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Mechanical analysis of al/foam composite sandwich panels under elastic and elastoplastic states

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Abstract: This study performs mechanical analysis for Al/Foam composite sandwich panels under 3-point bending using numerically and experimentally. The flexural rigidity, elastic deflections, and normal, shear stresses are obtained by analytical calculations of the Timoshenko beam equation and compared finite element (FE) models for 3-point bending loading conditions. The FE models are constructed using 2D single-layer shell and 3D solid discrete-layer models. The validity of FE models at the analysis is evaluated for Al/PVC Foam sandwich composites for the elastic state. The experimental bending results of Al/XPS Foam sandwich composites are compared with numerical models at elastic and elastoplastic states. The elastic results indicate that the out-of-plane deflection results agree well across numerical and analytical models. Normal stresses at the core are higher in 3D discrete-layer solid models compared to laminated shell theory-based models for thick plates, due to the more accurate characteristics of the discrete-layer solid models. The Timoshenko beam theory-based analytical bending results show a good correlation with the results from laminated shell theory-based finite element method (FEM) analyses. Elastoplastic FEM analysis indicates that discrete-layer-based 3D solid FEM models effectively predict local effects dependent on indentation failure.

Keywords: Sandwich Panels, Timoshenko Beam Theory, Composite Laminate Modeling, Discrete-layer Modeling, Elastic and Elastoplastic Finite Element Analysis (FEA).

1. Introduction

A sandwich structure is a special class of composite structure commonly used in engineering and manufacturing. It consists of two outer layers, called face sheets, and a core material sandwiched between them. This design offers a combination of lightweight construction and high stiffness, making it ideal for various applications across different industries [1]

The core material is positioned between the facesheets and is crucial in determining the structural properties. It is chosen based on the desired characteristics of the sandwich structure, such as weight reduction, stiffness, insulation, or impact resistance. Common core materials include foams, honeycomb structures, and balsa wood [2]

Aluminum polymeric foam sandwich structures combine aluminum facesheets with a polymeric foam core to create lightweight composite materials. These sandwich structures offer a unique combination of properties that make them valuable in various engineering and manufacturing applications. Aluminum facesheets are combined with a foam core to create a lightweight structure, which is critical for applications where weight reduction is required. Aluminum enhances the strength of the structure, ensuring it can withstand mechanical loads and stresses. [3].

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Over the last half-century, various theories have been developed to accurately and effectively analyze composite structures. These include the equivalent single-layer theory, layerwise theory, zig-zag theory, and 3D elastic methods, among others [4].

Equivalent single-layer theories, such as classical laminated plate theory and first-order shear deformation theory, effectively predict the global responses of thin laminated composite plates and shells. However, they struggle to accurately capture the behavior of thick laminated composites, particularly regarding local responses such as the distribution of ply-level stresses. This limitation stems primarily from the continuous assumption of in-plane displacements inherent in these theories [5].

Numerous studies in the literature have employed the equivalent single-layer approach, incorporating 2D finite element (FE) shell models, to conduct comprehensive investigations of laminated composites and sandwich plates in both elastic and elastoplastic regions [6-8].

Shear deformations are important for sandwich panels where the core is relatively thick compared to the facesheets. The Timoshenko beam theory, also known as the first shear deformation theory, considers the effect of shear deformation in addition to classical bending. In theories like the first-order shear deformation theory, where transverse shear strains are assumed to be constant through the thickness direction, shear correction factors are required.

The accuracy of solutions obtained from the first-order shear deformation theory heavily depends on the ability to predict more precise shear correction factors [5].

A FE formulation of the classical linear first-order shear deformation theory for layered shells can be found in Reddy's book [9]. Pagano's pioneering work on the three-dimensional layerwise elasticity solution provides a robust framework for analyzing interlaminar stress fields in multilayered composite plates under mechanical loading conditions [10]. Simple equivalent single-layer theories often fail to accurately characterize the three-dimensional stress field at the ply level, making them unsuitable for simulating damage in laminated composites [11]. Reddy introduced a generalized laminate plate theory that incorporates discrete-layer transverse shear and transverse normal effects, effectively reducing the 3D elasticity theory of plates into a 2D laminate theory [12].

The Layerwise Theory characterizes laminated composites by treating them as an assembly of individual layers. Alternatively, it employs one-dimensional interpolation functions to model the displacement and stress fields along the thickness direction. This approach enables a detailed representation of the behavior of each layer within the composite structure, capturing the complexities of interlaminar interactions and allowing for accurate analysis of laminate performance [11]. The discrete-layer-based layerwise method typically offers more precise predictions of stresses and deformations within the sandwich panel by explicitly modeling the composite's layering and facilitating detailed stress analysis in each layer. It is a valuable tool for analyzing sandwich panels, especially when dealing with composite materials with complex layering and when detailed information about interlaminar stresses and failures is required. It allows for a comprehensive understanding of the structural behavior of these composite structures. [13].

Discrete-layer implemented FE shell modeling is a common approach for modeling laminated composites both in linear and nonlinear cases, as demonstrated by Mawenya and Davies [14] and Reddy [15]. When modeling sandwich panels, it is crucial to consider various failure modes, such as delamination between layers, core shear, indentation, and local buckling, depending on the application and loading conditions. [16-18]

The interaction between the facesheets and the core material is crucial in determining failure modes. A comprehensive FEA study should consider these interactions and provide insights into the structural performance and safety of the sandwich panel under various loading conditions. For detailed analysis of sandwich panels, especially for critical engineering applications, finite element analysis (FEA) is often employed to account for both bending and shear deformation. FEA allows for accurate modeling of complex geometries and material properties and can consider discrete deformation modes simultaneously [19].

The 3D displacement-based finite element method (FEM) can provide precise displacement and stress field solutions, but it demands substantial computational resources [11-12]

3D FEM discrete-layer models can capture local failure and debonding characteristics. These models permit the definition of interface damage. Abrate and coworkers investigated the cohesive zone delamination of interface layers using a 3D FEM discrete-layer model [20]. Höwer and coworkers studied the effects of fiber bridging on the delamination of the face sheet and core of honeycomb sandwich panels using a FE model [21].

