Finite Element Modeling of Water Slamming on Sandwich Hull Structures

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Abstract *— This article evaluates the structural response of ship hull sandwich panels subjected to water slamming. Structural responses were obtained from several finite element (FE) model simulations developed by using the commercial code LS-DYNA. Models were analyzed for hull sandwich panels impacting initially calm surface water at two different deadrise angles 10° and 15°, under three impact velocities, 5 m/s, 4 m/s, and 3 m/s. Structural responses were dependent of the slamming conditions as hydrodynamic pressures propagate from the keel to the chine. Panel's deflection, core shear stresses, and skin tensile stresses showed to be decreased at lower impact velocities and higher deaderise angles.*

Keywords *— Finite Element Analysis, Fluid-Structure Interaction, Sandwich Composite Hulls, Water Slamming.*

INTRODUCTION

Sandwich composite structures are widely used in marine and aerospace industries due to their high flexural stiffness and low weight properties. These characteristics make sandwich composites very attractive, particularly in applications in which improved efficiency, enhanced performance, and reduced operational costs are primary concerns. For instance, sandwich panels are currently being implemented in the construction of hull structures in lightweight high-speed marine crafts. Sandwich composite panels consist of two thin and stiff face skins bonded to both sides of a thick and lightweight core by an adhesive material (Figure 1). When these panels are subjected to flexural loading, as in the case of water slamming (see Figure 2), it is assumed that the face skins carry all the tensile stress whereas the core material carries the shear stress [1].

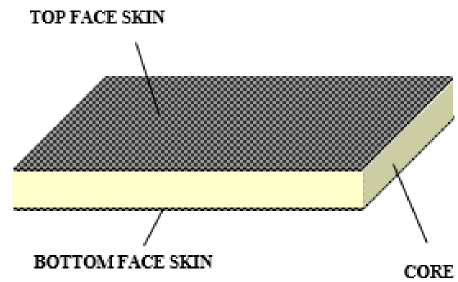

Figure 1
General Sandwich Structure

In rough sea conditions, repeated slamming events cause the stresses in the panels to fluctuate with high-stress rates, eventually producing fatigue failure of the structure. The predominant mode of failure of sandwich panels under cyclic flexural loading has been core shear, even though in some cases, skin tensile failure has also occurred [2 – 7]. Therefore, the evaluation of the structural response of the sandwich panels (e.g. deflection, core shear stress, and skin tensile stress) subjected to water slamming is critical for achieving an optimal design.

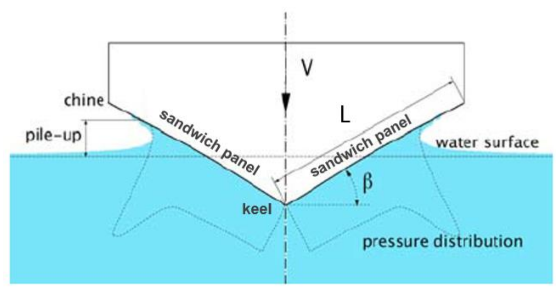

Figure 2
Schematic Water Slamming on Ship Hull [8]

This article presents the results of finite element (FE) simulations of a single slamming event between a sandwich panel and an initially calm water surface. The FE models were developed using the commercial code LS-DYNA, which is well suited for dynamic simulations of fluid-structure interaction (FSI) problems [8–12]. The structural responses of the sandwich panels for different impact conditions, impact velocity (V) and deadrise angle (β), are compared and analyzed. It is well known that during the impact between panel and water, a peak in the hydrodynamic pressure rapidly propagates from the keel to the chine of the hull [13–18]. The magnitude of this pressure peak increases when either, the impact velocity increases or the deadrise angle decreases. The dynamic response of the panel strongly depends on the magnitude of the pressure exerted by the water on it. The pre-knowledge of the characteristic behavior of the hydrodynamic pressure was used in this work to design the FE mesh. The mesh density must be high enough in order to accurately predict the hydrodynamic pressure but not too high that the simulations become excessively time-consuming.

