INTERSECTII
INTERSECTIONS
http://www.intersections.ro
ISSN 1582-3024

Numerical Investigations of Stresses and Damage Distributions on the Layers of a Sandwich Beam with Composite Laminated Faces Subjected to Bending

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Summary

The sandwich elements are multi-layered structures made of two strong and stiff thin exterior faces, bonded by a lightweight thick core, such that the structural properties of the entire assembly are superior to those of the separate components.

The composite laminates are build up by stacking two or more unidirectional fibre reinforced composite laminas, with different or same fibre orientation angles, thicknesses and materials constituents.

The design flexibility of composite structures is a great challenge since the advantage of orienting the composite laminas in the needed directions leads to improved structural properties of the whole assembly.

The paper presents the flexural response of a sandwich beam with exterior layers made of laminated composites with different fibre orientations. The results are presented in terms of distribution of stresses on the layers of the composite sandwich beam. The failure and the damage occurrence on the plies of the laminated facings are investigated according to the maximum strain failure criterion and to the modified Puck failure criterion.

KEYWORDS: sandwich beam, composite laminate facings, stresses distributions, fibre orientations.

1. INTRODUCTION

When compared to the traditional materials, composites have improved performances, such as high stiffness and strength, low density, high fatigue endurance, corrosion and wear resistance, environmental stability, tailoring advantages and adaptability to the intended function and requirements of the structure [1].

The unidirectional composite lamina is the simplest element of the composite material, formed by unidirectional fibres embedded in a matrix [2]. Moreover, a lamina can be considered an elementary layer of a composite laminate, which is made by stacking two or more plies, with different fibre orientation angles. The most important aspect of using composite laminates is the possibility of tailoring the stiffness and strength in the needed direction, through the suitable selection of the fibre orientations and stacking sequences [3].

The simplest types of sandwich elements are those which are composed of two strong and stiff thin exterior layers, separated by a low density continuous thick core [4-6]. The main functions of the faces of the sandwich beam are to take over the direct stresses, to provide the bending stiffness of the structure and to ensure the general stability of the element. The core should be stiff enough in order to provide the shear strength and to ensure that the exterior layers do not slide over each other [7-8]. Combining the advantages of the sandwich beams and of the composite laminates respectively, an improved element can be achieved, such as a sandwich beam with composite laminated faces.

