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

Author: Luis J. Rivera Santos
Advisor: Andres Cecchini, Ph.D.
Mechanical Engineering Department

Abstract

This project 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 were compared to a fixed-supported panel case and showed to be significantly different.

Introduction

Sandwich composite structures are widely used in marine and aerospace industries due to their high flexural stiffness and low weight properties. 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].

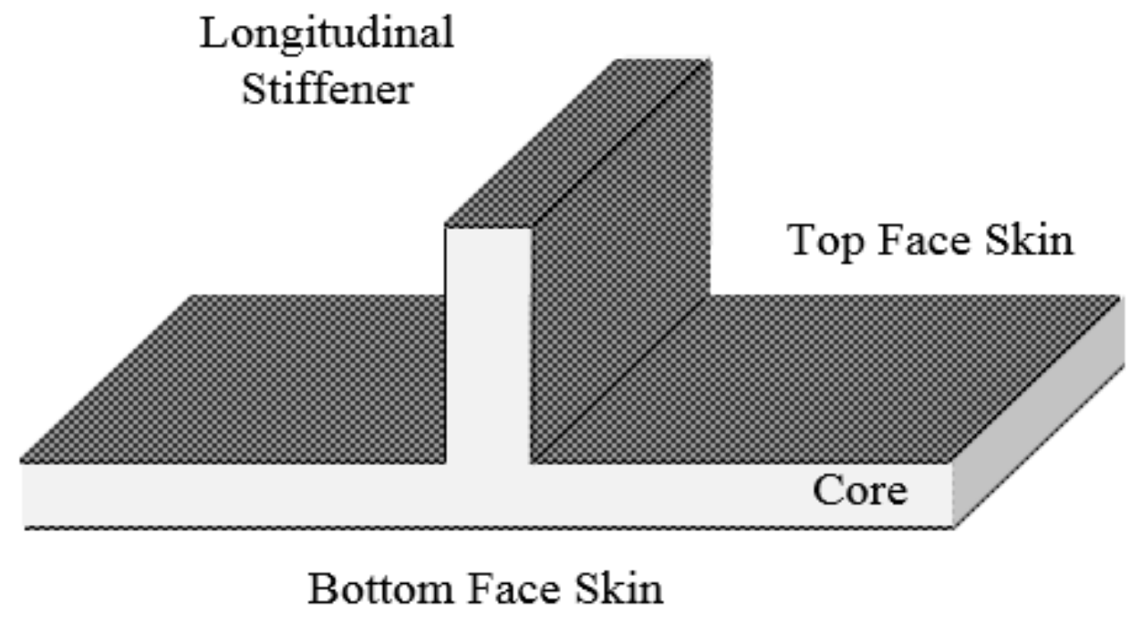

Figure 1. Detail of sandwich T-joint longitudinal stiffener.

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.

Background

The classical approach used to study the hull-water slamming problem is the two-dimensional water entry model depicted in Figure 2.