In this study elastic properties of Al/foam sandwich panels are obtained by simple mechanics of materials approach and compared with commercial FEA code Ansys results namely 2D single-layer Shell and 3D discrete-layer solid modeling approaches. Shear terms are considered both in analytical and numerical calculations. The FEA 2D Shell model is based on the laminated shell theory namely the Mindlin plate shell approach. Shell elements have been shown to yield accurate results for thin-walled composite plates when considering the first-order shear deformation theory [22]. The effectiveness of 3D solid single-layer and discrete-layer FEM models in the nonlinear zone is established and compared with experimental test results.

2. Materials Method

2.1. Sandwich Beams Bending Equations

In Timoshenko's theory for sandwich beams, deflection is typically calculated using beam bending theory. Timoshenko's theory accounts for shear deformations in addition to bending, providing a more accurate prediction of deflection compared to the Euler-Bernoulli beam theory, which neglects shear effects [23].

The displacement field in Timoshenko beam sandwich beam theory

$$u(x,z) = u_0(x) - z\,\emptyset_x \quad (1)$$

$$w(x) = w_0(x) \quad (2)$$

The strain fields is defined as follow

$$\varepsilon_x = \frac{du_0}{dx} + \frac{d\emptyset_x}{dx} \quad (3)$$

$$\gamma_{xz} = \frac{dw_0}{dx} + \frac{dU}{dz} \quad (4)$$

Here $u(x,z)$ is the axial displacement across the thickness, ε_x and γ_{xz} are the axial and shear strain of the composite, u_0, w_0 is the axial and transverse displacement of the midplane, $\emptyset_x$ is the rotation of the cross section according to the x axis.

The governing equations bending for a Timoshenko sandwich beam with transverse uniform external load q(x), which include the effects of bending and shear deformation, can be formulated as follows

$$\frac{dN}{dx} = 0 \quad (5)$$

$$\frac{dQ}{dx} + q(x) = 0 \quad (6)$$

$$\frac{dM}{dx} - Q_x = 0 \quad (7)$$

The stress resultants namely axial force, moment and shear forces can be written as follows [24]

$$N_x = A\frac{du_0}{dx} + B\frac{d\emptyset}{dx} \quad (8)$$

$$M_x = B\frac{du_0}{dx} + D\frac{d\emptyset}{dx} \quad (9)$$

$$Q_x = k_s G_c A_c\left(\frac{dw}{dx} + \emptyset_x\right) \quad (10)$$

Here A,B and D are the extensional, coupling and bending stiffness respectively, k_s is the shear correction factor, G_c is the shear modulus of the core, A_c is the cross - sectional area of the core. The governing differential equations can be obtained by combining stress resultants.

The following assumptions are used in formulations of symmetric laminated beam theory [24]

$M_{yy} = M_{xy} = Q_y = \emptyset_y = 0$, w_0 *and* $\emptyset_x$ are the functions of x and $q(x) = F_0$ is defined as transverse point load.

The out-of-plane deflections are considered in the analysis A and B stiffness are zero in the absence of plane forces at symmetric laminate beam theory. The three-point bending problem with transverse point load, the moment, and shear resultants are given as follows by these assumptions.

$$M(x) = D\frac{d\emptyset}{dx} = \frac{F_0 x}{2} \quad (11)$$

$$Q(x) = k_s G_c A_c\left(\frac{dw}{dx} + \emptyset_x\right) = \frac{dM}{dx} = \frac{F_0}{2} \quad (12)$$

The stress resultants are solved according to the simply supported boundary conditions below and integration constants are found.

$$x = 0,\ w(0) = u(0) = 0,\ x = L, w(L) = 0,\ \emptyset_x\left(\frac{a}{2}\right) = 0$$

The $\emptyset_x$ *and* w_x values are obtained respectively with boundary conditions, maximum transverse deflection is occurs at the x=a/2 is given in the following formula.

$$w_{max} = \frac{PL^3}{48D} + \frac{PL}{4K\ G_cA_c} = \frac{PL^3}{48(EI)_{eq}} + \frac{PL}{4\,(AG)_{eq}} \quad (13)$$

Here $D = (EI)_{eq}$, $G_cA_c = (AG)_{eq}$ is the equivalent elastic and shear rigidity, and K is a shear correction factor.

The equivalent elastic properties of the sandwich composite are obtained using the parallel axis theorem below [25]

$$(EI)_{eq} = \frac{E_f b\, t^3}{6} + \frac{E_c^* b\, c^3}{12} + \frac{E_f btd^2}{2} \approx \frac{E_f b\, c^2}{2} \quad (14)$$

Sandwich composites typically consist of two facesheets bonded to a lightweight core material. Here E_f, E_c^* are the face material and core materials' elastic modulus, respectively.

t is the facesheet thickness, L is the face sheet span length, b is the facesheet width, c is the core thickness, and d is the total beam thickness seen in Figure 1.

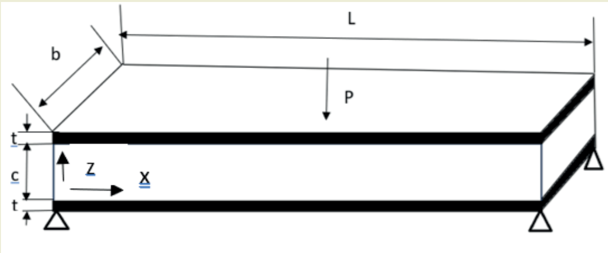

Figure 1. Sandwich beam in three-point bending with central transverse load

The equivalent shear rigidity is given below.

$$(AG)_{eq} = \frac{bd^2G_c}{c} \quad (15)$$

This equation assumes that the facesheets contribute negligibly to the overall shear stiffness compared to the core material. When a sandwich beam is subjected to bending, it experiences bending and shear deformation. This deformation results in both normal and shear stresses within the beam. The studies indicate that the core experiences negligible normal stresses, while its main function is to withstand shear loads [26]. The maximum normal stresses at the core and facesheets and shear stresses at the core of a sandwich beam are typically calculated using appropriate stress formulas derived from both bending and shear deformation theories [25].

$$\sigma_c(z) = \frac{M_zE_c^*}{(EI)_{eq}} = \frac{PL}{4btc}\frac{E_c^*}{E_f} \quad (16)$$

$$\sigma_f\,(z) = \frac{M_zE_f}{(EI)_{eq}} = \frac{PL}{4btc} \quad (17)$$

$$\tau_c(z) = \frac{P}{2(EI)_{eq}}\left[\frac{E_ftd}{2}\right] \approx \frac{P}{2bc} \quad (18)$$

2.2. Finite Element (FE) Modeling of Sandwich Composites

In this study, numerical modeling of Al/foam sandwich composites is conducted using shell laminated single-layer modeling and solid discrete-layer approaches. The validity of these models under elastic conditions is discussed, and numerical examples are provided for Al/PVC Foam sandwich composites. The solid discrete-layer model and solid laminated single-layer models are also compared with experimental results for Al/XPS Foam sandwich composites under three-point bending.