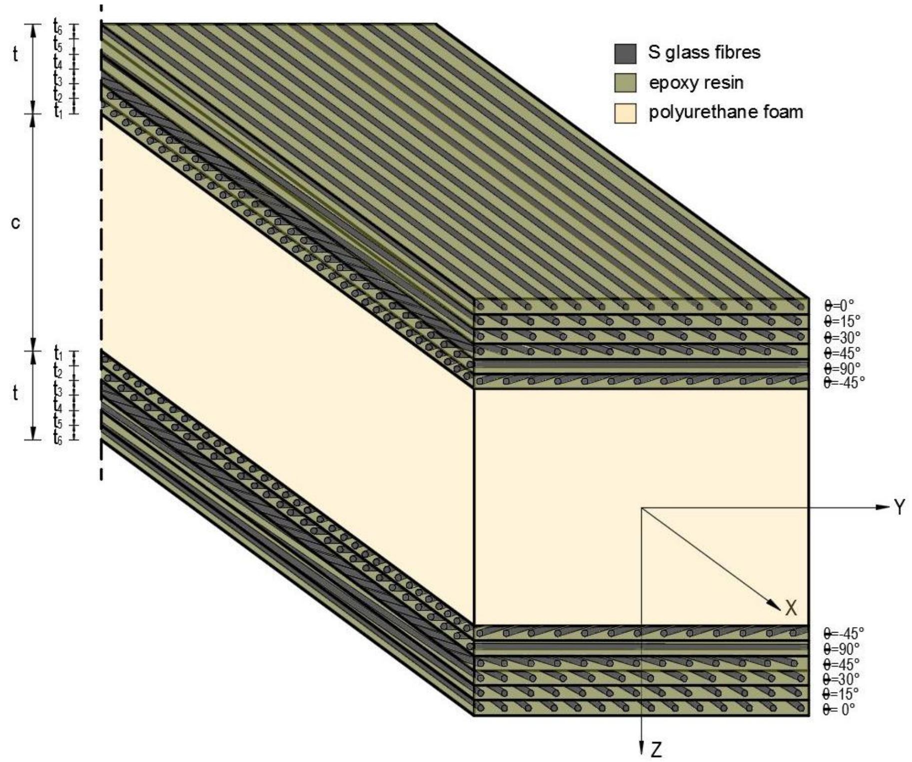


Figure 1. Sandwich beam with laminated composite facings

The present paper is focused on the study of the stresses distributions on the layers of a continuous core sandwich beam with exterior layers made of laminated composites, subjected to bending. The analysis is based on a symmetrically balanced composite laminate with the following stacking sequence

$[0/15/30/45/90/-45]_s$, which has been previously proven [9] to have a gradual failure when subjected to uniaxial loads, due to the different fibres orientation angles. A continuous core is disposed of as an intermediate layer between the laminated composite facings, such that the sandwich effect can be achieved, as shown in Figure 1.

Each layer of the composite laminates has 0.25 mm thickness and it is made of S-glass fibres embedded in an epoxy resin, while the core is realised of polyurethane foam, with a thickness of 60 mm. The in-plane dimensions of the sandwich beam have been selected as 100 mm wide and 400 mm long, according to ASTM C393 [8, 10]. The total height of the analysed layered element has resulted equal to 63 mm. The simply supported beam is subjected to bending produced by an equivalent load of 45 kN, uniformly distributed on the upper face of the sandwich element.

The mechanical properties of the unidirectional lamina and the elastic modulus of the polyurethane foam core are presented in Table 1.

Table 1. Mechanical properties of the materials [11]

	S glass_epoxy lamina				polyurethane foam
Stiffness properties	Longitudinal modulus E_1 [GPa]	Transverse modulus E_2 [GPa]	Shear modulus G_{12} [GPa]	Poisson's ratio ν_{12}	Elastic modulus E [MPa]
	52.94	13.93	5.07	0.292	37.9
	S glass_epoxy lamina				
Strength properties	Longitudinal tensile strength f_{Lt} [MPa]	Longitudinal compressive strength f_{Lc} [MPa]	Transverse tensile strength f_{Tt} [MPa]	Transverse compressive strength f_{Tc} [MPa]	In-plane shear strength F_{LTs} [MPa]
	2836	1122	62.53	125.1	58.29

The main purpose of the paper is to evaluate the damage localisations on the layers of the sandwich facings, which have different orientation angles. The plies sequence failure predictions of the composite exterior layers subjected to bending can be considered a serious concern.

2. FAILURE CRITERIA APPLIED IN THIS STUDY

The investigation of the failure index in each layer of the laminated composite is a necessity in order to verify that the plies contribute to the overall stiffness of the sandwich element or they have to be discounted from the calculation of the assembled stiffness matrix of the laminate, at a given loading. Different failure modes can be associated with composite elements, such as fibres rupture (tension of the fibres), fibres kinking (compression of the fibres), matrix cracking (tension of the matrix), matrix crushing (compression of the matrix) or interface delamination [12, 13].

The failure criteria selected in the study are the maximum strain failure criterion and the modified Puck failure criterion.

2.1. Maximum strain failure criterion

According to the maximum strain failure criterion, the failure occurs in the composite lamina when the strains along any principal material directions exceed the corresponding ultimate strains, as follows [14]:

$$\begin{gathered}-\varepsilon_{Lc} < \varepsilon_1 < \varepsilon_{Lt} \\ -\varepsilon_{Tc} < \varepsilon_2 < \varepsilon_{Tt} \\ -\gamma_{LTf} < \gamma_{12} < \gamma_{LTf}\end{gathered} \tag{1}$$

where:

$\varepsilon_{Lt}, \varepsilon_{Lc}$ - the ultimate tensile and compressive strains in the longitudinal direction;
ε_{Tt}, ε_{Tc} - the ultimate tensile and compressive strains in the transverse direction;
γ_{LTf} represent the ultimate in-plane shear strain.

