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A Methodology for Enhancing the Shear Response of Sandwich Composite Panel: Sandwich Composite Panel with Stair Keys

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Abstract

Objectives: In composite sandwich panel, delamination between the foam core and face sheet is due to inability to withstand shear load. Hence a methodology of introducing shear keys for enhancing the shear response to resist delamination is analysed in the present study. **Methods/Statistical Analysis**: The conventional sandwich panel under analysis is composed of Glass Fibre Reinforced Polymer (GFRP) skin with PVC (Polyvinyl chloride) foam core impregnated with epoxy resin. The present study is to introduce stair keys in between GFRP and PVC which are made by overlapping GFRP face sheets, with the length and depth to get the required step size. Parametric Finite Element (FE) investigation using ANSYS software has been performed to evaluate the foam core performance by grooving the foam material as stepped shapes. The effect of different length of the stepped grooves in foam material are analysed and its results are compared with conventional sandwich panel. The stair key response for number of steps ranging from n=1, 3, 5 and 7 are investigated. **Findings**: The FE results showed an improvement in the shear stress response of the sandwich panel with stair grooved foam core with stair keys compared to conventional model. Also the stair inserts between the GFRP skin and the foam core increases the initial shear stiffness and ultimate shear strength of the proposed model of the sandwich panel. **Application/Improvements:** The present methodology acts as a new model of peel stopper mechanism, where the shear failure due to debonding of face sheet and foam core is rerouted to foam core. Also it is free from initial damage as there is no loss of solidarity of the bulk material at the foam core, cost effective and easy to design and manufacture compared to other pinning and stitching process.

Keywords: Delamination, FEM Analysis, Sandwich Composite, Shear Response, Stair Keys, PVC Foam

1. Introduction

The composite sandwich panel is designed by attaching two thin stiff face sheets and a lightweight core which is bonded with resin in between them. Composite sandwich structures are widely used in aerospace, civil and marine applications. It hasless weight to strength ratio and high bending stiffness. In sandwich structure the bending loads are carried by the face sheets while the shear loads are carried by the lightweight core. The core offers high moment of inertia while face sheets are strong and stiff to carry tensile and compressive loads. The sandwich structure operates like the traditional I – beam which has two flanges and a web connecting the flanges.

The major disadvantage of sandwich panel is skin core debonding while applying shear load. In order to enhance the interaction between the skin and core, several methodologies are adapted. But the mechanisms proposed are difficult to incorporate which weakens the structural strength of sandwich panel. By introducing shear keys of semicircular shapes[1] between the foam core and the skin enhances the shear response of sandwich panel. The shear keys are manufactured by Vacuum Assisting Resin Transfer Moulding process (VARTM). The efficiency of

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the sandwich panel with shear keys improves the shear performance with a considerable percentage compared to the conventional model. Shear key characteristics in terms of material, shape, size and orientation influence the shear stress capability. The effect of distance and diameter of stitching thread[2] cannot increase the bending fatigue strength due to the resin build up around the stitching thread. The effect of thin pins[3] in isotropic laminates leads to out of plane crimping and in plane distortion. The tensile strength decrease linearly with the increase in the pin density and size. By effective core design delamination crack[4]can be deflected towards the sandwich core. A series of experiments using aluminum peel stopper embedded in sandwich core showed that the crack deflection did not occur. The CFRP pyramidal lattice cores[5] with 3D woven face sheets infused with epoxy resin improves the strength and moduli which is due to the combination of increase in foam strength and retention of CFRP truss less susceptible to buckling. The stress analysis[6]investigation of laminates using stepped lap joint scheme improves the strength.

Numerical investigation[7] on the effect of shear keys diameter and its orientation on the shear performance of the sandwich panel with foam core. The failure mode changed from skin core debonding to shear key - core debonding at its interfacial area. Also shear key orientation of +60° model provides the highest shear strength with strong interaction between the key- core mating surfaces.

