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The Blast Response of Sandwich Composites with In-Plane Pre-Loading

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ABSTRACT

The in-plane pre-loading in the ship hull structures during their service life will likely change the dynamic behavior of these structures under transverse blast loading. In the present study, the dynamic behavior of E-glass Vinyl Ester composite face sheet / foam core sandwich panels with in-plane pre-loading is investigated under shock wave loading. A special test fixture was designed which enables the application of uni-axial in-plane compressive loading when the panels are subjected to transverse blast loading. Blast tests are carried out under two levels of pre-loading and with no pre-loading using a shock tube apparatus. A high-speed side-view camera system and a high-speed back-view Digital Image Correlation (DIC) system are utilized to acquire the real time deformation of the sandwich panels. The results show that the in-plane pre-loading induced buckling and failure in the front face sheet. This mechanism greatly reduced the blast resistance of the sandwich composites. The back face deflections, back face in-plane strains, and mitigated energies were also experimentally quantified.

INTRODUCTION

Ship hull structures always undergo longitudinal compressive loading and their longitudinal strength is the most fundamental and important strength to ensure the safety of a ship structure [1]. When these pre-loaded structures are subjected to transverse blast loading, the coupling of the in-plane pre-load and transverse blast loading will likely reduce the blast resistance of the structures. Composite materials, such as sandwich structures, have important applications in such ship structures due to their advantages, such as high strength/weight ratio and high stiffness/weight ratio. Unfortunately, the most recent research focuses on the blast resistance of composite structures without an in-plane pre-load [2-4]. To date, no experimental investigations on pre-loaded structures under blast load have been done.

The dynamic responses of in-plane pre-stressed composite structures under low-velocity transverse impact have been studied. Heimbs et al.[5] tested carbon-fiber/epoxy laminated plates under an in-plane compressive pre-load. An increased deflection and energy absorption was observed under a pre-load of 80% of the buckling load. Sun et al. [6] and Choi [7] analytically investigated the effects of pre-stress on the dynamic response of composite laminates. They found that the initial in-plane tensile load increased the peak contact force while reducing the total contact duration and deflection. The compressive load reacted oppositely. However, contact impact loading will induce localized damage, which is different with blast loading. Thus, these results cannot be extended to the blast response of composite structures. The absence of experimental data of pre-stressed structures under blast loading also makes it impossible to verify the numerical models. Therefore, there is an urgent need to investigate the pre-loading effect on the dynamic behavior of composite materials under blast loading.

The present paper experimentally studies the dynamic behavior of pre-loaded sandwich composites under blast loading. The sandwich panels are composed of E-glass Vinyl Ester composite face-sheets and Corecell P600 Foam core. A fixture was designed in order to enable different static in-plane compression loadings on the sandwich panels prior to transverse blast loading. Two levels of pre-loading and zero pre-loading cases were chosen to study the effect of the pre-loading on the dynamic response of the sandwich composites. A high-speed photography system with three cameras is utilized to capture real-time motion images. Digital Image Correlation (DIC) techniques will be utilized to obtain the details of the deformation of the sandwich panels during the events. Post mortem visual observations of the test samples will provide more evidence to indentify the failure modes. These results were used to analyze the mechanism of dynamic failure of the pre-loaded sandwich composites.

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2. MATERIAL AND SPECIMEN

The skin materials that were utilized in this study are E-Glass Vinyl Ester (EVE) composites. The woven roving E-glass fibers of the skin material were placed in a quasi-isotropic layout $[0/45/90/-45]_s$. The fibers were made of the 18 oz/yd^2 area density plain weave. The resin system used was Ashland Derakane Momentum 8084 and the front skin and the back skin consisted of identical layup and materials. The core material used in the present study was Corecell^{TM} P600 styrene foams, which is manufactured by Gurit SP Technologies specifically for blast defence applications. Table 1 lists important material properties of this foam from the manufacturer's data [8].

Table1. Material properties of the foam core [8]

Foam Type	Nominal Density (kg/m^3)	Compression Modulus (MPa)	Compression Strength (MPa)	Shear Elongation %
Corecell P600	122	125	1.81	67%

The VARTM procedure was carried out to fabricate sandwich composite panels. The overall dimensions for the specimen were 102 mm wide, 254 mm long and 33 mm thick. The foam core itself was 25.4 mm thick, while the skin thickness was 3.8 mm. The average areal density of the samples was 17.15 kg/m^2. Fig. 1 shows a real image of a specimen and its dimensions.

