Finite Element Analysis of Sandwich T-Joints Subjected to Water Slamming Loads

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Abstract *— This article evaluates the structural response of a sandwich ship hull with T-joint longitudinal stiffeners subjected to water slamming. Finite element analysis was conducted using the commercial code LS-DYNA. The T-joint stiffeners were modeled as linear elastic springs allowing the vertical displacement and rotation at the panel ends. Three different stiffnesses and two impact velocities were considered. Results showed to be significantly different from the fixed-supported panel case.*

Keywords *— Finite Element Analysis, Fluid-Sandwich Composite Hulls, Structure Interaction, T-Joint, 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 for applications in which improved efficiency, enhanced performance, and reduced operational costs are primary concerns. Particularly, sandwich panels are currently being implemented in the fabrication of hull structures for lightweight high-speed marine crafts. Typically, 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. To improve transverse strength, these panels are supported by longitudinal stiffeners. The most common configuration of perpendicular longitudinal stiffeners for sandwich structures is the T-joint [1], shown in Figure 1. When sandwich panels are subjected to flexural loadings, as in the case of water slamming, it is assumed that the face skins carry all the tensile stress whereas the core material carries the shear stress [2].

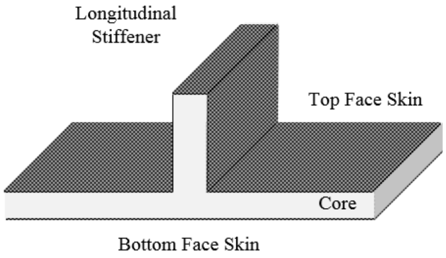

Figure 1
Detail of Sandwich T-Joint Longitudinal Stiffener

Variable slamming conditions induce high-rate fluctuating stresses in the panel constituents, which eventually cause fatigue failure of the structure. The predominant mode of failure of sandwich panels under cyclic flexural loading is core shear, in some cases skin tensile failure has also been observed [3–8]. Consequently, the evaluation of the structural response of sandwich panels with T-joint supports subjected to water slamming is critical for the design of light-weight marine vehicles. The classical approach used to study the hull-water slamming problem is the two-dimensional water entry model depicted in Figure 2.

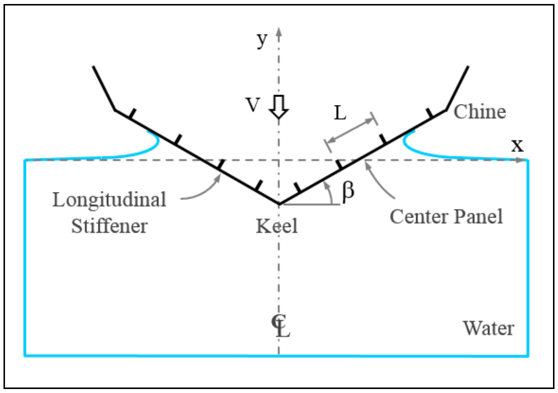

Figure 2
Schematic Water Slamming on Ship Hull

In this model, an elastic hull structure hits an initially calm water surface with constant vertial velocity V [9]. The angle of incidence between the undeformed structure and the undisturbed water surface is reffered to as the deadrise angle β. Longitudinal supports are commonly assumed rigid which prevents the local vertical displacement and rotation of the panel ends. This causes high magnitude and high rate shear stresses in the core near the panel supports. In this article a comparative analysis between the structural response of sandwich panels with fixed supports and that with T-joint stiffeners is presented. The objective of this research is to determine how the stiffness of longitudinal supports affects the magnitude and rate of core shear stresses. For this, finite element (FE) models were developed using the commercial explicit code LS-DYNA, which is well suited for dynamic simulations of fluid-structure interaction (FSI) problems [10–14].

