Shear properties evaluation of a truss core of sandwich beams

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Abstract. The open-cell cores of sandwich structures are locally bonded to the face layers by means of adhesive resin. The sandwich structures composed of different parent materials such as carbon fibre composites (laminated face layers) and metallic core (aluminium truss core) brings the need to closely analyse their adhesive connections which strength is dominated by the shear stress. The presented work considers sandwich beams subjected to the static tests in the 3-point bending with the purpose of estimation of shear properties of the truss core. The main concern is dedicated to the out-of plane shear modulus and ultimate shear stress of the aluminium truss core. The loading of the beam is provided by a static machine. For the all beams the force - deflection history is extracted by means of non-contact optical deflection measurement using PONTOS system. The mode of failure is identified for each beam with the corresponding applied force. A flexural rigidity of the sandwich beams is also discussed based on force - displacement plots.

1. Introduction
Sandwich structures with a pyramidal truss core have been widely used in the form of plates, beams, or cylindrical shells. Their open-cell core construction gives the advantage of free fluid flow as well as the high specific stiffness and strength ratio with respect to mass. The exceptional stiffness-to-weight properties of the sandwich structures are due to high bending stiffness of the face sheets separated with a low density core. A comprehensive amount of scientific work was devoted to the failure analysis of truss core sandwich structures [1, 2]. Also the strength and stiffness characteristics of those kind of structures were already studied exclusively [3, 4]. Sandwich structures with metallic open-cell core are assembled by local bonding of the core to the face layers. The emergence of new types of truss core sandwich structures composed of different parent materials such as carbon fibre composites (laminated face layers) and metallic core (aluminium truss core) requires to use adhesive materials for the local bonding realisations. This, in turn, brings the need to closely analyse their adhesive connections which strength is dominated by the shear stress.

The present work utilises the test method which covers determination of the core shear properties of truss core sandwich beams subjected to flexure [5]. The selected loading configuration is the 3-point bending. The shear properties of interest are out-of plane shear modulus and ultimate shear stress of the aluminium truss core. Additionally the flexural rigidity of the sandwich beam is also inspected.
2. Materials and samples
The strength and stiffness properties of a pyramidal truss core of sandwich panels were investigated in the present study. Five sandwich panels were manufactured for the experimental purposes. The panels had length $L$, width $B$, and core height $H_c$ (Table 1). A global Cartesian co-ordinate system $(x, y, z)$ was located in the corner of the panel, with $z$ axis upward and normal to the face layer (Figure 1). Each sandwich panel was composed of two parent components: (1) a laminated unidirectional carbon fibre reinforced plastic (CFRP) was used for the face sheets; (2) the aluminium alloy PA6 was used for the pyramidal truss core. The face sheets were cut out of a long unidirectional CRFP tape, which were proven to be good candidates for structural stiffness improvement [6]. The top and bottom face sheets were identical and had the thickness $t_f$. A co-ordinate system $(1, 2, 3)$ has been assigned to the laminated face sheets with the direction 1 along the lamina fibres, 2 transverse to this direction, and 3 - through the thickness direction. The pyramidal truss core was assembled from separate pieces which were cut out of an aluminium plate by means of water-jet cutting. The pieces were bonded together with a thermoset epoxy adhesive to form a continuous pyramidal truss core. The dimensions of the truss core single cell element were as follows (Figure 1): $t = 4.0\, \text{mm}$, $h = 3.0\, \text{mm}$, $d = 2.76\, \text{mm}$, $e = 0.71\, \text{mm}$, $w = 3.0\, \text{mm}$, $l_1 = 22.80\, \text{mm}$, $l_2 = 43.43$, $l_3 = 47.30\, \text{mm}$. The parent components were bonded together to form a sandwich panel with the same thermoset epoxy adhesive as used for the core manufacture. The epoxy adhesive was applied locally on the face sheets where the contact with the core existed.

Prior to the complete assemblage of the sandwich panel, the stiffness characteristics of the parent components were estimated in a non-destructive manner. To do so, the inverse technique procedure based on modal data was applied as described in [7, 8, 9]. The estimated material properties of PA6 alloy and the unidirectional CFRP tape are given in Table 2.

3. Flexure of sandwich beams
The sandwich beams are subjected to a loading force by means of the cross head located at the middle of the the span length $l_s$ (Figure 1). The midpoint deflection of the sandwich beam loaded in the 3-point bending is the sum of flexural and shear deflection given as:

$$\delta = \frac{Pl_s^3}{48(El_{eq})} + \frac{Pl_s}{4(AG)_{eq}}$$

where: $P$ is applied force; $l_s$ is span between the supports; $(EI)_{eq}$ is sandwich flexural rigidity; $(AG)_{eq}$ is sandwich shear rigidity.