By the application of shear key[8]the results have shown 25% improvement in delamination resistance capacity than the conventional model. The literatures study reveals that a methodology for improving the shear response will not be cost effective and also degrades the foam structure. In the design of tapered laminate[9] compositesthe strength of the drop off reduced decreasingly with the increase in number of ply drop-offs. The ply should be dropped in decreasing order of stiffness which ensures smooth transfer of load and reduces stress concentration.

Alternative methodologies such as stitching and z-pinning are investigated to enhance the shear performance. Stitching methodology involves introducing yarn through the composite material using an industrial sewing machine. Though it improves the skin core bonding nature, the in-plane shear deterioration makes it difficult to use[10–13]. The Z pinning method involves the insertion of pins by vibration and pressure from a foam bed which may lead to degradation of z-pinned laminate. But the process of Z- pinning causes out-of-plane crimping[14–18-] near the Z-pins.

For the flexural modulus parameters[19]unidirectional laminates have enhanced flexural resistance than angle-ply laminates. Numerical studies[20] on CFRP laminate shave shown that increasing the thickness of laminates increases the structural rigidity of laminates.

The present work investigates numerically the effect of the stepped keys on the shear resistance capacity of the GFRP sandwich panels with PVC foam core. Variation in shear response is observed for different number of steps by varying length of stepped stair keys. Finally a comparison between all the models are presented in terms of shear stress vs shear strain. The result of the present approach provides a first step in establishing the potential of stair keys and enhancing the shear response of sandwich panel.

2. Methodology

The Stair keys are constructed by overlapping laminatedglass fiber reinforced polymer (GFRP) by changing its length and depth to get the desired step size. The foam is Diviny cell H100 of density 100kg/m^3 which is milled, in terms of stair grooves where gradual increment of step sizes will be opposite to the applied force on its top and bottom surfaces. The exploded view of conventional sandwich panel is shown in Figure 1(a). The sandwich panel designed with stair key concept is shown in Figure 1(b). The stair key inserts in the foam core can be of different number of steps with various length and depth and of any material. It improves the shear resistance of sandwich panel which enhances bonding and interaction between the face sheet and core. The shear load applied on the face sheet surface will be transferred as normal force to key core mating surface in the vertical direction. As the stiffness of the stair key laminates is high, it results in increasing the shear strength and stiffness of the sandwich panel. This methodology prevents catastrophic delamination between the face sheets and core similar to the proposed peel stopper mechanism[13]and stepped laminates[6].The manufacturers could provide the foam sheets with any desirable stair size cuts. In addition, the skins are kept intact with no modifications which means in-plane mechanical properties will not be affected. The numerical simulations based on ASTM C273 have been discussed in the following sections. The material properties of PVC foam and GFRP for numerical analysis is shown in Table 1.The PVC foam core with stair grooved model with

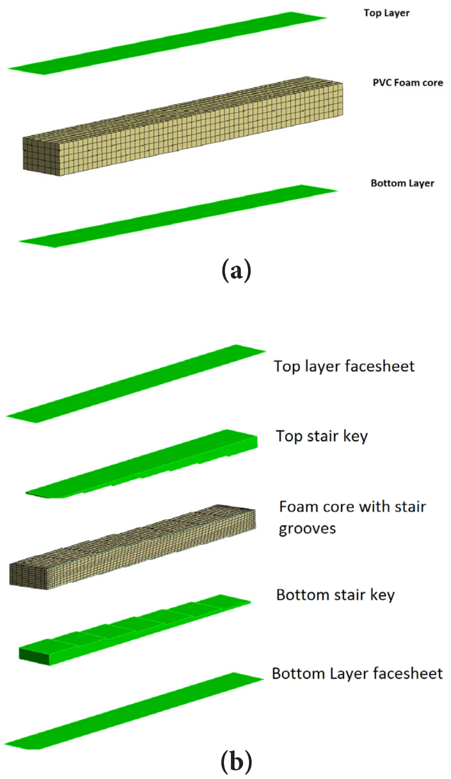

Figure 1. **(a)** Sandwich composite panel **(b)** Sandwich composite panel with stair keys.

