Mechanical performance evaluation of sandwich panels exposed to slamming impacts: Comparison between experimental and SPH results

Omar Hashim Hassoon, Mostapha Tarfaoui, Ahmed El Moumen, Y. Qureshi, Hamza Ben Yahia, Mourad Nachtane

Mechanical performance evaluation of sandwich panels exposed to slamming impacts: Comparison between experimental and SPH results

O. H. Hassoon [1 (a,b)], M. Tarfaoui [1 (a)], A. El Moumen [(a)], Y. Qureshi [(a)], H. Benyahia [(a)], M. Nachtane [(a,c)]

[(a)] ENSTA Bretagne, IRDL - UMR CNRS 6027, F-29200 Brest, France

[(b)] University of Technology, Bagdad, Iraq

[(c)] FSAC - UH2C, Laboratory for Renewable Energy and Dynamic Systems, Morocco

Abstract

Slamming is a dynamic phenomenon in which a high magnitude pulse peak pressure occurs in a short time duration when the bottom structure of a ship impacted against the sea surface. This phenomenon can cause damage in the structure due to fluid-structure interaction (FSI) thus, plays a vital role in designing and manufacturing of ships for naval applications. In this paper, high performance sandwich structure, having many opportunities and challenges for the marine structural design, were studied experimentally using a high-speed shock test machine to examine the water entry problem. In addition, a velocity control system was used to calibrate and preserve the approximately uniform velocity throughout the slamming impact. Sandwich panels with different thicknesses i.e. 27mm and 37mm therefore, having different stiffness's were exposed under constant impact velocities of 6 and 8 m/s at the deadrise angle 10°. Experimental results were then compared and verified by the numerical investigation based on explicit Smoothed Particle Hydrodynamics (SPH) method. This study focuses on the overall structural response, deformation, and hydrodynamic response of the structure during the dynamic impact designed for naval applications.

Keyword: Sandwich plates; Slamming Impact; Fluid-Structure Interaction; SPH; Constant impact velocity.

[1]Corresponding author. Tel: +33687917124. E-mail address: mostapha.tarfaoui@ensta-bretagne.fr / omar.hassoon@ensta-bretagne.org

1. Introduction

The slamming impact can be characterized as a longitudinal and transverse loading which occurs when the structure is severely hit by the water surface. Besides that, the vessel speed had also become an important aspect in marine design. Moreover, the structural responses were dominated by local loads rather than global loads. Therefore, examination of the hull response to static and dynamic loadings should be a prerequisite in ship design. Thus, design requirements had been optimized in relation to the structural weight. For this reason, now-a-days, vessel structures are usually manufactured using composite materials and sandwich panels.

When the structures are submerged in the water, both hydrodynamic and hydro-elastic effects are vital to consider. These effects can cause the water flow to change because of the structural elastic vibrations, and the difference in hydrodynamic pressure in the particular locations [1]. This phenomenon can change the fluid-structure interaction (FSI) and can be observed in high-speed vessels under slamming impact. This situation had been observed by other researchers, who had pointed out in their research that the loads on elastic plates differ from those experienced by rigid plates [2]. Panciroli et al. [3, 4] studied the dynamic response of deformable wedges entering the water. The experimental and numerical results showed that the structural deformation had negligible effect on the pressure build between the fluid/structure interface. The center for Advanced Composite Materials, of the University of Auckland [5, 6, 7, and 8] performed several experiments on the deformable composite panels use in high-speed marine craft to examine the hydro elastic effects on them because of the fluid-structure interaction. In addition, numerous other works had also been reported in literature in which composite structures were studied under the impacts generated with a calm water surface [3, 4, 5, 6].

The Fluid-Structure Interaction problem is an important part of estimating and analysing structures for variety of engineering applications and is considered as a great challenge for many researchers because of its nonlinear nature. The FSI is a phenomenon which happens when the structure interacts with the internal surface and the surrounding boundaries of the fluid domain. This phenomenon occurs mostly with deformable structures. Furthermore, the deformation of the structure can also modify the fluid flow, thus moderating the hydrodynamic pressure acting on these structures. The smoothed particle hydrodynamics (SPH) is an effective tool to study and manipulate the FSI phenomenon because in this approach the fluid is replaced by the particles using a Lagrangian approach without mesh. This method was firstly developed by Gingold and Monaghan [7]. The basic formulation of this method is based on the interpolation procedure of velocity, mass, force and density for each particle. Therefore, this method requires extensive computational time to solve the problem and this is considered to be the main drawback of this technique. Moreover, Oger [8] extended the SPH approach by introducing a new technique based on the particle sampling technique for the water-entry problem. These numerical results were verified by comparing them with the analytical and experimental approaches however, the results obtained by numerical simulations were very dependent on the number of practices. Veen and Gourlay [9] numerically investigated the slamming impact on the hull section using the SPH. They calculated the slamming load caused by the vertical velocity in hull cross-sections and added the strip theory to determine three-dimensional nonlinear ship motions. They also recommended not to implement the SPH method to study events that had a long duration because it requires significant computation time. Panciroli et al. [10] studied the hydro-elastic effects of deformable wedges using the SPH method by utilizing a commercial code LS-Dyna. Numerical results were in good agreement with experimental data and they also observed that the different mode shapes dominated the structural deformation when there was an increase in the hydro-elastic effects. However, the divergence from experimental behavior recorded in their numerical results was attributed to the trapped air that occurred during the impact event. Therefore, they suggested in their study to integrate this effect in the numerical model for more accuracy in results.

For high-speed crafts, the move to new materials was firstly driven by a need to obtain stronger and lighter vessels, with complex geometries and adjusting the mechanical properties of the material to the requirements of the design. This investigation is focused in reproducing the actual slamming peak loads in the sandwich panels using a choc machine. The main target is to compare improvement in impact resistance of two types of sandwich panels. Details of the experimental set-up are the same for both panels, and a comparison can be stablished for the selected testing conditions that are representatives of a particular vessel. The sandwich panels were characterized with 500x250mm in dimensions and consisted of glass/vinylester skins and PVC foam cores. The sandwich panels consisted of different thicknesses: the semi-flexible (thickness =37 mm) and the flexible (thickness =27 mm). The effect of impact velocity and structural flexibility were studied. In addition, the critical regions due to slamming impact were clarified, which could assist vessel designers in integrating this influence during structural modeling. The second part of this paper is devoted to the development of a numerical model using SPH simulation capable of reproducing the impact tests.

2. Experiment setup

2.1. Materials and properties

High performance sandwich structures were studied experimentally using a high-speed shock test machine to examine the water entry problem. In addition, a velocity control system was used to calibrate and preserve the approximately uniform velocity throughout the slamming impact.