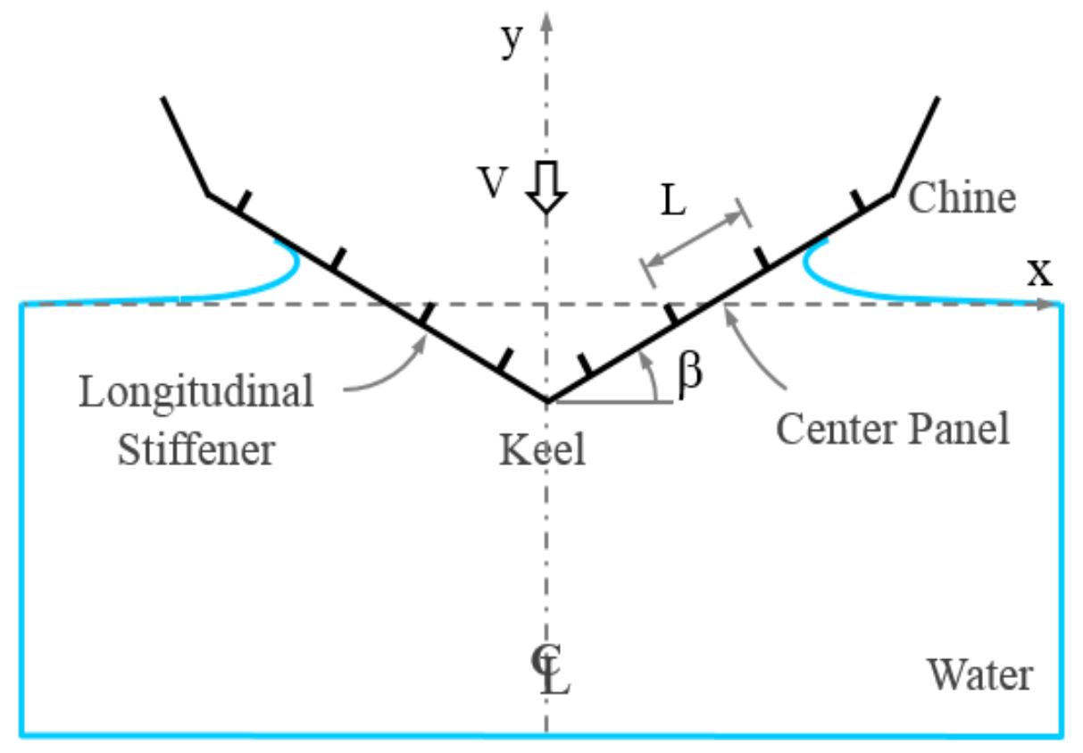

Figure 2. Schematic water slamming on ship hull.

In this model, an elastic hull structure hits an initially calm water surface with constant vertical velocity V [9]. The angle of incidence between the undeformed structure and the undisturbed water surface is referred 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.

Problem

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].

Methodology

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.

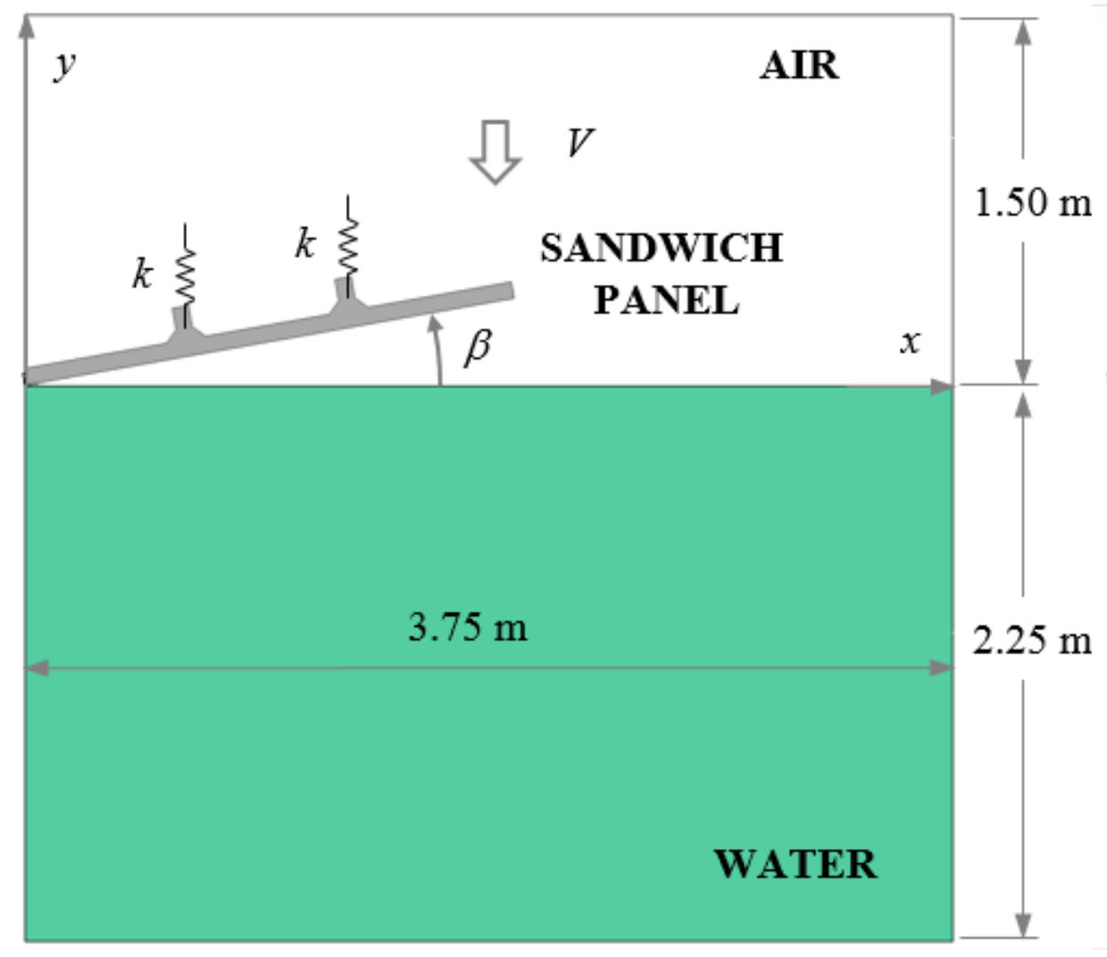

Figure 3. LS-DYNA finite element model.