Laminated Shell Model

Layer-based shell and solid elements are a known approach used in FEA to simulate the behavior of sandwich structures [27]. The shell layer-based models simplify the complex three-dimensional geometry of the sandwich structure into two-dimensional shell elements with an equivalent single-layer theory approach.

Shell modeling balances computational efficiency and accuracy, making it a widely used approach for analyzing sandwich composites in engineering applications. This study utilizes the Mindlin shell theory in the numerical model. The mechanical properties of Al / PVC Foam sandwich composites are given in Table 1 [28]. The three-point bending dimensions in the analysis are determined according to the ASTM C393 standards.

The shell model and simply supported boundary conditions are given in Figure 2.

The two-dimensional quadratic type element Shell281

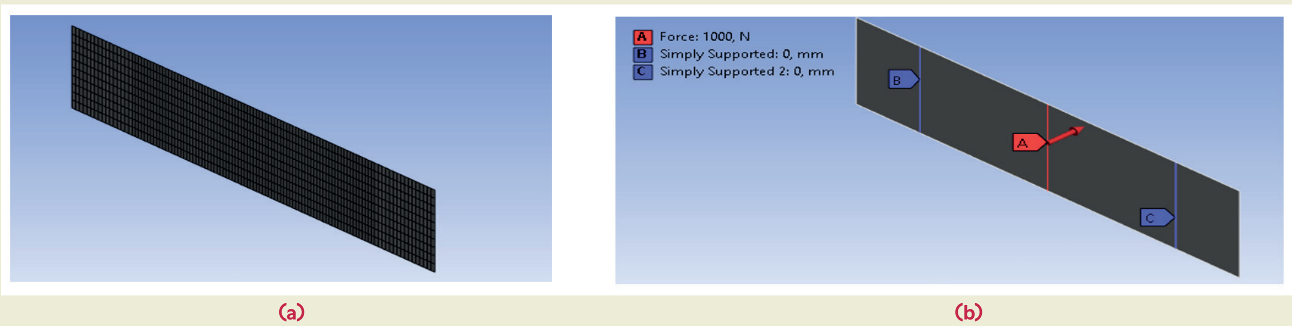

Figure 2. The shell laminated single-layer model **a**) Mesh **b**) Boundary conditions

Table 1. The Mechanical Properties of Al/ PVC Foam Sandwich Composites

PVC Foam Elastic Modulus [MPa]	PVC Foam Shear Modulus [MPa]	PVC Foam Density [kg/m^3]	PVC Foam Thickness [mm]	Al Sheet Elastic Modulus [MPa]	Al Sheet Density [kg/m^3]	Al Sheet Thickness [mm]
104	30	80	15	70000	2710	1.5

uses 1120 elements in the shell FE model, considering convergence seen in Figure 3. The midspan load is 1000N considering elastic loading conditions. Beam width (c) is 75mm and beam span length (L) is 200mm in the analysis.

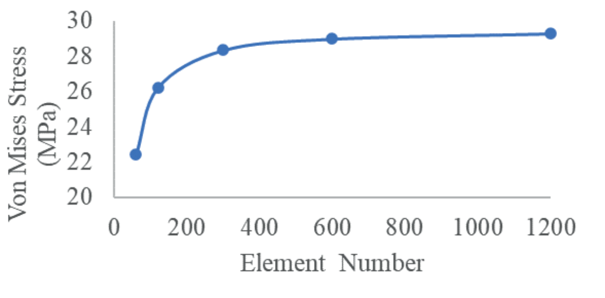

Figure 3. The convergence study at the shell model

Discrete-Layer Sandwich Composite Model

Discrete-Layer sandwich model is a composite structural analysis that accounts for the individual layers within a sandwich structure, considering their specific material properties and orientations. In the solid discrete-layer finite element model, the three-dimensional quadratic type element Solid186 is utilized, incorporating 7200 elements. This model considers both convergence and computational time factors. The hex-dominant multizone mesh and node merging command are employed at the interface between facesheets and the core to ensure continuity of load transfer. The FE solid model and boundary conditions are depicted in Figure 4.

2.3. Three-Point Bending Test of Al/XPS Foam Sandwich Panels

To assess the effectiveness of the discrete-layer model in the plastic region, experimental three-point bending results, specifically load-deflection data, for Al/XPS Foam sandwich composites are compared. The dimensions for the three-point bending test are obtained for three specimens according to ASTM C393 standards. The experimental setup and deflection scenes are depicted in Figure 5. The beam geometry, face, and core material properties are given in Table 2. The XPS mechanical properties are obtained from compression tests from the literature [29].

Here (E_f, E_c) is the elastic modulus of the Aluminum sheet and XPS foam core respectively, $(\sigma_{fy}, \sigma_{ft})$ is the yield and tensile strength of Aluminum sheet respectively, $(\varepsilon_{f,ult}, \varepsilon_{c,ult})$ is the ultimate strain at break of facesheet and core material respectively, $\sigma_{c,c}$ is the compressive strength of XPS foam, (ρ_f, ρ_c) are the density of the facesheet and foam core respectively.

In this research, the mechanical properties of XPS Foam are determined through the results of compression tests. A multilinear kinematic hardening model is employed to obtain accurate material behavior data for XPS foam compression stress-strain curves, and the multilinear isotropic hardening material model is used for the modeling of Al 1050, as seen in Figure 6 below.

