A methodology for improving shear performance of marine grade sandwich composites: Sandwich composite panel with shear key

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ABSTRACT

Researchers have developed several measures to improve shear resistance capacity of sandwich structures composed of thin composite face sheets of E-glass/epoxy and low density PVC foam core, but these methodologies are either costly or result in damage to the sandwich composites before being placed for production. A novel, innovative cost-effective methodology of introducing fiberglass shear keys attached to face skins to improve the stiffness and strength of the sandwich composite panel is being proposed in this manuscript. Manufacturing of the sandwich composite panels along with experimental and numerical investigations have been performed in this manuscript to demonstrate the potential of the proposed simple methodology which can be utilized for shear-sensitive design and analysis of sandwich composite structures and/or components. A parametric study has also been carried out to determine the effect of change in shape, size, spacing and material of the shear keys on the sandwich composite panel global response.

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1. Introduction

Sandwich panels represents a special form of laminated composite material in which a relatively thick, lightweight and compliant core material separates thin and strong face sheets. Typically for marine applications, the face sheets are made of laminated polymer based composite materials, such as glass fiber reinforced polymer or carbon fiber reinforced polymer; the cores are typically made of balsa wood or foam materials such polyethylene, poly-vinyl-chloride or polyurethane foams. The faces and core are joined by adhesive bonding with epoxy or vinyl-ester resins. The potential benefits of incorporation of sandwich composites in construction of marine and naval vessels are innumerable. In comparison to conventional metallic structural components, sandwich composites have high strength to weight ratio (which results in increase of military payload, provides greater range and/or reduced fuel consumption), extended operational life, lower maintenance cost (due to less corrosion, and resistance to marine boring organisms), as well as a range of integrated functions, such as thermal and sound insulation, excellent signature properties, fire safety, good energy absorption, directional properties of the face sheets enabling optimized design and production of complex and smooth hydrodynamic surfaces. Thereby, over the past few decades, sandwich composite structures have found wide use in marine industry [1,2]. Examples of sandwich composite construction include ship hulls of patrol boats (e.g. KNM Skjød of Royal Norwegian Navy); mine-counter-measure vehicles (MCMV) (e.g. Landsort class MCMV by Royal Swedish Navy); Visby Corvettes (e.g. NGPV class of Royal Swedish Navy); Superstructure of naval boats (e.g. La Fayette class frigates of French Navy); Advanced Enclosed Mast/Sensor (AEM/S) for the US Navy; propellers, propulsors and propulsion shafts along with secondary structures, machinery and fittings for numerous naval vessels.

Inspite of innumerable advantages of using composite sandwich panels as a structural material, these structures are notoriously sensitive to failure by shear load. Shear strength is one of the primary design criterion in application of these structures for marine environment. An example application area is the bottom of large high speed ships subjected to high sea pressures which might result in shearing of the bottom along its perimeter.

2. Previous research efforts

A number of research ideas have been briefly presented which dealt with improving the shear properties of sandwich composite panels. It is to be noted that there have been research articles, within the perspective of material science, on improving the properties of the core using functionally graded materials [3]. However, these research within the perspective of material science have not been considered in this manuscript and only those research articles which presents a structural solution of improving the properties of the sandwich composite panels have been presented.

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End grain balsa sheets have been utilized as a structural alternative to using foam materials as the core material in sandwich composites. In fact, a typical end grain balsa core, with a density around 155 kg/m³, possesses a slightly higher quasi-static shear strength in comparison to a PVC foam core of the same density. However, the typical end grain arrangement does not fully utilize the anisotropy of balsa wood for the benefit of shear properties. A new arrangement of balsa blocks in a sandwich core was developed and numerically analyzed to obtain superior shear stiffness [4].

Z-pinning [5–9] is another established methodology of improving the shear properties of composite sandwich. This process refers to insertion of metallic or fibrous pins/rods (which can be of carbon and glass fiber, titanium, stainless steel, aluminum, etc.) through the thickness of the uncured laminate using an ultrasonic insertion technique. An extensive literature review on manufacture, mechanical performance advantages and disadvantages of introducing Z-pins are presented in the review paper by Mouritz [10]. Studies have also been performed on the failure mechanism of sandwich composites with Z-pins [11]. Above presented manuscripts on Z-pinning and the references cited within them have demonstrated, through experimental and numerical simulations, that significant gain can be obtained in the mechanical performance of sandwich composites with Z-pinning.