The strains along the principal material directions ($\varepsilon_1, \varepsilon_2$, γ_{12}), which corresponds to a stress σ_x, can be determined according to Eq. (2):

$$\begin{gathered}\varepsilon_1 = \frac{\sigma_x}{E_1}\left(\cos^2\theta - \nu_{12}\sin^2\theta\right) \\ \varepsilon_2 = \frac{\sigma_x}{E_2}\left(\sin^2\theta - \nu_{21}\cos^2\theta\right) \\ \gamma_{12} = \frac{\sigma_x}{G_{12}}\sin\theta\cos\theta\end{gathered} \tag{2}$$

where:
θ is the fibre orientation angle;

E_1, E_2 and G_{12} represent the elastic engineering constants along the principal material axes.

For the maximum strain failure criterion, the stresses interaction is not considered, except for the effect of Poisson's coefficient.

This failure criterion identifies three types of possible failure modes, such as longitudinal failure, transverse failure and shear failure.

2.2. Puck failure criterion

The greatest advantage of using Puck failure criteria leads to the distinguish between fibre failure and matrix failure.

2.2.1. Fibre Failure

The failure in the fibre direction is evaluated similar with the maximum stress failure criterion (Eq. 3a) or according to the maximum strain failure criterion, as it was previously presented (Eq. 3b):

$$-\sigma_{Lc} < \sigma_1 < \sigma_{Lt} \tag{3a}$$

or

$$-\varepsilon_{Lc} < \varepsilon_1 < \varepsilon_{Lt} \tag{3b}$$

where

$\sigma_{Lc} = f_{Lc}$,

$\sigma_{Lt} = f_{Lt}$ and

σ_1 is stress in the fibre direction.

2.2.2.a Matrix Failure (Simple Puck failure criterion)

According to the simple Puck failure criterion, the failure occurs in the matrix when the left-hand side of the Eq. (4) reaches 1, as follows [15]:

$$\left(\frac{\sigma_2}{f_T}\right)^2 + \left(\frac{\tau_{12}}{f_{LTs}}\right)^2 = 1 \tag{4}$$

where σ_2 and τ_{12} are the in-plane stresses along the principal material directions, f_T refers to both compressive f_{Tc} and tensile f_{Tt} failure stresses, depending on the stress state, and f_{LTs} represents the in-plane shear strength.

ISSN 1582-3024

2.2.2.b Matrix Failure (Modified Puck failure criterion)

The modified Puck failure criterion is different from the simple Puck formulation, only in case of matrix failure. An improvement of the relation criterion consists in the simultaneous implication of both compression and tensile stresses [15]:

$$\frac{\sigma_2^2}{f_{Tt} \cdot f_{Tc}} + \frac{\tau_{12}^2}{f_{LTs}^2} + \left(\frac{1}{f_{Tt}} + \frac{1}{f_{Tc}}\right) \cdot \sigma_2 = 1 \tag{5}$$

For the failure analysis performed in the numerical modelling, the modified Puck criterion was considered.

3. NUMERICAL MODELLING

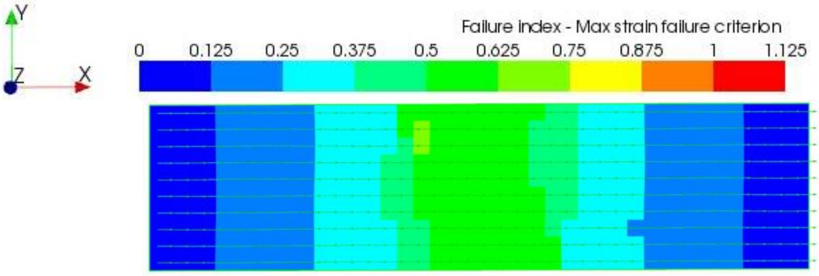
The flexural response of the composite sandwich beam is carried out in ANSYS Composite Prep/Post, in order to define the stacking sequence of the laminated facings and of the sandwich element, respectively. Moreover, the results can be visualised in terms of plies groups, depending on the fibres orientation angles.