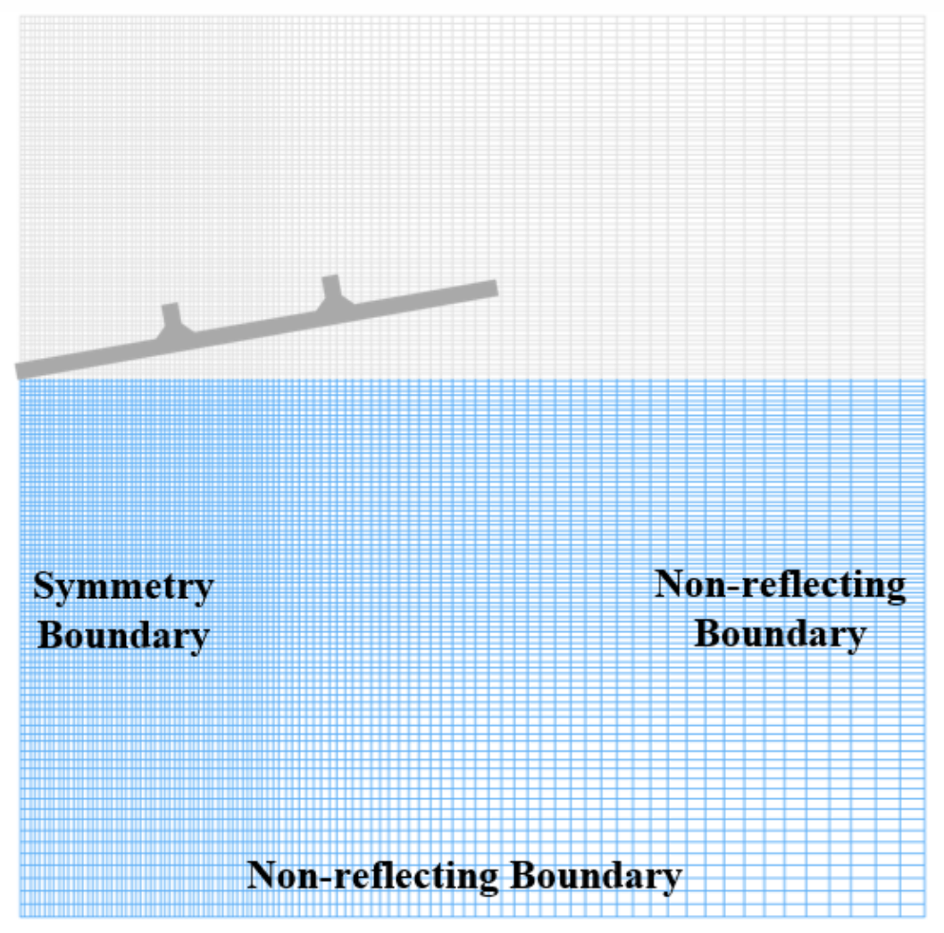

Figure 4. FE mesh and boundary conditions.

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). 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 boundary 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.