Table 2. Al/XPS sandwich beam geometry and face/ core material properties

Beam Geometry [mm]				Face Material Al 1050					Core Material XPS Foam			
b	c	t	L	E_f [GPa]	σ_{fy} [MPa]	σ_{ft} [MPa]	$\varepsilon_{f,ult}$	ρ_f $[\frac{kg}{m^3}]$	E_c [MPa]	$\sigma_{c,c}$ [MPa]	$\varepsilon_{c,ult}$	ρ_c $[\frac{kg}{m^3}]$
75	19.5	2	200	70	45	120	0.35	2710	7	0.150	0.25	28

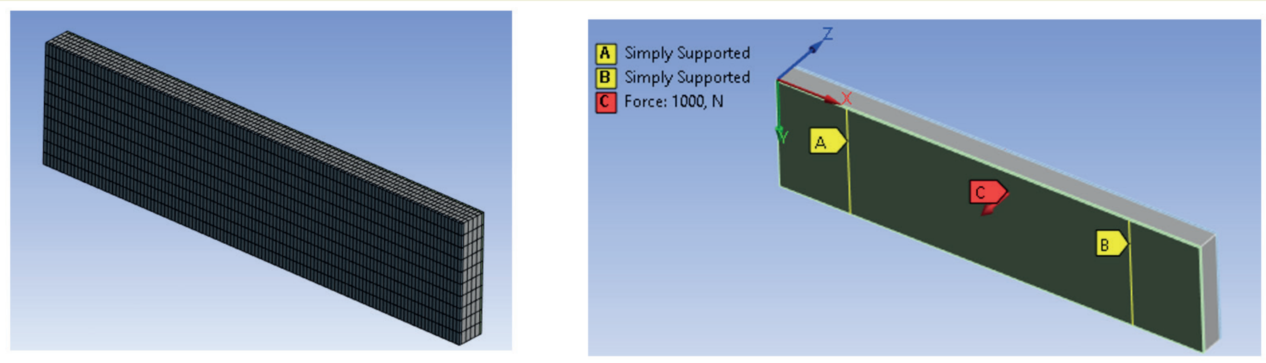

Figure 4. The discrete-layer model a) Mesh b) Boundary conditions

3. Results and Discussion

3.1. Laminated Shell Model Results

This section presents the results of the laminated shell model derived from the 2D shell model for Al/PVC Foam sandwich composites subjected to three-point bending. These results are compared with those from the Timoshenko sandwich beam model.

The shell layer-based single-layer theory approach has been shown to provide results that correlate well with the Timoshenko beam theory for bending isotropic and functionally graded beams [30]. This correlation is also