3.1. Failure index evaluation

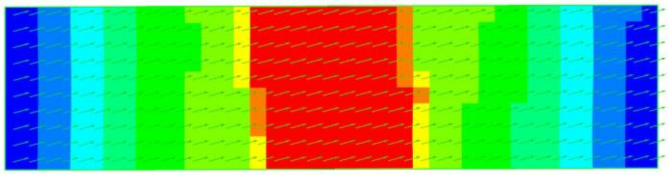
The evaluation of the failure index was carried out for each layer of the laminated composite facing, with respect to both failure criteria. The distributions of the failure index for the inferior laminate composite face are presented in Fig. 2 and Fig. 3.

A failure index greater than 1 indicates that the breakage of the composite lamina has occurred. According to the results obtained by maximum strain criteria, the shear failure occurs in the plies with the fibre orientation angles of 15°, 30° and 45°, while the ply 5 (90°) fails due to transverse stresses. Moreover, the failure of the layer with 45° fibres orientation is caused by both shear and transverse stresses.

The critical failure mode that has occurred according to Puck criterion is caused by the failure of the matrix. However, the fibres orientation angles have a major influence on the distribution of principal stresses.

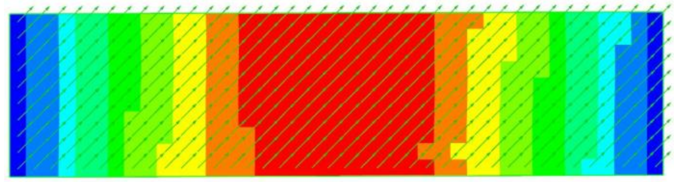


a) ply 1, 0° fibre orientation

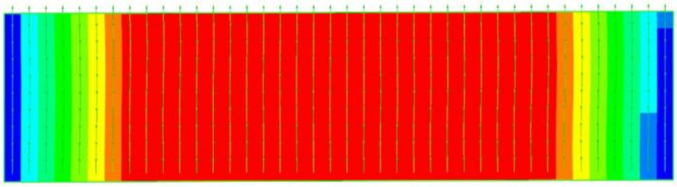


b) ply 2, 15° fibre orientation

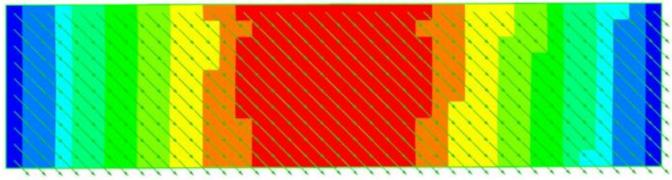
c) ply 3, 30° fibre orientation



d) ply 4, 45° fibre orientation

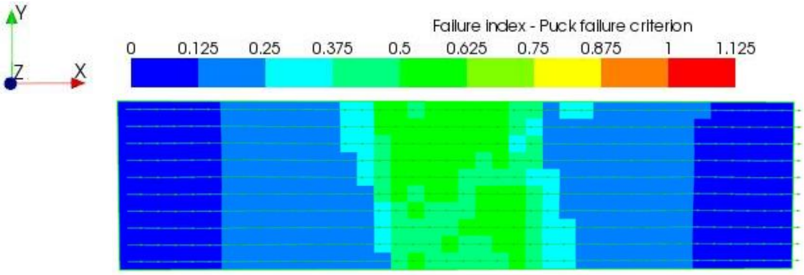


e) ply 5, 90° fibre orientation

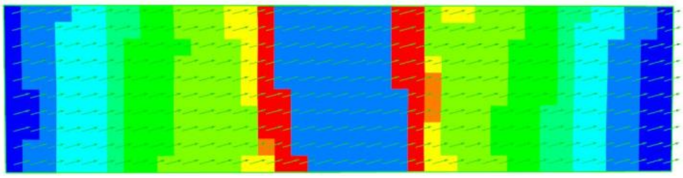


f) ply 6, -45° fibre orientation

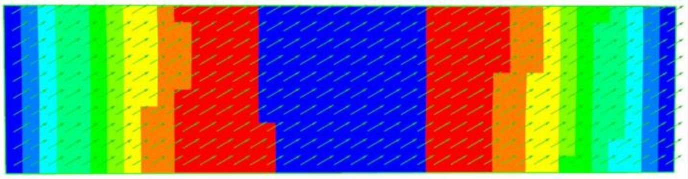
Figure 2. Failure index on the inferior facing layers, according to maximum strain failure criterion