FINITE ELEMENT MODEL

The two-dimensional hull-water slamming problem was modeled using the commercial FE software LS-DYNA. The model consisted of two fluid domains, water and air, and a sandwich composite panel oriented at a particular deadrise angle β with impact velocity V, as shown in Figure 3. Due to the symmetry of the problem along the centerline (see Figure 1), only one half of the hull geometry was modeled. Water and air domains are 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 impact. The sandwich panels and the T-joint supports 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 translational stiffness of the T-joints were modeled using linear springs of stiffness k. The rotation of the T-joints was not restricted. The keel and chine boundary conditions were fixed. The interaction between fluid and structure was managed by the penalty coupling algorithm [15]. The materials for the sandwich constituents were selected based on data reported in the literature [16–18]. The face skins were assumed to be made of orthotropic carbon-fiber/epoxy-resin fabric with a lay-up sequence of [0/90]. AIREX C70.130 cross-linked foam was used for both the core material and the T-joint stiffeners. All constituents are assumed to behave linearly-elastic during the water slamming. The corresponding materials models in LS-DYNA were 002-ORTHOTROPIC_ELASTIC, 001-MAT_ELASTIC and S01-SPRING_ELASTIC for the face skins, core material and springs respectively. The geometric configuration and material properties of the sandwich panel are listed in Table 1.

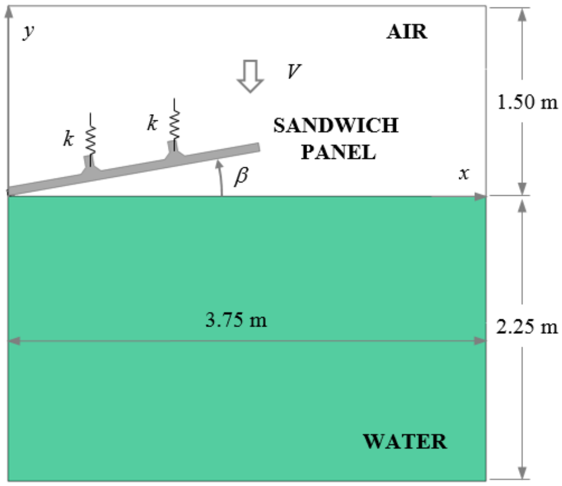

Figure 3
LS-DYNA Finite Element Model

The mesh extent in z-direction was 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).

Table 1
Sandwich Panels Materials 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	-

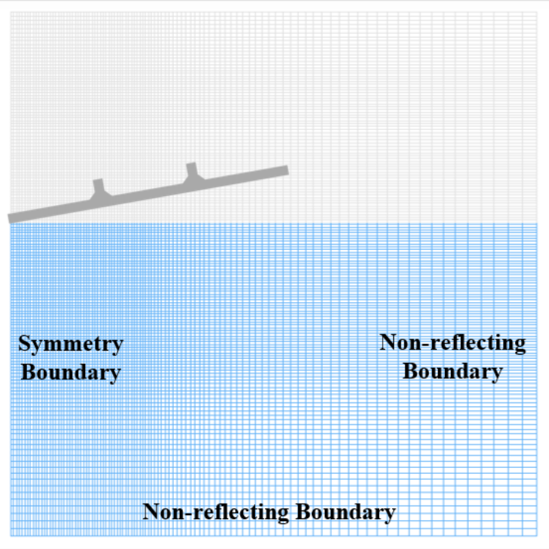

Figure 4
FE Mesh and Boundary Conditions

Non-reflecting boundary conditions were defined along the other boundaries of the model simulating a semi-infinite fluid domain. Furthermore, the sandwich hull was modeled using three equal panels of length 0.5 m connected with T-joint supports (see 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 the hull structure. Numerical pressure sensors were placed along the center panel to measure the slamming pressure during the simulation.

