IOP Conference Series: Materials Science and Engineering

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To cite this article: Saeed Hosseinzadeh *et al* 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1288** 012017

A Numerical Sensitivity Analysis of Fluid-Structure Interaction Simulations on Slamming Loads and Responses

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Abstract. This paper presents a parametric study on the Multi Material Arbitrary Lagrangian–Eulerian (MMALE) method for hydroelastic analysis of a non-prismatic stiffened aluminium wedge. An explicit finite element formulation with a penalty-based coupling technique is employed to evaluate the impact-induced loads and responses during free-fall water entry. Based on the penalty factor, damping factor, and number of coupling points, a sensitivity analysis is carried out. It is shown that the penalty coupling method can generate high-frequency oscillations due to the nature of the phenomenon that may affect the predicted results of slamming loads. The computed results on the stiffened and unstiffened plates of the wedge are compared with published experimental data in terms of vertical acceleration, pressure distributions, and strain responses at different locations. A reasonable agreement can be found between the numerical results and the measured values. It is found that a combination of penalty and damping can improve the simulation results and reduce numerical instabilities in hydroelastic slamming simulations.

1. Introduction

Ship slamming is a critical phenomenon that needs to be accurately calculated during ship design. As part of the concept and detailed design process, ship designers need to assess the conditions that lead to slamming and how the structure responds to such events. Numerical simulations have become a powerful tool for predicting and understanding slamming loads, as well as for designing the structure. Simulation-based methods can accurately capture the hydrodynamic and structural interaction between the ship hull and the water surface [1-4]. Moreover, they can provide insight into the physics of the problem and enable designers to identify the areas of the ship that are subjected to the slamming phenomenon. In order to obtain reliable numerical solutions, the physical behaviour of slamming needs to be accurately modelled. This includes the pressure, acceleration and hydrodynamic loads that occur during slamming events. It is also important to consider the hydrodynamic behaviour of the ship in order to properly analyze the structural response. Despite the fact that numerical models are useful tools for predicting impact-induced loads, the simulation results are highly dependent on the solvers used and the setup implemented. Therefore, it is important to conduct a thorough sensitivity analysis to ensure that the results are reliable.

The Arbitrary Lagrangian-Eulerian (ALE) method is commonly used to simulate fluid-structure interaction problems, such as slamming loads on marine structures. Souli et al. [5] presented the ALE formulation for fluid–structure interaction problems. Aquelet et al. [6] developed a coupling algorithm to predict local high pressure loads on a rigid structure using the ALE approach. They pointed out that the penalty coupling algorithm can produce high frequency oscillations due to the nearly incompressible nature of the fluid and the strong coupling between the fluid and the structure [6]. The influence of hydroelastic effects during the water entry impact of an elastic panel was studied by Stenius et al. [7] using an explicit finite element method. They concluded that at high impact velocities, insufficient penalty contact can result in large non-physical penetrations, disrupting the flow field and causing leakage in the Lagrangian structure. An analysis of the penalty factor, mesh density, and contact stiffness on a two-dimensional rigid wedge was conducted by Luo et al. [8]. Souli and Benson [9] highlighted the capability of penalty coupling algorithms by simulating a 2D wedge with 10 deadrise angle and demonstrated that the local peak pressure is sensitive to the penalty factor. Cheon et al. [10] used the ALE algorithm to simulate the water entry problem of a deformable flat stiffened panel. They examined the effects of mesh sensitivity, structural flexibility, and penalty factors on the results. The effect of damping factors on the impact loads was not considered in their study [10]. A study of the numerical uncertainty caused by discretization for the ALE method in predicting impact-induced loads on rigid and elastic flat plates was conducted by Wang et al. [11]. In spite of the extensive research on slamming loads on rigid and elastic structures based on ALE method, there are few papers that study the effect of numerical instabilities on the results of ALE coupling algorithm. The lack of research into numerical instabilities could lead to inaccurate results, and therefore, it is important for further research to be done to ensure the accuracy of the results. Additionally, the study of numerical instabilities could provide insight into how to optimize the ALE coupling algorithm for greater efficiency.