The characteristics of machine used for experimental tests were given in our previous work concerning the characterization of unidirectional polymer composites [9, 10] and is shown in Fig. 1. The sandwich panels were characterized with 500x250mm in dimensions and consisted of polymeric skins and PVC foam cores, manufactured by EADS Composites. A fixture system made of steel 355S having a weight of 58.5 kg was used to fix these samples in the machine. Experimental characterization of these specimens under static loading has been presented in the previous works [11, 12]. The material properties are presented in Table 1. The fluid part consisted of water contained in a tank with 3m of length, 2m of width and 2m of depth.

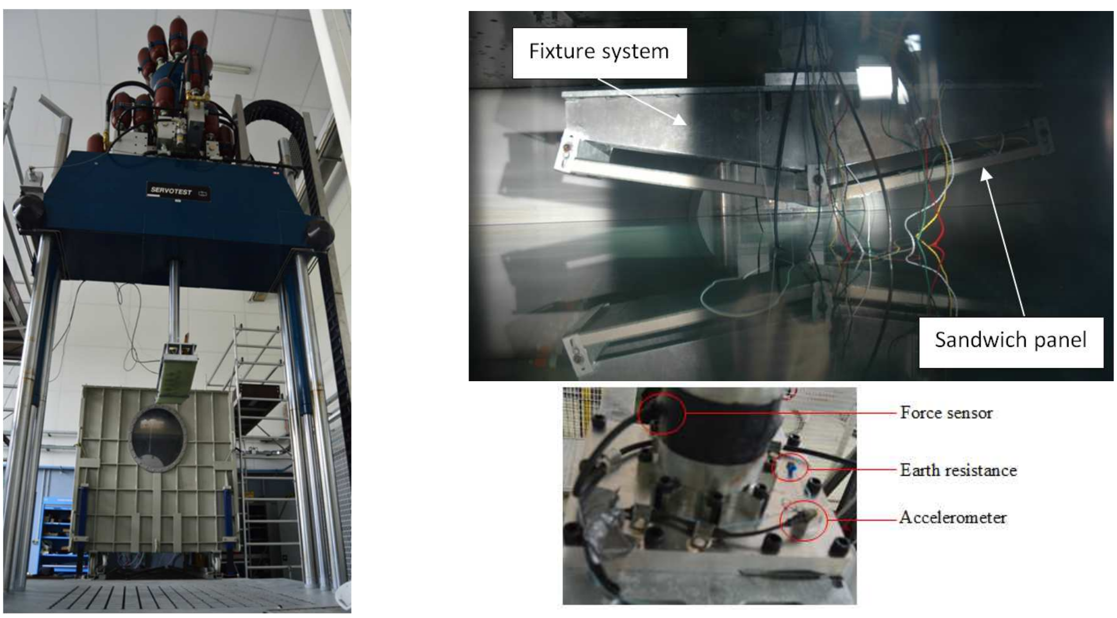


Fig. 1. Experimental setup.

2.2. Test procedure

The sandwich panels were inserted in the machine by fixing the two ends (keel and chine) using clamps and the other two edges were free, as shown in Fig. 2. In this investigation, all specimens were studied at a deadrise angle of 10° because it had been reported previously by Faltinsen that hydro elasticity effects had greater influence on impacted wedges for the deadrise angles (5° to 30°) [3]. The strain gauges (SG) were installed at various locations along the span of the panel to accurately record the natural frequency of each mode shapes.

	Density (kg/m^3)	**t (mm)**	**Elastic moduli (GPa)**			**Poisson's ratios (-)**			**Shear moduli (GPa)**		
			E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
Skin	*1960*	t_f=7	48.16	11.21	11.21	0.274	0.274	0.096	4.42	4.42	9
Core	80	t_c 20 *and* 30	0.077	0.077	0.110	0.3	0.3	0.3	0.029	0.029	0.029

Table 1. Sandwich panel mechanical properties

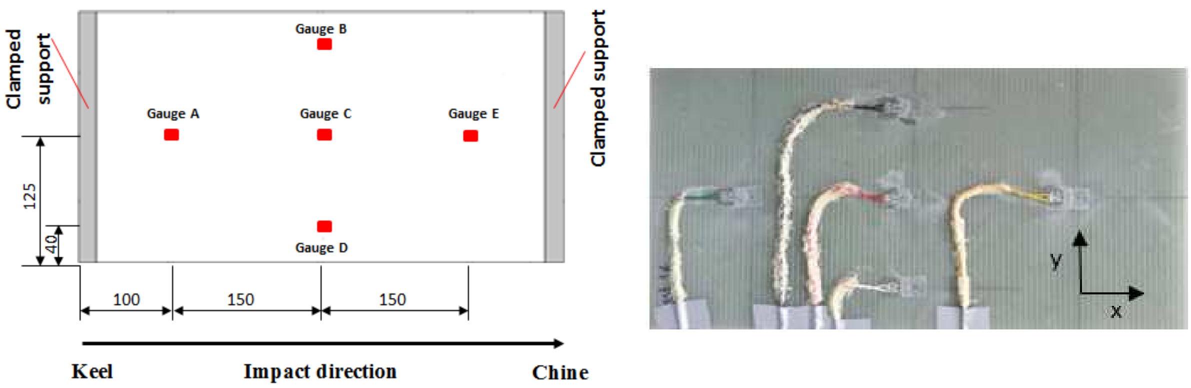
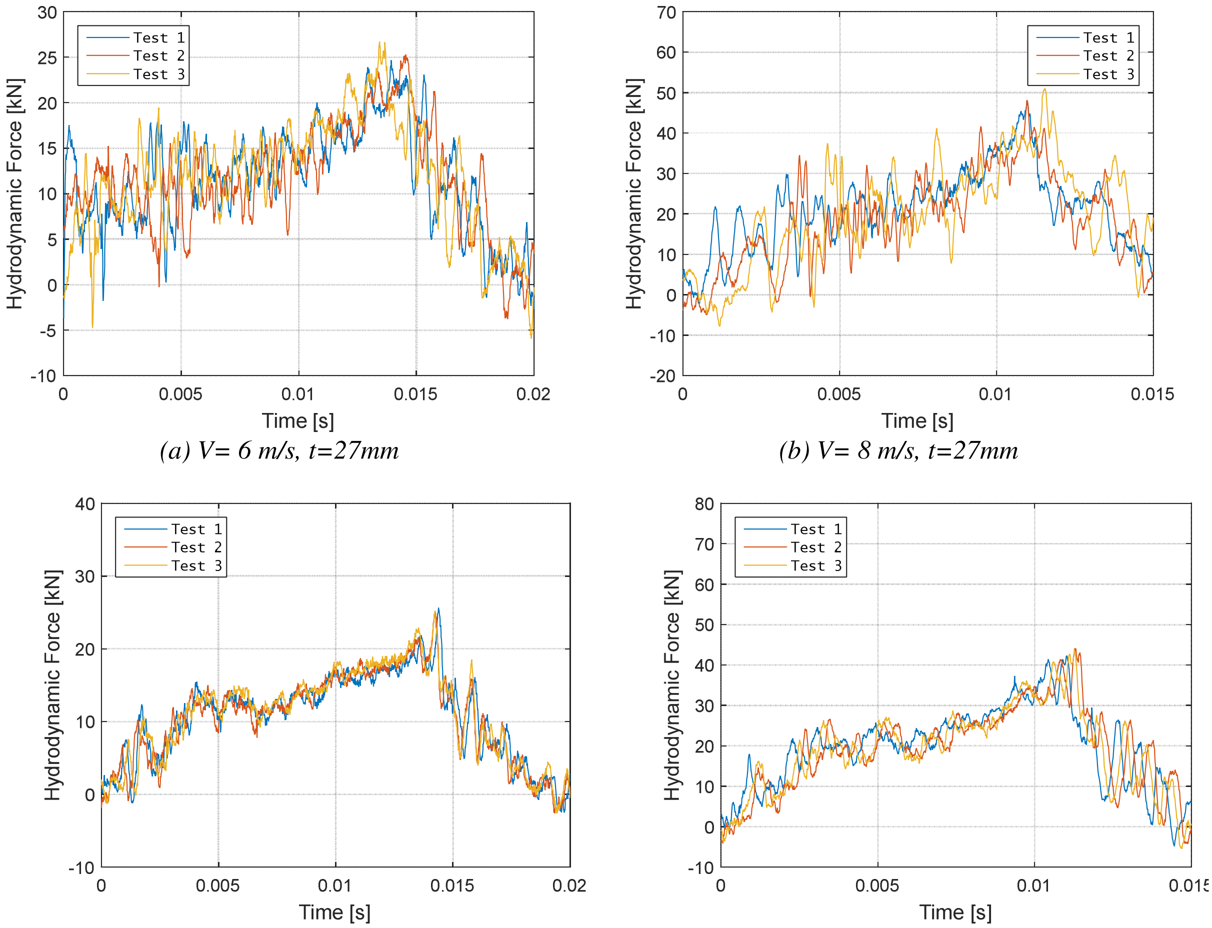