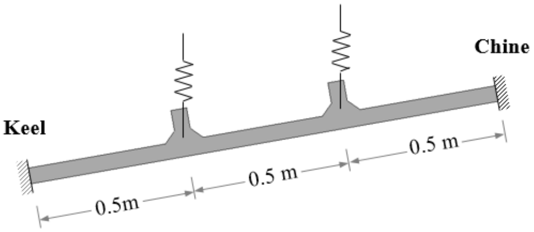

Figure 5
Boundary Conditions for Sandwich Panels

RESULTS AND DISCUSSION

FE simulations were conducted for three different T-joint stiffnesses (0.005, 0.010, and 0.020 kN/mm) and two impact velocities (5 and 4 m/s). The deadrise angle was maintained constant at 10°. For each slamming condition the slamming pressure and the structural response of the center panel was studied. The simulation time was 35 milliseconds for V = 5 m/s and 40 milliseconds for V = 4 m/s. This was determined in order to achieve complete submergence of the center panel. Slamming pressure distribution along the center panel for V = 5 m/s and V = 4 m/s are shown in Figure 6 and Figure 7, respectively. It can be noticed that the effect of increasing the T-joint stiffness affect the magnitude of the pressure peak. Slamming pressure results are consistent with experimental data reported in the literature for elastic and rigid sandwich panels [19, 20].

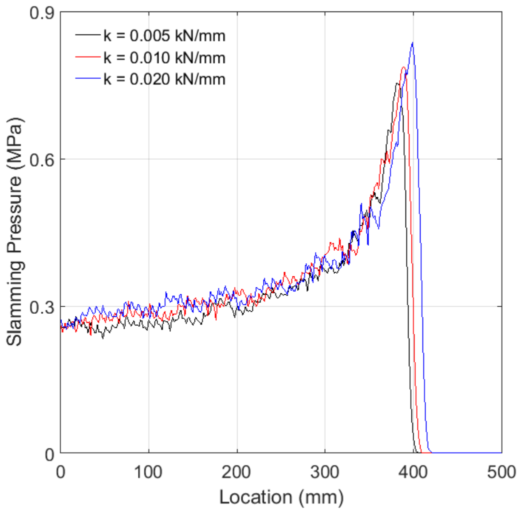

Figure 6
Pressure Distribution for *V* = 5 m/s and *t* = 25.5 ms

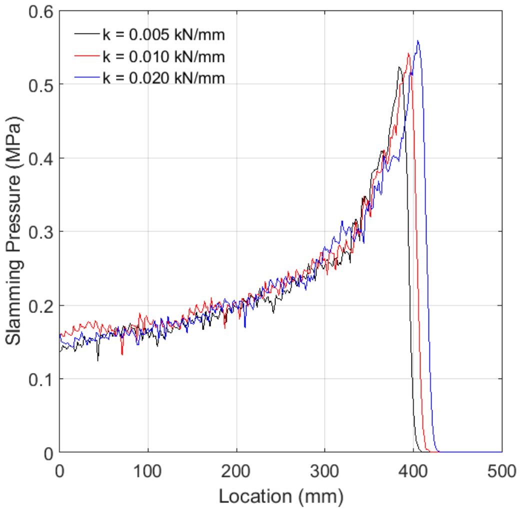

Figure 7
Pressure Distribution for *V* = 4 m/s and *t* = 26.6 ms

In order to evaluate the stiffness of the T-joint supports, the vertical displacement was plotted for each case, as shown in Figure 8 and Figure 9. In Figure 8, which corresponds to V = 5 m/s, the maximum displacements occurred at the right-hand T-joint. The magnitude of the maximum support displacement is clearly a function of the stiffness k. In all cases, the right-hand T-joint displacement is 50% higher than that of the left-hand T-joint. Similar results were obtained for the case V = 4 ms (see Figure 9).

The center panel mid-span deflection was also plotted for the three stiffness cases and compared with the mid-span deflection of the fixed-supported panel (Figure 10 and Figure 11). The fixed-supported solution was the result of a previous work [21]. The increment in maximum mid-span deflection was directly associated with the displacement of the left-hand T-joint support. Water pressure distribution and corresponding core shear stresses at three different times are shown in Figure 12 and Figure 13, respectively.

