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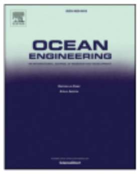

Optimization and crush characteristic of foam-filled fender subjected to transverse loads

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ABSTRACT

This research analyzed the energy absorption characteristics and crashworthiness design of a regular ship fender structure with varying geometric dimensions such as single foam fender (SFF), empty double fender (EDF), and foam-filled double fender (FDF). Furthermore, the research determined specific energy absorption (SEA) and maximum crushing force efficiency (CFE) of foam-filled fender. To calculate the crash responses, non-linear finite element analysis is used using the explicit ABAQUS and the result compared to relevant reference. Therefore, this research aims to optimize the crashworthiness indicators of aluminum foam-filled fenders subjected to transverse loads. Multi-objective using NSGA II is applied to obtain the Pareto optimal solutions for maximum Crush Force Efficiency (CFE) and maximum Specific Energy Absorption (SEA). From the optimization result, it is found that FDF has the best performance, however it is recommended to change the conventional fender design.

1. Introduction

The principal role of a marine fender is to absorb the impact energy of a berthing vessel by converting kinetic energy to other forms, such as strain energy (MostofiA, 2012). Reliant on the frequency and magnitude of the impact energy is the purpose of the mode of energy dissipation. An ideal fender system offers dissipation of high input energy induced in moored or berthing ships at reasonable construction and maintenance costs (Lee, 1968). One of the main reasons for the prevailing use of elastic impact energy absorbers in marine fender systems is the utilization of elastomeric foams, rubber, or springs as the primary energy-absorbing element by the cost-effectiveness criterion of an ideal marine fender system. Elastic fender systems are widely used at commercial facilities with various ship types, sizes, and hull configurations (Spencer, 2004). Elastic energy absorbers are suitable for low energy collision without significant permanent damage due to the elastic nature of the fender system and berthing structure (Voyiadjis, 2008). However, where the system suffers permanent damage due to high energy collision, elastic energy absorbers with highly non-linear material responses are likely to become unsuitable. In addition, the reaction forces and energy-absorbing characteristics of elastic absorbers are directly related to the material's stiffness which is highly dependent on temperature and impact velocity. However, the structural crashworthiness of marine fenders and the safety of occupants are significantly improved when impact energy is dissipated in a controlled manner with an appropriate force/deceleration level. Studies have been conducted on the strategies used to characterize the non-linear behaviour of impact energy absorbers in a progressive and controlled manner through plastic deformation with good repeatability using experimental and numerical methods. The key factors for converting kinetic energy into plastic deformation comprise the magnitude and method load application, transmission rates, deformation patterns, and material properties (Alghamdi, 2001). These studies also investigated and proposed various geometries and materials of deformable impact energy absorbers. The dominant type amongst these studies is a metallic tubular absorber with a plastic model of collapse (Salehghaffari et al., 2010; Zhang et al., 2009; Yuen and Nurick, 2008). Due to the presence of various buckling modes, this type of plastic energy absorbers has been discussed as the most efficient energy-absorbing element, with inconsistent crushing loads and energy-absorbing characteristics (Yuen and Nurick, 2008). Metallic tubes require a high initial force that capable of damaging berthing structures and likely to cause injuries to the occupants of colliding vessels (Alghamdi, 2001; Zhang et al., 2009; Hassan et al., 2015). Therefore, this prompted studies on the investigation of new geometries, configuration and materials combinations to determine the plastic impact energy absorbers' necessity for further structure optimization

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(Hassan et al., 2015).