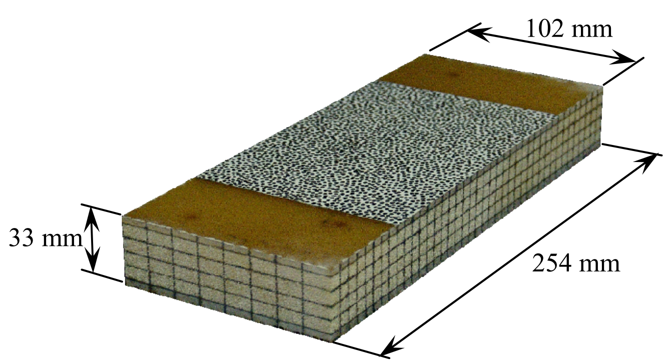


Fig. 1 Real specimen and its dimensions

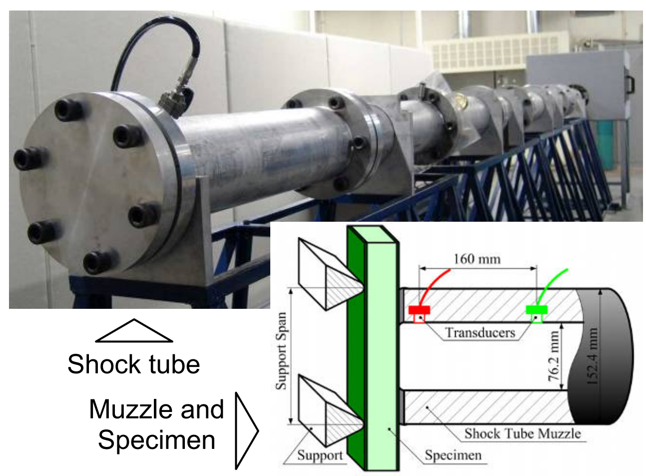


Fig. 2 Shock tube apparatus

3. EXPERIMENT SETUP AND PROCEDURE

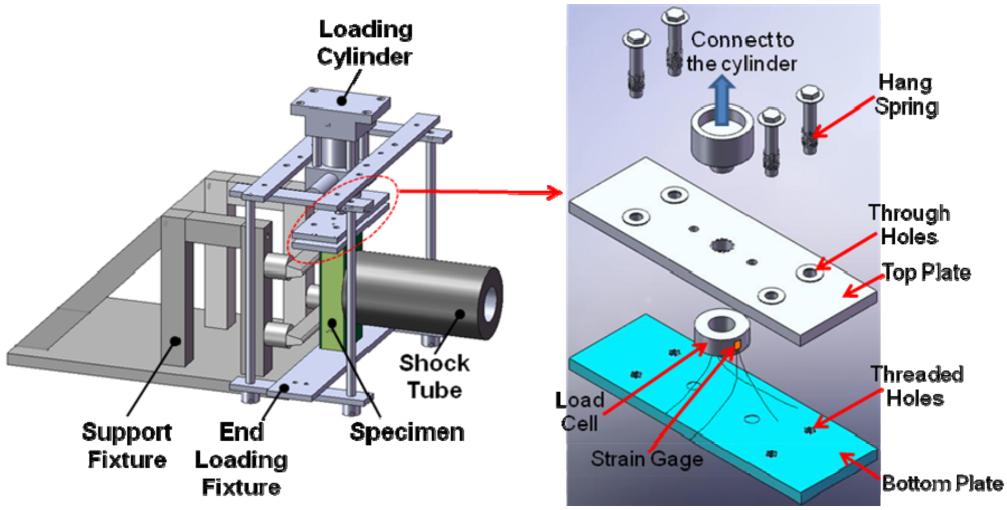
3.1 SHOCK TUBE

The shock tube apparatus was utilized in present study to obtain the controlled blast loading. The detail of this apparatus can be found in Ref.[4]. Fig. 2 shows the shock tube apparatus with muzzle detail. The final muzzle diameter is 76.2 mm. Two pressure transducers (PCB102A) are mounted at the end of the muzzle section with a distance 160 mm. The support fixtures ensure simply supported boundary conditions with a 152.4 mm span.