FINITE ELEMENT MODEL

Two-dimensional symmetric FE models were developed using the commercial explicit code LS-DYNA. Each model consisted of two fluid domains, water and air, and a sandwich composite panel with specific impact velocity V and deadrise angle β (Figure 3). The total length of the panel was 1.5 m. Water and air domains were modeled using an Eulerian mesh (fixed in space), with solid one point (Gauss quadrature integration) Arbitrary-Lagrangian Eulerian (ALE) multi-material elements (ELFORM 11). ALE multi-material formulation allows water material to flow through the air mesh during the impact. The sandwich panels were modeled using a Lagrangian mesh (attached to the panel), with shell elements for both face skins (ELFORM 2) and fully integrated quadratic solid elements for the core (ELFORM 3). The interaction between fluid and structure was managed by the penalty coupling algorithm [19]. The materials for the sandwich constituents were selected from the literature [20–22]. The face skins were assumed to be made of orthotropic carbon-fiber/epoxy-resin fabric with a lay-up sequence of $[0/90]_S$, whereas the core material used was AIREX C70.130 cross-linked foam. Both constituents are assumed to behave linearly-elastic during the impact. The corresponding materials models in LS-DYNA were 002-ORTHOTROPIC_ELASTIC and 001-MAT_ELASTIC for the face skins and core respectively. The geometric configuration and material properties of the sandwich panel are listed in Table 1.

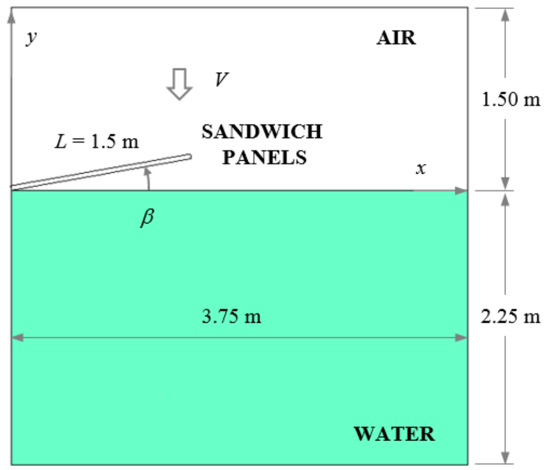

Figure 3
LS-DYNA Finite Element Model

The FE mesh was designed based on the worst impact case scenario under study, i.e. maximum impact velocity (V = 5 m/s) and minimum deadrise angle (β = 10°). These impact conditions required the highest mesh density due to the pronounced pressure peak exerted by the water on the structure.

Table 1
Sandwich Panels Material Properties

Property	Core	Skin Face
Density (kg/m^3)	130	1600
Thickness (mm)	50	2.5
Elasticity Modulus (MPa)	110	70000
Shear Modulus (MPa)	50	5000
Poisson's Ratio	0.10	0.10
Tensile Strength (MPa)	-	600
Shear Strength (MPa)	2.3	-

The resulting mesh was also appropriate for simulations of less severe impact conditions. The mesh extent in z-direction was 1 mm (one element). The analysis was restricted to the x-y plane by constraining all nodes in the z-direction. Symmetry boundary conditions were applied to the water domain along the y-axis (Figure 4).

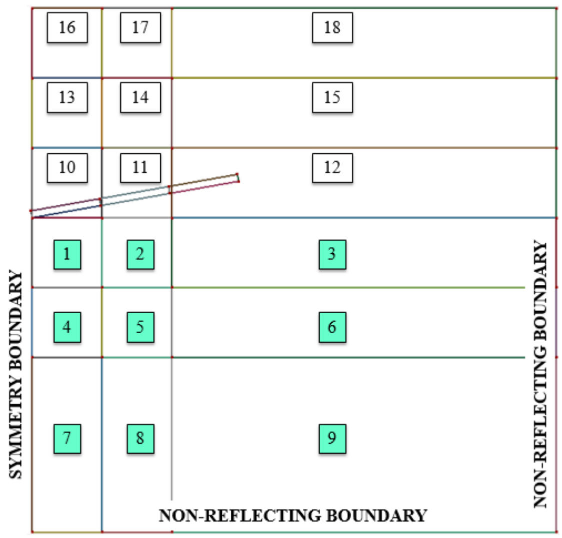

Figure 4
FE Sectioned Model

Non-reflecting boundary conditions were defined along the other boundaries of the model simulating a semi-infinite fluid domain. Furthermore, the sandwich panel was divided into three equal spans of length 0.5 m connected with clamped boundary supports (Figure 5). This approach was implemented to isolate the structural response of the central panel from any boundary effect, emulating the conditions of a typical panel in a hull structure.