steps is shown in Figure 2. The model is constructed in design modeler of workbench with the specified dimensions as shown in Figure 3.The core material is applied with PVC material properties while the top and bottom layer are designated with GFRP material properties in Layered section with required thickness of 30mm with eight layers of 2x2 twill weave E-glass GF4285T2/1270 GFRP face and ply orientations $(0/90/+45/-45)_s$. The dimensions for sandwich panel is chosen as 400 x 50 x 30mm as per ASTM C273 for shear test specimen. The stair keys are modelled as different number of steps from n = 1,3,5,7 with the required length c ranging from 50mm, 80mm,100mm, 200mm and its depth, d= 0.5 mm as shown in Table 2.

The dimensional constraints of the step size are given by

c – Step size length,
d – Step size depth,
n - Number of steps,
L –Length of sandwich panel
t – Thickness of sandwich panel
W – Width of sandwich panel

Table 1. Mechanical properties of materials

Material	Test	Property	Mean
GFRP	Tension Test	Elastic Modulus (E), GPa	15
		Poisson's ratio(υ)	0.28
		Ultimate Strength (σ_{ult}) ,Mpa	243.51
		Ultimate Strain(ε_{ult}), mm/mm	0.0270
PVC Foam	Shear test	Shear modulus (G), Mpa	40.25
		Ultimate strain (γ_{ult}),(angle- deg)	9.688
		Ultimate Strength, (τ_{ult}), Mpa	1.31
Panel with PVC foam core	Shear Test	Shear modulus(G) , Mpa	40.16
		Ultimate Strength , (τ_{ult}), Mpa	1.3
		Ultimate strain (γ_{ult}), (angle- deg)	9.688

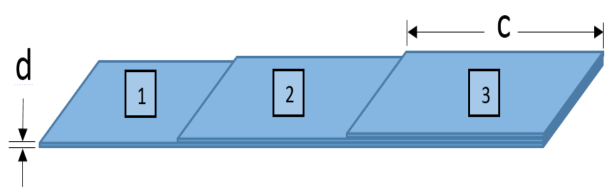

Figure 2. Stair key face sheet with variable steps, n=3.

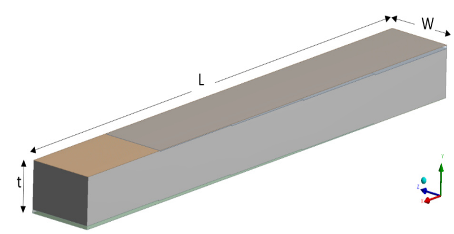

Figure 3. Stair key sandwich model with stair keys, n=3.

Table 2. Summary of stair key geometry

Number of Steps, n	Length, L (mm)	Depth, d (mm)
1	200	0.5
3	100	0.5
5	80	0.5
7	50	0.5

3. Finite Element modelling of Composite panel

The four layers on the top and bottom face sheets along with foam core are modelled as quad elements. The contact interface between the face sheet with core and sandwich panel with shear jig are modelled as surface to surface contact. The skin core interaction is provided frictionless which allows debonding while the key core interaction is frictional. Since the failure occurs in PVC foam before GFRP face sheet, GFRP is considered to be having linear characteristics. For FE modelling ANSYS is used for designing the sandwich panel with stair keys. The foam core with stair groove material experiences nonlinear behavior, hence nonlinear effects are taken into account. For plasticity approach, the material shear stress vs. shear strain values are embedded in engineering material section of ANSYS and isotropic hardening characteristics of foam core material is used. The skin core interaction is provided frictionless which allows debonding while the stair key with stair groove foam core interaction is frictional. Large deflection option is selected for geometric non linearity. ANSYS uses Newton Raphson method which applies the load gradually on the face sheet in multiple sub steps. In the nonlinear simulation, the relation between the force and displacement is as follows:

$$[K_T]\{\Delta u\} = \{F\} - \{F_{nr}\}$$

where,

K_T - Tangent Stiffness matrix
Δu – Displacement increment
F – External load vector
F_{nr} –Internal Force vector