The method of Stitching of sandwich materials have also been developed quite recently and represents another alternative methodology of improving the shear properties of the composite sandwich. As the name suggests, this process is one of the techniques for composites fabrication, which basically involves sewing high-tensile-strength yarn (e.g., glass, carbon or Kevlar), through a sandwich composite using an industrial sewing machine. An extensive literature review [12] is presented on the in-plane performance of stitching of composite laminate structures in which the researchers indicated that stitching affects strength, stiffness, and fatigue performance of a laminate. A number of researchers have reported significant gains in mechanical performance of these structures [13–17]. Research and parameter studies have also been performed to demonstrate improvements in performance of angled stitched sandwich composites in comparison to vertical stitched sandwich composites [18,19]. Above presented manuscripts on stitching of sandwich composites and the references cited within them have demonstrated, through experimental and numerical simulations, that significant gain can be obtained in the mechanical performance of sandwich composites with stitching.

Even though research on the above mentioned methodologies have reported significant gains in mechanical performance, specially shear strength, in comparison to the conventional sandwich composites; these processes have their own disadvantages. It has been pointed out that the process of Z-pinning is a slow and expensive process [17] and has thereby been primarily limited to the aerospace market and probably not a cost-effective solution to the naval industry. Moreover introduction of Z-pins results in initial damage to the structure and may result in the mechanical performance being compromised [10]. For the stitching methodology, it has been reported that the load bearing fibers may be distorted or damaged while weaving due to the repeated action of abrasion and bending as the yarns are fed through a loom. It has been reported that the tensile strength of carbon yarns are reduced by up to 12% due to abrasion and bending [20]. Fibers are also distorted and cramped during weaving, and this can lead to significant in-plane tow waviness in 3D woven composites [21,22]. The combined effects of fiber damage and tow waviness have an adverse effect on the in-plane mechanical properties of 3D woven composites.

Thereby, the objective of this research has been to present an alternative novel cost-effective methodology of improving the shear properties of composite sandwich panels without inducing significant initial damage to the panels.

3. Sandwich composites with shear keys: proposed novel methodology

Sandwich composites with shear keys have been proposed as an alternative to using the above discussed methodologies for increasing the shear properties of composite sandwich panels. This novel mechanism of increasing the shear performance of sandwich composite panels is based on introduction of a new concept of inserting shear keys in the PVC core. The cross section of both conventional sandwich composite panel and panel designed based on the novel concept of sandwich composites with shear keys are shown in Fig. 1a and b respectively. The shear-key inserts in the foam core may be of any shape, size and of any material. The spacing in between the shear keys can also be varied in a specimen.

The shear-key inserts would typically improve the shear resistance of the sandwich panel by improving the bonding between the fiberglass face sheets with the core. The superior strength and stiffness of these shear-key inserts in comparison to the foam core would also result in increase in shear strength and stiffness of the sandwich composite. With introduction of glass fiber shear-key inserts, the face sheet also contributes to resistance in shear in addition to the conventional concept of foam core resisting shear. This new design methodology would also prevent propagation of delamination cracks between the face plates and the core, similar to the proposed “peel-stopper” mechanism [23,24]. However, the effectiveness of this new methodology to prevent propagation of delamination between the face plates and the core is beyond the scope of this manuscript. This topic is currently being researched by the authors and would be discussed in future publications.

The proposed novel methodology would be cost-effective in comparison to the costly process of Z-pinning. Moreover, in comparison to the stitching methodology, the sandwich composites manufactured based on this novel methodology would be free from initial damage being introduced into the material due to abrasion and bending during the process of stitching. Thereby, this methodology represents a viable alternative for increasing the shear properties of sandwich composites. It should also be mentioned at this point, that the proposed methodology is compara-
tively new in comparison to the other established methodologies such as Z-pinning and stitching. A number of research programs have been undertaken to demonstrate the advantages of Z-pinning and stitching in variety of other application areas apart from increasing the shear properties of the sandwich composites. Thereby, more research programs are warranted for this new cost-effective methodology to establish it as a suitable competing alternative to the process of Z-pinning and stitching in improving the mechanical performance of sandwich composite panels.