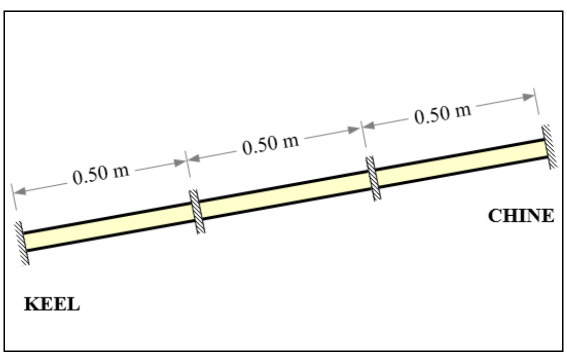

Figure 5
Boundary Conditions for Sandwich Panels

The pre-knowledge of the characteristics of the hydrodynamic pressure during the impact was used to determine that the optimal element size for the mesh, in the vicinity of the central panel, should be approximately 1.5 mm [9]. Based on that, the fluid domain was divided into 18 zones which were meshed as follows: water zones 1, 2, 4, and 5, with uniform element size (1.5 mm), water zones 3, 6, 7, 8, and 9, with expanding element size toward the boundaries with increment ratio r = 1.012; air zones 10, 11, 13, and 14, also with uniform element size (1.5 mm), air zones 12, 15, 16, 17, and 18, with expanding element size toward the boundaries with increment ratio r = 1.012. A similar pattern was implemented for the structural mesh: uniform element size in the first and second panel (1.5 mm), and expanding element size in the third panel. This resulted in a mesh size of 3 million nodes approximately.

Results And Discussion

FE analysis of sandwich composite panels slamming an initially calm water surface was conducted. The impact pressure and structural response of the central panel for different slamming conditions were studied. Two deadrise angles were analyzed, 10° and 15°, and three impact velocities, 5 m/s, 4 m/s, and 3 m/s. Pressure data on the central panel was collected by numerical sensors placed at the bottom face skin, which was in contact with the water. Impact pressure time histories at different locations on the central panel for $\beta = 10°$ and $V = 5$ m/s are shown in Figure 6 and Figure 7. The simulation time for this case was 30 milliseconds (ms), time required by the pressure peak to propagates from the keel to half-length of the third panel. Complete submergence of the second panel is essential in order to evaluate its structural response during the slamming event. At the initial stages of the impact (Figure 7), the maximum impact pressure recorded by the sensors was in the order of 1 MPa, which is consistent with analytical results [13–18] and experimental measurements [23] [24].

As the slamming event progressed, the impact pressure slightly decreased to 0.8 MPa, to finally reach its maximum peak value of 1.2 MPa (Figure 7). Submergence of the central panel occurred within the 11–23 ms interval, approximately.