Fig. 2. Boundary conditions, panel dimensions and strain gauge location.

2.3. Experimental results

The impact force was measured by using force sensor that mounted on the machine piston as shown in Fig. 1. Due to the location of this sensor, the force did not represent the real hydrodynamic force of impacted panels, as some inertial force of the fixture system and panels led to some variation in the total hydrodynamic force. For this reason, an accelerometer (model EGAS-FS-250/V12/L8M/X) was used to measure the acceleration. Therefore, the hydrodynamic force was determined by subtracting the inertial load from the total experimental load to take the inertial load effect of the fixture system and composite from impact force. For each panel, impact velocities 6 and 8m/s was considered.

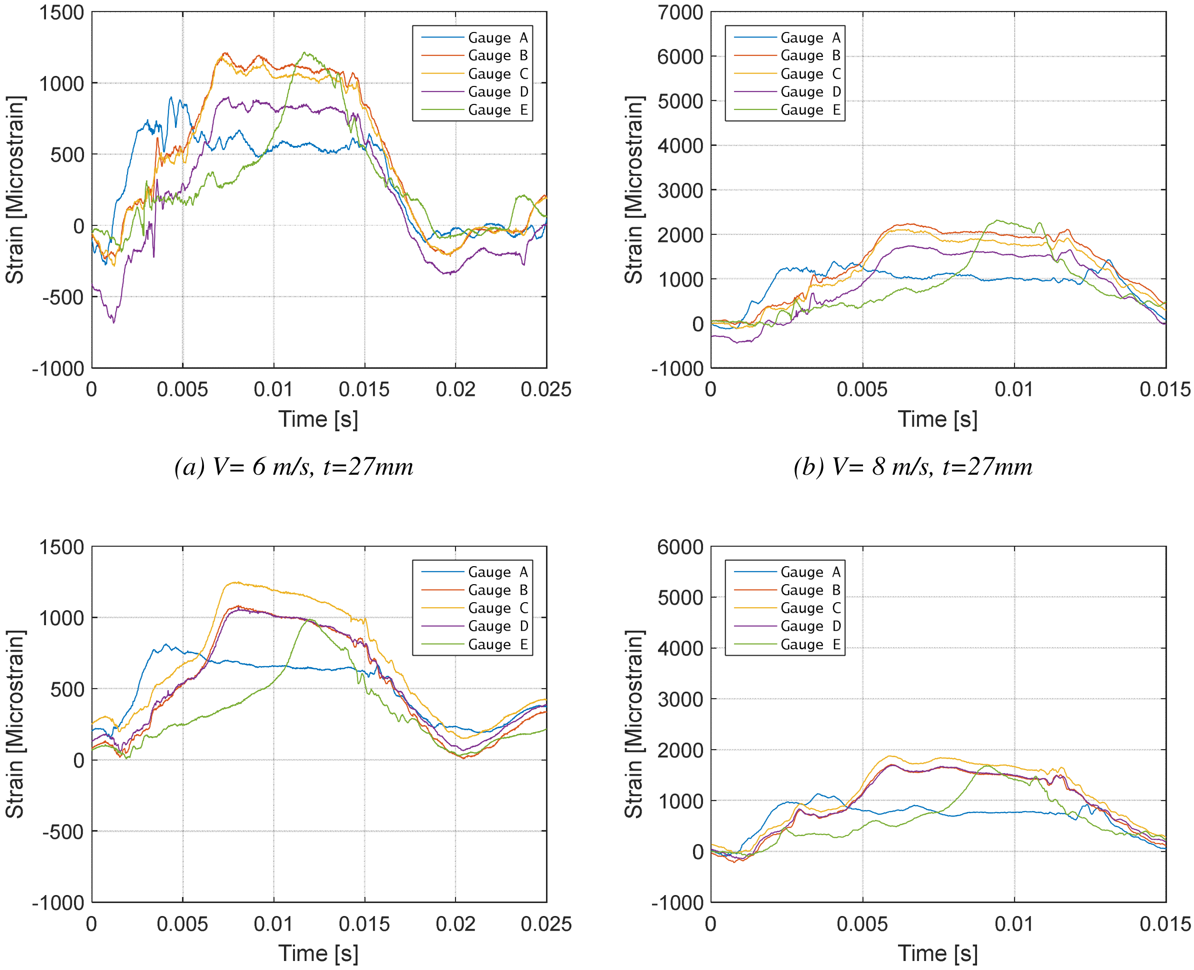


(a) V= 6 m/s, t=27mm *(b) V= 8 m/s, t=27mm*

(c) V= 6m/s, t=37mm *(d) V= 8m/s, t=37mm*

Fig. 3. Repeatability of tests on PVC sandwich for different impact velocities and different thickness.