It should also be mentioned that the proposed methodology of shear-key inserts may also be utilized as a complementary method to both the process of Z-pinning as well as stitching. Combining the shear-key methodology with the process of Z-pinning and/or stitching may lead to significant improvements in mechanical performance of resulting sandwich composite panel. However, this area of combination of the methodologies is beyond the scope of the present manuscript and would be investigated later.

Since the objective of this research is demonstrating improvements in shear performance of sandwich composites with use of the novel methodology of shear-key inserts; manufacturing process of the samples, experimental investigations and numerical simulations based on ASTM C273 have been discussed in the following sections.

4. Sample manufacturing

The core material chosen for sandwich composite construction in this research is a closed cell semi-rigid PVC foam with a density of 100 kg/m³ manufactured by DIAB Inc. and marketed by the trade name of Divinycell H100. The foam-core thickness considered for the experimental investigation is 30 mm and the foam material has a cell size of approximately 400 μm. The foam is sandwiched between two glass-fiber face sheets, each of which is composed of two alternate layers of chopped strand mat (CSM) and woven roving (WR) fiberglass mats. For the current manufacturing, the weight of CSM is 0.44 kg/m² while for WR is 0.61 kg/m². A two part epoxy adhesive, designated as West 105B Epoxy resin and West 206C slow hardener, used in a 5:1 proportion of resin and hardener was utilized for the vacuum resin infusion methodology. The preform (facesheet and the core) is covered by a porous teflon film and a highly permeable breather cloth. Resin infusion and suction lines are placed at appropriate locations after which the entire part is placed in a vacuum bag. The resin flow through the preform is primarily assisted through the vacuum alone. Upon complete part wetting, the infusion lines are blocked and is vacuum cured at room temperature for 6–7 h. For sandwich composites manufactured with the novel methodology of shear keys, grooves were created in the foam core using a handmill so as to place the shear-key inserts in those grooves. The foam-core grooves can be of any shape, size and spacings. The foam-core grooves are filled up with glass-fiber prepregs. The glass-fiber prepregs that fills up the foam-core grooves were made by vacuum resin infusing glass fiber strands obtained from WR fiberglass mats. The glass-fiber prepreg filled up grooved foam core is then sandwiched between two facesheets and the final specimen is manufactured by similar vacuum resin infusion methodology described in the previous paragraph. A manufactured specimen is shown in Fig. 2.

In order to perform a parametric investigation, a number of different variations were considered such as different diameter of semicircular grooves, different groove shapes and also the orientation of grooves in the foam. The results obtained from using the shear-key variations in comparison to the conventional sandwich composite specimens are evaluated and discussed in the following sections.

5. Experimental investigations

Experimental investigation of in-plane shear response of sandwich composite panels were performed as per recommendations of ASTM C273 “Standard test method for shear properties of sandwich core materials”. The test was carried out on a INSTRON 1331 Universal testing machine where rate of displacement is kept constant at 2 mm/min. The shear jigs were made out of steel, which were used in in-plane shear tests for both the foam as well as the sandwich composite. Fig. 3 below shows the manufactured shear jig along with its attachment to the INSTRON machine and the specimen to be tested. The specimens (406 × 50 × 30 mm) were attached to the shear jig by means of structural glue DP460NS which is a high performance, non-sag, two part epoxy adhesive (B-Epoxy and A-Amine; Mix ratio 2:1) offering shear strength of 32 MPa at room temperature along with high levels of durability.

5.1. Failure mode

Failure was observed as interfacial decoherence of the skin from the core for the conventional sandwich composite specimen. Small
visible cracks originated at the skin–core interface of the samples and a near complete delamination of the skin from the core was observed at the final load, as shown in Fig. 4. The failure observed was primarily an adhesive debond failure between the surfaces of the skin and the core.

