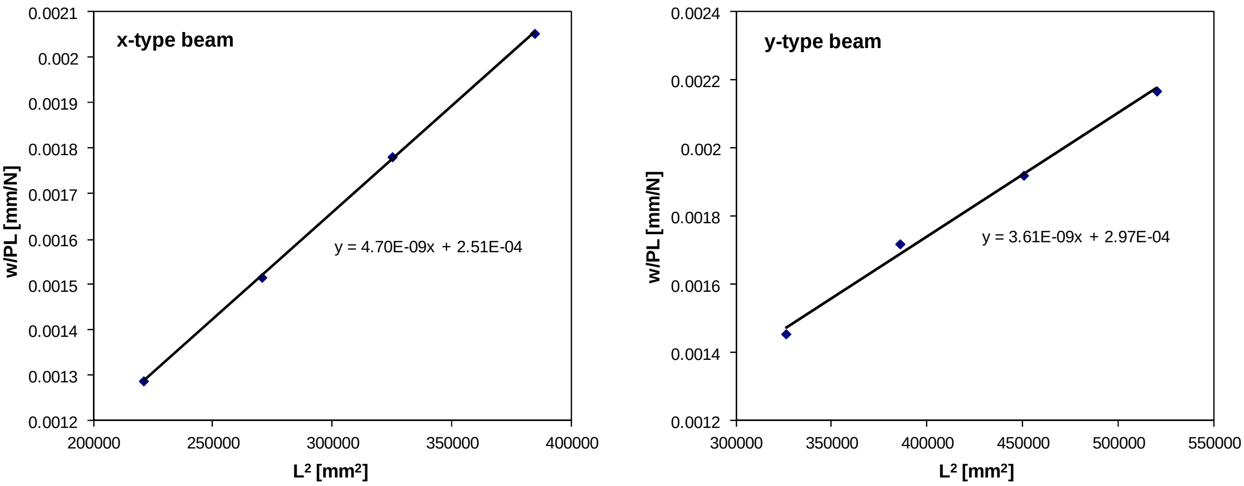

Figure 5: Experimental results of the variable span TPB tests on x- and y-type sandwich beams.

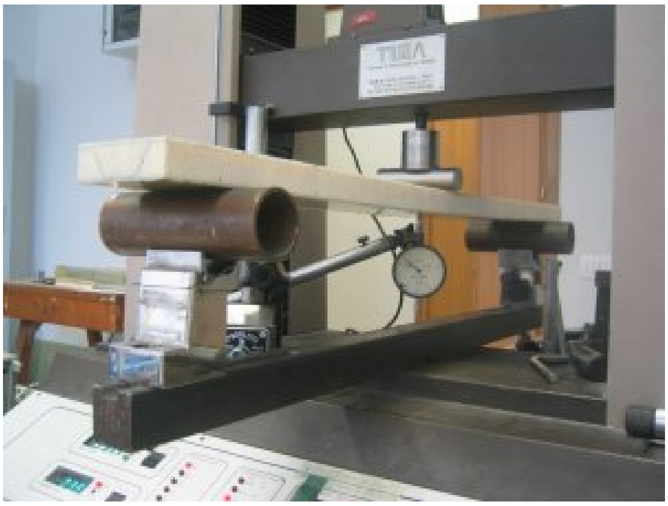

Figure 6: Experimental setup for the TPB tests.

			x-type beam			
Span [mm]	620	570	520	470	D_x [Nmm]	D_{Qx} [N/mm]
D'_x [Nmm]	3.9E6	3.8E6	3.7E5	3.57E3	4.43E6	9.96E2
			y-type beam			
Span [mm]	721	671	621	571	D_y [Nmm]	D_{Qy} [N/mm]
D'_y [Nmm]	5E6	4.9E6	4.7E5	4.66E3	5.76E6	8.42E2

Table 3: Results of TPB tests on x- and y-type sandwich beams: apparent and corrected values of stiffness.

Application to coupled mode cases

In the cases studied so far, only uncoupled load configurations were analysed. Aim of this work is to give a versatile numerical tool able to simulate a complex case where coupling between flexural deformation in x and y direction and torsional deformation can occur. For this reason two cases have been simulated for which no closed form solution exist. Both loading schemes depicted in Fig. 8 are characterized by the presence of multiple terms in the matrix D.

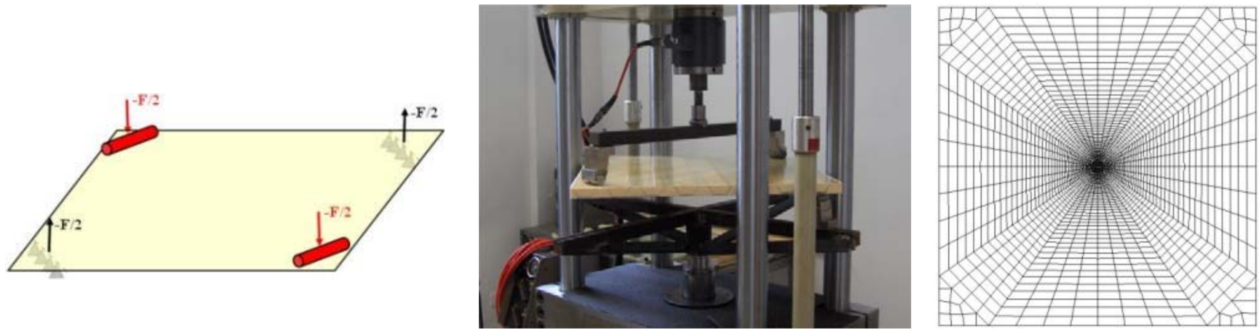

Figure 7: Determination of the torsional stiffness: loading scheme 1 (left), experimental setup (middle) and FEM model (right).