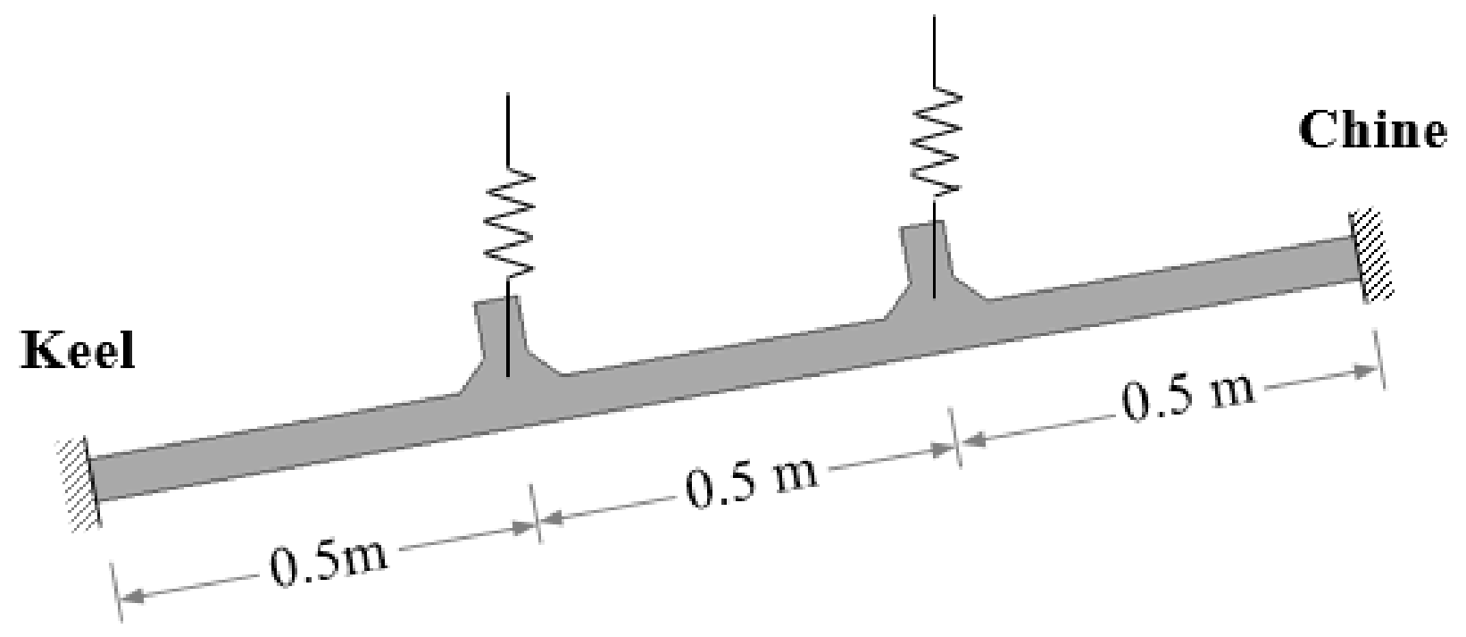

Figure 5. Boundary conditions for sandwich panels.

Results and Discussion

FE simulations were conducted for three different T-joint stiffnesses and two impact velocities. The deadrise angle was maintained constant. For each slamming condition the slamming pressure and the structural response of the center panel was studied. Slamming pressure distribution along the center panel for V = 5 m/s shown in Figure 6. It can be noticed that the effect of increasing the T-joint stiffness affect the magnitude of the pressure peak.