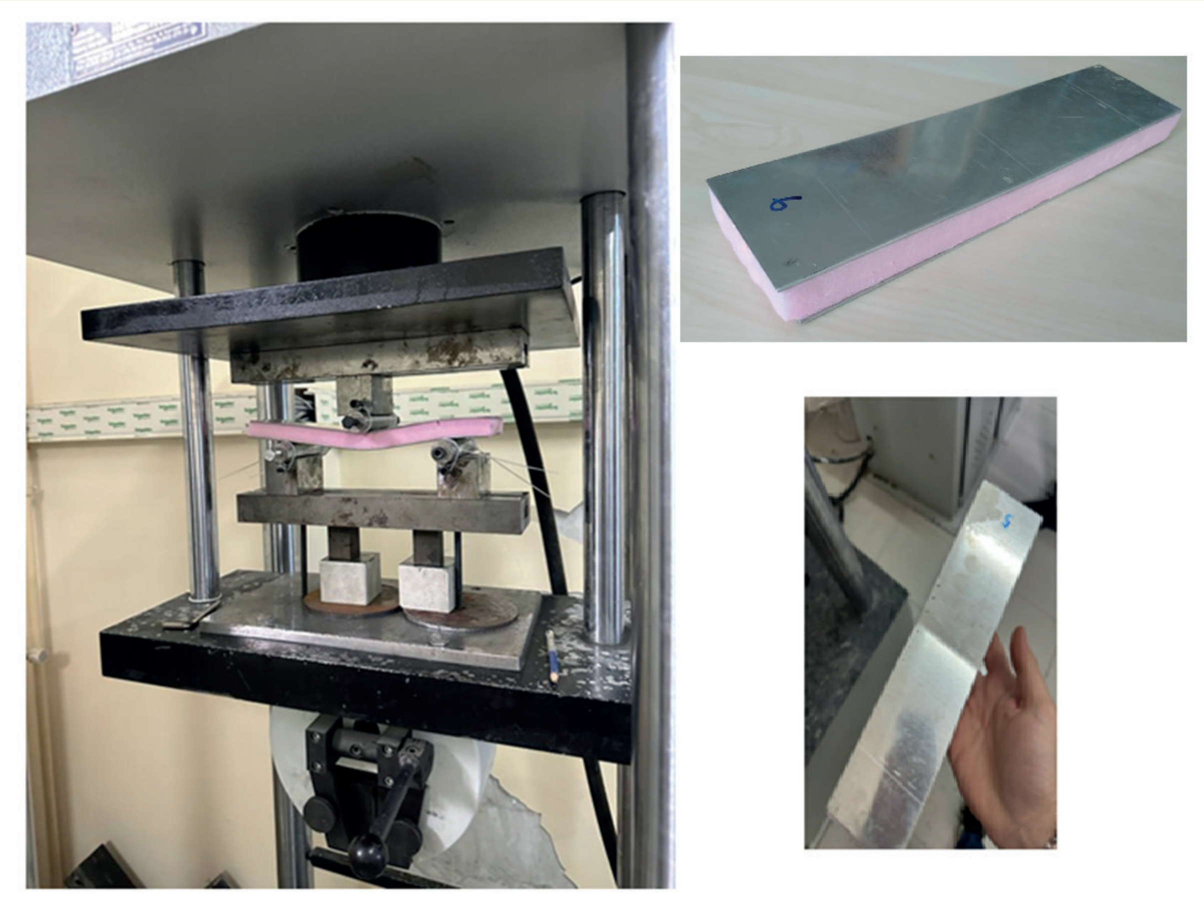

Figure 5. Three-point bending test setup and samples

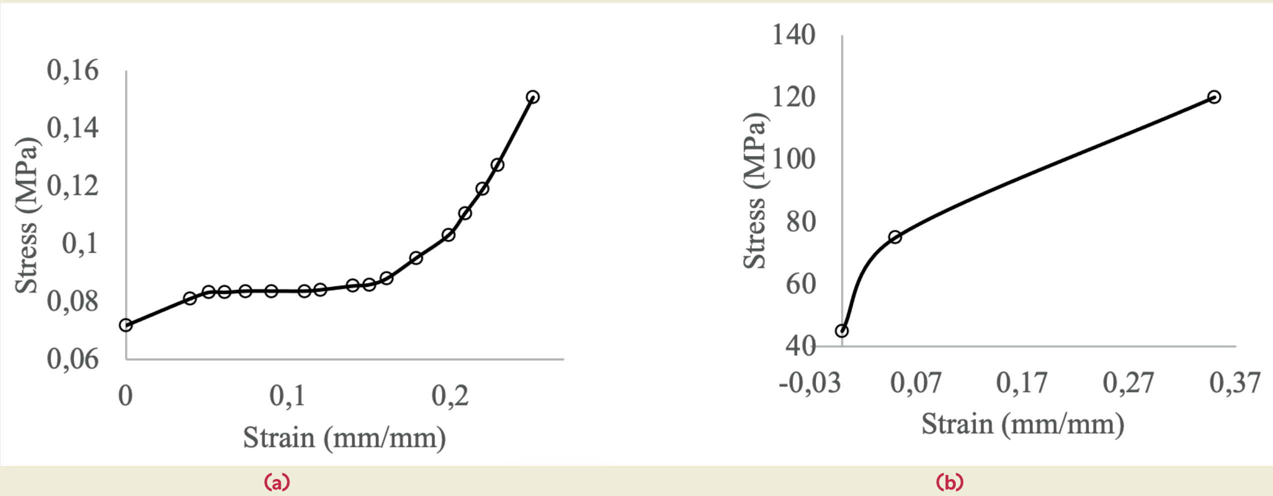

Figure 6. Materials models definitions at fem analysis **a)** Multilinear kinematic hardening model of XPS foam **b)** Multilinear isotropic hardening model of aluminum

demonstrated in Kholkin's study on the 3-point bending characteristics of laminated composite beams [31].

The normal stress results are shown in Figure 7 below.

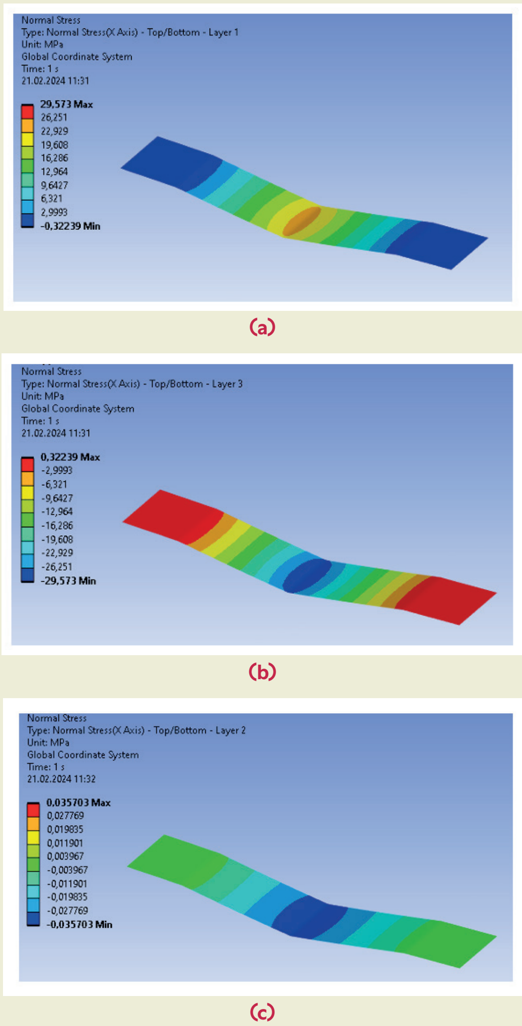

Figure 7. Normal stresses shell model a) Outer face sheet b) Inner facesheet c) Core

The normal stress results indicate that the core experiences compressive stress at the top and tensile stress at the bottom surface. The facesheets also experience maximum normal stresses during bending. The outer facesheet on the tension side experiences maximum tensile stress, while the inner facesheet on the compression side experiences maximum compressive stress.

Shear stresses are typically highest at the interface between the facesheets and the core material. Shear stresses in the core usually peak near the neutral axis as seen in Figure 8 below.

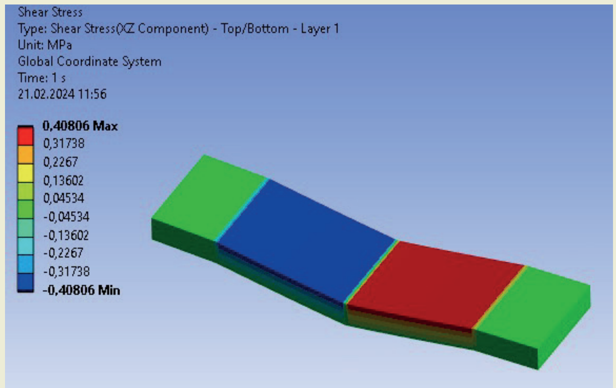

Figure 8. Shear stresses of the core at the shell model

The analytical results obtained from the Timoschenko sandwich beam model are compared with a laminated beam sandwich composite using a 2D Shell FE model, as seen in

Table 3. In Table 3 analytical and shell model results are denoted by subscripts "A" and "SH" respectively. The facesheet and core are denoted by "F" and "C" respectively. The maximum deflection, bending, and shear stresses are denoted by symbols $\delta, \sigma\ and\ \tau$ respectively.

3.2. Discrete-layer Sandwich Composite Model Results

The results of the discrete-layer solid model obtained for Al/PVC Foam sandwich composites under three-point bending are presented. These results are compared with those from the laminated shell model. The normal and shear stress results are shown in Figure 9-10 below. It is seen from the figures that the stress zones in the discrete-layer solid model correlate with those in the shell model, whereas the local load-affected zone is more pronounced in the discrete-layer model.

The numerical results obtained from the discrete-layer model is compared with the Shell model at the following Table 4. In the table, SOL" denotes solid model results.

A good correlation is observed in the deflection and normal/shear stress results of the core material within the elastic region. However, underestimated results are

Table 3. The shell model results versus analytical results.