The latest amendments in rules associated with the classification of sea-going steel ships with fenders and similar structures in collision areas require the enhancement of side plates of the dredgers (Rules for classification, 2008). Engineering ships such as barges and dredgers are often equipped with fender systems. The presence of fender structures offers a mechanism for absorbing or dissipating a large fraction of the collision energy of the berthing ship without causing permanent deformation to the ship-side structures. According to (Zhao et al., 2000), timber, rubber, steel, and pneumatic fenders are various ship fenders. In addition, due to the relatively low costs, excellent energy-absorption capability, and high strength–weight ratio, steel fenders are still widely used by small and medium-sized vessels (Yamazaki and Han, 1998). Fig. 1 provides a view of a small-sized ship with fenders on both sides. Fender structures often experience severe crushing-induced kinematic deformation, therefore, maximizing their energy-absorption capabilities as well as lowering the crushing forces during impact to protect the hull plates have been two major challenges in designing thin-walled structures (Jiang and Gu, 2010). Liu (Liu et al., 2018) determined the ultimate strength of a ship model subjected to transverse loads experiment using experiment method and for Naval and Offshore Applications (João Pedro et al., 2019), geometric Evaluation of Stiffened Steel Plates Subjected to Transverse Loading.

The crashworthiness of the structures could be improved using advanced materials according to previous numerical analysis and experiments (Jacob et al., 2002; Liu, 2008a) or by shaping configurations optimization (Yamazaki and Han, 2000). Yamazaki and Han (Kim, 2002) carried out a research to optimize the designs of cylindrical shells in order to increase their crushing energy (Kim, 2002). A novel type of section with various squared cells attached to the corner was also developed by Kim (Army Corps of Engineer, 2005). Furthermore, Hou et al. (Jiang and Gu, 2010) and Liu (2008a) studied the optimal designs of multi-corner structures with sound crash performances. According to preliminary studies, when the crashworthiness characteristics of conventional structures are enhanced, the geometric dimensions or sectional profiles are reconfigured and optimized. However, little attention has been drawn to designing optimized aluminum foam-filled fenders with crashworthiness. This is because the crash performances and durability of many fenders are far from satisfactory. The increasing use of fenders by medium-sized vessels due to economic reasons has necessitated the need to optimize the geometric parameters to achieve the best possible crashworthiness during impact. Therefore, this research provides an optimum design of an aluminum foam-filled fender structure to maximize its energy absorption efficiency and improve the structural safety of vessels.

Aluminum foam as new cellular material has become attractive for energy absorption and load attenuation due to its relatively low density and high performance on load resistance (Sun et al., 2019; Banhart, 2001; Banhart, 2011; Djamaluddin et al., 2015; Djamaluddin et al., 1204). It has been proven as an effective way to further enhance crashworthiness and lightweight with various hybrid applications using metallic or composite hollow structures (Duarte et al., 2014; Fang et al., 2014a; Renreng et al., 2020; Djamaluddin, 2019). Due to the development of metallic foam materials over the last two decades, this research focuses on the crashworthiness of foam-filled columns. Mirfendereski et al. (2008) carried out a research on the experimental and numerical analysis of the crashworthiness characteristics of foam-filled straight, double-tapered, triple-tapered, and frusta geometries for static and dynamic impact loads. The research showed that the initial peak load decreased as the number of oblique sides increased (Mirfendereski et al., 2008). According to Ahmad and Thambiratnam a foam-filled conical column significantly absorbs more energy and has a higher mean crush load than an empty one (Ahmad and Thambiratnam, 2009). Goel (2015) compared the energy absorption capability of empty and foam-filled columns with different cross-sections under impact loading and determined that when filled with bi-tubular and tri-tubular structures, it absorbs more energy than mono-tubular foam-filled columns. Altin et al. (2017) performed the axial crushing tests of empty and partially foam-filled thin-walled circular and realized that the square columns displayed the highest crash performance (Altin et al., 2017). The energy absorption capacity can be increased by using metallic foams. However, to improve the crashworthiness performance, the effects of cross-sectional geometry and foam densities were widely investigated. Langseth and Hopperstad (Langseth et al., 2003) stated that increasing the wall thickness and foam density enhanced the SEA values of the columns under axial loading conditions. The crushing behaviour of circular and square columns filled with aluminum foam under static and dynamic loads was investigated by Hanssen et al., 2000a, 2000b, 2001a. Furthermore, Sun et al. (2018) carried out a research with theoretical formulations used to predict the average force, the maximum force, and the effective crushing distance developed on a foam-filled thin-walled circular. The result showed that the crashworthiness performance of functionally graded foam-filled column is better than the uniform foam-filled column and the energy absorption capacity was dependent on the foam density. The effect of low-density filler material on the axial crushing resistance of square columns under quasi-static loading condition was studied by Santosa and Wierzbicki (Santosa et al., 2000). The energy absorption of an aluminum honeycomb-filled square column was significantly larger than that of an empty square box column (Santosa et al., 2000). The most commonly used crashworthiness

