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1 Introduction

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Static flexural response of sandwich beams with aluminium and 3D printed composite truss core

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Abstract

Sandwich beams with a pyramidal truss core are more and more considered to be essential elements of civil, automotive and aerospace structures. The truss core, made of aluminium or 3D-printed composite, has recently gained scientific attention in the above applications. The objective of the present work is to study a static response of sandwich beams which are composed of laminated face sheets and truss core made of aluminium alloy or 3D-printed composite developed with CF-PA-12 filament. The three-point bending configuration was selected for experimental and numerical investigations. The experimental failure modes and load - displacement curves are closely inspected for guidance in numerical model development. A manufacturing methodology of the beams is provided focusing on adhesive joints for both the assembly process of beams and modelling aspects. The experimental observations motivated for application and calibration of a non-linear material model for the CF-PA-12 based on the hyperelastic theory.

Keywords: sandwich beam, additive manufacturing, short fibre filament

1 Introduction

Truss core sandwich composites have recently gained the attention of a scientific community. This is attributable to the engineering advantages that these structures possess. In particular, they exhibit high specific bending stiffness [1] , weight efficiency, and good thermal [2] and acoustical insulation [3]. The studies performed on the sandwich composites flexure indicate that their behaviour under a static load is governed by the geometrical characteristics of the parent components (face sheets and core), as well as their constituent materials' properties [4]. From the geometrical point of view the key parameter in terms of stiffness performance is a relative density, which favourable value is $\rho = 2 \div 7$ % [5]. A selection of a material used for core manufacturing is also an important factor in the overall core stiffness. The usual choice of the material is isotropic (aluminium, stainless steel, titanium alloys) or anisotropic (laminated composites strengthened with carbon fibres). However, a new group of materials can be found as a competitive replacement for the composite laminates. They are polymeric filaments used in the additive manufacturing process. Among them, the polyamide filaments strengthened with continuous or chopped carbon fibres are the most suitable for industrial application. The variety of materials used for core manufacturing compels the use of different constitutive material models for an appropriate description of the core behaviour. For the case of polyamide filaments with chopped carbon fibres a hyperelastic material model serves as a reasonable approach [6]. In the hyperelastic theory the stress-strain relationship is derived from a strain-energy function. In most cases, but not limited to, the energy function is used in the form of Mooney-Rivlin [7], Polynomial Form [8], Ogden [9], Marlow [10]. For an incompressible material under a combined load case the set of three static tests is required to correctly describe the hyperelastic material model. These test are uni-axial tensile test, biaxial tension test, and pure shear test. However, less number of tests can be used is a structure deforms for example in tension only [11].
A sandwich structure is typically created through adhesive joints between the core and face sheets. If all materials are metal, brazing or laser welding is used for joining the parent materials [1]. For hybrid structures like laminated face sheets and 3D printed cores, epoxy adhesive is used, but it might cause relative displacements between core and face sheets. From the numerical point of view, this effect can be accounted for using Finite Element Method (FEM). As concluded in [12], in order to gain an appropriate response confidence, the adhesive layers shall be included in the FEM model of a sandwich structure being studied.

The purpose of the present study is to analyse a linear and non-linear static response of the pyramidal truss core sandwich beams. The three-point bending test configuration is used for experimental and numerical investigations. The beams are composed of laminated face sheets and the pyramidal truss core made of aluminium alloy PA6 or 3D-printed composite truss. The 3D printed truss was developed with CF-PA-12 filament – a polyamide strengthen with short carbon fibres. The main objectives of the experimental investigation include establishing the primary failure modes of the beams, examine the reliability of the proposed joint connection, and establish the mechanical response of the beams in terms of linear or non-linear material behaviour. Numerical analyses are also provided using a three-dimensional FEM model. Based on experimental observation two material models for the core are examined: isotropic linear elastic for the PA6 core and isotropic non-linear hyperelastic for the CF-PA-12 core. An efficient approach for the adhesive joint modelling is also presented. In addition, results of the calibration procedure for the hyperelastic material are presented. The experimental data required for the calibration process were obtained for a static uni-axial tensile tests performed on 3D printed samples.