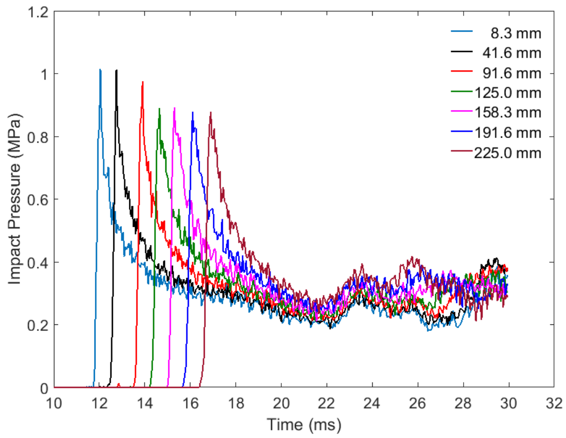

Figure 6

Pressure Time Histories for $\beta = 10°$ and $V = 5$ m/s

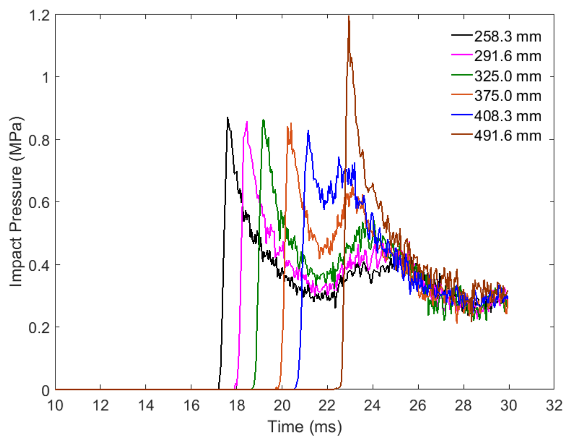

Figure 7

Pressure Time Histories for $\beta = 10°$ and $V = 5$ m/s

Mid-span deflection of the central panel was plotted in Figure 8. The maximum mid-span deflection was 8 mm (which represents the 16% of the core thickness), and was estimated to take place a short time after complete submergence of the panel (25 ms). This demonstrates the effect of the after-slamming stage on the structural response. From Figure 8, it can be seen that the deflection rate is quasi-linear for these slamming conditions. Figure 9 shows the core shear stress time histories near the panel's supports. The maximum shear stress in the core was 3 MPa close to the right-hand support, at the end of the panel submergence stage (23 ms). Another peak stress of magnitude 2.8 MPa occurred near the left-hand support, but much later than the occurrence of the first one (29 ms). At both locations, the maximum shear stress exceeded the shear strength of the core material (see Table 1). As a result, core shear failure was predicted in a single impact event under the current conditions ($\beta = 10°$ and $V = 5$ m/s).

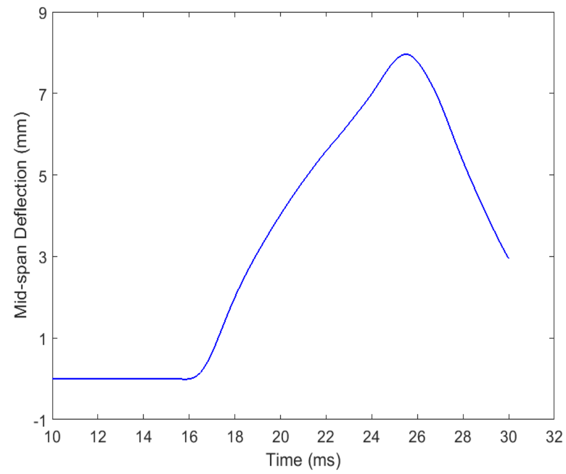

Figure 8

Mid-span Deflection for $\beta = 10°$ and $V = 5$ m/s

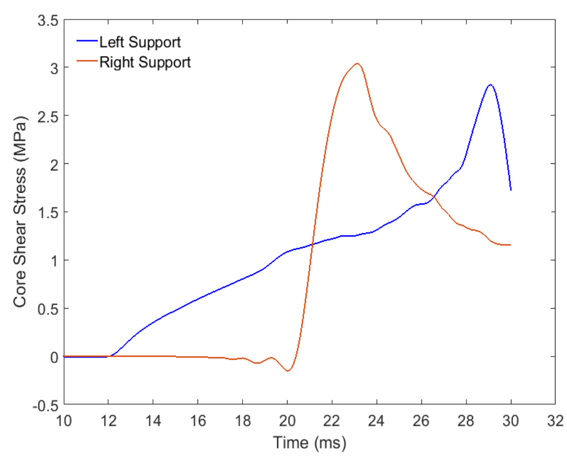

Figure 9

Core Shear Stress for $\beta = 10°$ and $V = 5$ m/s

The other failure mode considered in this work was skin tensile rupture. The tensile stresses on the bottom face skin near the panel's supports were plotted in Figure 10. A significant difference between both maximum stresses can be clearly observed. The tensile stress close to the right-hand support presented a distinctive peak of 375 MPa whereas the maximum tensile stress near the other support was in the order of 250 MPa.

In both cases, the maximum stresses were well below the tensile strength of the skin material (see Table 1). Therefore, skin failure was not anticipated under the current slamming conditions.