By default for all nonlinear problems, ANSYS uses direct sparse solver which can address Lagrange multipliers and negative indefinite systems. Workbench uses Von mises criteria to define the yield strength behavior, where a stress state reaches yield state when the von mises stress equals the uni axial shear strength. The yield surface is a cylindrical surface aligned with axis. The present simulation is based on the recommendation of ASTM standards as discussed below. The tensile strength of composite laminates are based on ASTM D3039 (standard test for tensile strength of composite laminates as shown in Figure 4a.Uniaxial tensile test simulations are also carried out based on ASTM C297 (standard test method for flat wise tensile strength of sandwich constructions) as shown in Figure 4b. After the material achieves the yield point, the material experiences kinematic hardening. The simulated response using isotropic hardening method for the PVC foam material are in good co relation with experimental values as shown in Figure 4b.Uniaxial compressive test simulation is based on ASTM C365 (standard test method for flatwise compressive properties of sandwich cores) as shown in Figure 4c. The multilinear isotropic hardening characteristics are embedded in ANSYS engineering section which will be used for nonlinear behavior in plasticity region. Hence brittle failure cannot be simulated in tension for the foam core as shown in Figure 4c. The inplane shear test simulation is performed based on recommendations of ASTM C273 (Standard test method for shear properties of sandwich core material) as shown in Figure 4d.The stress state is divided into volume change

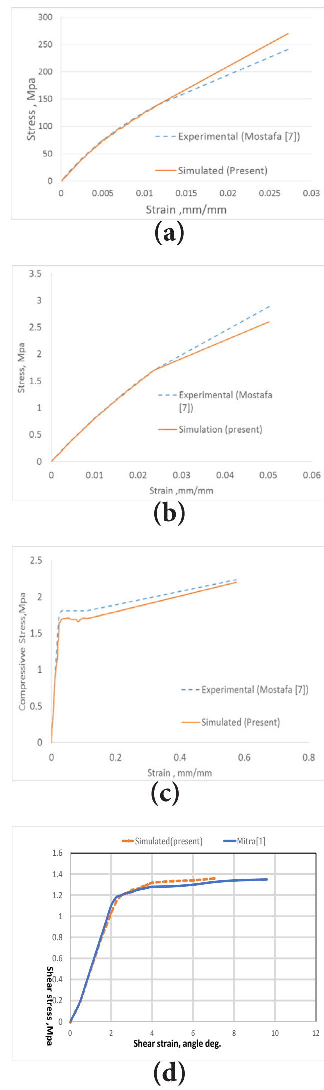

Figure 4. **(a)** Tensile test of GFRP laminate **(b)** Tensile test of PVC foam core **(c)** Compressive test of PVC foam core **(d)** Shear stress – strain response of PVC Foam core.

by hydrostatic stress, and angular distortion by deviatoric stress. In ANSYS the yield surface is modelled as cylinder aligned with axis, σ1, σ2, σ3.The hardening rule describes the change of yield surface due to plastic deformation. There are two hardening rules which involves constant yield surface as kinematic hardening, and uniform change in yield surface in all directions as isotropic hardening. The load is applied on top shear jig while the bottom shear jig is modelled as fixed support as shown in Figure 5.

4. Results and Discussions

The numerical response of shear stress vs. shear strain of stair key sandwich panel are analysed with the variations of number of stair keys. For all the models, a significant increase in shear stiffness and strength is observed compared to the conventional model. The foam core with stair groove model of 50mm length and 0.5mm depth is more suitable for resisting the delamination capability as the ultimate stress value is higher than other models considered. It is observed that under elastic strain conditions the FE results is almost similar for all models where the load applied in transverse direction through stair key is gradually transferred to the foam core. As the number of step size increases, increase in initial

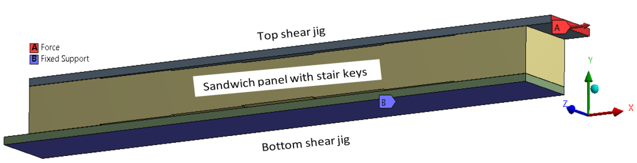

Figure 5. Load applied on the top shear jig and fixed support on bottom shear jig.