A series of three experimental tests were performed for each sandwich panel under various impact velocities to characterize their response including the hydrodynamic force and the panel deformation. The repeatability of the results was confirmed by testing at least three panels for each impact velocity, Fig. 3. This figure shows the variation of hydrodynamic force during the impact time, for each sandwich panel at impact velocities of 6 and 8m/s. It can be noted that the elasticity of sandwich panels had a significant influence on the dynamic noise and the peak force. It was also observed that the change in the local deadrise angle and the panel deflection along the FSI was because of the dynamic noise. The maximal force of 50 kN was observed in the case of flexible sandwich panel with higher elasticity i.e. with 27 mm thickness while 40 kN force was recorded for the case of panels with 37mm thickness. The sandwich panels withstand greater deformation as the impact velocity was increased, as shown in Fig. 4. However, it should be noted that both types of sandwich panels had similar deformation behavior for each impact velocity.

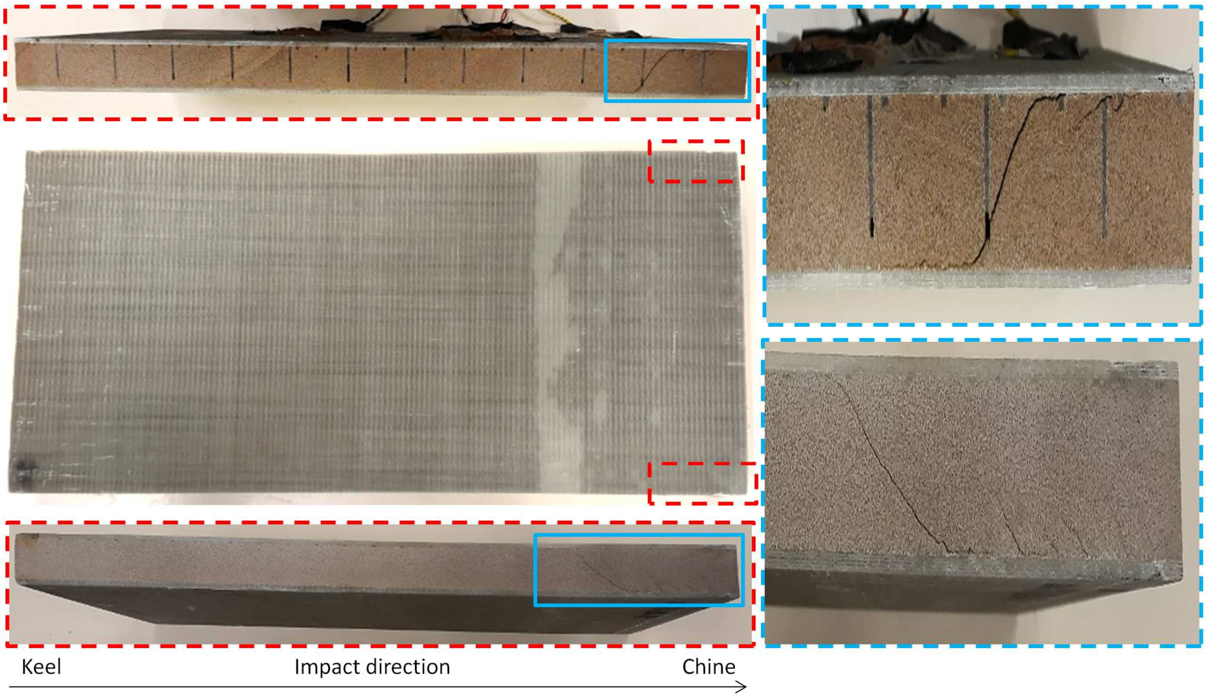


(a) V= 6 m/s, t=27mm *(b) V= 8 m/s, t=27mm*

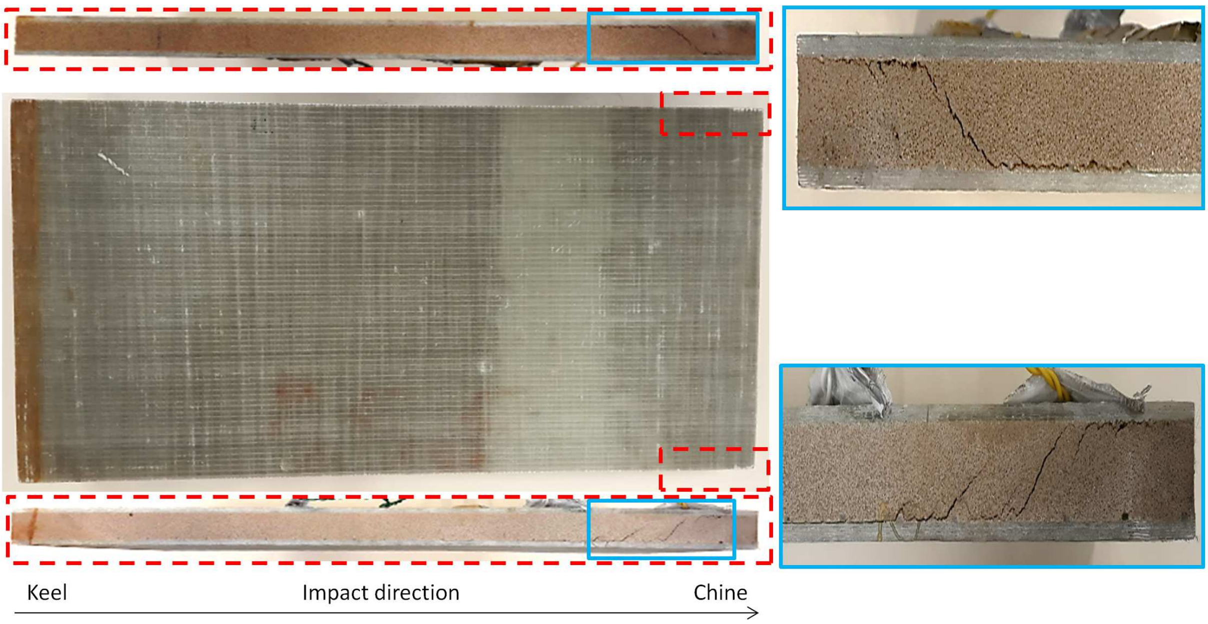
(c) V= 6 m/s, t=37mm *(d) V= 8 m/s, t=37mm*

Fig. 4. Measurement of the deformation of the two sandwich plates.

Fig. 5 shows post-impact images of damaged (a) flexible and (b) semi-flexible sandwich panels. The failure modes are illustrated in different configurations including separation on the interface between the skin and the core and propagation of cracks in the core due to the shearing force. The initiation of cracks through the core usually occurs firstly. Therefore, this promotes the skin/core debonding to initiate and propagate; the failure always occurs at weakest regions. A large deformation of the structure exposes the core to a compressive shear stress and a high bending tensile shear stress above and below the neutral plane. Thus, the crack cannot be easily propagated vertically through the thickness. For this reason, the crack propagates with an oblique angle due to a large difference between the skin and core shear stresses. On the other hand, the shear stress in the core is higher compared to the normal stresses. Therefore, failure in the core due to shear stress occurs.