δ_A [mm]	$\sigma_{A,F}$ [MPa]	$\sigma_{A,C}$ [MPa]	$\tau_{A,C}$ [MPa]	δ_{SH} [mm]	$\sigma_{SH,F}$ [MPa]	$\sigma_{SH,C}$ [MPa]	$\tau_{SH,C}$ [MPa]
1.073	29.62	0.044	0.444	1.072	29.57	0.035	0.408

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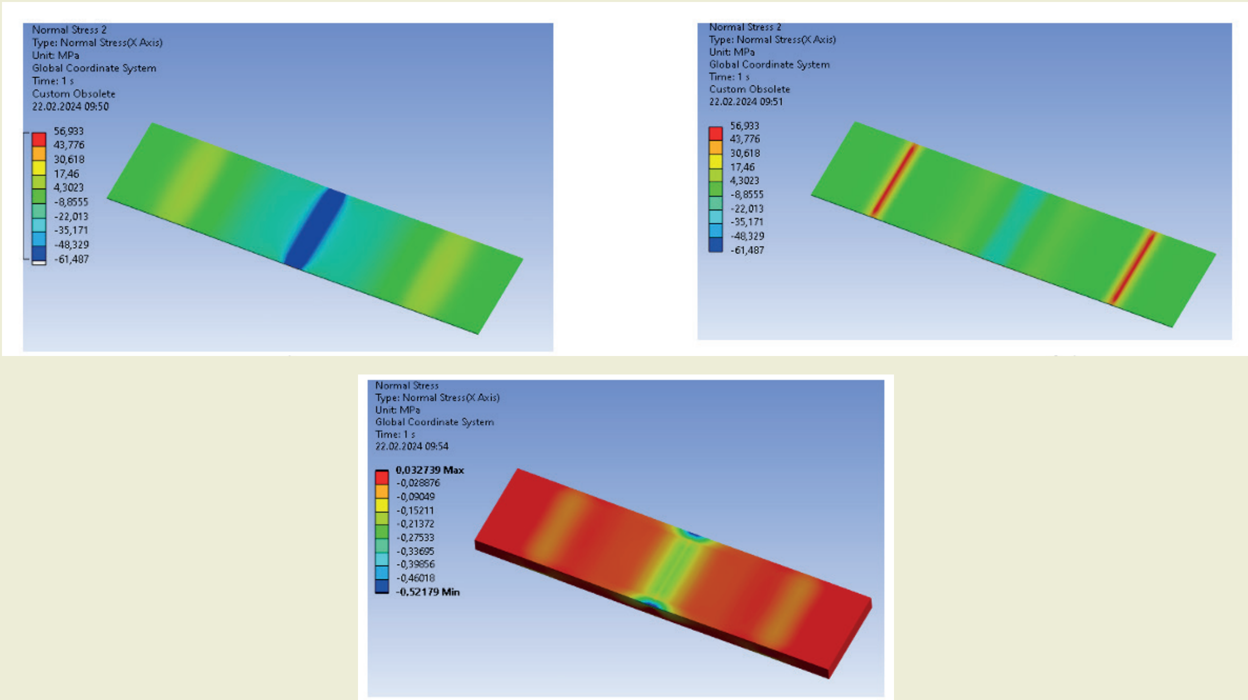

Figure 9. Normal stresses of discrete-layer model a) Outer facesheet b) Inner face sheet c) Core

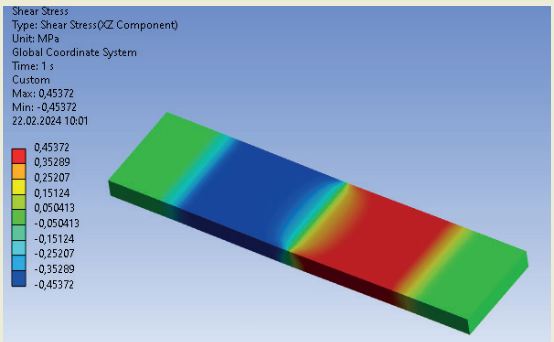

Figure 10. Maximum shear stresses at the core at discrete-layer model

noted for the facesheet stresses, which are particularly crucial for the failure analysis of sandwich composites.

It is evaluated that the discrete-layer model offers more precise predictions of stresses and deformations within the sandwich panel due to its explicit modeling of the composite's layering, enabling detailed stress analysis within each layer. The effectiveness of the discrete-layer model in elastoplastic states is studied in the following section to make predictions regarding the failure analysis of sandwich panels.

3.3. Effectiveness of Discrete-layer Model at Elastoplastic Region

Discrete-layer models are particularly suitable for capturing nonlinear deformations in sandwich composite structures, including plastic deformation, in contrast to laminated shell models. These models offer a more detailed representation of the composite's behavior by accounting for variations in material properties and deformations through the thickness of each layer. Radhakrishnan and coworkers show that the discrete-layer solid FEM model provides results that correlate well with 3-point bending experimental results of Al sandwich composites for different support span-to-thickness ratios and width-to-thickness ratios [32]. The experimental three-point bending results, specifically load-deflection data, for Al/XPS Foam sandwich composites are compared with the discrete-layer model in Figure 11.

Table 4. The discrete-layer solid model results versus laminated shell single-layer model results.

δ_{SOL} [mm]	$\sigma_{SOL,F}$ [MPa]	$\sigma_{SOL,C}$ [MPa]	$\tau_{SOL,C}$ [MPa]	δ_{SH} [mm]	$\sigma_{SH,F}$ [MPa]	$\sigma_{SH,C}$ [MPa]	$\tau_{SH,C}$ [MPa]
1.049	56.93	0.032	0.45	1.072	29.57	0.035	0.408