3.2 IN-PLANE PRE-LOADING FIXTURE

Fig. 3 shows the fixture used to apply the in-plane static compression loading on the sandwich composite panels. The loading head is connected to a hydraulic loading cylinder, which is mounted on the frame. An aluminum cylinder with an outer-diameter Ø50.8 mm and an inner-diameter Ø38.1 mm is positioned between two plates.

Two strain gages, which are attached on this aluminum cylinder, measure the deformation of this cylinder and then calculates the load applied on the specimen. The support fixture and in-plane pre-loading fixture are all securely fastened inside a dump tank.



(a) Fixture assembling (b) Load head

Fig. 3 In-plane pre-loading fixture

3.3 HIGH-SPEED PHOTOGRAPHY SYSTEMS

Two high-speed photography systems were utilized to capture the real-time 3-D deformation data of the specimen. Fig. 4 shows the experimental setup. It consisted of a back-view 3-D Digital Image Correlation (DIC) system with two cameras and a side-view camera system with one camera. All cameras are Photron SA1 high-speed digital camera, which have an ability to capture images at a frame-rate of 20,000 fps with an image resolution of 512×512 pixels for a 1 second time duration. These cameras were synchronized to make sure that the images and data can be correlated and compared.

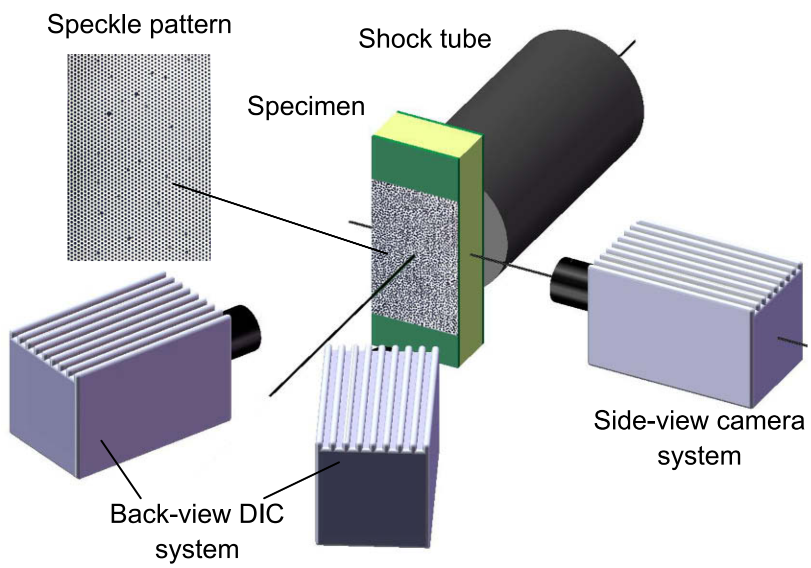


Fig. 4 High-speed photography systems

The 3-D DIC technique is one of the most recent non-contact methods for analyzing full-field shape, motion and deformation. Two cameras capture two images from different angles at the same time. By correlating these two images, one can obtain the three dimensional shape of the surface. Correlating this deformed shape to a reference (zero-load) shape gives full-field in-plane and out-of-plane deformations. To ensure good image quality, a speckle pattern with good contrast was put on the specimen prior to experiments.

3.4 EXPERIMENTAL PROCEDURE

In the present study, the shock wave loading has an incident peak pressure of approximately 1 MPa and a wave velocity of approximately 1030 m/s. The in-plane compression loading was applied on the specimen and held at a constant level until the specimen is subjected to the transverse shock wave loading. Three levels of static compression loading were chosen: 0 kN, 15 kN, 25kN. For each compression loading, at least two samples were tested. When the shock wave was released, the computer and high-speed photography system were triggered to record the pressure data and deformation images.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 REAL TIME DEFORMATION