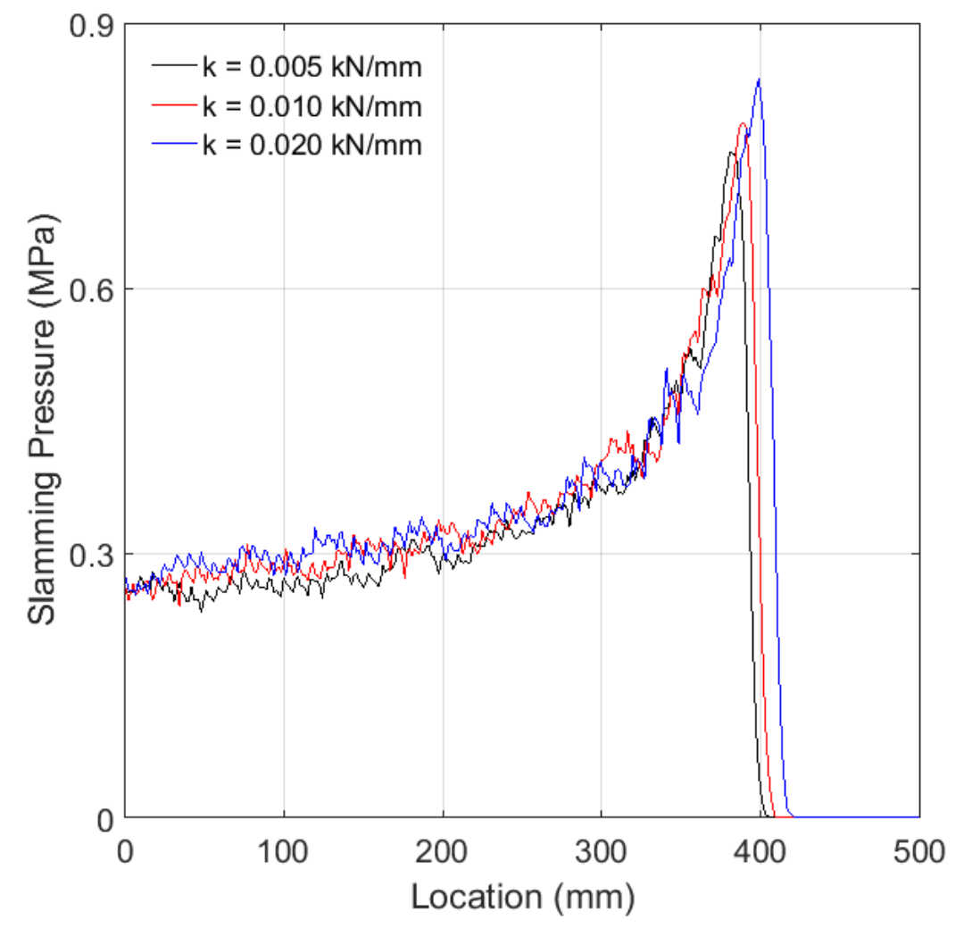

Figure 6. Pressure distribution for *V* = 5 m/s

In order to evaluate the stiffness of the T-joint supports, the vertical displacement was plotted, as shown in Figure 7. 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.

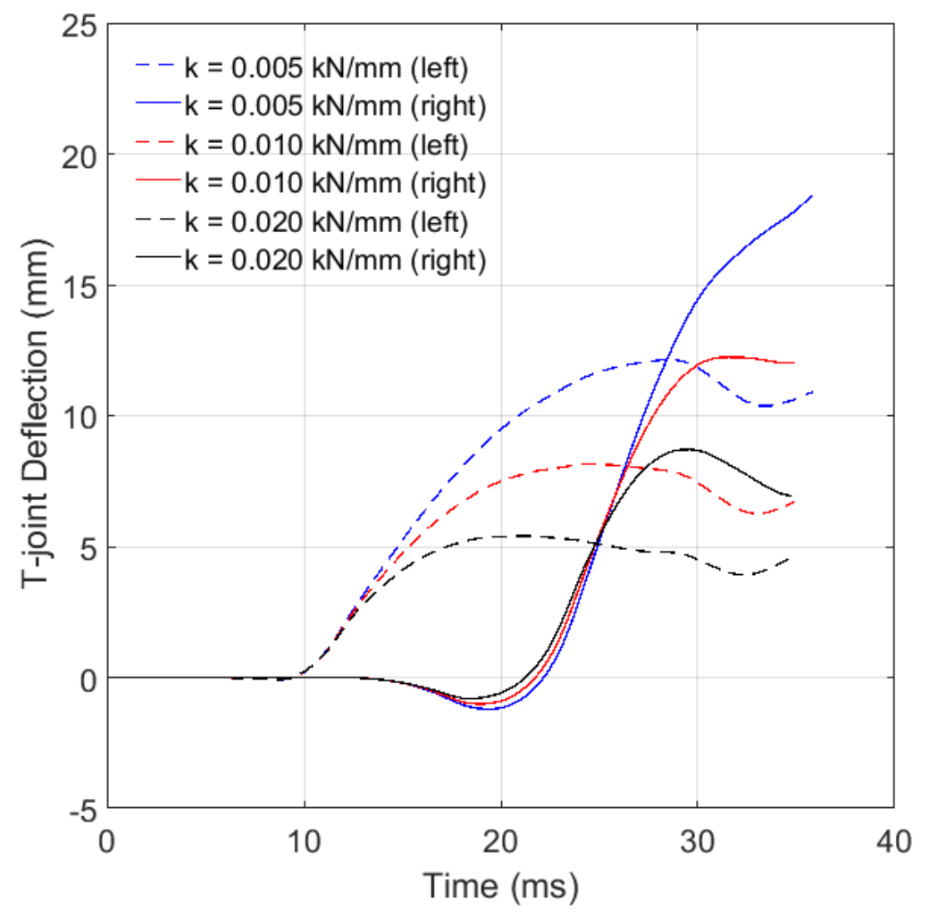

Figure 7. T-joint deflection histories for *V* = 5 m/s.

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 8). 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.