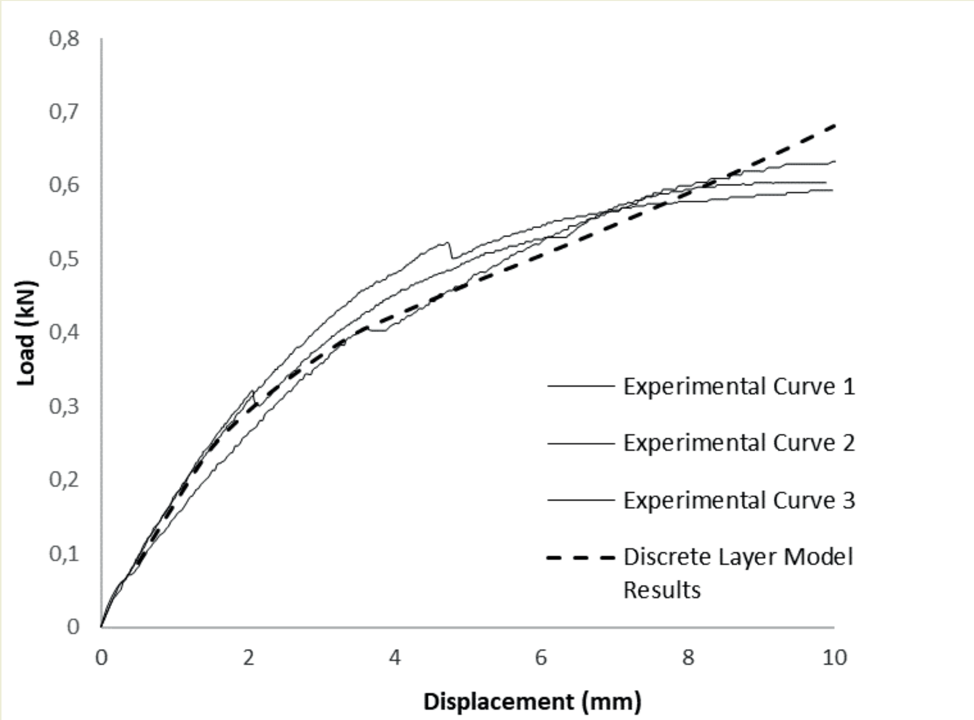

Figure 11. Load- deflection curves of Al/Xps foam sandwich panels under transverse load

The failure study focuses on facesheet yield and indentation. This study can extended by counting other failure types such as core shear and debonding failures, particularly with higher core layer thickness ratios.

The load-deflection results indicate that the discrete-layer model predicts well in the elastic region, and approximate results are obtained in the elastoplastic regions. However, it is observed that the ultimate failure is not well predicted, which highlights the limitations of the multilinear kinematic hardening model and the poor bonding at sheet-core interfaces observed in experiments.

Uzay and coworkers [18], as well as Alshahrani and coworkers [33], noted in their numerical and experimental studies that under 3-point bending loading conditions, the predominant failure modes of foam core-based composite sandwich panels can be summarized as a tensile failure, local indentation, upper skin debonding at the impact point of the indenter, and delamination through the thickness of the sandwich composites. Similar correlated results are observed in our study.

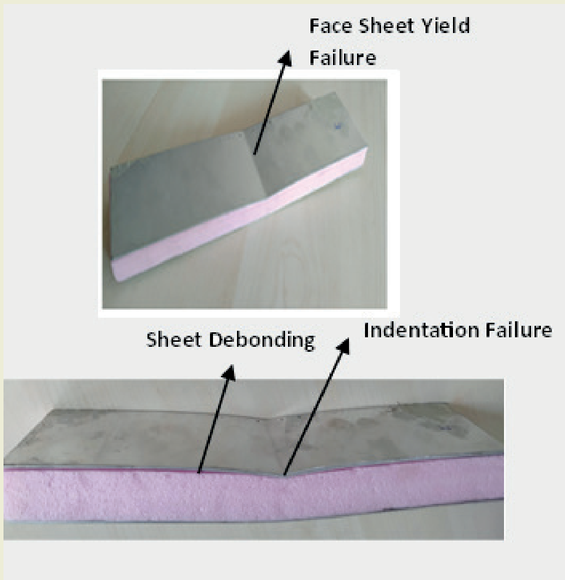

Figure 12. Failure zones occurred during the three-point bending test of the Al/XPS sandwich plate

The types of failures observed in the experiments are summarized in Figure 12 below.

A modification is made to a discrete-layer model to analyze the effects of indentation by adding supports, potentially roller supports, particularly in the plastic region seen in the following figures. The results of the discrete-layer model are compared with those of the laminated solid composite single-layer model in Figure 13.

The figures indicate that the face yield zone is larger for discrete-layer models than for laminated composite models. Additionally, discrete-layer models more accurately predict local strains. Both discrete-layer and