The flexural rigidity of the sandwich beam is given as:

$$(EI)_{eq} = \frac{1}{2}E_fBt_fd^2$$

where: $E_f$ is effective longitudinal Young’ modulus of the face sheets (in the 1 direction); $d = H_c + t_f$.

The shear rigidity is given as:

$$(AG)_{eq} = \frac{Bd^2}{H_c}G_{13}$$

| Sample      | $L$ [mm] | $B$ [mm] | $H_c$ [mm] | $t_f$ [mm] |
|-------------|----------|----------|-------------|------------|
| Sandwich 1  | 380.1    | 49.95    | 19.91       | 1.48       |
| Sandwich 2  | 380.2    | 49.18    | 19.75       | 1.53       |
| Sandwich 3  | 380.4    | 49.95    | 19.67       | 1.51       |
| Sandwich 4  | 380.1    | 49.25    | 19.73       | 1.68       |
| Sandwich 5  | 380.4    | 49.94    | 20.03       | 1.52       |
where: $G_{13}$ is the out-of-plane shear modulus of the truss core.

### 3.1. Failure modes

The main concern of the present work is the behaviour of the truss core in the state of shear stress. In order to achieve the shear stress dominated state of the beam the span length was chosen to be no longer than 8-9 times the total height of the sandwich beam. In such loading case the expected failure modes are: facesheet delamination, core-to-facesheet disbond, partial core fracture, and local core crushing.

### Table 2. Properties of the parent materials.

| Material | $E_f$ [GPa] | $E_c$ [GPa] | $G_{12}$ [GPa] | $\nu_{12}$ | $\nu$ | $\rho$ [kg/m$^3$] |
|----------|-------------|-------------|----------------|-----------|------|----------------|
| CFRP     | 142.2       | -           | 7.8            | 0.38      | -    | 1540.0         |
| PA6      | -           | 66.2        | -              | -         | 0.25 | 2700.0         |

### 4. Experimental procedure

The realisation of the laboratory testing was done on a static machine combined with an optical non-contact sensing of deformations. The loading was provided by the INSPECT 600 machine having the force range of 0 – 600kN and was applied to the beam in the half span length between the supports. The tests were conducted on short specimens in order to determine the core shear modulus. For the known facing effective modulus, a short span beam can be tested and the calculated bending deflection can be subtracted from the beam’s total deflection. This gives the shear deflection from which the transverse...
shear modulus can be determined. Therefore the span length was \( l_s = 189 \text{mm} \) for all beams. The cross head displacement speed was set up to \( 6 \text{mm/min} \). Force versus displacement was recorded continuously by optical sensing device PONTOS. The initial failures were recorded with the corresponding force and displacement data.

4.1. PONTOS system
PONTOS is a non-contact optical 3D measuring system. It analyses, computes and documents object deformations. PONTOS provides dynamic, precise and synchronous position detection for many measuring markers (reference points) defined by the user prior the test starts. A digital stereo camera system records different movement states. The software assigns 3D coordinates to the image pixels, compares the digital images and computes the displacement of the reference points. Image recording is flexibly triggered and synchronized with the test set-up, providing the possibility to additionally record and process analog values. Measuring process for PONTOS starts at defining the reference point markers and freely positioning the PONTOS camera on a stand in front of the measuring object (Figure 2). After creating a new deformation project in the software, the system is calibrated and the desired images are recorded through a trigger during the deformation process. The software reads in these images as stages and automatically computes the 3D coordinates of the reference points and thus their position. They are displayed in the 3D view as a point cloud. In order to assess the deformation of the object, all stages are aligned to the reference stage based on components and fixed points which have to be specified. During the following identification, the IDs of the uncoded reference points which the system randomly assigns will be renumbered automatically so that the same points in all stages will have the same ID. A displacement field, to be defined by selecting an area of points, marks the area for which the software will display the computed deformation through all stages. The deformation is calculated automatically as soon as the stage is identified.

5. Shear analysis
The current work aims to present calculations of the core shear modulus and core shear ultimate stress of the truss core sandwich beams using deflection data from 3-point bending tests. It is assumed in the following calculations that the facing effective modulus \( E_f \) is known.