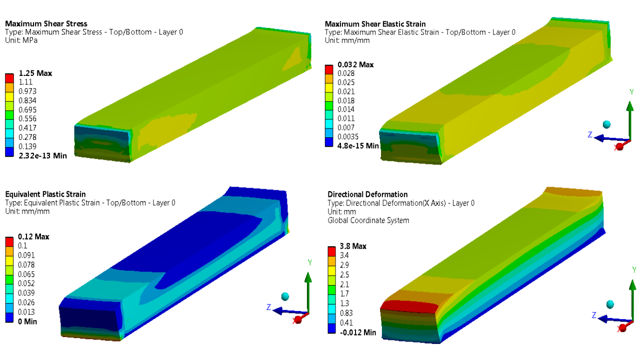

Figure 6. Conventional sandwich panel stress - strain distribution plots.

stiffness and ultimate shear stress is observed and hence shear resisting capability increases which is shown in Figure 6.The shear strain distribution in the PVC foam core with stair grooves under in-plane shear is shown in Figure 7.The strain distribution pattern is not having much significant change. The effect of strain near to the stair corners is higher in the tensile region and lower in the compressed region. The numerical simulation response for the conventional model compared with the stair key model shows increase in global initial stiffness. The vertical corner of the foam core with stair grooved are subjected to compression, while the horizontal faces are subjected to tension. It can be observed that the shear stress distribution initiated at the edge of stair groove on top surface are propagated towards the opposite tip on the bottom side of the stair grooved foam core edges. Hence the failure arises in the foam core with stair grooves and stair key interface area before delamination of the face sheet. At the interface of stair key and foam core with stair groove, high stress concentration region is observed near to the corners of the stair where crack originates as shown in Figure 8. The equivalent plastic strain plot of present simulation from Figure 9 showed improvement in plastic region than the conventional model. The plastic nature of the foam is enhanced by the proposed model. Hence the shear load is transferred and shared to the foam core with stair grooves and stair key, which enhances the shear load carrying capability of the sandwich panel. The equivalent plastic strain distribution in the stair grooved foam core is shown in Figure 10.The plastic strain value developed between stair grooved foam core edges is low compared to the diagonal edges from top to bottom surface. Also the plasticity property of foam core is used for enhancing the shear response of the sandwich panel. Hence the increase of step size in stair grooved foam core significantly affects this property. As the step increases the plastic strain value between the step decreases, which provides strong interaction between the core and face sheet. The total deformation plot of sandwich models within the stair grooved foam core with variable step sizes and step numbers is shown in Figure 11.As the length of the steps decreases and number of steps increases, the total deformation decreases. Although the foam core is milled which reduces its strength, the advantage of higher shear strength comparing to other models outweighs as the foam is grooved in stepped format.

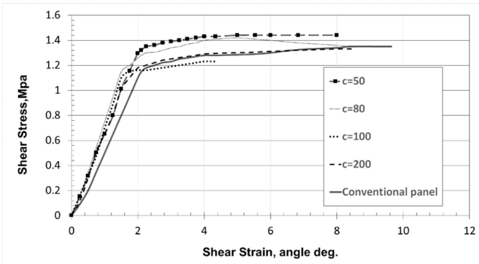

Figure 7. Shear – stress response of stair grooved models and conventional model.