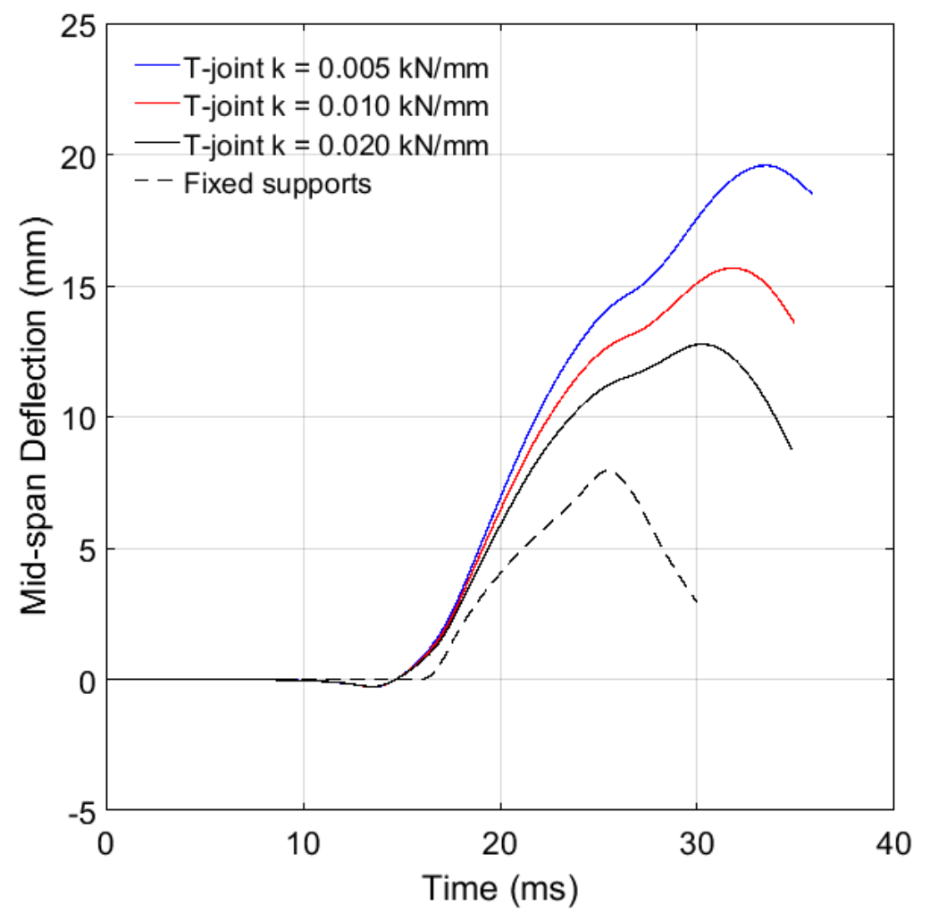

Figure 8. Mid-span deflection for *V* = 5 m/s.

The maximum transverse shear stresses occurred near the T-joint supports. Core shear stresses were plotted in Figure 9 for the left-hand T-joint and compared with the fixed-supported panel solution.