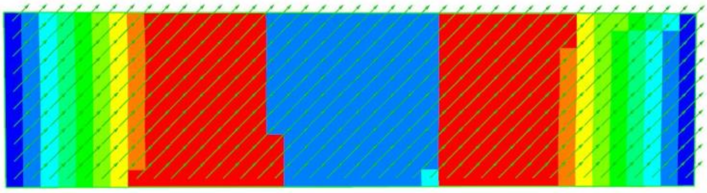
a) ply 1, 0° fibre orientation



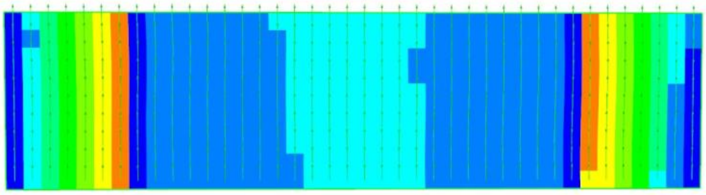
b) ply 2, 15° fibre orientation



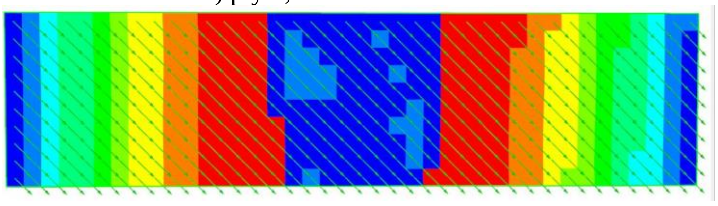
c) ply 3, 30° fibre orientation



d) ply 4, 45° fibre orientation



e) ply 5, 90° fibre orientation



f) ply 6, -45° fibre orientation

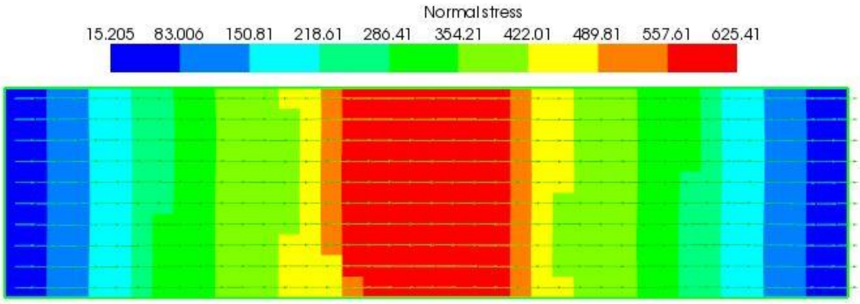
Figure 3. Failure index on the inferior face layers, according to Puck failure criterion

3.2. Direct stresses distribution

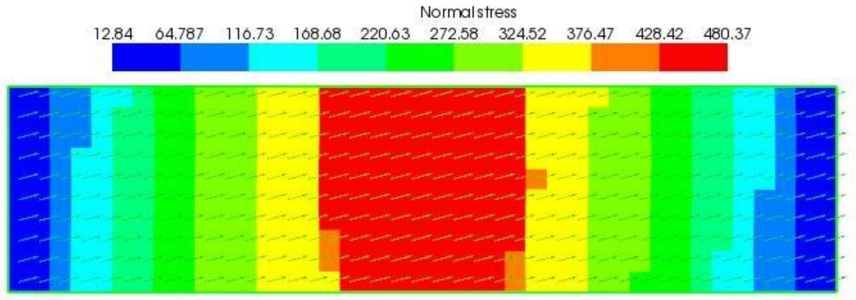
The distribution of the direct stresses of the sandwich beam is illustrated in Fig. 4, both for the inferior facing made of multi-layered composite and for the core of the sandwich beam.

The influence of the fibre orientation angles on the variation of direct stresses of the composite laminate facing can be noticed according to the stresses distribution reflected in each layer with a different orientation.