2 Materials and methods

2.1 Samples manufacturing

The objects of the current study are sandwich composite beams. The sandwich beams were composed of two parent components (Figure 1): (1) upper and lower face sheets made of an unidirectional laminated carbon fibre reinforced plastic (CFRP); (2) aluminium (PA 6) or polyamide (CF-PA-12) 3D printed pyramidal truss core. The CF-PA-12 filament had a 15% by weight ratio of chopped fibres. The pyramidal truss core was assembled from separate parts (longitudinal and transverse), which were manufactured by means of 3D printing in a heated and closed chamber or by means of water-jet cutting in case of the aluminium parts. All the parts of the trusses were developed in a plane orientation (Figure 2). I the context of the 3D printing process, it refers to as a flat orientation. The printing process parameters were set as follows: layer thickness 0.2 [mm], nozzle diameter 0.4 [mm], infill 100.0 [%], infill pattern (raster) - rectilinear $+45 - 45$] [deg], nozzle temperature 270.0^{o}[C], bed (table) temperature 100.0^{o}[C], chamber temperature 50.0^{o}[C]. The longitudinal and transverse parts of the truss core were then bonded together with a thermosetting epoxy adhesive (Loctite EA 9514). After a curing process a continuous pyramidal truss core was obtained. In a final step, the parent components were bonded together to form a sandwich beam. The Loctite EA 9514 was used for this purpose as well. The epoxy adhesive was applied locally at the contact spots between the sheets and the core. Three sandwich beams for each truss core material were manufactured for experimental investigation. The characteristic dimensions of the beams are given in Table 1. The geometry of a single unit cell is given on Figure 3 for which the relative density of the core was obtained as ρ =3.05% [13]. Besides the sandwich beams, samples for the static tensile tests were manufactured. The samples were 3D printed with the same filament, pattern, and printing parameters as the truss core parts. The type IV geometry of the tensile sample was taken according to the ASTM D638–14 standard [14]. 10 samples were fabricated for the tensile tests.

2.2 Numerical model

The Finite Element Method (FEM) was used to developed the model of the sandwich beams. The Simulia/Abaqus software was used as a pre- and post-processor. For the CFRP laminated face sheets a lamina coordinate system (1, 2, 3) was defined with the direction 1 along the fibres of the face sheet, 2 transverse to this direction, and 3 through the thickness direction (Figure 3). A lamination angle (Φ) of the fibres was defined between the 1-axis and the x-axis of a global coordinate system (Figure 4). The FEM model was assumed to

Table 1. Characteristic dimensions of sandwich beams.

Sample	Core material	l [mm]	a [mm]	h [mm]	t [mm]	Φ [deg]
Sandwich 1	PA6	386.4	50.0	22.80	1.4	0.0
Sandwich 2	PA6	386.1	50.0	22.79	1.4	0.0
Sandwich 3	PA6	386.3	50.0	22.80	1.4	0.0
Sandwich 4	CF-PA-12	386.7	50.0	22.81	1.4	0.0
Sandwich 5	CF-PA-12	386.5	50.0	22.80	1.4	0.0
Sandwich 6	CF-PA-12	386.2	50.0	22.79	1.4	0.0

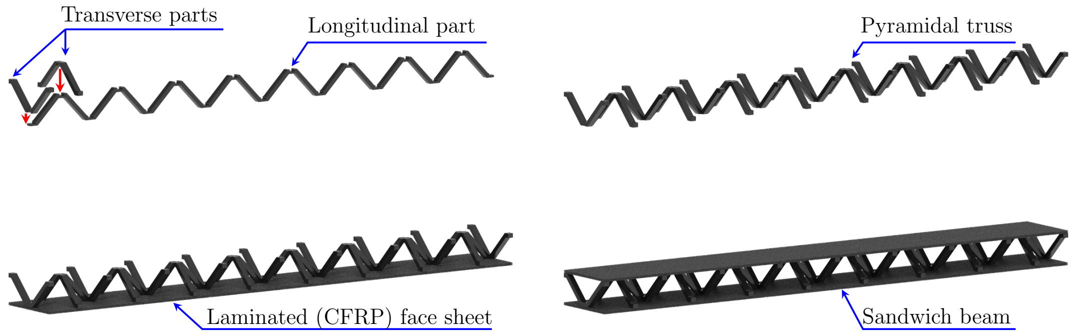

Figure 1. Fabrication process of the truss core sandwich beam: (top) PA-CF-12 pyramidal truss core assembly; (bottom) assembly of laminated face sheets and pyramidal core into a sandwich beam.