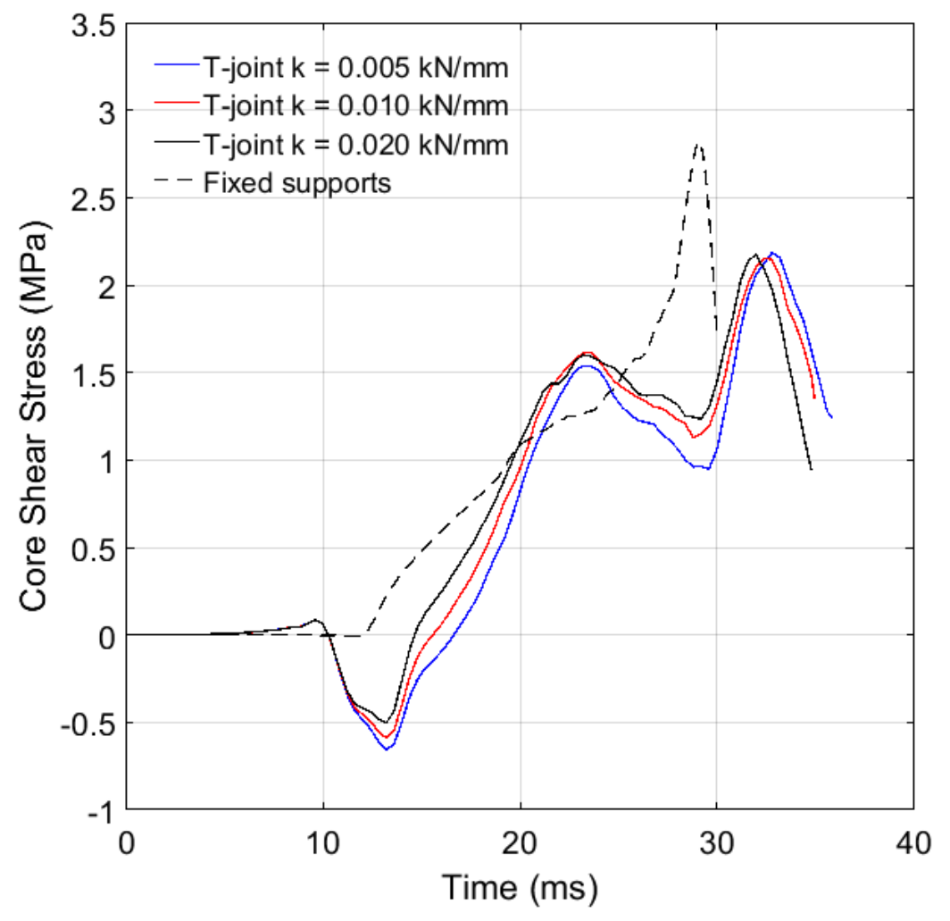

Figure 9. Core shear stress for *V* = 5 m/s (left T-joint)

Similarly, core shear stresses at the right-hand T-joint are shown in Figure 10. 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.

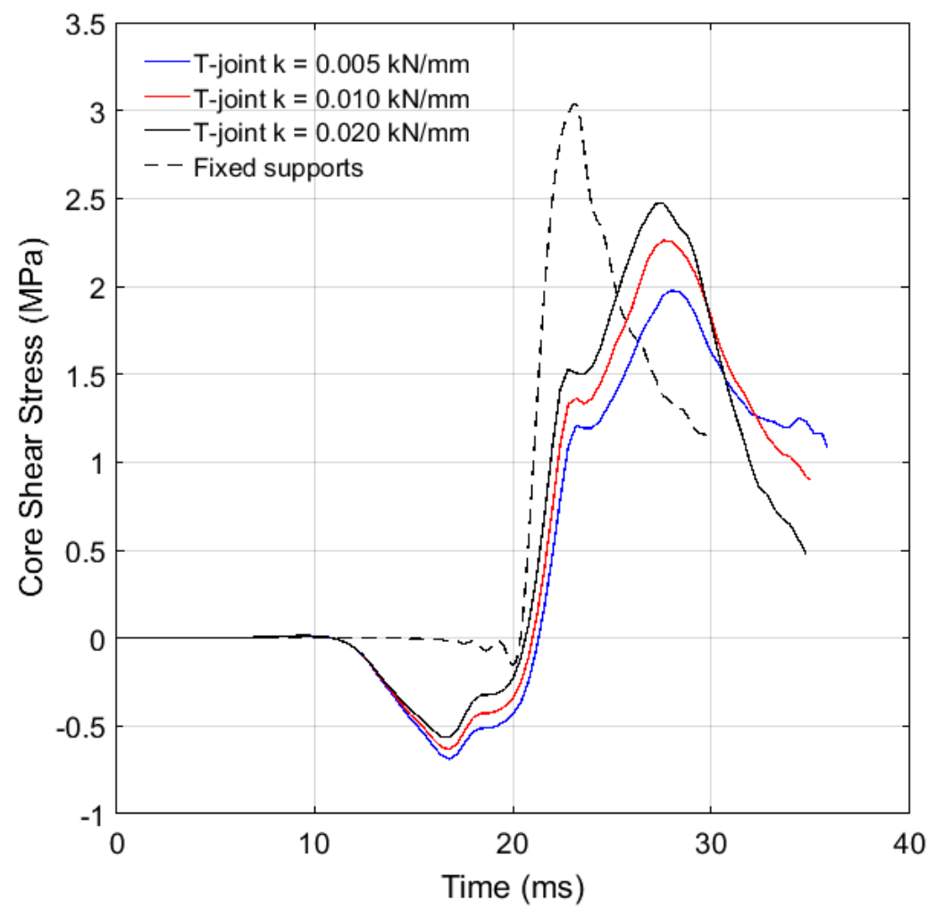

Figure 10. Core shear stress for *V* = 5 m/s (right T-joint).

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 $\beta = 10^{\circ}$, 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.