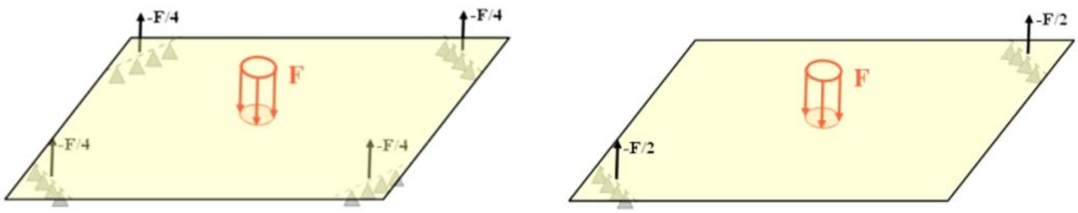

Figure 8: Loading scheme 2 to couple flexural stiffness in x and y (left) and loading scheme 3 to couple flexural and torsional stiffness (right).

In particular, scheme 2 on the left of Fig. 8 couples terms D_x and D_y of the total stiffness matrix. The scheme 3 on the right, loaded in the centre and supported on two opposite vertex, couples flexural and torsional stiffness. This scheme can be considered as the superposition of scheme 1 (torsion dominated) and scheme 2 (x plus y flexion dominated), when the total load applied in scheme 1 is a half of the one applied to scheme 2. Panels have been tested and slopes of the load vs. displacement curves evaluated. Same loading schemes were applied to the FEM model in fig. 7 right and the slope of loading curves calculated. Results for loading scheme 2 are: 380 N/mm from experiments and 400 N/mm from numerical analysis. For loading scheme 3 are: 108 N/mm from experiments and 107.5 N/mm from numerical analysis.
In TPB tests on x- and y- type beams, it was noted how transversal shear can play important role, especially when dealing with not particularly slender samples, as panels tested in this work. In numerical analyses performed to obtained results in sec. 3.2. and 3.3, to take into account of transversal shear deformation, a complete formulation of the shell element was used where terms D_{Qx} and D_{Qy} were added. This entities were calculated from TPB tests on the beams and reported in Tab. 3.

CONCLUSIONS

The present work develops an analytical homogenisation model of the behaviour of a fully composite sandwich panel with a corrugated, trapezoidal shaped, core. The model is based on the reduction of the sandwich elementary cell unit, representative of the sandwich corrugation pattern, to a thick plate subject to small deformations, according to the approach proposed by Libove et al. [21,22]. An extension of the treatment in [21,22] is in particular proposed, able to consider the intrinsic ortotropy of the sandwich constituent elements, i.e. skin faces and corrugated laminate, when these are made of symmetric FRP laminates of equal thickness and lay-up.
The present analysis has considered only the analytical evaluation of the flexural and torsional rigidities of the homogenised element, and the implementation of this formulation into a shell element of the ANSYS library.
The compliance of the analytical homogenised model has been directly compared to the response obtained by a purely numerical three-dimensional model of the elementary sandwich cell. The values of the elastic constants obtained by the numerical simulation have resulted in good agreement with the analytical predictions.
A number of experimental coupled and decoupled flexural and torsional tests have been performed on beam and panel sandwich elements, specifically designed in order to determine the experimental out-of-plane compliance response of the sandwich. All tests have indicated a significant influence of the transverse shear deformation component, indicating that the out-of-plane shear rigidity cannot be neglected. In the present work an experimental evaluation of the shear rigidity

was obtained from the flexural tests of the beam samples, performed at various span values. Adding the transverse shear rigidity in the formulation of the shell element has allowed the homogenised model to well predict all the experimental results.
A number of future developments are then identified in order to complete the potentialities and effectiveness of the presented homogenised model. These developments comprise: the analytical formulation of the transverse shear rigidity; the experimental validation of the membrane behaviour of the homogenised model; the extension of the model to cases where the skin and core laminates have different lay-ups.

APPENDIX

In-plane elastic stiffness of the sandwich can be stated as follows:

$$E_x^* = E_x\left(2t_s + A_c\right) \tag{A.1}$$

$$E_y^* = \frac{2\left[E_{mx}E_{my}t_s\left(2t_s + A_c\right)\right]}{2E_x t_s + E_x A_c - E_x \nu_{xy}^* \nu_{yx}^*\left(2t_s + A_c\right) + 2E_{my} t_s \nu_{xy}^{*2}} \tag{A.2}$$

where A_c is the area, per unit width, of the corrugation cross section, ν_{ij}^* are in-plane Poisson coefficients of the laminate.

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