4.1.1 SIDE-VIEW IMAGES

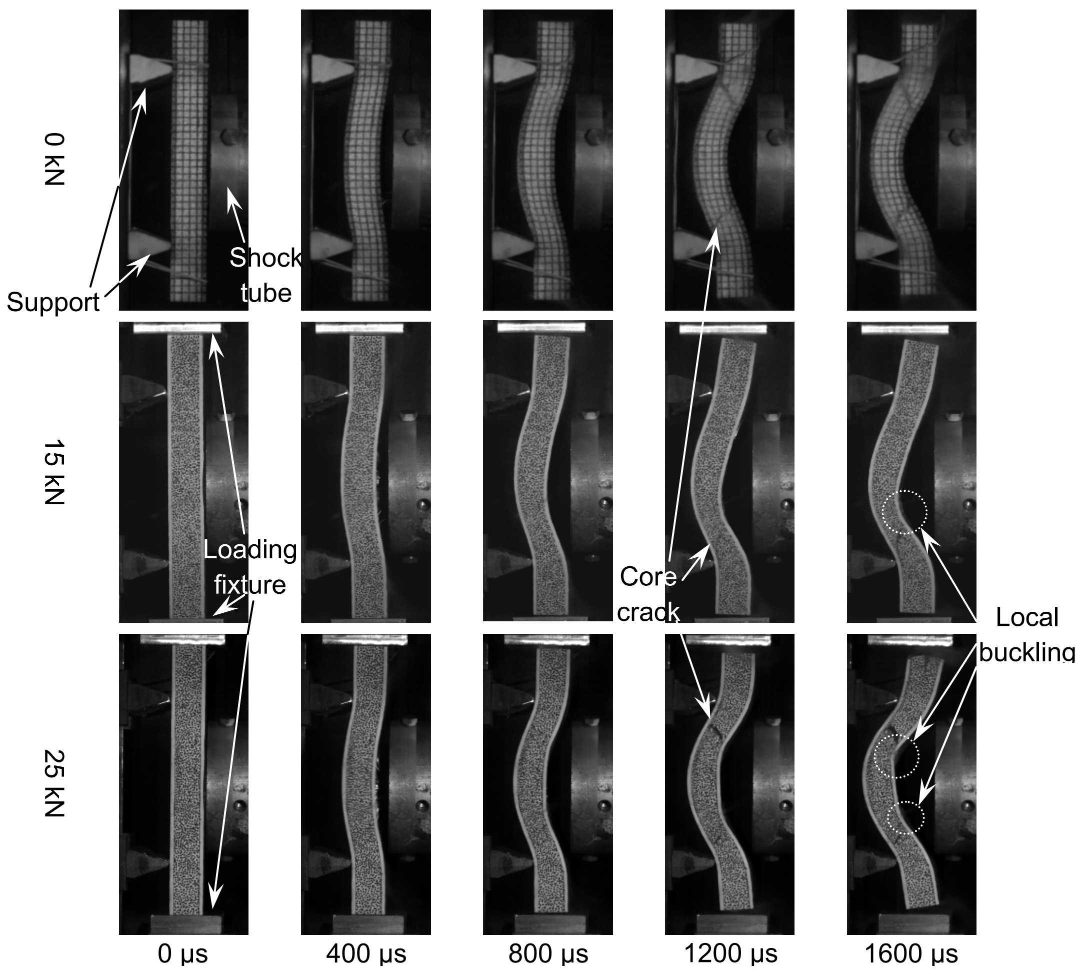


Fig. 5 Real time side-view deformation of sandwich composites with pre-loadings

Fig. 5 shows the real time side-view images of sandwich composites with different levels of compression pre-loading. The shock wave propagates from the right side of the image to the left side. Some deformation details are pointed out in the images.

From the images, it can be clearly seen that the initial deformation modes (prior to 400 μs) for the sandwich composite with different levels of pre-loading are very similar. They all show global bending with a typical double wing shape, which means that the core is under intense shear loading. Then, the sandwich composite without pre-loading (0 kN) continues bending symmetrically. The front face-sheet shows a profile with a smooth curvature. This means there is no local buckling in the front face. For the sandwich composite with 15 kN pre-loading, the initial deformation with a symmetric profile shifts to an asymmetric mode. The section of the front face-sheet close to the lower support exhibits more curvature than the section close to the upper support. This asymmetrical phenomenon indicates that there is local buckling at the lower section of the front face-sheet. At approximately 1600 μs, the fiber debonding of the front face-sheet shows clearly that local buckling is evident (shown in the white circle). For the sandwich composite with 25 kN pre-loading, there are two obvious kinks in the front face-sheet. The middle section between these two kinks shows a flat profile, which means that no moment is applied on this section. It indicates that there are two failure hinges, such as local buckling, happened at the kink positions.