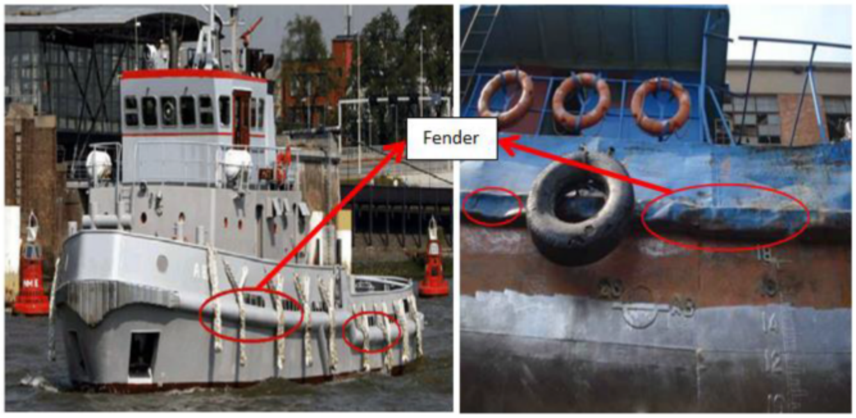

Fig. 1. Fender of ship (Jiang and Gu, 2010).

performance metrics used to define an energy absorber are SEA and CFE. A high value of these metrics with a high value of energy absorbed per unit mass lowers the force transferred to the passenger side. Foam-filled thin-walled structures have drawn increasing attention to optimize their density optimization and maximize the SEA and CFE (Song et al., 2013; Kavi et al., 2016; Li et al., 2014). The wall thickness of expert substantial affects the energy absorption capacity of foam-filled columns (Li et al., 2012; Fang et al., 2014b; Djamaluddin et al., 2015). Therefore, it is necessary to determine the optimal foam density and wall thickness values for an efficient design.

One of the major challenges in crashworthiness optimization studies is the high computational cost of crash simulations. RBF or meta-models that approximate the simulation model results are generally used to address computational challenges. Furthermore, meta-models were employed in the optimization studies to investigate the crashworthiness of these structures by concentrating mainly on the energy absorption capabilities of thin-walled structures (Lee et al., 1999; Xiang et al., 2006; Liu, 2008b; Baykasoglu and Baykasoglu, 2016; Taştan et al., 2016; Tanlak, 2016; Karagöz and Yıldız, 2017). Several studies have been conducted on the optimization of foam density and wall thickness to improve the crashworthiness capability of foam-filled columns. For instance, Hou et al. (2009) carried out a research to optimize square monotubular foam-filled crash absorbers using multi-objective optimization methods. The research showed that foam filler increases SEA and enhances crashworthiness performance with a rise in peak crush force (Hou et al., 2009). Design and optimization study for foam-filled mono- and tri-tubular columns were carried out by Bi et al. (2010). Zarei and Kröger, 2007, 2008 optimized the mono-tubular and tri-tubular columns of a multi-criteria design optimization technique to maximize SEA capacity by comparing the energy absorption capacity of empty, honeycomb-filled, and foam-filled square columns under dynamic crushing loading and demonstrated the advantages of using foam-filled columns for energy absorption (Zarei and Kröger, 2007). The foam-filled columns also have the ability to absorb 19% more energy than the optimum empty column (Zarei and Kröger, 2008). The crashworthiness performances of empty and foam-filled bi-tubular square columns studied by Zhang et al. (Yin et al., 2014a) maximized the foam-filled bi-tubular design. Yang and Qi (Zheng et al., 2014) studied the effect of load angle, geometry, and material parameters on SEA and the peak force for empty and foam-filled thin-walled square columns. The research showed that Foam-filled square columns exhibit higher and lower crashworthiness performance under pure axial loading and at oblique impact angles. Furthermore, Yin et al. (2014a) carried out a research on the crashworthiness optimization of foam-filled multi-cell thin-walled columns and stated that those with nine cells were the most efficient design in terms of energy absorption capacity.