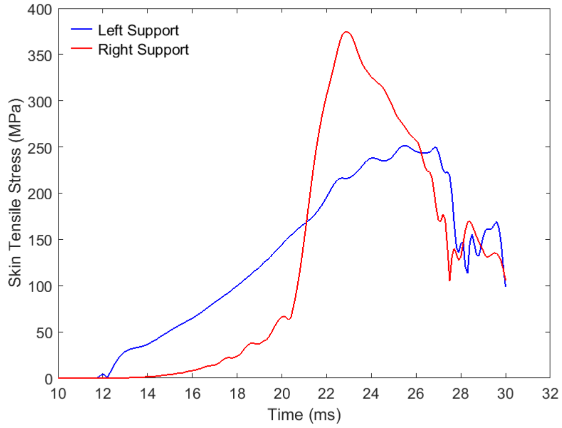

Figure 10

Skin Tensile Stress for $\beta = 10°$ and $V = 5$ m/s

In order to investigate the effect of the impact velocity on the panel's structural response, the same analysis was conducted using $V = 3$ m/s and $V = 4$ m/s, maintaining the deadrise angle constant ($\beta = 10°$). The results were compared with the previous case ($V = 5$ m/s). Mid-span deflections for the three impact velocities are shown in Figure 11. It was evident that the maximum deflection of the sandwich panels was proportional to the impact velocity, as expected. A similar effect was observed on the core shear stress (Figure 12 for left-hand support and Figure 13 for right-hand support). The maximum shear stresses in the core for 3 m/s and 4 m/s were 1.7 and 0.8 MPa, respectively.

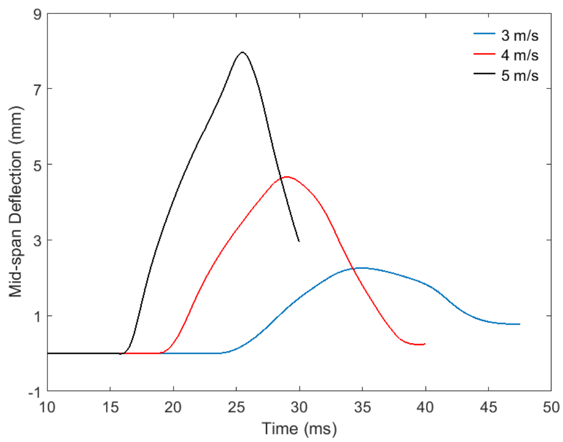

Figure 11

Effect of impact velocity on mid-span deflection

In both cases, the maximum shear stress did not exceed the shear strength of the core material. Consequently, core shear failure was not predicted for a single slamming event with impact velocities below 5 m/s. Similarly, skin tensile rupture was not predicted either for these slamming conditions (see Figure 14 for left-hand support and Figure 15 for tight-hand support).