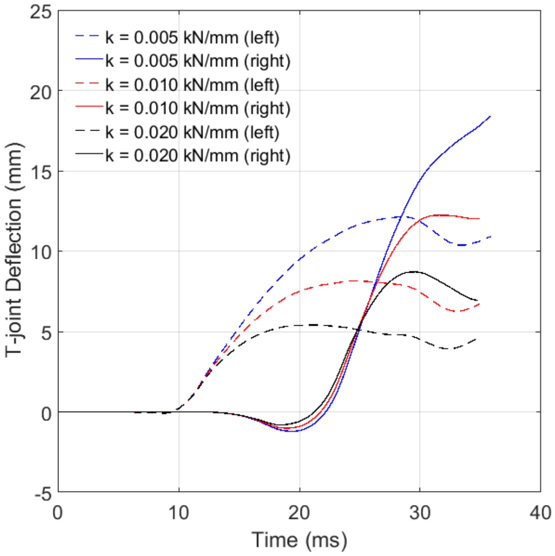

Figure 8

T-Joint Deflection Histories for *V* = 5 m/s

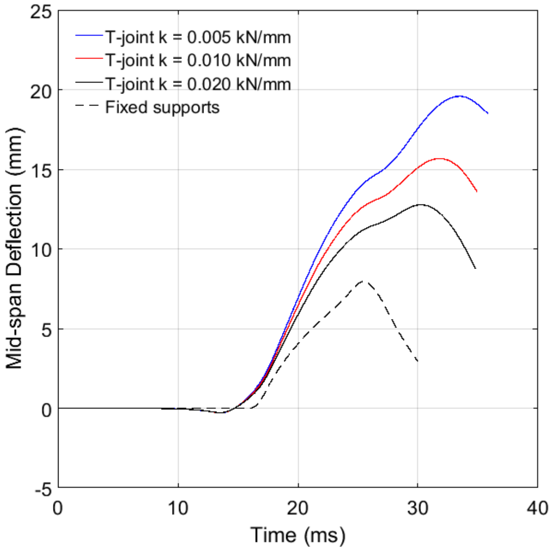

Figure 10

Mid-Span Deflection for *V* = 5 m/s

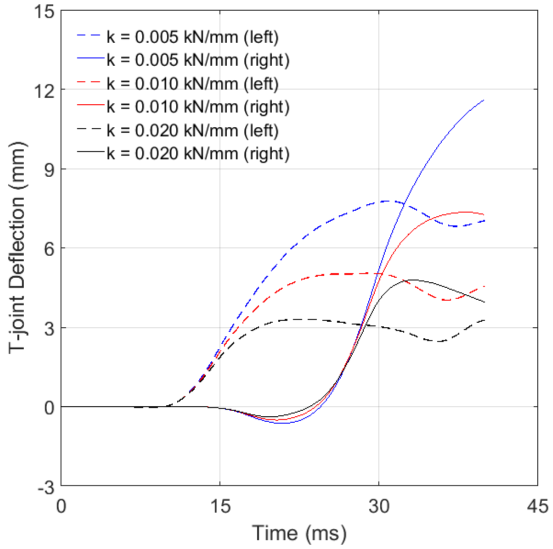

Figure 9