(a) Semi-flexible panel (thickness=37mm), V=8m/s



(b) Flexible panel (thickness=27mm), V=8m/s

Fig. 5. Damage modes in sandwich panel.

3. Numerical investigation

3.1. SPH formulation

The Smoothed Particle Hydrodynamic (SPH) method was used to simulate the slamming event and the meshed elements of the fluid domain were replaced by particles.

The SPH method was based on the interpolation of the points [13]. It means that these points could be described by differential equations without any mesh. The Lagrangian derivative $\frac{d\rho}{dt}$ and $\frac{d\vec{v}}{dt}$ for each point (particle) of the fluid was determined relative to the time integration. In addition, the quantities $\rho\vec{\nabla}.\vec{v}$ and $\frac{\vec{\nabla} P}{\rho}$ were also determined for each point, thus the spatial derivatives were determined using the Kernel function between the point and the domain surrounding the other points. Then each point had discrete quantities of ρ, P and $\vec{v}$.

The integral interpolation for any function f(r) can be defined as [8]:

$$f(r) = \int f(\vec{x})\ W(\vec{r} - \vec{x}, h) d\vec{x} \tag{1}$$

The gradient of any function can be written in the form:

$$\vec{\nabla} f(r) = \int \vec{\nabla} f(\vec{x})\ W(\vec{r} - \vec{x}) d\vec{x} \tag{2}$$

Where W is the Kernel function, h is the smooth length.

For the slamming event with free surface flow, the classical Navier-Stokes equations need to be solved. Assuming the fluid was non-viscous, and the shear stresses were neglected, then Euler equations can be presented as follows [8]:

$$\frac{d\vec{v}}{dt} = \vec{g} - \frac{\vec{\nabla} P}{\rho} \tag{3}$$

$$\frac{d\rho}{dt} = -\rho\vec{\nabla}.\vec{v} \tag{4}$$

Where $\vec{g}$, ρ, P and $\vec{v}$ are the body forces, density of the fluid, pressure and velocity of the fluid respectively.

With interpolation of the points through the domain D, the particle can be introduced:

$$\int f(\vec{x})dx = \sum_i f_i w_i \tag{5}$$

Where i represents each interpolation point with the domain D, w_i weight term and has the dimension of a volume.

Using the Lagrangian derivative and Euler equations, the formulation of the momentum equations can be written [8]:

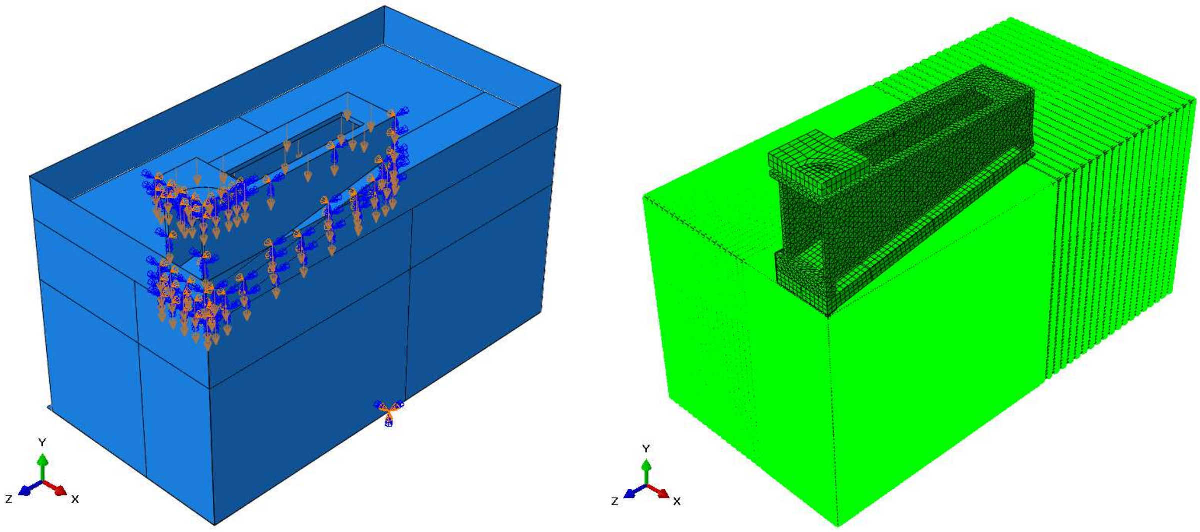
$$\frac{d\vec{v}}{dt} = \vec{g} - \sum_j m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2}\right) \vec{\nabla} W(\vec{x_i} - \vec{x_j}, h) \tag{6}$$

$$\frac{d\rho_i}{dt} = \sum_j m_j (\vec{v_i} - \vec{v_j}) \vec{\nabla} W(\vec{x_i} - \vec{x_j}, h) \tag{7}$$

The numerical results for sandwich panels subjected to the slamming impact were obtained by implementing the above define smoothed particle hydrodynamics (SPH) approach in the commercial code ABAQUS/Explicit.

3.2. Model creating and meshing

The slamming model was constructed similar to the experimental setup in three-dimension scheme based on the Smoothed Particles Hydrodynamic (SPH) using commercial software (Abaqus/Explicit). The full slamming model was decreased to a 3D quarter model to minimize the computational time, Fig. 6a. About 543388 particles were generated for fluid domain, and it should be kept in mind that the particles had to be intensive and uniform in all directions to ensure fewer densities toward the extremes, Fig. 6b. The sandwich panel consisted of 2918 elements with the element type SC8R linear quadrilateral elements.

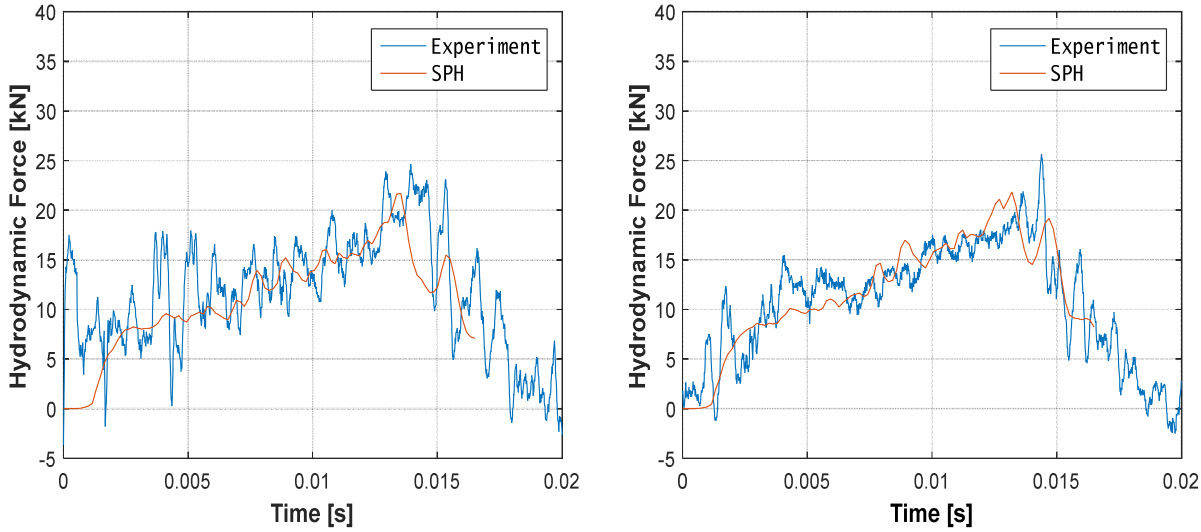


(a) Boundary conditions *(b) SPH fluid particles and FE mesh of structure*

Fig. 6. Numerical slamming model.