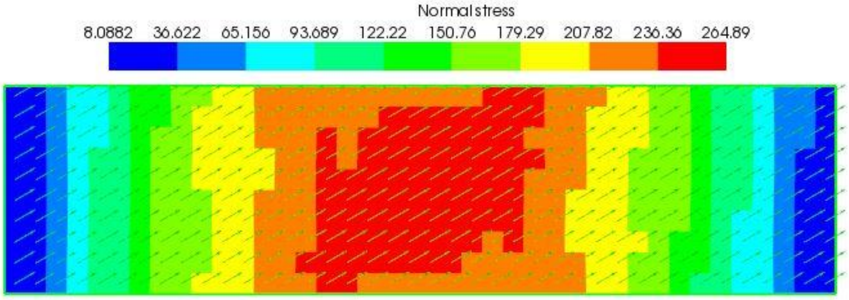
According to the analogy between the sandwich beam and a double T beam, the obtained results confirmed that the exterior layers have to withstand the maximum direct stresses, while the normal stresses in the core are negligible.



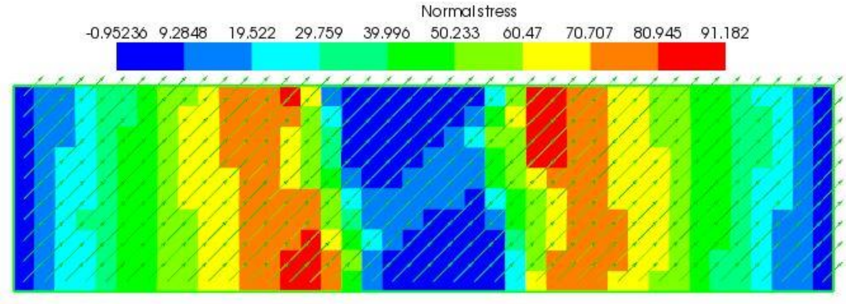
a) ply 1, 0° fibre orientation



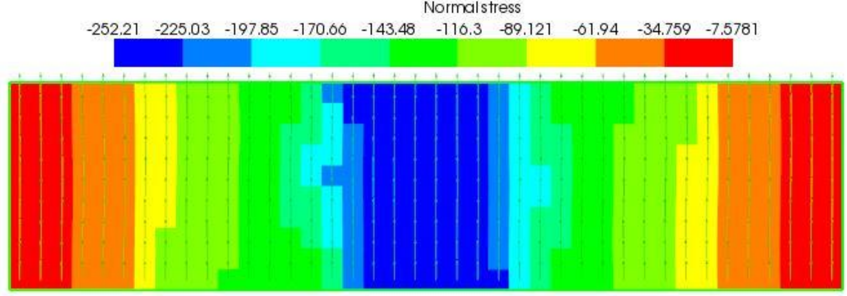
b) ply 2, 15° fibre orientation



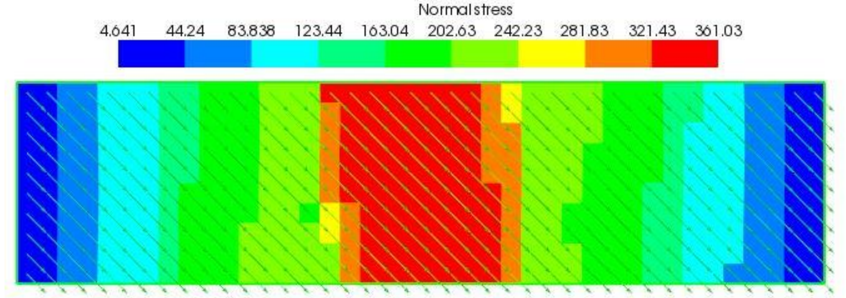
c) ply 3, 30° fibre orientation



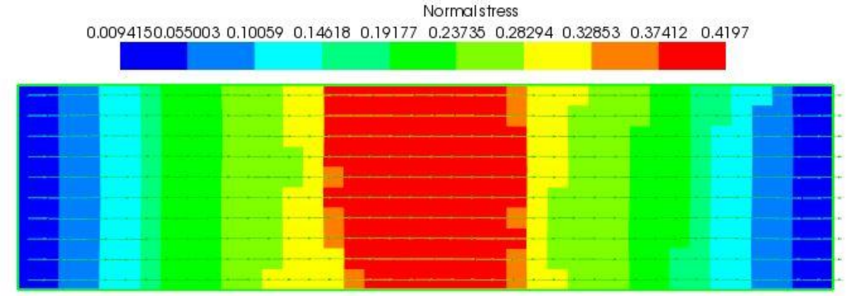
d) ply 4, 45° fibre orientation



e) ply 5, 90° fibre orientation



f) ply 6, -45° fibre orientation

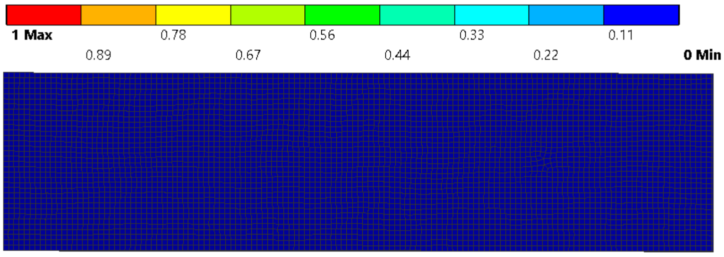