T-Joint Deflection Histories for *V* = 4 m/s

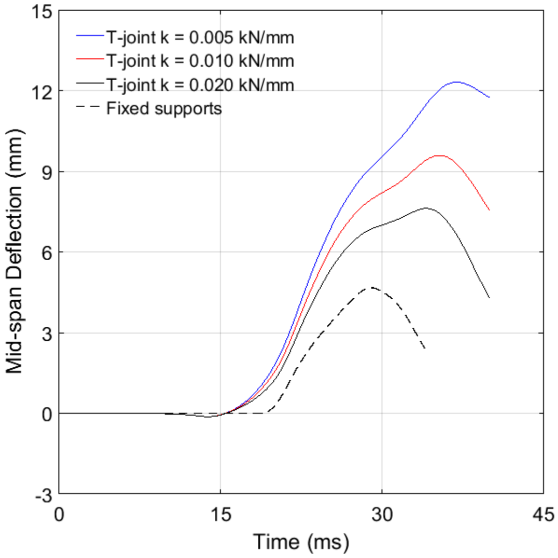

Figure 11

Mid-Span Deflection for *V* = 4 m/s

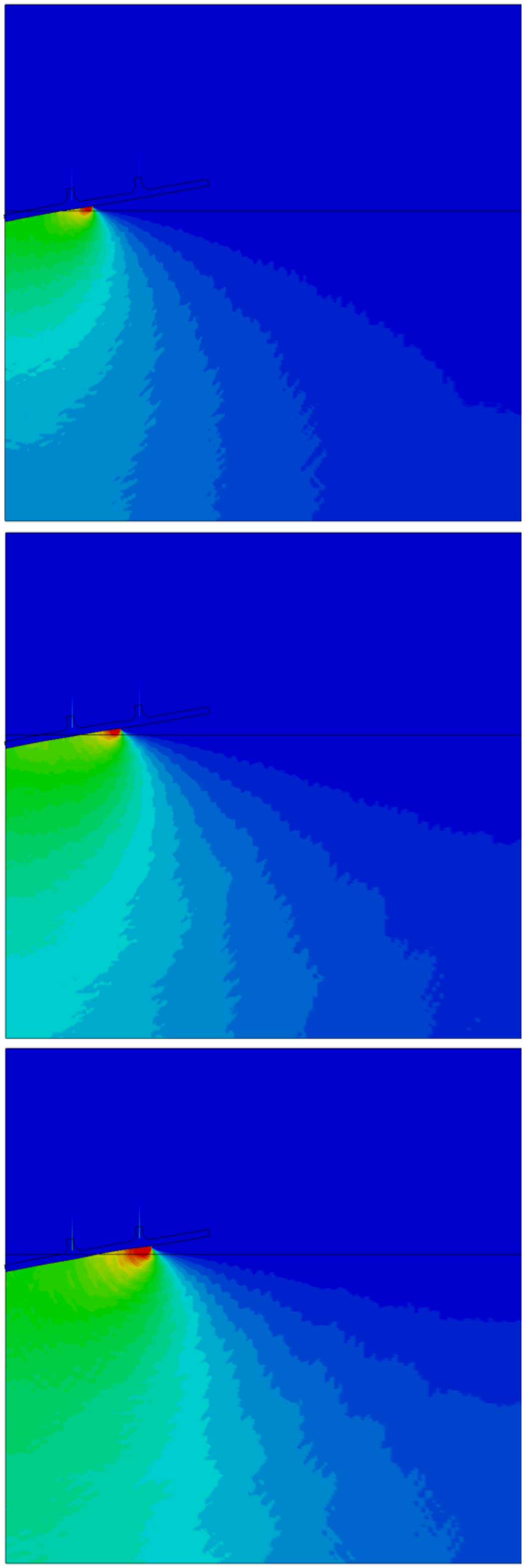

Figure 12
Water Pressure Distribution *V* = 5 m/s at 15 ms (top), 20 ms (middle), and 25 ms (bottom)