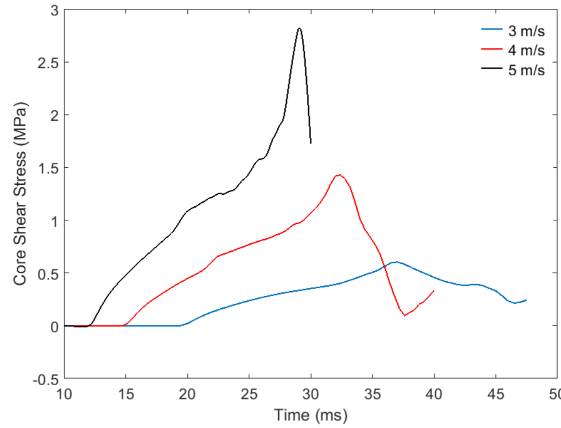

Figure 12

Effect of Impact Velocity on Core Shear Stresses

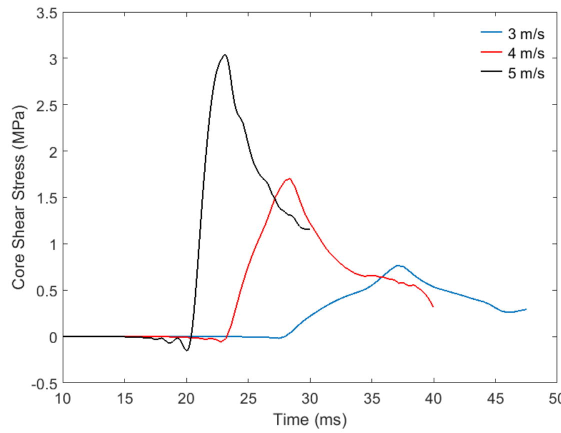

Figure 13

Effect of Impact Velocity on Core Shear Stresses

Additionally, the effect of the deadrise angle on the structural response of the sandwich panels was also investigated. Two case scenarios were considered, $\beta = 10°$ and $V = 5$ m/s, and $\beta = 15°$ and $V = 5$ m/s. Mid-span deflections for these cases are shown in Figure 16. The maximum mid-span deflection experienced a significant reduction with the increased deadrise angle. A similar effect was observed on the core shear stress and on the skin tensile stress. Figure 17 and Figure 18 show the core shear stresses near the left-hand support and right-hand support, respectively. Figure 19 and Figure 20 show the skin tensile stresses near the left-hand support and right-hand support, respectively.