be an assembly of three components (instances), namely laminated face sheets, pyramidal truss core and the adhesive material. The laminated face sheets were modelled using S4R single layer shell elements with an orthotropic, linear elastic material properties. The aluminium (PA6) and 3D printed (CF-PA-12) pyramidal core were considered as a solid 3D body and were discretised with 8-node linear brick elements C3D8RH. Isotropic behaviour of the C3D8RH elements was assumed for the both core materials. However, the linear elastic behaviour was assumed for the PA6 core and a non-linear hyperelastic behaviour for the CF-PA-12 core. An additional material of adhesive joints between the pyramidal truss and the face sheets was modelled using continuum hybrid solid-shell elements SC8R. The SC8R elements behave like three-dimensional continuum solids, but they have kinematic and constitutive behaviour that is similar to conventional shell elements. The advantage of the SC8R elements is that they exhibit fast element convergence along the thickness direction. One element in the thickness direction was sufficient in order to gain the results convergence for a present study. The isotropic elastic material model was applied for the adhesive layers. The only simplification of the model was that no adhesive connections between the longitudinal and transverse parts of the core were modelled. The material properties of the sandwich beams constituents are listed in Table 2 and have the source of [12]. The material parameters required for the CF-PA-12 are to be evaluated within the scope of the current study. The calibration process of the hyperelastic material model for the CF-PA-12 is described in the subsequent paragraph. The length $l = 386.4$ [mm] of the beam was set as the mean value of the beams' lengths given in Table 2. The rest of the beam's dimensions were set as: $a = 50.0$ [mm], $h = 22.8$ [mm] and $t = 1.4$ [mm]. The lamination angle was set to $\Phi = 0$ [deg]. The thickness of the adhesive layers was set to 0.1 [mm]. The assembly of the sandwich beam with the adhesive layers was performed by means of the two tie contact interactions at each adhesive joint as given on Figure 3. In order to simulate the three-point bending configuration, two supports were modelled and a cross head. The translation degrees of freedom of the supports were blocked on each direction. For the cross head, the translation on y direction was allowed. The surface

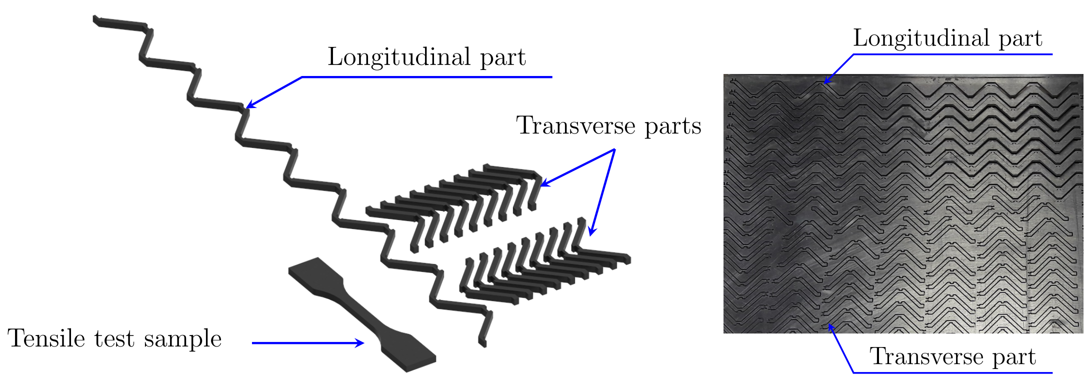

Figure 2. (left) 3D printing pattern of the truss core parts and samples for static tests; (right) water-jet cutting of the PA6 truss core parts.