g) core layer

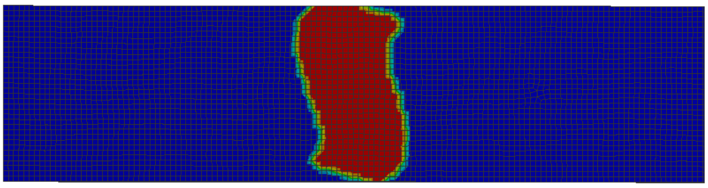
Figure 4. Normal stresses distributions on the layers of the sandwich beam

3.3. Damage identification

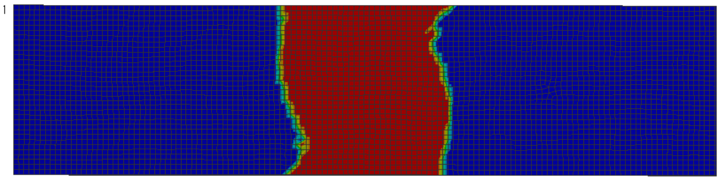
The identification and progression of damages are generally performed based on failure criteria and a damage evolution law. The progressive failure analysis carried out in this paper is based on both proposed failure criteria. Moreover, the considered damage evolution method is the material property degradation procedure. The selected coefficient of stiffness degradation is 0.9, which means that the composite material can be degraded up to 90%.