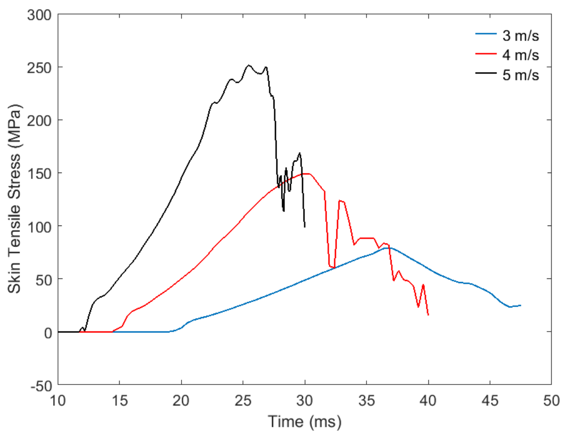

Figure 14

Effect of Impact Velocity on Skin Tensile Stresses

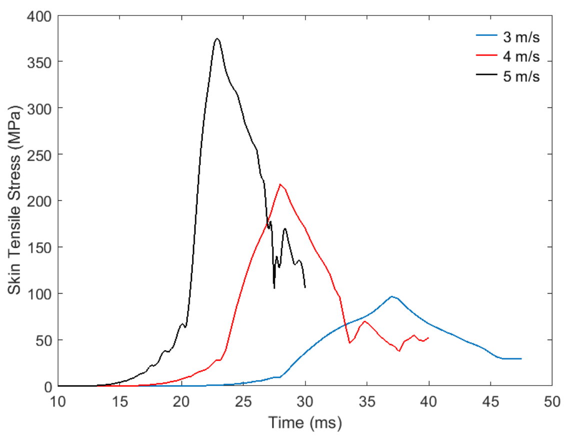

Figure 15

Effect of Impact Velocity on Skin Tensile Stresses

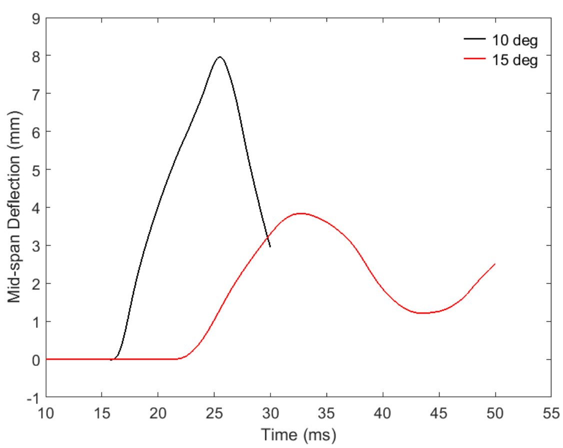

Figure 16

Effect of Deadrise Angle on Mid-Span Deflection

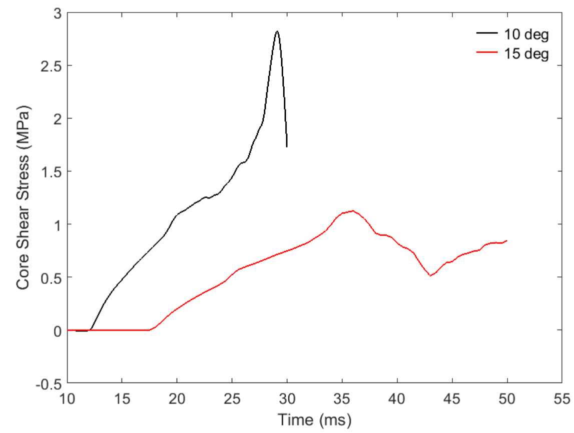

Figure 17

Effect of Deadrise Angle on Core Shear Stresses

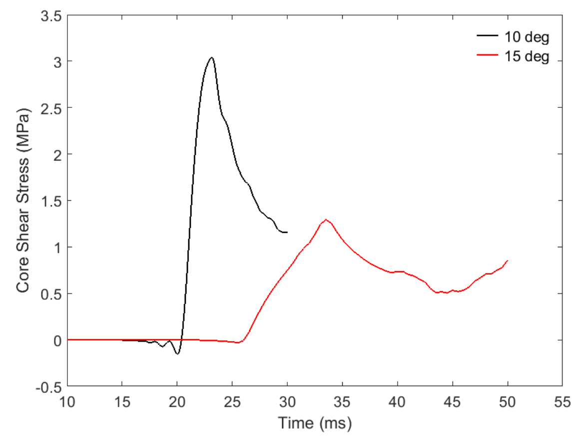

Figure 18

Effect of Deadrise Angle on Core Shear Stresses

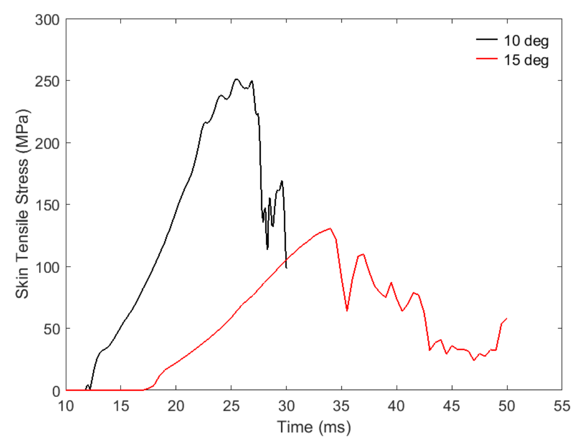

Figure 19

Effect of Deadrise Angle on Skin Tensile Stresses

Clearly, neither core shear nor skin tensile failure was predicted for a single slamming event with deadrise angle of 15° and impact velocity of 5 m/s.

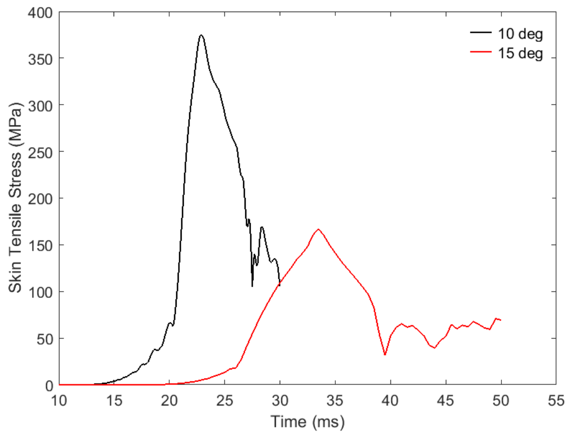

Figure 20

Effect of Deadrise Angle on Skin Tensile Stresses

CONCLUSIONS

FE analysis of a single impact event between a sandwich panel and an initially calm water surface showed a strong dependence of the panel's structural response with the slamming conditions. Particularly, panel's mid-span deflection, core shear stresses and skin tensile stresses experienced a significant reduction when the impact velocity was reduced or when the deadrise angle was increased. Of all slamming conditions studied in this work, only the case with $\beta = 10°$ and $V = 5$ m/s produced core shear failure near the panel's supports in a single impact event. Skin tensile failure was not predicted for any of the conditions considered here.

ACKNOWLEDGEMENT

The authors of this article wish to thank the Mechanical Engineering Department and the Graduate School Office at Polytechnic University of Puerto Rico for their support to this work.

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