The failure pattern observed in sandwich samples with shear keys is significantly different in comparison to the conventional ones. For sandwich samples with shear keys, cracking is observed to initiate at the junction of the prepreg glass-fiber shear keys with the foam and then it propagates in the foam as a diagonal shear crack. Fig. 5 shows crack observed in sandwich composite panel with shear keys.

Shear stress–strain distribution for both conventional and the specimens developed using the novel methodology is shown in Fig. 6. An increase in approximately 25% in shear stress capacity is observed with introduction of 4 mm semicircular shear keys that are spaced such that the location of the bottom shear key is in between two top shear keys and vice versa.

6. Numerical simulations

Numerical simulations were carried out using a commercially available continuum finite element programme ABAQUS. The constitutive models used to capture the response of different components of the sandwich composite such as foam, WR and CSM were based on experimental response of the specimens in tension, compression and shear.

Linear elasticity with a stiffness of 13.0 GPa for WR and 12.4 GPa for CSM was chosen to represent the fiberglass layers. Poisson’s ratio for WR was determined as 0.01 whereas for CSM as 0.4. The stiffness and Poisson’s ratio calibrations were based on ASTM D3039 tests for tensile strength of composite laminates. The constitutive model utilized for the foam is “Crushable foam plasticity” model in ABAQUS. The yield surface of the material model, defined in the $p$–$q$ stress field, is represented as an ellipse. The Mises stress $q$ is represented as $\sqrt{3} J_2$, where $J_2$ represents the second invariant of the deviatoric stress tensor; the hydrostatic stress $p$ is represented as $I_1/3$, where $I_1$ is the first invariant of the stress tensor.

Uniaxial compressive test, based on ASTM C365 “Standard test method for flatwise compressive properties of sandwich cores”, was utilized to determine the compressive response of the foam. Elastic modulus and the Poisson’s ratio parameter were calibrated from this investigations along with the compression hardening response. Fig. 7a shows simulated and observed compressive response of the foam specimen. Uniaxial tensile tests were also carried out for foam samples as per recommendations of ASTM C297 “Standard test method for flatwise tensile strength of sandwich constructions”. The tensile response as observed from experimental investigations is brittle in nature, however that behavior could not be reproduced since a plasticity model has been utilized to simulate the behavior of foam. Fig. 7b shows simulated and observed tensile response of the foam specimen. In-plane shear test on the foams was performed as per recommendations of ASTM C273 “Standard test method for shear properties of sandwich core materials”. Fig. 7c shows simulated and observed shear response of the foam specimen.

As shown in Fig. 7, simulated responses were obtained using volumetric and isotropic hardening models. Since no difference in simulated compressive response is observed with volumetric or isotropic hardening model, Fig. 7a shows only one plot for the simulation. It should be noted that for an isotropic hardening envelope, hydrostatic stress ($p$) in tension is considered to be same as that of hydrostatic stress ($p$) in compression, and thereby the center of the ellipse is at the origin of the $p$–$q$ stress plane. Moreover for the isotropic hardening model, the hardening envelope is same for tension as that in compression. The hardening envelope for the compression response is similar to that in tension. On the other hand, for the volumetric hardening model, the hydrostatic stress in tension does not change or evolve. These two types of possible hardening models also define different evolution of the yield surface. The evolution of the yield ellipse is controlled by a plastic strain measure, which is the volumetric compacting plastic strain (or trace of plastic strain tensor) for the case of volumetric hardening model; and equivalent plastic strain, which is defined as the absolute value of the axial plastic strain for a bar loaded in uniaxial compression, for the case of isotropic hardening.  

Fig. 7b typically demonstrates the limitation of the “Crushable foam plasticity model” since the numerical model with isotropic hardening provides similar response for both tension and compression, whereas clearly the yield stress of the foam material is different in tension and compression. Moreover being a plasticity based model it cannot simulate the brittle failure in tension for the foam.
Ideal plasticity is observed in both tension and shear for volumetric hardening model which is not a true representation of foam behavior; since a better representation would be hardening model instead of ideal plasticity (refer Fig. 7c), the isotropic hardening response has been considered for latter simulations.