This study presents a numerical sensitivity analysis of impact-induced loads and responses using a multi-material ALE solver in LS-DYNA that allows modelling materials with different densities and viscosities in the same simulation. A two-way coupling technique is applied to model the relative displacement between the fluid and the structure. In order to minimize the high frequency oscillations that occur due to the nature of the water entry problems, a penalty coupling method is used to enforce the boundary conditions at the fluid-structure interface. Both penalty and damping factors are applied in the present numerical simulation. As tuning appropriate contact factors requires an intensive process of trial and error, the numerical results are presented in a way that illustrates how each parameter affects the simulation. The results of vertical acceleration, impact pressure, and strain responses are compared with experimental data.

2. Numerical Setup

The aluminium wedge with non-prismatic characteristics is numerically modelled using an explicit finite element scheme under free-fall impact. To analyze the effect of structural rigidity on the impact induced loads and responses, the bottom of the wedge was designed with two different plates (stiffened and unstiffened) with varying deadrise angles from 20 to 30 degrees. The total mass of the wedge is 55 kg. The details about the material properties and dimensions of the wedge, properties of the longitudinal and transverse stiffeners, and sensors arrangement can be found in Hosseinzadeh et al. [12].

This numerical simulation models the wedge section using the Lagrangian method with shell elements. The material types called Elastic and Rigid are used to define the material of the wedge section and top frame, respectively. The fluid domain including water and air is modelled based on ALE multi-material formulation with solid elements. The penalty-based method is used to model the interaction between the fluid and the structure, allowing for an accurate FSI simulation of the wedge section. This method transports history variables in the direction of the flow, which makes it delicate to prevent leakage through the FSI interface, especially for high pressure flows to the structure [13]. Additionally, a number of integration points must be defined through the shell thickness, and five integration points were selected based on previous work [14]. The Lobatto integration method is adopted as it does not require interpolation for stress and strain values on the top and bottom surfaces of the shell element [15]. The modified advection method is used which employs a looser constrained for the advection process. This method can better preserve the material interface for ALE materials [16]. A summary of the numerical model, mesh study, and domain and elements sizes can be found in Hosseinzadeh et al. [14].

The numerical model setup for simulating the water entry problem of the 3D wedge is shown in Figure 1(a). The mesh regions of the numerical model with water (blue) and air (green) are illustrated in Figure 1(b). A fine mesh is required in the impacts area to minimize numerical issues and achieve accurate results, while coarse meshes are used in areas far from the areas of interest to reduce computational time. Figure 1(c) depicts the stiffened and unstiffened bottom plates, along with the locations of the strain and pressure sensors.

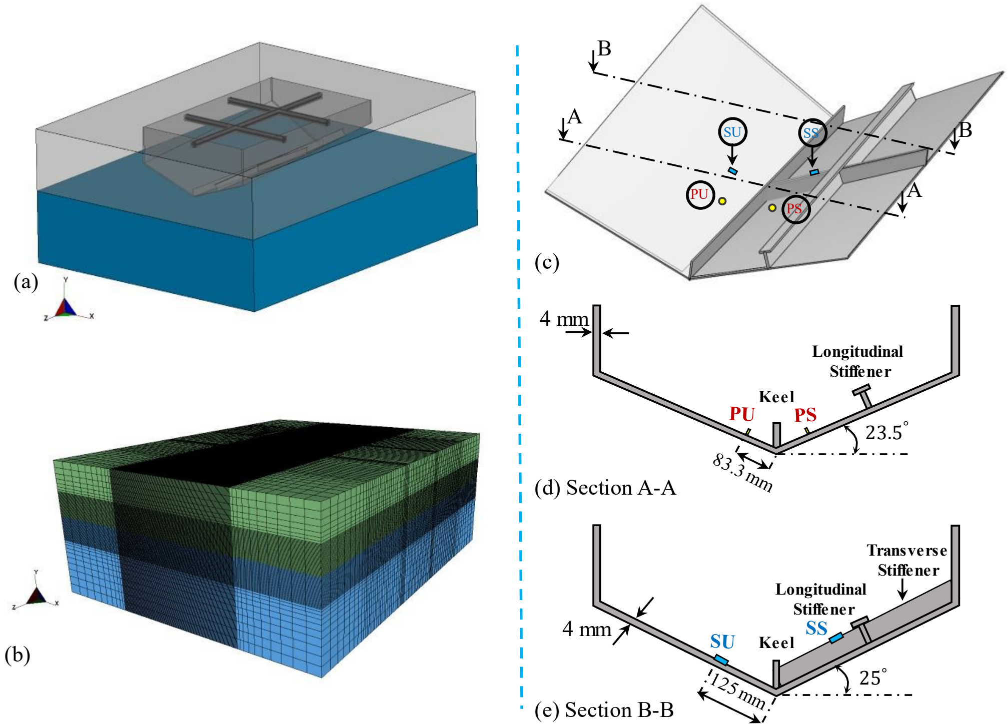


Figure 1. Finite Element setup in LS-DYNA; (a) numerical domain including water and air, (b) mesh regions of fluid domain, (c) bottom stiffened and unstiffened plates and sensor arrangement, (d) location of pressure sensors on section A-A with 23.5º deadrise angle, (e) location of strain gauges on section B-B with 25º deadrise angle.