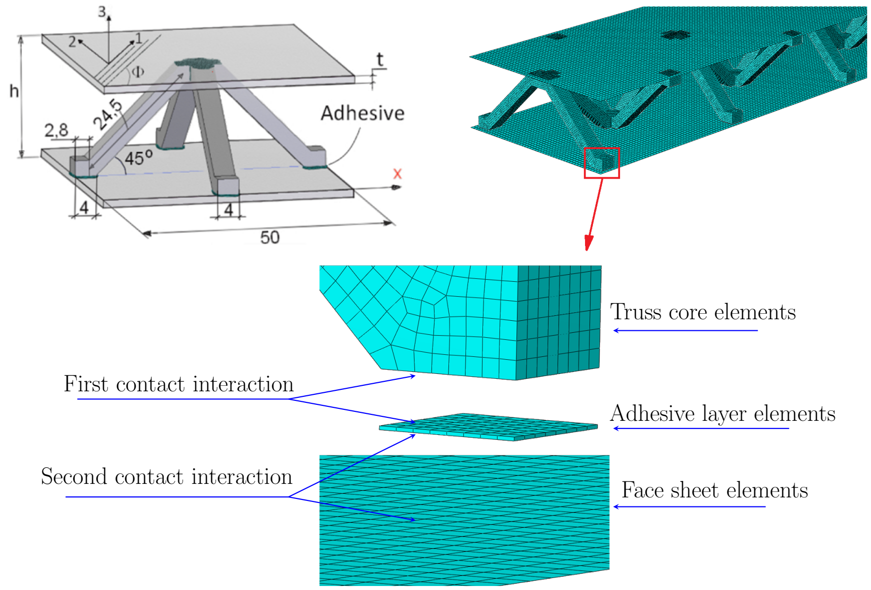

Figure 3. Sandwich beam assembly: (top left) single unit cell; (top right and bottom) numerical model assembly.

to surface contacts were modelled between the beam and the supports as well as the cross head (Figure 4). In order to gain a solution stability a friction parameter of 0.01 was introduced. The mid-span beam deflection and reaction forces at the supports were obtained by imposing an initial displacement $U_y \neq 0$ of the cross head. For the current problem, the non-linear static solution was selected and the analyses were performed.

2.3 Hyperelastic material model

A general constitutive relation for a hyperelastic material has a physical expression in the form of:

$$\mathbf{P} = \frac{\partial W(\mathbf{F})}{\partial(\mathbf{F})} \tag{1}$$

where $\mathbf{P}$ is the first Piola-Kirchhoff stress tensor and $\mathbf{F}$ is the deformation gradient, W is a strain-energy function. The Equation 1 can be equivalently expressed in terms of other deformation measures, for example, left and right Cauchy - Green deformation tensors $\mathbf{B}$ and $\mathbf{C}$ respectively or left and right stretch tensors $\mathbf{V}$ and $\mathbf{U}$ respectively. For a continuum solid located at Cartesian coordinate system with unit basis vectors $\{e_i\}$ for $i = 1, 2, 3$, the function W can be also equivalently expressed in terms of principal invariants (I_i) or principal

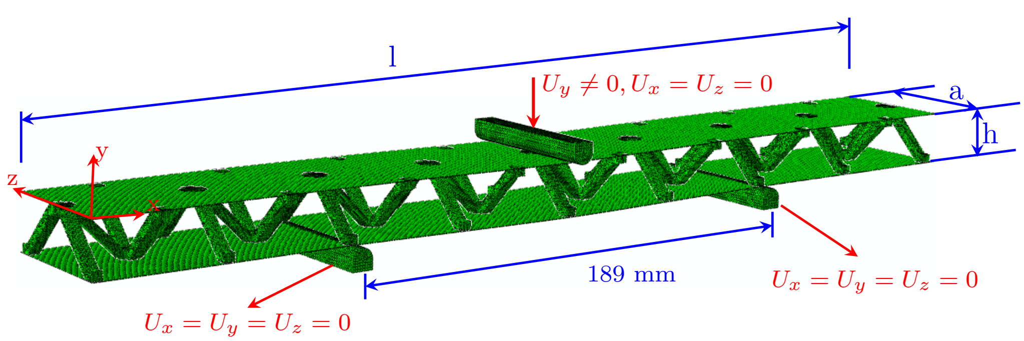

Figure 4. Three-point bending test FEM model of the sandwich beam.

Table 2. Elastic properties of the parent materials.