Fig. 6 shows the back face out-of-plane deflection contours of sandwich composites with different levels of compression pre-loading from DIC technique. It can be seen that the deflections of the points through the width of the panels are almost same. The deflections of the panels with 0 and 15kN pre-loading are very similar. The panel with 25 kN pre-loading has higher deflection.

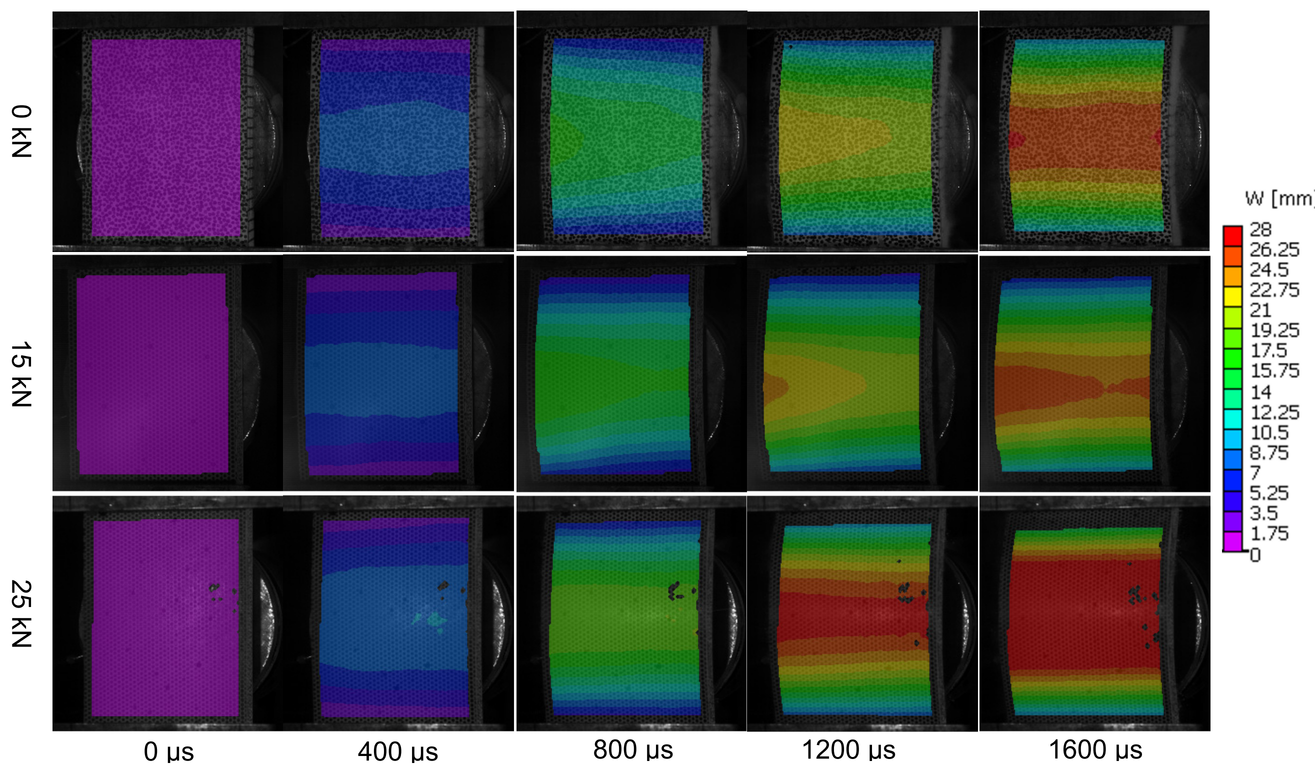


Fig. 6 Out-of-plane deflection contour of sandwich composites with pre-loadings

4.1.2 DEFLECTION AND IN-PLANE STRAIN OF THE FACE-SHEET

Fig. 7 shows the deflections of the middle point located on the front and back faces from the side-view high-speed images. From the plots, the defections of the front and back faces for each panel are almost overlapped. This means that there is no core compression in the core thickness direction. The panels with 0 and 15kN pre-loading have similar deflections while the deflection of the panel with 25 kN pre-loading is higher. This is evident in fig. 6.