The pressure sensors are located on 23.5-degree deadrise angle and denoted as PU and PS for unstiffened and stiffened bottom plates, respectively (Figure 1d). In addition, the strain gauges are placed on the 25-degree deadrise angle and indicated as SU and SS for unstiffened and stiffened bottom plates, respectively (Figure 1e). One of the major challenges in modelling fluid-structure interactions with the ALE approach is calibrating the coupling algorithm. The proper coupling parameters are usually determined through a trial-and-error process. Therefore, the effects of the penalty factor and the damping coefficient on the numerical results are fully investigated. Table 1 presents the number of simulations conducted in this study. In order to determine the effect of PFAC (penalty factor) and DAMP (damping factor) on the numerical results, a total of 30 runs were conducted.

Table 1. Number of simulations with different PFAC and DAMP factors

Run No.	PFAC	DAMP				
1-5	0	0	0.05	0.1	0.5	1
5-10	0.004	0	0.05	0.1	0.5	1
10-15	0.02	0	0.05	0.1	0.5	1
15-20	0.1	0	0.05	0.1	0.5	1
20-25	0.5	0	0.05	0.1	0.5	1
25-30	1	0	0.05	0.1	0.5	1

3. Results and Discussion

The effects of Euler-Lagrange coupling parameters are fully examined in this study, including vertical acceleration, total force, pressure, and strain. The numerical results are compared with experimental data [12] both for stiffened and unstiffened plates. An initial impact velocity of 4.00 m/s is applied to all simulations. The numerical simulations with different values of PFAC and DAMP are carried out. The parameter PFAC refers to the penalty factor ($0 < p_f < 1$), a scale factor used for scaling the estimated stiffness of the interacting fluid-structure system. On the other hand, DAMP is referring to the damping factor (ξ) which can be between 0 and 1. This parameter is used to scale down the critical-damping force and a value of 1 is used for a critically damped case [16].

Figure 2 illustrates the numerical results with different values of PFAC and DAMP. It is apparent that a higher value of DAMP reduces the noise in the rigid body acceleration time history. Moreover, in the case of highest damping factor (PFAC = 0.5 and DAMP = 1), there is an error in the finite element calculation which is due to the numerical instability in the simulation. The influence of the damping factor on the rigid body acceleration noise is less at higher values of the penalty factor. That is; with PFAC = 0, there is a notable difference in the maximum acceleration when comparing the cases of DAMP = 0 and DAMP = 1. However, with PFAC = 0.5, the difference is not as much. Therefore, with respect to rigid body acceleration, it can be concluded that the damping factor is more crucial at lower values of PFAC (see Figure 2). The influence of these two parameters is observed on the noise of vertical acceleration but not on its magnitude. In addition, the effects of PFAC and DAMP on the total force acting on the wedge section are illustrated in Figure 3. Unlike the rigid body acceleration, PFAC has a direct influence on the rigid body force. With no damping, the peak force in the case of PFAC = 0 is around 10.5 kN, whereas in the case of PFAC = 0.02 the force is around 9.5 kN. Interestingly, with PFAC = 0.5, the force is around 11.0 kN. As for the damping factor, increasing it has no significant influence on the peak force. The results also demonstrate that a high penalty factor, coupled with a low damping factor (PFAC = 0.5 and DAMP = 0) leads to high frequency oscillations on vertical forces. Generally, it is shown that the maximum vertical force and curve shape do not vary significantly when different coupling configurations are used, except when numerical instabilities are present.