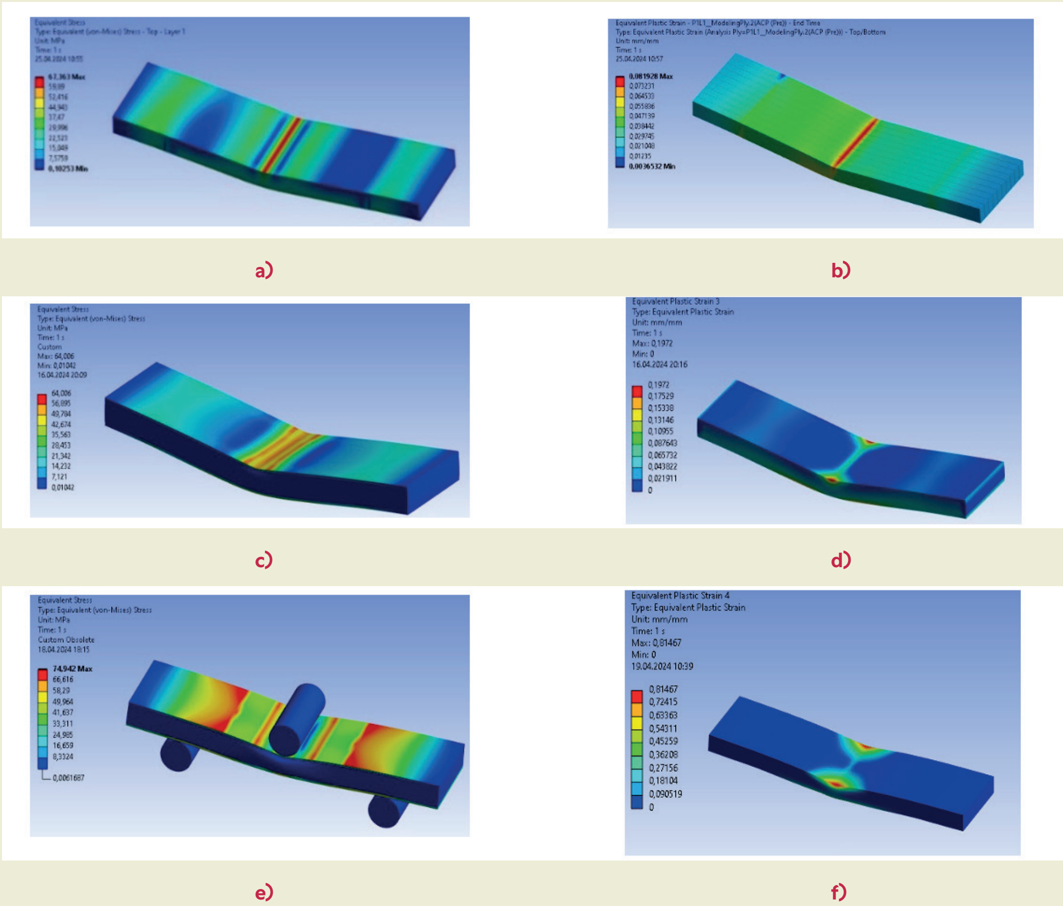

Figure 13. Three-point bending results a) Laminated model von Mises stresses b) Laminated model core plastic strains c) Discrete-layer model 1 Von Mises stresses d) Discrete-layer model 1 core plastic strains e) Discrete-layer model 2 Von Mises stresses f) Discrete-layer model 2 core plastic strains

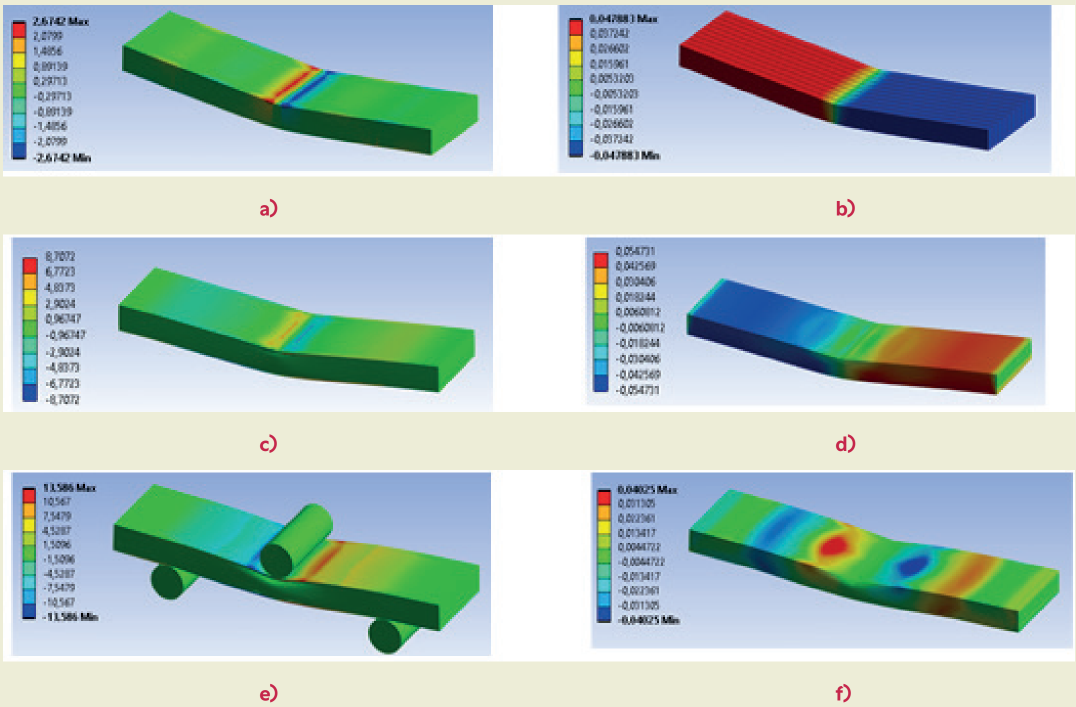

Figure 14. Three-point bending results a) Laminated model shear stresses at face sheet b. Laminated model shear stresses at core c. Discrete-layer model 1 shear stresses at face sheet d. Discrete-layer model 1 shear stresses at core e. Discrete-layer model 2 shear stresses at face sheet f. Discrete-layer model 2 shear stresses at the core

composite models predict the face yield failure. The local strains effective in the larger face yield zone and indentation failure are predicted more accurately by the discrete-layer models. The sheet debonding failure at the core and sheet interface is another issue observed at experiments due to the interlaminar shear stresses and poor bonding of epoxy. The shear stress results obtained from the discrete-layer models and the laminated composite model are compared in Figure 14.

Shear stresses are critical in the failure of sandwich panels, with core shearing failure occurring when the shear stress in the core reaches the yield strength of the core material. Face debonding and indentation occur when the loading is extremely localized [34]. In our study, the discrete-layer solid FEM model results, seen in Figures 13 and 14, correlated with experimental results, indicate that the face yield affected plastic strain and shear stress zones in the core are localized. This localization is the reason for the indentation and debonding at the interface. The indentation failure is more accurately predicted by adding roller supports.

4. Conclusions

In this study, the effectiveness of the shell-based laminated single-layer composite model versus the discrete-layer solid FE model is focused on Al/foam sandwich composites. The sandwich beam three-point bending calculations derived using the Timoschenko sandwich beam model are compared with results from shell-based and discrete-layer solid FE models in the elastic region. The results indicate that the shell-based FE model results agree well with Timoshenko's sandwich beam theory. The normal and shear stress effective zones correlate in both shell-based and discrete-layer solid FE models. However, the face sheet stresses, crucial for face sheet failure analysis, are higher in the discrete-layer solid model. The studies in the literature note that discrete-layer solid models typically offer more detailed information, especially in capturing nonlinear behavior and stress distributions within individual layers of the sandwich composite.

The effectiveness of the discrete-layer model in the nonlinear zone is verified through experimental study. The possible failure modes according to the load span to thickness ratio are face sheet yield and interface delamination. The analysis results obtained from the discrete-layer model align closely with calculations and experimental results. The stress intensity-based local strains, crucial for understanding indentation failure, typically exhibit higher values in discrete-layer models than in laminated composite models. This localized strain can lead to indentation or deformation at the interface between the core and face sheets, compromising the structural integrity of the sandwich panel.

Research Ethics

Ethical approval not required.

Author Contributions

The author(s) accept full responsibility for the content of this article and have approved its submission.

Competing Interests

The author(s) declare that there are no competing interests.

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