The analysis of the core shear modulus is based on the Eq.1, Eq. 2, and Eq. 3. The procedure starts with calculating the flexural stiffness of the sandwich beam using Eq. 2. Then the core shear rigidity \((AG)_{eq}\) is calculated for the midpoint deflections for a series of applied forces up to the maximum applied force (first failure point) based on Eq. 3. The values of \((AG)_{eq}\) should be calculated for a minimum of ten force levels evenly spaced over the force range. Having calculated the values of the shear rigidity the core shear modulus \(G_{13}\) can be calculated based on Eq. 1. Finally the average value of the core shear modulus is calculated using the values calculated at each force level for each beam. Then an overall average core shear modulus is calculated using the values from all tested beams.

The core shear ultimate stress is calculated based on the ASTM standard [5]. The following formula represents the shear ultimate stress:

\[
E_{s,ult} = \frac{P_{\text{max}}}{(2H_c + 2t_f)B}
\]

where: \(P_{\text{max}}\) is the maximum force prior to the first failure occurrence (first drop of the force value on the force - deflection plot).

6. Results
Five bending tests were conducted on the manufactured sandwich beams. The deflection of the beams was measured at the midpoint between the supports. The example of the deflection results recording by the PONTAS system is given on Figure 3. From the stored deflection data, the force - deflection plot for each beam was created. The five plots of the beams are given on Figure 4. The maximum force used
Figure 2. Experimental set-up: 1) INSPECT 600; 2) PONTOS system.

Figure 3. Example of PONTOS results display: (a) real time displacemnten recording; (b) failure initiation stage; (c) disbond of the node connection.

in Eq. 4 can be read in the first point of the sudden drop of the applied force value. The force values and the corresponding deflections used in the calculation of the shear modulus (Eq. 1 - 3) were read from the force - deflection plot in the 10 evenly spaced points between the starting point of the plot and the maximum force. Having calculated the the values of $F_{ult}^n$ and $G_{13}$ for each beam the average values of these indices were calculated. The analysis was closed by the statistics calculation were the standard deviation $S_{n-1}$ was calculated. All the calculated results are given in Table 3. It should be pointed out that
the results obtained for the beam Sandwich 3 were rejected from the calculation. The reason to do so was that the force - deflection plot was of a poor quality having some non-linearity in the beginning region. Also as given in Table 3 the value of the shear modulus for Sandwich 3 differs considerably from the others values. As expected, the failure mode of the sandwich beams were the core-to-face sheet disbond. It was the case for all tested beams. The location of the first disbond was at the vicinity of the supporting point (Figure 3). The precise localization of the failure initiation point was successfully performed using the pictures which were recorded by the digital camera of the PONTOS system.

Additionally, it may be observed from the force - deflection plots (Figure 4), that the flexural rigidity of the beams is very similar to each other. The slopes at the starting part of the plots have a similar angle for all beams, except the Sandwich 3.

### Table 3. Results of the calculations.

| Beam          | $F_{\text{ult}}$ [MPa] | $S_{n-1}$ % | $G_{13}$ [MPa] | $S_{n-1}$ % |
|---------------|------------------------|-------------|----------------|-------------|
| Sandwich 1    | 0.751                  | -           | 95.90         | -           |
| Sandwich 2    | 0.649                  | -           | 81.29         | -           |
| Sandwich 3*   | 0.541                  | -           | 39.03         | -           |
| Sandwich 4    | 0.452                  | -           | 85.55         | -           |
| Sandwich 5    | 0.475                  | -           | 114.29        | -           |
| Average       | 0.582                  | 24.58       | 94.26         | 15.59       |

*Results rejected from the calculations

![Figure 4. Force - deflection history after 3-point bending tests.](image)

### 7. Conclusions

Five sandwich beams were subjected to the static tests in the 3-point bending configuration. For the all beams the force - deflection history was extracted by means of non-contact optical deflection measurement. The shear stiffness and strength properties of the aluminium truss core of the beams were established based on the beam flexure formula. The location and failure mode were identified taking the advantage of the digital camera which was the part of the PONTOS system. The statistics calculations
were performed although the beams population was limited to four only. The relatively high values of the standard deviation parameters are believed to be due to manufactured errors of the beams. Geometrical and technological (bonding process) imperfections might occurred during the assemblage of the beams. However, a good coincidence of the beams’ slopes were noted from the force - deflection plots what indicates that a repeatable flexural rigidity of the manufactured beams was achieved. Summing up, the analytical prediction of the shear stiffness and strength properties of the truss core should be performed to fully cover the problems which were considered in the paper.

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