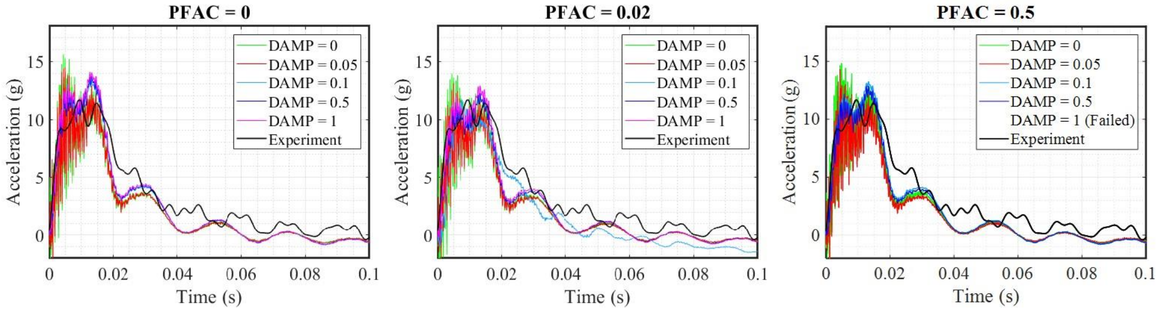


Figure 2. Time histories of vertical acceleration at 25-degree deadrise angle with different PFAC and DAMP factors compared with experimental data.

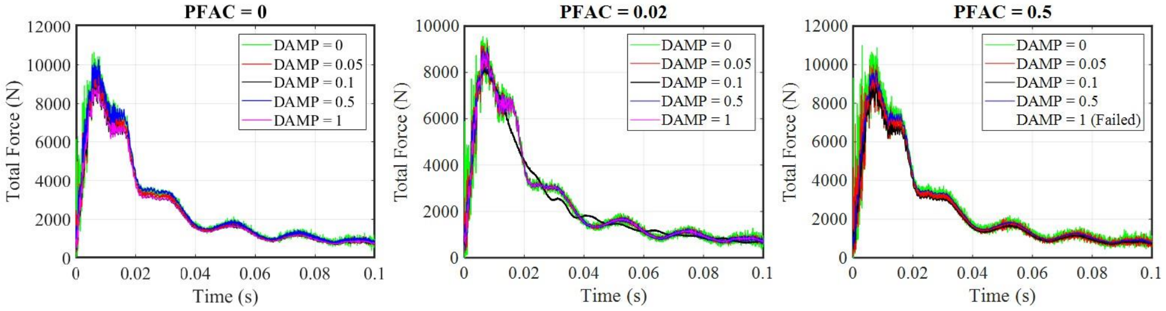
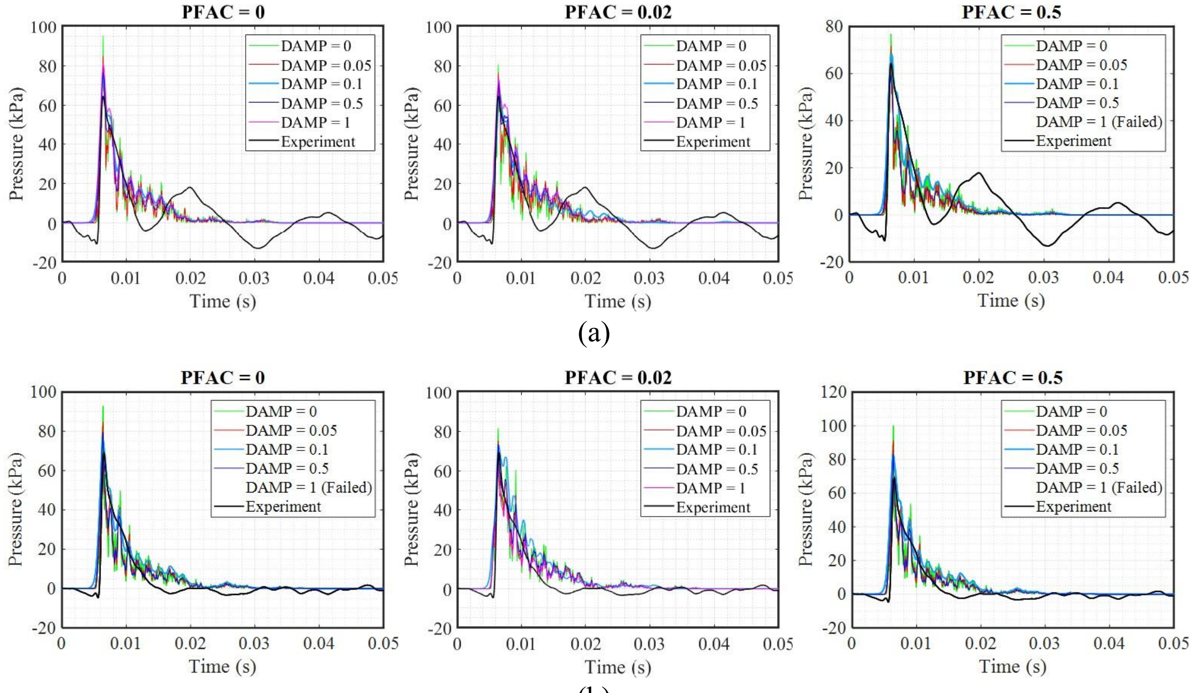