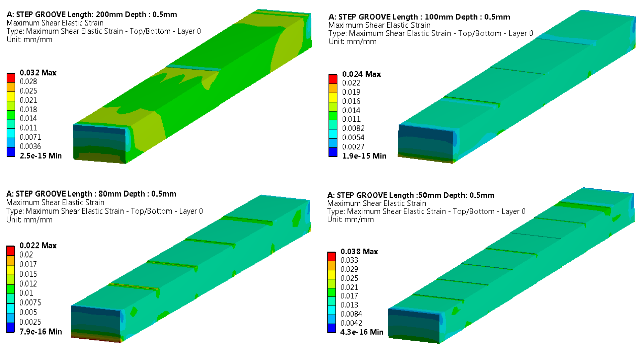

Figure 8. Shear strain response of foam core.

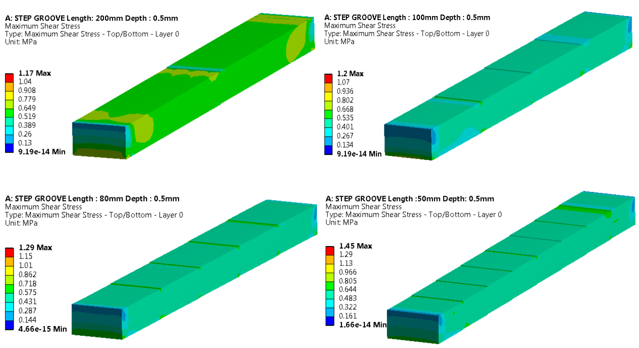

Figure 9. Shear stress distribution of foam core.

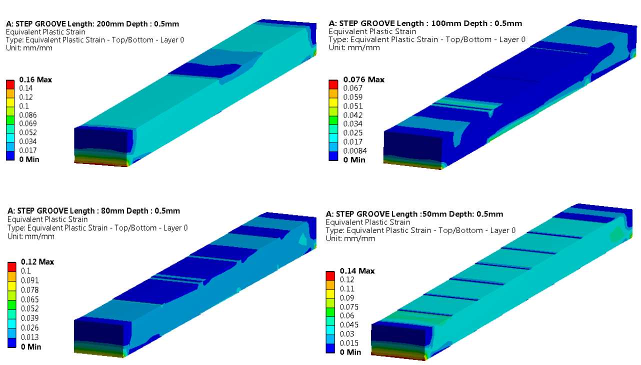

Figure 10. Equivalent plastic strain distribution plot of foam core.

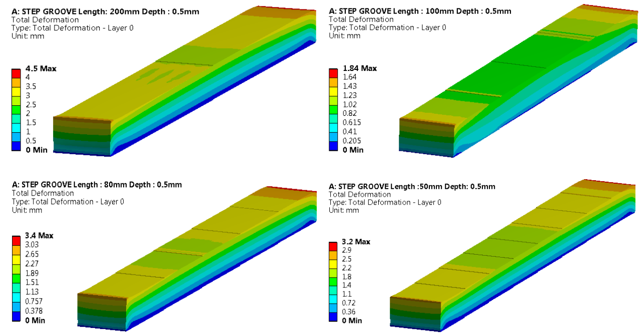

Figure 11. Total deformation plot of foam core.

5. Conclusion

The composite sandwich panelin corporated with variations in number of steps of stair keys has been investigated numerically to obtain the most suitable model for enhancing the shear response.

- The non linear FE simulations have been used to analyse the effect of stair key inserts in the sandwich core material. The stair inserts between the GFRP skin and the foam core increases the initial shear stiffness and ultimate shear strength.
- The FE model reveals that the model with number of steps ,n=7, with length 50 mm provides highest shear strength compared with other models. The failure mode is transferred from skin – core debonding to key – core debonding around the stair keys.

Hence this methodology act as a new model of peel stopper mechanism, where the shear failure due to debonding of face sheet and foam core is rerouted to foam core. However this new methodology of incorporating different stair key shapes can be analysed numerically for future work as it is cost effective. To develop a comprehensive model, various parameters will be analysed initially with numerical simulations before experimental investigation. The behavior of the stair key methodology will be investigated experimentally to develop a cost effective alternative to stitching and z-pinning which will be covered in the future publications.

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