Fig. 8 shows the in-plane strain eyy of the middle point of the back face from the DIC technique. Here, the vertical direction is y axis. It can be see clearly that the trend of the in-plane strains is much different from that of the out-of-plane deflections. Though the deflections are almost identical, the back-face in-plane strain of the panel with 15 kN pre-loading is much higher than that with 0 kN pre-loading. This shows that the in-plane pre-loading reduces the blast resistance of the sandwich composites. It can also be seen that the in-plane strains are almost identical for all levels of pre-loading prior to 400 μs, which means that the deformation mechanisms are very similar. This is also evident in the side-view high-speed images (Fig. 5).

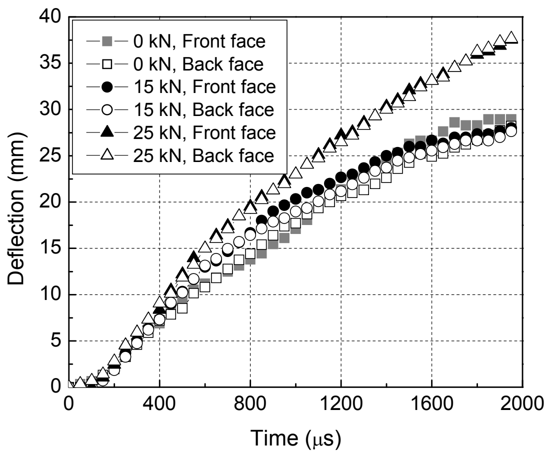


Fig. 7 Deflections of middle point at back and front faces

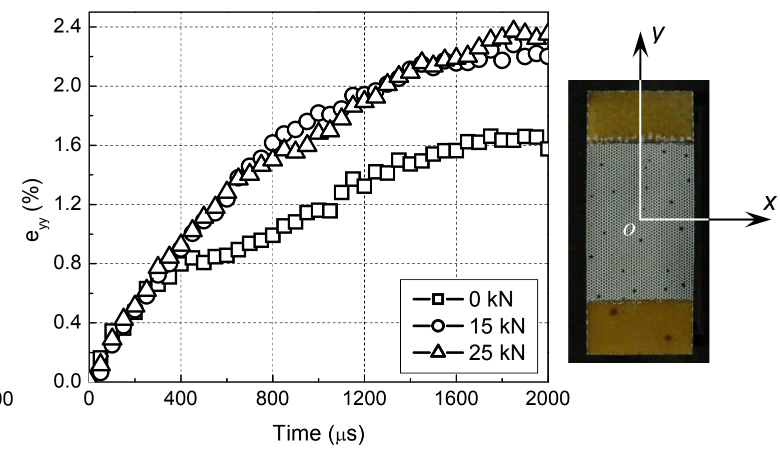


Fig. 8 In-plane strain on the back face

4.2 POST MORTEM ANALYSIS

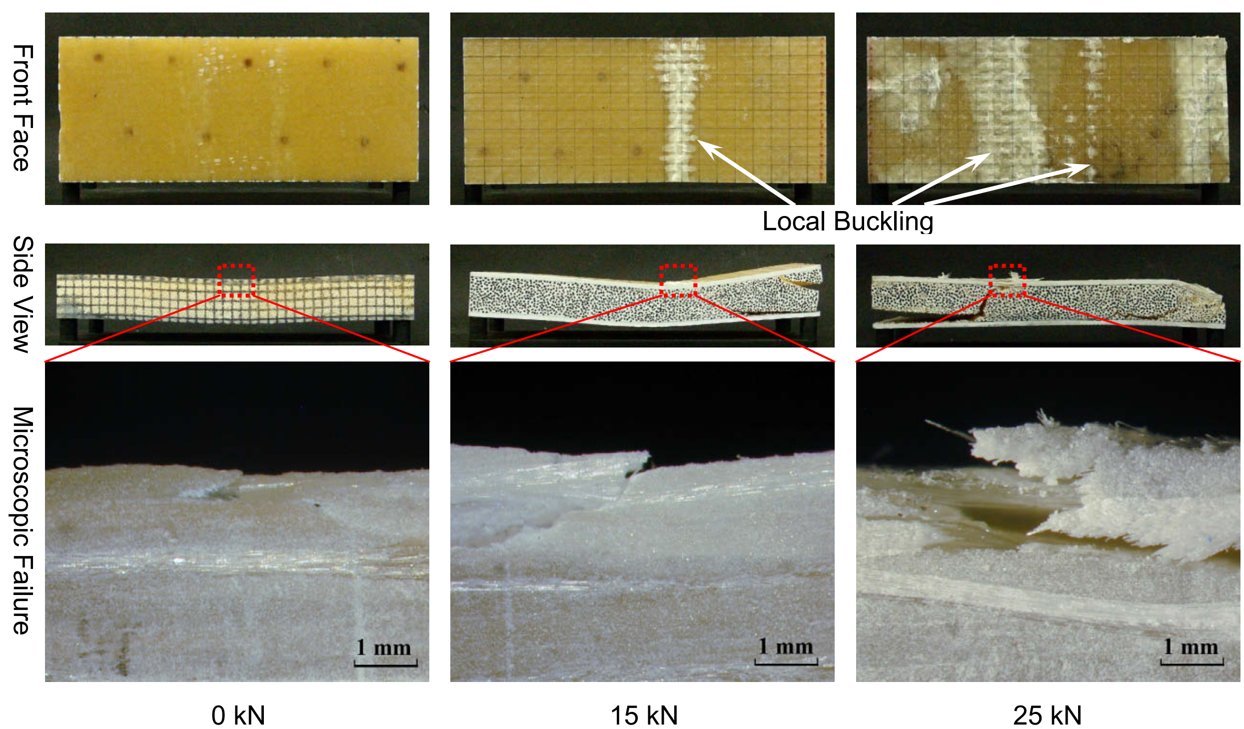


Fig. 9 Post mortem images of sandwich composite with different pre-loading

The damage patterns of the sandwich panels after the shock event occurred were visually examined and recorded using a high resolution digital camera and are shown in Fig.9. Since the back face sheets don't show any change after the experiments, we don't show them here. From the front face-sheet images, the local buckling positions demonstrate an apparent trend. Note the yellow color is the original color of the specimen and the white color signifies fiber delamination and face-sheet buckling. For the panel with 0 kN pre-loading, there is no buckling on the front face. For the panel with 15 kN pre-loading, the buckling only occurred at one position, which is correlated to the section with large curvature in the side-view high-speed image. For the panel with 25 kN pre-loading, buckling occurred at two positions beside the center of the specimen, which are correlated to