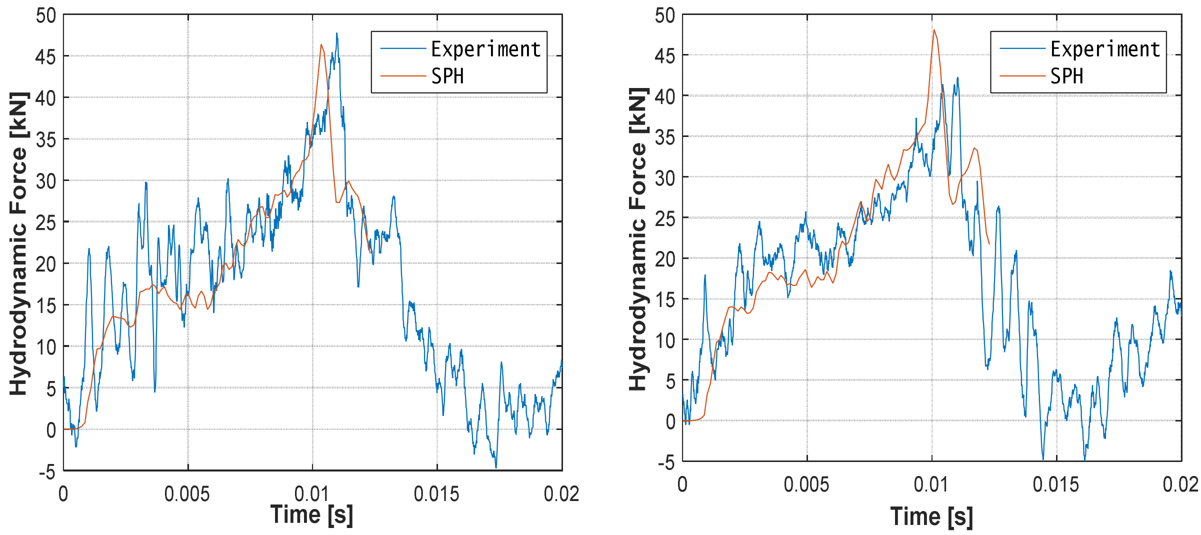
3.3. Comparison: experimental tests vs numerical results

Comparison of experimental and numerical results for the incompressible fluid is presented in Fig. 7 and Fig. 8. The results presented a good correlation in estimating the maximum force and its mode shape. A small difference in the peak force was observed which could be because of the slight variation in impact speed during experiment, which is not really constant through experimental impact duration comparing with numerical model that defined with a constant velocity, Fig. 9. The acceleration phase before the initial water/structure contact is not also taken into account. Indeed, the acceleration phase can be defined in the numerical model. However, the computational time has increased significantly. It is difficult to control all the factors during the experimental procedure unlike numerical simulations in which the impact speed was constant throughout the test.



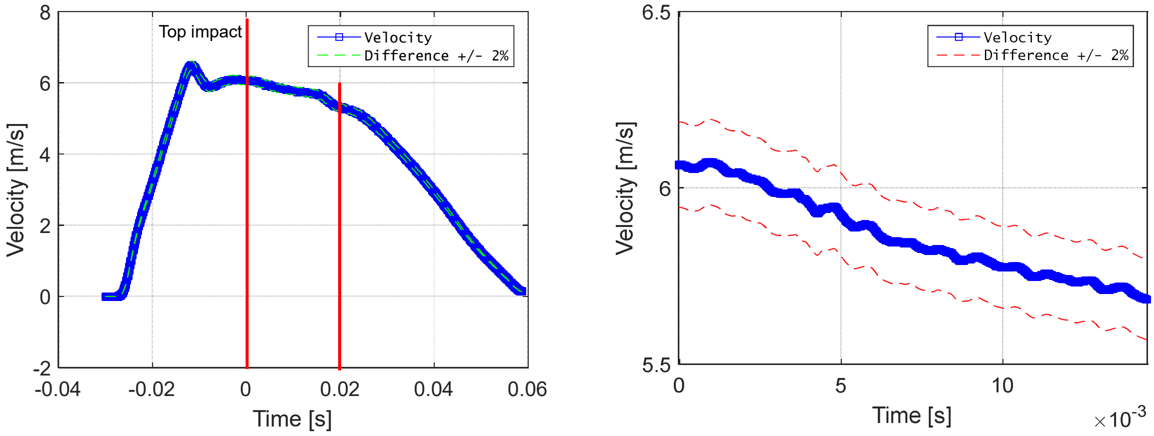
(a) Sandwich thickness 27mm *(b) Sandwich thickness 37mm*

Fig. 7. Comparison between the experimental and numerical results, impact velocity 6 m/s.



(a) Sandwich thickness 27mm *(b) Sandwich thickness 37mm*

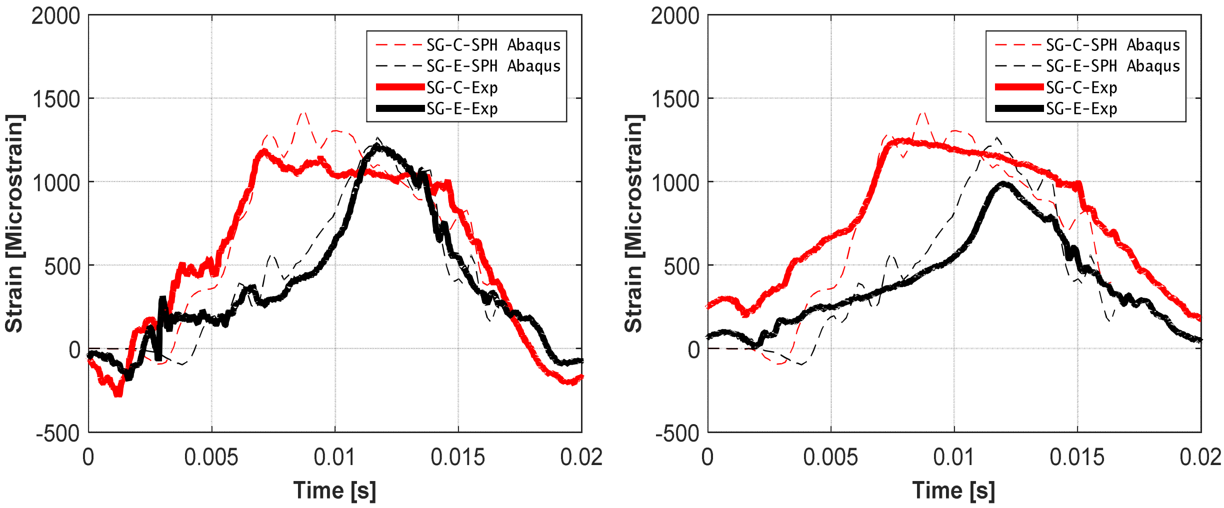
Fig. 8. Comparison between the experimental and numerical results, impact velocity 8 m/s.