The data obtained from the above simulations reveal that the following material model input parameters provide a reasonable correlation between simulated and observed response within the elastic range. The input parameters for the foam material that was utilized to generate the above simulations were $E = 60 \text{ MPa}; \nu = 0.1; \ k_c = 2.0; \ k_t = 1.9; \ \gamma_p = 0.0$, where $k_c$ is represented as the ratio of initial uniaxial compressive stress ($p^b$) to the initial hydrostatic compressive stress ($p^h$). In addition to the parameters for modulus of elasticity $E$, Poisson’s ratio $\nu$ and parameter $k_c$; models for Isotropic hardening requires an input parameter for $\nu_p$ which represents the plastic Poisson’s ratio defined as the ratio of the transverse to the longitudinal plastic strain under uniaxial compression; whereas the model for Volumetric hardening would require an input parameter for $k_t$ which represents the ratio of hydrostatic tensile stress ($p^t$) to the initial hydrostatic compressive stress ($p^h$).

All of the above as well as the following numerical simulations were carried out using an explicit, central difference integration scheme in ABAQUS. In the central difference integration scheme, the nodal accelerations are used to advance the velocity solution to time $t + \Delta t/2$, which in turn is used to calculate the displacements at time $t + \Delta t$. The central difference operator is conditionally stable for time increments that are smaller than the Courant limit, which is dependent on the smallest element dimension. Thereby, the time increments provided for the explicit scheme should be very small, however since it is not an iterative solution scheme, the computations are relatively inexpensive.

6.1. Shear simulation of sandwich specimen

The shear response of sandwich composite panels was simulated as per recommendations of ASTM C273. Each of the four layers in the top and bottom skin along with the foam core were modeled using continuum linear brick elements. The interface between the skins and the core were modeled as a perfect surface-to-surface connection. Perfect surface-to-surface contact was also utilized to model connection of the sandwich composite panel with the steel shear jigs. One end of the steel shear jig was kept fixed against movement in one of the planar directions while a uniform displacement, through a smooth ramp, was applied at the other end. The boundary condition, loading as well as the meshed assembly are shown in Fig. 8a.

Good correlation with regards to initial stiffness in the elastic regime could be observed between simulated and experimental model of the conventional sandwich composite panel, as shown in Fig. 8b. Differences are observed in the post-yield plateau for the experimental and the simulated specimen because of limitations of the numerical model. In experimental observations, cracks originate at the adhesive interface between the skin and the core and slipping is initiated at the interface region which explains for a lower post-yield stress of the conventional model. At time steps near the yield region of the simulated global shear stress–strain, a diagonal distribution of normal stresses ($\sigma_{11}$) is observed in the specimen (shown in Fig. 9) which represents diagonal shear stress failure pattern; the stress component ($\sigma_{22}$) was observed to be significantly less than the yield tensile stress of the foam. A low value of $\sigma_{22}$ in the foam signifies that failure was purely an adhesive type of failure and the response obtained in Fig. 4 is a correct representation of the behavioral response. Complex damage modeling of tangential slip between the two surfaces in contact is beyond the
scope of the current manuscript and will be dealt with in later publications. Typical stress distributions observed within the foam in simulations of the conventional sample are shown in Fig. 9.

An increase in global initial stiffness with introduction of shear keys is observed in the numerical simulation, similar to experimental observations, is shown in Fig. 10. Fig. 11 demonstrates that one edge of the foam grooves are subjected to compressive loads while the opposite edge are subjected to tension. High stress concentrations ($\sigma_{11}$ greater than the tensile yield strength) are observed in regions near to the grooves from where the cracks originate. Similar behavior has also been observed in cracks observed from experimental investigations in Fig. 5. Fig. 5 also demonstrate cracks observed at the interface region of the skin and the core; however since a fully tied interface is modeled in the simulated specimen this feature could not be captured in the simulated response observations.