the two kinks in the side-view high-speed image. Those white areas at the end of the specimen are not due to local buckling induced by the pre-loading. It is due to the collision between the specimen and shock tube during the blast loading process. From the side view images, the core crack and delamination between the core and face sheets also increase with the increase of the in-plane pre-loading.

Microscopic analysis of the buckling region observed in the sandwich panels was done using a Nikon SMZ microscope. These micro images, also shown in Fig. 9, make apparent an obvious trend. For the panel with 0 kN pre-loading, there is almost no crack in the front face. For the panel with 15 kN pre-loading, the crack crossed the first two fiber layers of the front face sheet. For the panel with 25 kN pre-loading, the crack was totally opened and propagated more deeply into the face sheet. The edge of the crack shows the evidence of tearing.

5. CONCLUSIONS

Sandwich composites, with E-glass Vinyl Ester composite face sheet and CoreCell™ P600 foam core, were put under an in-plane pre-load prior to being subjected to a transverse shock wave loading. Three levels of pre-loading were chosen to study the effect of pre-stresses on the dynamic behavior of the sandwich composites. A high-speed photography system and the Digital Image Correlation (DIC) technique were utilized to obtain full-field 3-D deformation data. The results show that the in-plane pre-loading induced local buckling in the front face sheet of the sandwich composites during the blast loading process. This mechanism changed the deformation mode of the sandwich composites. It is clear that higher levels of pre-loading caused more damage in the front face sheet, larger out-of-plane deflection, and higher in-plane strain on the back face sheet. Consequently, the over-all blast resistance of sandwich composites was significantly reduced.

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