(a) Velocity profile *(b) Zoom of interested velocity*

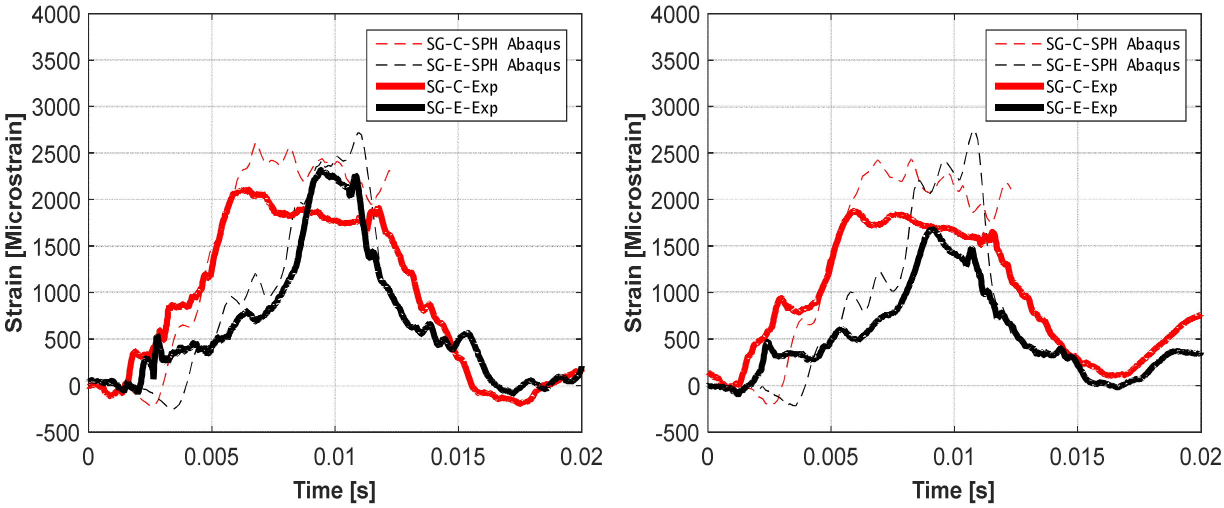
Fig. 9. Experimental velocity variation, V=6 m/s.

The longitudinal strain results measured at gauges C and E during the experimental test and the predicted numerical simulations for both velocities 6 and 8m/s are presented in Fig. 10 and Fig. 11. It should be kept in mind that it is important to define the acceleration phase in the numerical simulation to have the good agreement between the experimental and numerical results. In addition, boundary conditions defined in the experimental test played a vital role in the numerical model. The snapshots for the simulation are presented in Fig. 12 and Fig.13.



(a) Sandwich thickness 27mm *(b) Sandwich thickness 37mm*

Fig. 10. Compare of longitudinal strain between experimental and numerical results, V= 6 m/s.



(a) Sandwich thickness 27mm

(b) Sandwich thickness 37mm

Fig. 11. Compare of longitudinal strain between experimental and numerical results, V=8 m/s.

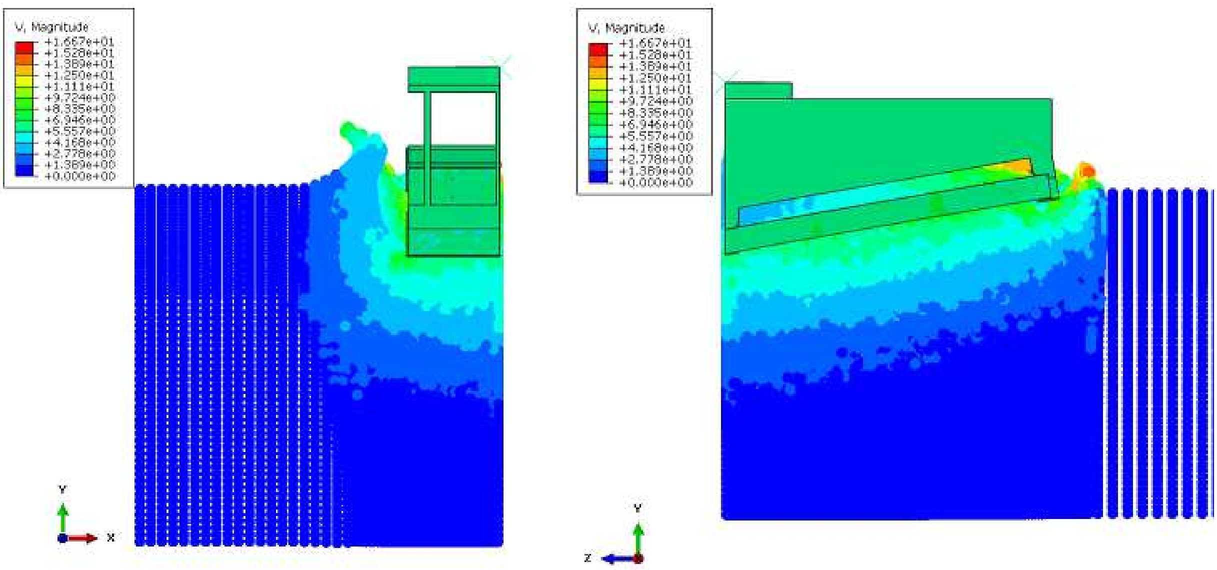


Fig. 12. Snapshots of SPH simulation - Sandwich t=37mm, V=6 m/s.