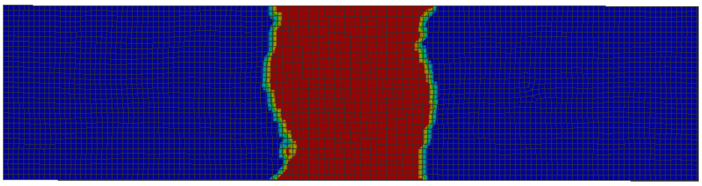
a) ply 1, 0° fibre orientation



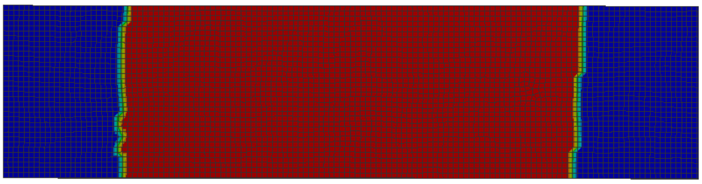
b) ply 2, 15° fibre orientation



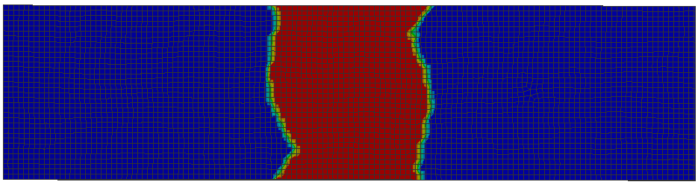
c) ply 3, 30° fibre orientation



d) ply 4, 45° fibre orientation



e) ply 5, 90° fibre orientation

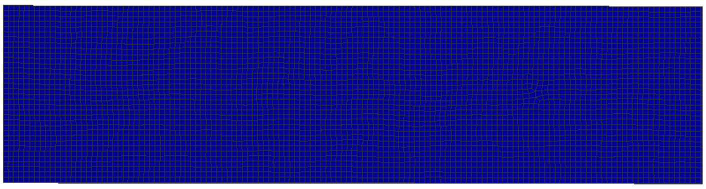


f) ply 6, -45° fibre orientation

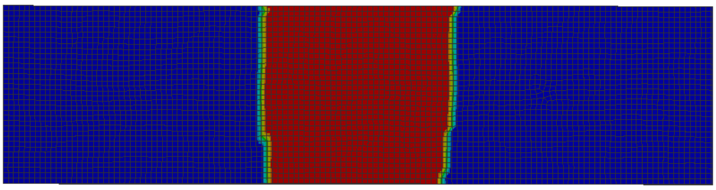
Figure 6. Damage distributions on the layers of the sandwich beam according to maximum strain failure criterion

Figs. 6-7 show the damage distributions on the laminated composite facing with layers of different fibre orientations, where *0* means undamaged and *1* is completely damaged.

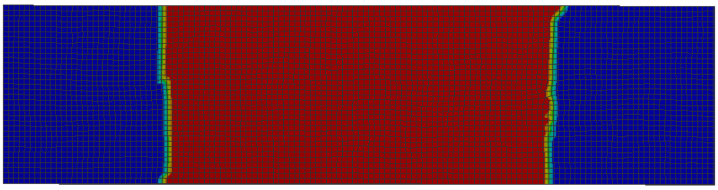
The most affected layers in the composite laminate facings are those with the fibre orientation of 90° because the transverse properties of the unidirectional reinforced laminas are much lower compared to the longitudinal ones. Reversely, the ply 1 (with 0° fibre orientation angle) is undamaged and it is the layer which withstands the highest stresses up to failure.



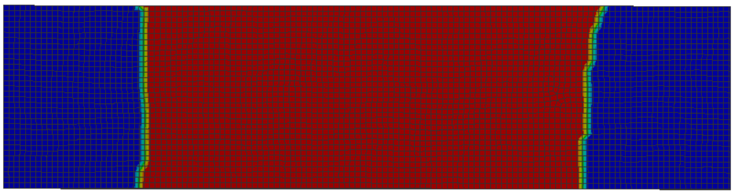
a) ply 1, 0° fibre orientation



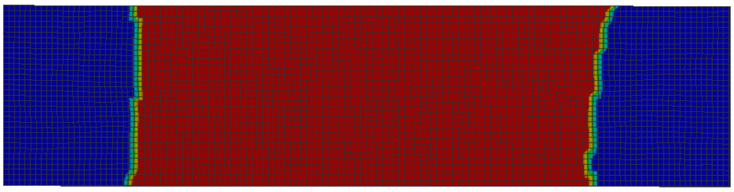
b) ply 2, 15° fibre orientation



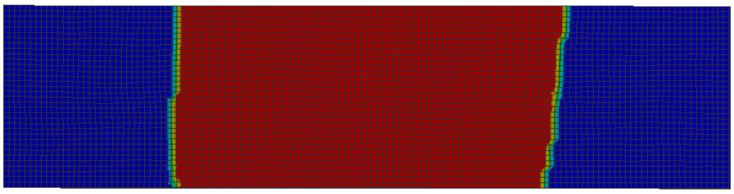
c) ply 3, 30° fibre orientation



d) ply 4, 45° fibre orientation



e) ply 5, 90° fibre orientation



f) ply 6, -45° fibre orientation

Figure 7. Damage distributions on the layers of the sandwich beam according to Puck failure criterion

4. CONCLUSIONS

A numerical study was performed in this paper, in order to investigate the flexural response of a sandwich beam with multi-layered composite facings. The direct stresses distributions were evaluated on the exterior layers and core, respectively. The failure index and the damages occurrence were identified on each layer of the composite laminate. Two failure criteria, namely the maximum strain criterion and Puck failure criterion were selected to establish the damage evolution law,

The results confirmed the analogy of the sandwich beam with an I beam and lead to significant direct stresses in the faces compared to those in the core. Moreover, the progressive failure of the balanced laminate facings is caused due to the different fibres orientation angles of the laminas. The damages evaluated with maximum strain failure criteria were caused by the transverse and shear failure, while in the case of the Puck failure criteria, the damages occur due to the failure of the matrix.

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