Parent Component	Material	E [GPa]	E_1 [GPa]	E_2 [GPa]	G_{12}[GPa]	G_{13}[GPa]	G_{23} [GPa]	ν_{12}	ν	Max. shear [MPa]
Face sheet	CFRP	-	142.2	10.5	7.8	7.8	3.8	0.3	-	-
Core	PA6	66.2	-	-	-	-	-	-	0.25	-
Adhesive	Epoxy	1.46	-	-	-	-	-	-	0.30	40.0

stretches (λ_i) (for example, of tensor **V**). The above can be written as:

$$W = W(I_1, I_2, I_3) = W(\lambda_1, \lambda_2, \lambda_3) \tag{2}$$

The main purpose is to specify the strain-energy function W, which properly describes the elastic response of a body. Many forms of the W have been developed and well described [15]. Limiting the current study to those functions available in Simulia/Abaqus library, the Odgen strain-energy function is to be evaluated. It has the following form:

$$W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} \left(\overline{\lambda}_1^{\alpha_i} + \overline{\lambda}_2^{\alpha_i} + \overline{\lambda}_3^{\alpha_i} - 3 \right) + \sum_{i=1}^{N} \frac{1}{D_i} \left(J^{el} - 1 \right)^{2i} \tag{3}$$

where: J^{el} – is the elastic volume ratio, $\overline{\lambda}_i = J^{-1/3}\lambda_i$ – are the reduced principal stretches with $J = (\lambda_1\lambda_2\lambda_3)^{1/2}$, N – the order of the Ogden function, μ_i – are the material constants related to shear modulus and given in [MPa], α_i – are dimensionless coefficients, D_i – are the incompressibility parameters expressed in [MPa]. The internal Simulia/Abaqus optimization tool was used to determine the optimal values of the parameters μ_i, α_i i D_i. The material parameters can be identified using as many test data as many deformation modes will appear in a structure under the applied load. Therefore, the crucial point is to acquire data which are most adequate to that deformation modes. The elements of the 3D printed core deform axially while the sandwich beam is subjected to the bending. Due to the above, to identify the material constants, the data of a stress-strain curves from uni-axial tensile tests were used.

3 Experimental procedure

The realisations of the laboratory tests in a three-point bending configuration were done on a static machine combined with an induction displacement sensor (Peltron) (Figure 5). The loading was provided by the INSPECT 600 machine having the force range of $0 - 600$ [kN] throughout the cross head. The loading was applied to the beam in the half span length between the supports. The span between the supports was set to $l_s = 189$ [mm]. The tests were conducted in room temperature in accordance to ASTM C393/C393M-20 [16]. The cross head displacement speed was set to 6 [mm/min]. Force versus midspan displacement was recorded continuously by displacement sensor. The tests were carried out until the first failure occurred. The tensile testing machine Zwick/Roell with a load cell of 10kN was used for a uni-axial tensile test. Optical sensing system ARAMIS was used for the strain recording purpose. The uni-axial tensile test set-up and the measurement methodology were developed according to the ASTM D638–14 standard [14]. The 3D printed samples were

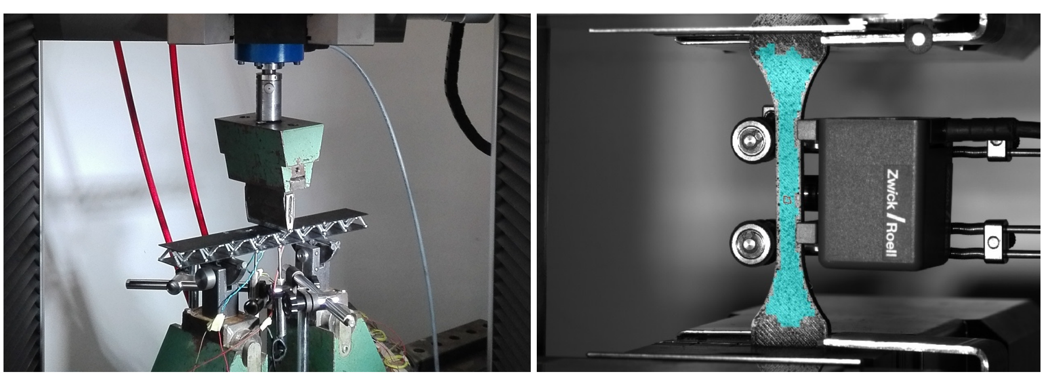

Figure 5. Experimental set-ups: (left) three-point bending test of sandwich beams, (right) uni-axial tensile test of 3D printed samples.

Table 3. Ogden's function parameters.