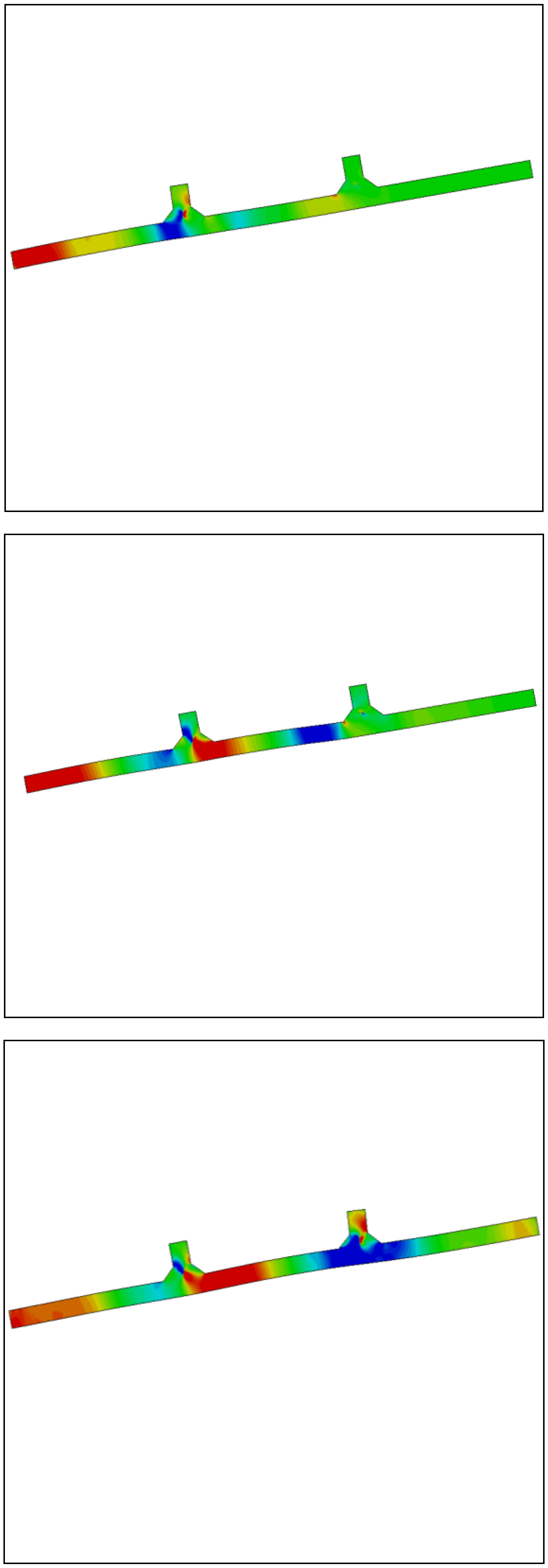

Figure 13
Core Shear Stresses for *V* = 5 m/s at 15 ms (top), 20 ms (middle), and 25 ms (bottom)

The results correspond to V = 5 m/s and t = 15, 20, and 25 ms. The propagation of the slamming pressure peak from the keel to the chine of the hull can clearly be observed from the contour plots in Figure 12. The maximum transverse shear stresses occurring near the T-joint supports can also be noticed from Figure 13. Core shear stresses were plotted in Figure 14 and Figure 15 for the left-hand T-joint and compared with the fixed-supported panel solution.

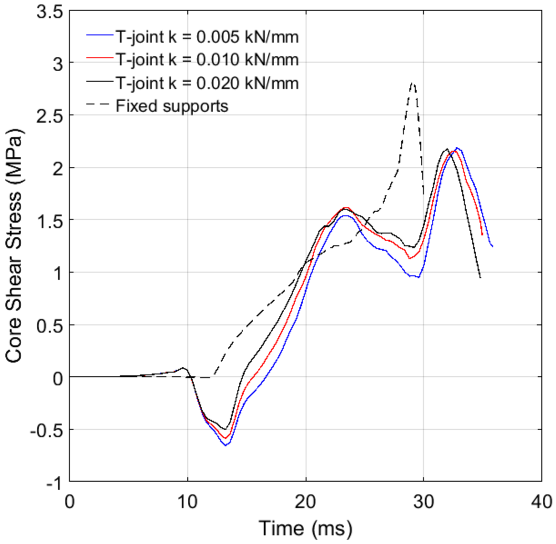

Figure 14

Core Shear Stress for *V* = 5 m/s (left T-joint)