Equivalent plastic strain (PEEQ) plots show that for the conventional specimen it is zero throughout the entire loading history whereas for the proposed specimen, a pattern is observed (shown in Fig. 12) signifying development of plasticity in the foam region. This demonstrates that plastic nature of the foam material is not utilized in conventional practice however can be utilized with the proposed approach. It can thereby be concluded that the entire behavioral response is governed by the adhesive interface between the foam and the skin for the conventional approach whereas the response if governed by the foam and shear key materials for the proposed specimens.

7. Parametric experimental investigations

Theoretically any shape, orientation and material can be utilized to fill up the foam-core grooves to create a shear-key insert. Parametric experimental investigations were carried out to determine the effect of adding in different materials for the grooves and also to determine variations with shape, size and orientation of the grooves. Different type of samples were manufactured and investigations were carried out as per ASTM C273 recommendations.

7.1. Case 1 – variation with different materials used as shear keys

Prepreg glass-fiber shear keys are rigid members and thereby there is a sharp change in stiffness from the foam to the glass-fiber shear keys resulting in high stress concentration in those regions. In order to prevent this, it was thought of as how to provide less...
7.2. Case 2 – variation in arrangement of top and bottom surface shear keys

The arrangement of shear keys in the top and bottom surface of the sandwich composite panel could be such that top and bottom shear keys are aligned just one above the other (collinear case) or they may be offset from each other by certain distance (off-center case). All the previous simulations with shear keys were an off-center case where it was arranged such that the bottom shear keys are placed in between two top shear keys. In this parametric investigation, comparison was observed between the global performance of an off-center case (spaced sample) with that of a collinear case (non-spaced sample), as shown in Fig. 13b. Even though the pattern of failure observed in both the cases were similar, the collinear case (non-spaced sample) resulted in lower strength and earlier strength loss in comparison to the off-center case (spaced sample). This can be explained since stress concentrations occur in the grooved foam regions, the effect of which are intensified if the foam-core grooves filled with shear keys are placed one above the other (collinear case) thereby resulting in lower strength and faster loss of strength.

7.3. Case 3 – variation with different shape of shear keys

The shape of groove in the foam for the shear keys also dictates the rate of strength loss. A triangular shape (or V shape) is compared with the semicircular shape and it was found that the semicircular shape resulted in better response in comparison to the V-shape. The global comparison is shown in Fig. 13c. A V-shaped groove results in higher stress concentrations at the edge regions of the triangle leading to rapid crack propagation within the foam and thereby rapid strength loss in comparison to the semicircular shaped grooves.

7.4. Case 4 – variation with grooves size for shear keys

It was also observed that the size of the groove also affects the global shear response of the specimen of depth 30 mm. Parametric
investigation is carried out for semicircular groove sizes of 4 mm and 8 mm radius and it was found that increasing the ratio of the groove depth size to the specimen depth adversely affects the shearing response of the sandwich composite panel as observed in Fig. 13d. The reason for this is if the ratio of groove depth size to the specimen depth is increased, the effective depth of the specimen is reduced which limits crack growth thereby leading to faster failure. Lower strength capacity is also observed with a 8 mm groove because of higher stress concentrations at interface of the groove surface and the prepreg glass-fiber shear key.

8. Conclusion

It has been demonstrated in the manuscript through experiments carried out as per recommendations of ASTM C273 that introduction of shear keys in a conventional sandwich sample is a cost-effective novel methodology which results in increase in initial stiffness and strength of in-plane shear response. Variation in response is observed with shape, size, orientation and material of the shear keys. Numerical simulations were also performed which provides a good correlation with experimental observations within the elastic regime. The post-yield simulations were inaccurate because of modeling limitations and will be addressed in later publications. The results of this research represents a first step in establishing the potential of this novel methodology of introduction of shear keys in improving the shear response of conventional specimen. It has also been hypothesized that this methodology would act as a “peel-stopper” mechanism in preventing core–skin delamination of sandwich panels which will be addressed in later publications. More dedicated research initiative in this methodology is required to establish it as a cost-effective alternative to established costly methodologies of stitching and Z-pinning in sandwich composites to improve mechanical performance.

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