Figure 3. Time histories of computed total force with different penalty and coupling factors.

Figure 4(a) displays the average pressure histories on the unstiffened panel (PU). It is observed that increasing the penalty factor from 0 to 0.5 decreases the average peak pressure from 95 kPa to 79 kPa, in the case of DAMP = 0. Likewise, increasing the damping factor decreases the average peak pressure. For PFAC = 0, the average peak pressures are 95 kPa and 76 kPa for DAMP equal 0 and 1, respectively. The average pressure histories on the stiffened panel (PS) are displayed in Figure 4(b). It is apparent that the influence of PFAC is significant on maximum value of pressure. In comparison to the experimental data, PFAC = 0.02 shows the lowest difference in peak pressure, whereas PFAC = 0 and 0.5 yield higher values. In addition to the peak pressure values, high-frequency fluctuations decrease with increasing damping factor. However, due to the non-physical behavior of the coupling algorithm at high damping factors, the simulation with PFAC = 0.5 and DAMP = 1 crashed (see Figure 4).

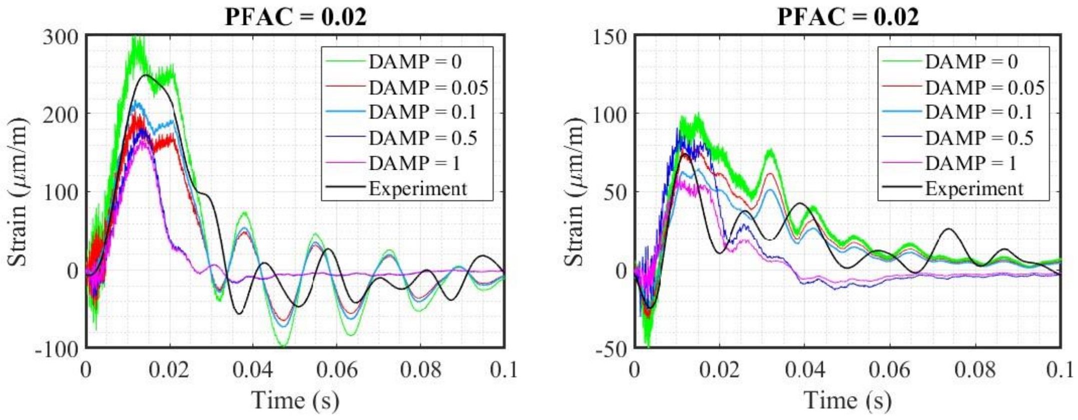
The strain responses of the sensors located on the unstiffened (SU) and stiffened (SS) plates with 25-degree deadrise angle are depicted in Figure 5(a) and (b), respectively. Unlike the vertical acceleration, the maximum strain is sensitive to the damping factor. With no damping in the fluid-structure coupling, the numerically calculated strain is larger than the experimental one for the unstiffened panel (SU). On the other hand, DAMP = 0.1 gives the best results for the stiffened plate and larger values will give more conservative results. It is shown that coupling parameters have a more significant effect on the strain response of the unstiffened plate (Figure 5a). This is because the strain sensor of the stiffened plate is located on the stiffener and do not have direct interaction with the water. It is important to note that the behaviour of the coupling system can change by using an excessively high factor that damps out the actual physical oscillations, which leads to inaccurate results.



(a)

(b)

Figure 4. Time histories of pressure results at 23.5-degree deadrise angle with different penalty and damping factors compared with experimental data on: (a) unstiffened plate (PU) (b) stiffened plate (PS).



(a) (b)

Figure 5. Time histories of strain responses at 25-degree deadrise angle with PFAC = 0.02 and different coupling factor compared with experimental result on: (a) unstiffened plate (SU) (b) stiffened plate (SS).