Function order	μ_1 [MPa]	α_1 [-]	D_1 [MPa]	μ_2[MPa]	α_2 [-]	D_2 [MPa]	μ_3 [MPa]	α_3 [-]	D_3 [MPa]	Δ %
N=3	-815.0 $\cdot 10^3$	2.0	2.48 $\cdot 10^{-16}$	504.0 $\cdot 10^3$	4.0	0.0	313.0 $\cdot 10^3$	-2.0	0.0	0.82

tested with a displacement speed of 1.5 [mm/min] at room temperature (22^oC). Based on the nominal stress and strain data, 10 stress-strain curves were derived. The average curve was then used for material properties calibration.

4 Results

The three-point bending tests were performed on the sandwich beams and the uni-axial tensile tests were conducted on 3D printed samples. The results of the three-point bending tests were stored for the beams and the mean curves were plotted on Figure 6. For each sample, the testing procedure was terminating after the first failure has occurred. By the samples inspection, it was noticed that the first failure mode for the PA6 truss core sandwich beams was truss delamination at the joint (Figure 7). The above indicates a cohesive failure of the joints. The failure occurred for the averaged mid-span displacement $U_y = 0.78$ [mm]. In case of CF-PA-12 truss core the first failure mode was the collapse of the longitudinal part of the truss (Figure 7) for the mid-span displacement $U_y = 2.15$ [mm]. For the two considered types of beams the adhesive joints were capable to withstand the applied load prior any other failure modes and having the stress level much below the allowable value (Figure 8). The obtained results allows considering such joints as reliable for further development of the sandwich truss core structures.
Next, the results of the uni-axial tensile tests were post processed in order to obtain an averaged stress-strain curve of the 3D printed tensile samples (Figure 6). The maximum nominal stress level was 49.0 [MPa] with a corresponding strain 3.0 [%]. The obtained stress-strain curve indicates the nonlinear behaviour of the CF-PA-12 material and justifies the use of hyperelastic material model for numerical analyses. The averaged data of the stress-strain curve were imported into the Simulia/Abaqus software for the evaluation of the hyperelastic material coefficients. The optimisation process was run for the Ogden function of order N=3. The process resulted with the material coefficients listed in Table 3. The obtained material coefficients were then used in the material card of the 3D printed truss core sandwich numerical model. The static nonlinear FEM analyses were run for the two considered beams. The initial displacement of $U_y = 0.78$ [mm] was imposed on the PA6 truss core beam model and $U_y = 2.15$ [mm] on the CF-PA-12 truss core beam model. The reaction forces at the two supports were stored versus the subsequent displacement giving load-displacement curves for the analysed models. By the inspection of the Figure 6 it can been concluded that the numerical model for the PA6 truss core was developed correctly. The FEM results coincide well with the experimental curve. As for the CF-PA-12 truss core beam, the non-linear behaviour of the beam was captured. However, the calculated reaction forces are overestimated regarding to the experimental curve. This indicates higher flexural stiffness

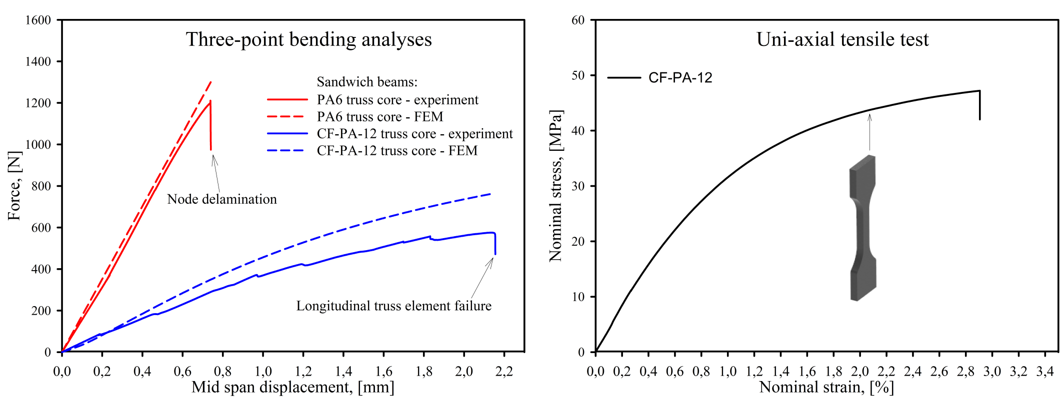

Figure 6. (left) Numerical and experimental results of the three-point bending tests analysis; (right) averaged stress-strain curve for the uni-axial tensile tests of 3D printed samples.

of the model versus the developed samples. To overcome this matter, compression or/and shear static tests of the printed samples might be used for calibration of the hyperelastic material coefficients. This would allow the material model to account for more response modes. However, the model was capable of correctly indicating the possible zone of truss failure. The maximum stress level occurred at the same location where the failure during the experimental tests (Figure 6 and Figure 7). Again, the maximum values of stress were overestimated compared to the expected ones.