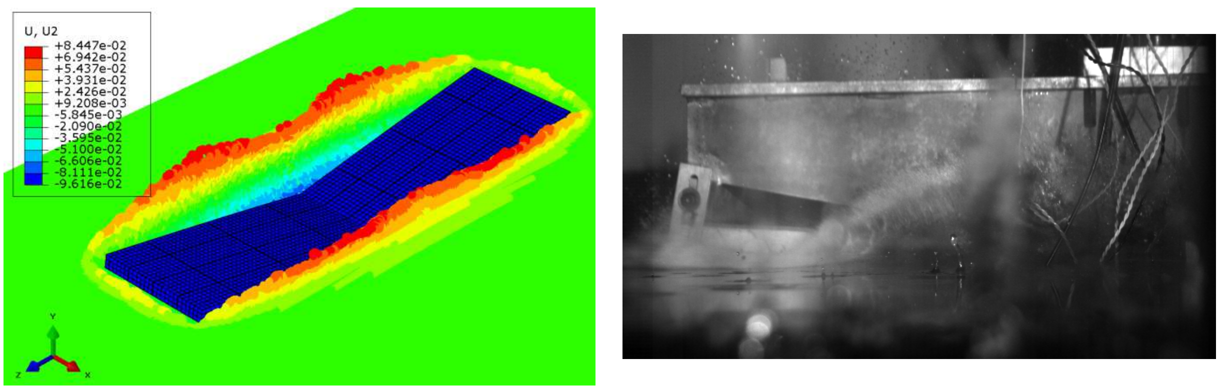


Fig. 13. Snapshot of impacted zone by sandwich panels and formation of the water jet.

4. Conclusions

For high-speed crafts, the move to new materials was firstly driven by a need to obtain stronger and lighter vessels, with complex geometries and adjusting the mechanical properties of the material to the requirements of the design. In this study, the main objectives were to study experimentally and numerically the response of deformable sandwich structures subjected to high speed dynamic phenomenon known as slamming. Slamming plays a vital role in determining the dynamic response of the structure for maritime applications. Experimental investigation was conducted on high performance and deformable sandwich panels using a high speed shock test machine. A finite element model was developed using SPH approach to study the slamming phenomenon and FSI of sandwich panels in detail and to validate the experimental study. Following conclusions were drawn:

- Experimental tests were performed for panels with different rigidities under various impact velocities in order to characterize the sandwich response including the hydrodynamic force and the panel deformation.
- The repeatability of the results was performed by testing at least three panels for each impact velocity, which showed great repeatability for all experiments.
- The flexibility of sandwich panels has a significant influence on the dynamic noise and the peak force.
- The change in the local deadrise angle and the panel deflection along the water structure interface was due to the dynamic noise.
- The maximal force was observed in the case of flexible sandwich; a value of 50 kN for panels with 27mm of thickness and 40 kN for the case of panels with 37mm was observed.
- It should be noted that both types of sandwich panels have similar deformations for an impact velocity of 6 and 8 m/s however, each panel withstand greater deformation response as the impact velocity was increased.
- The comparison of numerical and experimental results showed that the present numerical model based on SPH technique found to be successfully capable of predicting the slamming event and the structural response.
- It can also be used to simulate other forms of complex structures and large-scale vessel structures to estimate both global and local effects of the slamming phenomenon.
- The main drawback of SPH based numerical technique was the requirement of expensive computational time to solve the problem.

References

[1] M. Reinhard , A. Korobikin, M. Cooker , "Water entry of a flat elastic plate at high horizontal speed," *J. fluid mech,* vol. 724, pp. 123-153, 2013.

[2] O. M. Faltinsen, J. Kvålsvold, J. Aarsnes, "Wave impact on a horizontal elastic plate," *Journal of Marine Science and Technology,* vol. 2, pp. 87-100, 1997.

[3] O.H. Hassoon, M. Tarfaoui, El Malki Alaoui, "An experimental investigation on dynamic response of composite panels subjected to hydroelastic impact loading at constant velocities," *Engineering Structures,* vol. 153, pp. 180-190, 2017.

[4] O.H. Hassoon, M. Tarfaoui, El Malki Alaoui, A. El Moumen, "Experimental and numerical investigation on the dynamic response of sandwich composite panels under hydrodynamic slamming loads," *Composite Structures,* vol. 178, pp. 297-307, 2017.

[5] O.H. Hassoon, M. Tarfaouii, A. El Moumen, H. Benyahia ,M. Nachtane , "Numerical Evaluation of Dynamic Response for Flexible Composite Structures under Slamming Impact for Naval Applications," *Applied Composite Materials,* pp. 1-18, 2017.

[6] O.H. Hassoon, M. Tarfaouii, El Malki Alaoui, A. El Moumen, "Mechanical behavior of composite structures subjected to constant slamming impact velocity:An experimental and numerical investigation," *International Journal of Mechanical Sciences,* vol. 144, pp. 618-627, 2018.

[7] R.A. Gingold, J. J. Monaghan, "Smoothed particle hydrodynamics : theory and application to non-spherica lstars," *Mon.Not.R.Astron.Soc,* vol. 181, pp. 375-389, 1977.

[8] G. Oger, M. Doring, B. Alessandrini, P. Ferrant, "Two-dimensional SPH simulations of wedge water entries," *Journal of Computational Physics,* vol. 213, pp. 803-822, 2006.

[9] D. Veen,T. Gourlay, "A combined strip theory and Smoothed Particle Hydrodynamics approach for estimating slamming loads on a ship in head seas," *Ocean Engineering,* vol. 43, pp. 64-71, 2012.

[10] R. Pancirolia, S. Abrate, G. Minak, A. Zucchelli, "Hydroelasticity in water-entry problems: Comparison between experimental and SPH results," *Composite Structures,* vol. 49, pp. 532-539, 2012.

[11] Owaisur Rahman Shah, M. Tarfaoui, "Effect of adhesive thickness on the Mode I and II strain energy release rates. Comparative study between different approaches for the calculation of Mode I & II SERR's," *Composites Part B: Engineering,* vol. 96, pp. 354-363, 1 July 2016.

[12] I. M. Daniel, "Influence of core properties on the failure of composite sandwich beams," *Journal of mechanics of materials and structures,* vol. 4, no. 7-8, pp. 1271-1286, 2009.

[13] J. Monaghan, "Smoothed particle hydrodynamics," *Annu. Rev. Astron. Astrophys,* vol. 30, pp. 543-574, 1992.

[14] R. Panciroli, "Hydrodelactic impact of deformable wedges," in *Dynamic Failure of Composite and Sandwich Structrure*, New York, London, Springger Science, Business Media Dordrecht, 2013, pp. 1-45.

[15] R. Panciroli, S. Abrate, G. Minak, "Dynamic Responce of Flexible Wedges Entering the Water," *Composite Structures,* vol. 99, pp. 163-171, 2013.

[16] I. Stenius, A.Rose, J. Kuttenkeuler, "Hydroelastic interaction in panel-water impacts of high-speed craft," *Ocean Engineering,* vol. 38, pp. 371- 381, 2011.

[17] T. Allen, "Mechanics of Flexible Composite Hull Panels Subjected to Water Impacts," thesis, 2013.

[18] T. Allen, M. Battley, "Quantification of hydroelasticity in water impacts of flexible composite hull panels," *Ocean Engineering,* vol. 100, pp. 117-125, 2015.

[19] M. Battley, T. Allen, "Servo-hydraulic system for controlled velocity water impact of marine sandwich panels," *Experimental Mechanics,* vol. 52, pp. 95-106, 2012.