The obtained results are explained by how the penalty-based method of coupling algorithm works. The coupling algorithm searches for any overlaps or penetration between the structure segments and the fluid mesh. As soon as an interaction is detected, the algorithm applies a coupling force on the penetrating segments pushing them backwards and thus removing the penetration [9]. This force is expressed as follows:

$$F = kd = \left(p_f \frac{KA^2}{V}\right) d \tag{1}$$

where d is the penetration and k is the spring stiffness which depends on p_f is the penalty factor, K is the bulk modulus, A is the average area of the structure element, and V is the volume of the fluid element [16]. With higher values of the penalty factor, the contact stiffness is higher, and penetrations are minimized or eliminated. However, the virtual spring-mass system of the contact becomes of unstable and oscillates more violently. With the introduction of damping, the coupling force becomes:

$$F = kd + C\dot{d} = kd + \left(\xi\sqrt{kM}\right)\dot{d} \tag{2}$$

where ξ is the damping factor and M is the equivalent mass [16]. With higher values of the damping factor, the spring-mass system is more stable. It is important to note that the damping coefficient C depends on the mass as well, which is calculated based on the element size. Models with smaller element size and smaller material stiffness require larger values of damping coefficient.

In order to further analyse the role of coupling parameters in slamming simulations, the maximum values of acceleration, pressure, and strain are compared with the experimental data using the equation $\Delta(\square)_{max} = ((\square)_{\max\_MMALE} - (\square)_{\max\_EFD})/\ (\square)_{\max\_EFD})) \times 100$. Figure 6 summarizes the influence of penalty and damping factors on the maximum acceleration. With PFAC = 0.02, the maximum acceleration is acceptable regardless of the value of DAMP. This reveals that penalty factor is more crucial compared to the damping factor for acceleration results ($\Delta A_{max} = 3.1\%$). The most accurate numerical result is obtained when PFAC = 0.02 and DAMP = 0.1. It is worth noticing that these values are not true for all cases of fluid-structure interactions, as they depend on many parameters such as stiffness and thickness of the structure, properties of the fluid material, impact velocity, and the relative element size of the structure with respect to the fluid. However, it can be considered as a benchmark for tuning the most suitable values for coupling parameters in the slamming analysis of aluminium structures. Therefore, it is important to take into account the particularities of the study case in order to correctly setup the numerical model and obtain reliable results. These values can also be used to improve the accuracy of numerical simulations for similar types of problems.

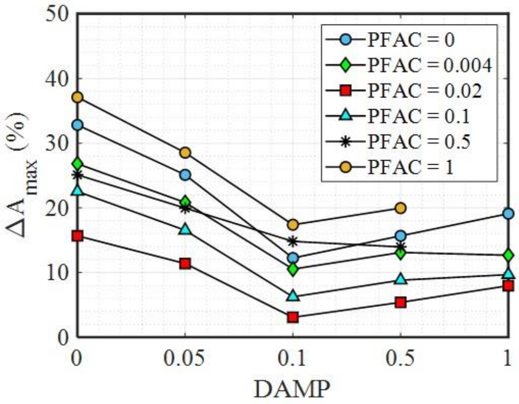
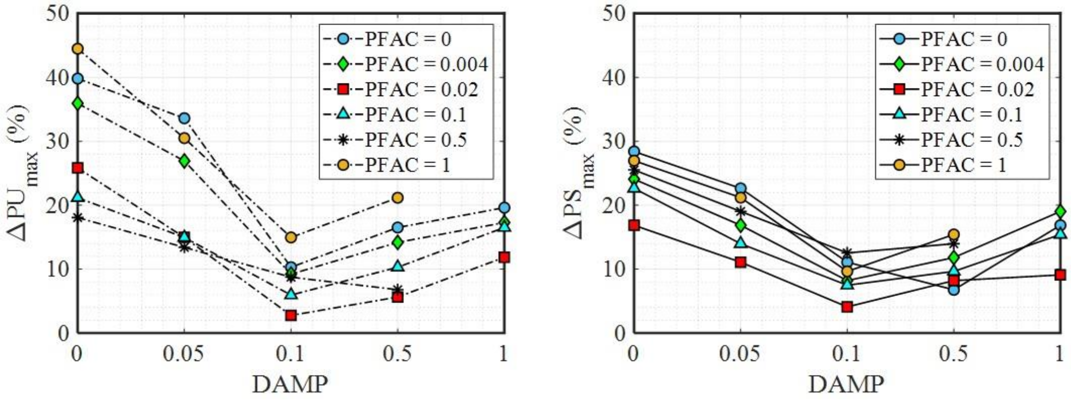