Future Work

The model was only simulated under a small range of slamming conditions. Since these simulations we're performed using the worst case conditions, this opens the door to a wide range of alternate cases that can simulated. Among these are cases where we further increase or decrease the stiffness outside of the ranges used, slower velocities and incrementing the deadrise angle

Acknowledgements

I would like to thank my mentor Andres Cecchini for all his guidance and patience during this project, as well as the Mechanical Engineering Department and the Graduate School Office at Polytechnic University of Puerto Rico for their support to this work.

References

1. Flett, J., Battley, M., Allen, T. Stress and strain fields in sandwich T-joints subjected to simulated slamming loads. 19th International Conference on Composite Materials. Montreal, Canada; 2013.
2. Zenkert, D. An introduction to sandwich construction. London: EMAS; 1997.
3. Shenoi, R. A., Clark, S. D., Allen, H. G. Fatigue behaviour of polymer composite sandwich beams. Journal of Composite Materials; 29, 18, 2423-2445; 1995.
4. Clark, S. D., Shenoi, R. A., Allen, H. G. Modelling the fatigue behaviour of sandwich beams under monotonic, 2-step and block-loading regimes. Composites Science and Technology; 59, 471-486; 1999.
5. Kulkarni, N., Mahfuz, H., Jeelani, S., Carlsson, L. A. Fatigue crack growth and life prediction of foam core sandwich composites under flexural loading. Composite Structures; 59, 499-505; 2003.
6. Sharma, N., Gibson, R. F., Ayorinde, E. O. Fatigue of foam and honeycomb core composite sandwich structures: A tutorial. Journal of Sandwich Structures and Materials; 8, 263-319; 2006.
7. Zenkert, D., Burman, B. Failure mode shifts during constant amplitude fatigue loading of GFRP/foam core sandwich beams. International Journal of Fatigue; 33, 217-222; 2011.
8. Chemami, A., Bey, K., Gilgert, J., Azari, Z. Behaviour of composite sandwich foam-laminated glass/epoxy under solicitation static and fatigue. Composites: Part B; 43, 1178-1184; 2012.
9. Wagner, H. Über stoß- und gleitvogänge an der oberfläche von flüssigkeiten. Zeitschrift für Angewandte Mathematik und Mechanik, 12, 4, 193-215; 1932.
10. Stenius, I., Rosen A., Kuttenkeuler J. Explicit FE modeling of fluid-structure interaction in hull-water impacts. International Shipbuilding Progress, 53, 103-121; 2006.
11. Stenius, I., Rosen, A., Kuttenkauler, J. Hydroelastic interaction in panel-water impacts of high-speed craft. Ocean Engineering; 38, 371-381; 2011.
12. Das, K., Batra, R. C. Local water slamming impact in sandwich composite hulls. Journal of Fluids and Structures; 27, 523-551; 2011.
13. Wang, S., Guedes Soares, C. Numerical study on the water impact of 3D bodies by an explicit finite element method. Ocean Engineering; 78, 73-88; 2014.
14. Cecchini A., Serrano D., and Just-Agosto F. A novel approach for fatigue life prediction of local hull structures subjected to slamming loads. International Shipbuilding Progress; 63, 1-2, 41-58; 2016.
15. Aquelet, N., Souli, M., Olovsson, L. Euler-Lagrange coupling with damping effects: Application to slamming problems. Computer Methods in Applied Mechanics and Engineering; 2005.
16. Battley, M. A., Lake, S. E. Dynamic performance of sandwich core materials. 16th International Conference on Composite Materials. Kyoto, Japan; 2007.
17. Clark, S. D., Shenoi, R. A., Allen, H. G. Modelling the fatigue behaviour of sandwich beams under monotonic, 2-step and block-loading regimes. Composites Science and Technology; 59, 471-486; 1999.
18. Shenoi, R. A., Clark, S. D., Allen, H. G. Fatigue behaviour of polymer composite sandwich beams. Journal of Composite Materials; 29, 18, 2423-2445; 1995.
19. Stenius, I., Rosen, A., Battley, M., Allen, T. Experimental hydroelastic characterization of slamming loaded marine panels. Ocean Engineering; 74, 1-15; 2013.
20. Breder, J. Experimental testing of slamming pressure on a rigid marine panel. Master thesis. Naval Systems KTH Aeronautical and Vehicle Enginnering, Stockholm, Sweden; 2005.
21. Rivera, J., Cecchini, A. Finite element modeling of water slamming on sandwich hull structures. Mechanical Engineering Design Project Article, Polytechnic University of Puerto Rico, 2017.