5 Conclusions

The experimental and numerical analyses of the sandwich beams with the aluminium and CF-PA-12 truss core have been performed. The adhesive joints developed with the thermosetting epoxy have proved their reliability. Based on the obtained results, it can be concluded that the 3D printed trusses made of CF-PA-12 filament can be considered as a potential solution for use in sandwich structures. For such a case, the hyperelastic material model is recommended for numerical analyses. However, the presented hyperelastic material model shall be further enhanced to account for more load cases such as uni-axial compression and pure or simple shear. Similarly, the developed numerical model will be further elaborated in order to account for the failure phenomenon as encountered from experimental tests.

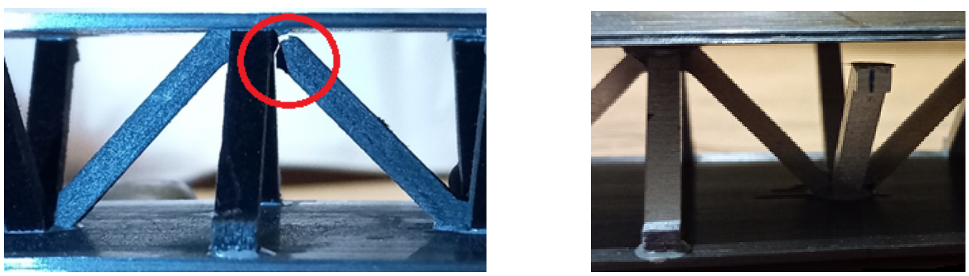

Figure 7. Failure modes of the sandwich beams due to bending: (left) delamination of a PA6 core; (right) CF-PA-12 truss longitudinal part collapse.

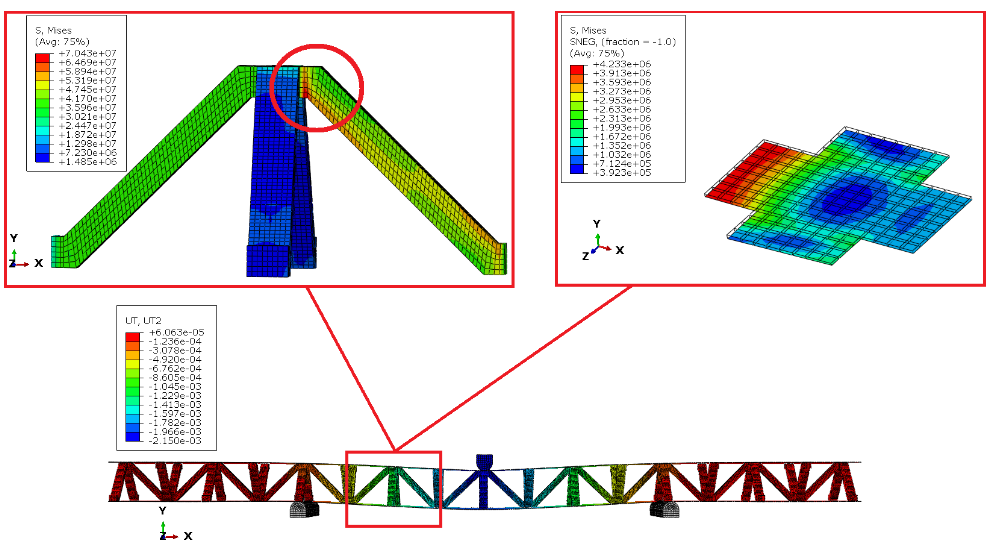

Figure 8. (bottom) CF-PA-12 truss core sandwich deflection shape in [m] with the corresponding: (top-left) stress field at truss core and (top-right) stress field at the adhesive layer - in [Pa].

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