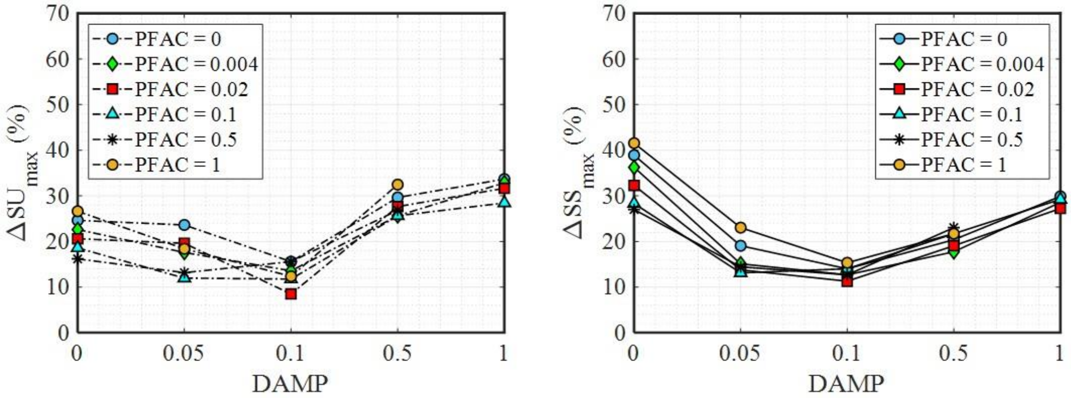
Figure 6. Difference of maximum acceleration using different penalty factor (PFAC) and damping factor (DAMP).

Figure 7 and Figure 8 illustrate the influence of penalty and damping factors on the difference of peak pressure and maximum strain, respectively. The same pattern as in Figure 6 can be observed. Penalty factor of 0.02 and damping factor of 0.1 yields the best numerical results. Higher or lower values in one or both of these factors increase the difference in the maximum pressure and maximum strain responses. Again, it is important that these two values do not hold true for all cases, and they vary from one application to another. It is found that the combination of a low penalty and damping factors leads to inaccurate results. As the penalty factor increases, the high-frequency oscillations increase. In addition, a high damping factor can cause unstable coupling.



(a) (b)

Figure 7. Difference of peak pressure using different penalty factor (PFAC) and damping factor (DAMP) on (a) unstiffened plate (b) stiffened plate.



(a) (b)

Figure 8. Difference of maximum strain using different penalty factor (PFAC) and damping factor (DAMP) on: (a) unstiffened plate (b) stiffened plate.

4. Conclusions

This paper studied hydroelastic slamming on a non-prismatic aluminium wedge section. A numerical model using an explicit finite element formulation based on the penalty coupling technique was used to simulate the described water entry phenomenon at high impact velocity. The wedge section and fluid domain were discretized with four-nodded shell elements and hexahedral elements, respectively. Understanding the influence of coupling parameters on numerical results is essential to successfully implement the MMALE coupling algorithm. Therefore, this study provides a comprehensive analysis of how the penalty factor and the damping coefficient affect the numerical results. The results of the simulations demonstrated that the presented MMALE method was able to accurately capture the behavior of the water entry phenomenon. The numerical model was validated with experimental data and showed good agreement with the results. It is found that although the coupling parameters have a minimal effect on the total force and its maximum value, they have a considerable influence on hydrodynamic pressure, vertical acceleration, and strain response. The results indicated that numerical instability may occur particularly for simulations with a high penalty factor. In addition, the simulations without a damping coefficient result in high frequency oscillations and make the coupling system unstable. These findings suggest that the coupling parameters should be carefully chosen in order to obtain a stable numerical model. Furthermore, a combination of penalty and damping factors is recommended to guarantee the stability of the FSI coupling system. Based on the benchmark study presented in this paper, the penalty factor and damping coefficient of 0.02 and 0.1 are recommended for hydroelastic slamming problems of aluminium structures.

Acknowledgements

This research work has been financially supported by the Estonian Research Council via the grant PRG1820 (Dynamic response of offshore structures). This help is kindly appreciated.

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