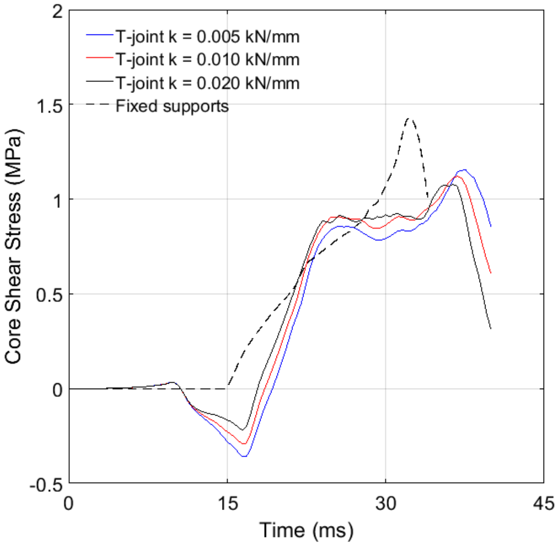

Figure 15

Core Shear Stress for *V* = 4 m/s (left T-joint)

Similarly, core shear stresses at the right-hand T-joint are shown in Figure 16 and Figure 17. A significant reduction in maximum core shear stress can be observed in all cases. Additionally, a slight increase in stress rates can be noticed at the left-hand support for both impact velocities. On the other hand, the stress rates at the right-hand support remained relatively the same as that in the fixed-supported sandwich panel.

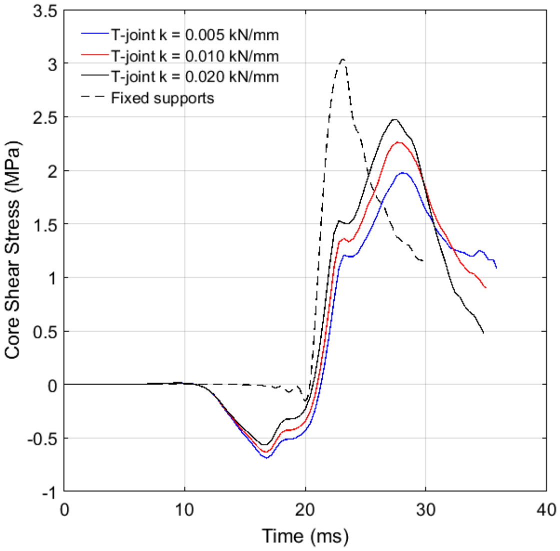

Figure 16

Core Shear Stress for *V* = 5 m/s (right T-joint)

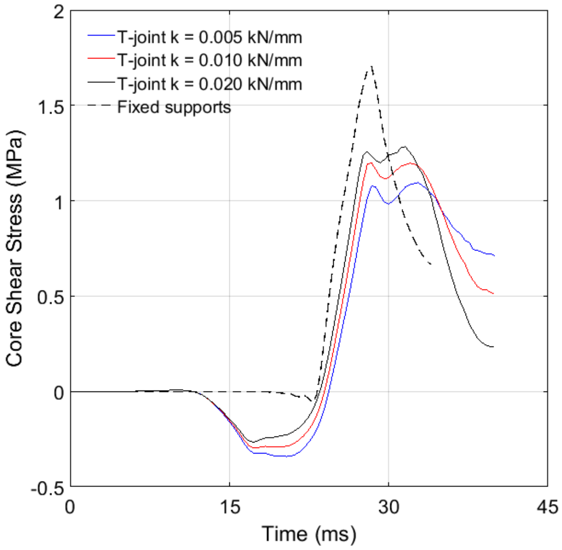

Figure 17

Core Shear Stress for *V* = 4 m/s (right T-joint)

CONCLUSIONS

FE analysis showed a strong relationship between the T-joint stiffness and the structural response of the panel. In particular the mid-span deflection was shown to significantly decrease when the T-joint stiffness was increased or when the impact velocity was decreased. On the other hand, core shear stresses increased when higher stiffness or impact velocities were used. Out of all the cases analyzed in this work only the case with conditions β = 10°, V = 5 m/s and a stiffness of 0.020 generated core shear failure near the T-joint stiffeners. A good correlation was achieved between the numerical results and experimental data available for elastic and rigid sandwich panels.

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