Zheng et al. (2014) researched eight different configurations of mono- and bi-tubular configurations under three different impact velocities and found that the best design varies with the impact. Crashworthiness designs with many optimization algorithms were used in a single and multi-optimization formulation such as Non-Dominated Sorting Genetic Algorithm (GA-II) (Tran et al., 1016; Tran et al., 2014; Sun et al., 2014), Multi-objective Particle Swarm Optimization (MOPSO) algorithm (Zhang et al., 2012; Gao et al., 2016a; Acar et al., 2011; Hanssen et al., 2001b), Genetic Algorithm (GA), etc (Tran et al., 1016; Tran et al., 2014; Hanssen et al., 2001b; Yin et al., 2014b).

The main objective of this study is to optimize the geometric and material property parameters of foam-filled ship fenders to determine the maximum parameters of CFE and SEA of the aluminum foam-filled fender. The non-linear explicit FEA software ABAQUS was used to determine the crash behaviour of the fender.

2. Materials and methods

2.1. Crashworthiness indicator of fender subjected to transverse loadings

Energy Absorption (EA), SEA, and PCF are used to efficiently evaluate the crashworthiness of structures and the energy-absorbance using indicators. EA is calculated as follows:

$$EA = \int_{0}^{\delta} F(\delta)d\delta \tag{1}$$

where, $F(\delta)$ denotes crushing force with a function of the displacement δ.

SEA denotes the absorbed energy (EA_{total}) per unit mass (M_{total}) of a structure as follows:

$$SEA = \frac{EA_{total}}{M_{total}} \tag{2}$$

Crush force efficiency is defined as the ratio of the average crush force (F_{agv}) to the peak crush force ($F_{\max}$),

$$CFE = \frac{F_{avg}}{F_{max}} \tag{3}$$

2.2. Finite element models of the fender

Fig. 2 shows the ship fender's schematic load with a height and length of 100 mm, and 600 (Guo and Yu, 2011a). There are three configuration of fender, namely single foam fender (SFF), empty double fender (EDF), and foam-filled double fender (FDF), as shown in Fig. 3. The rigid wall with an initial velocity of 1 m/s (approximately 2 knots) and weight of 1200 T is created to simulate the scenario of low-velocity impact often experienced by the fenders. The rigid wall as the impactor moves to crush these structures for the clearer observation of their deformation processes. From this condition, it is assumed that the most frequent condition of head-on berthing and the dynamic load on the studied length of the fender structure is uniform. Conversely, the impact could occur in an irregular way in rough and uneven surfaces of the fender structures (Jiang and Gu, 2010).

Fig. 3 shows the importance of designing new fender structures using a cross-section of three double circular tubes, namely single foam fender (SFF), empty double fender (EDF), and foam-filled double fender (FDF). The Finite Element (FE) code ABAQUS –Explicit was used to develop the aluminum foam-filled fender models and predict the response of thin-walled structures impacted by a free-falling impinging mass. The fender structure is modeled together with a hull plate which maintains a 'fixed' boundary condition during the simulation analysis.

Four node shell continuum elements with five integration points along the element's thickness direction were used to model the fender wall. Moreover, eight-node continuum elements with a reduced

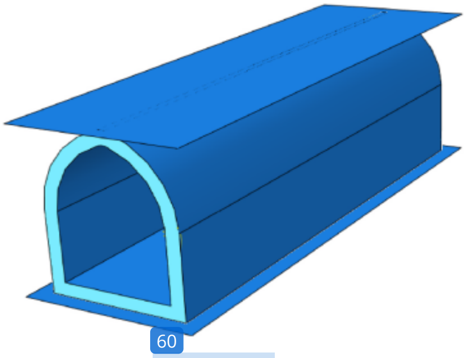

Fig. 2. The schematic of the fender structure.

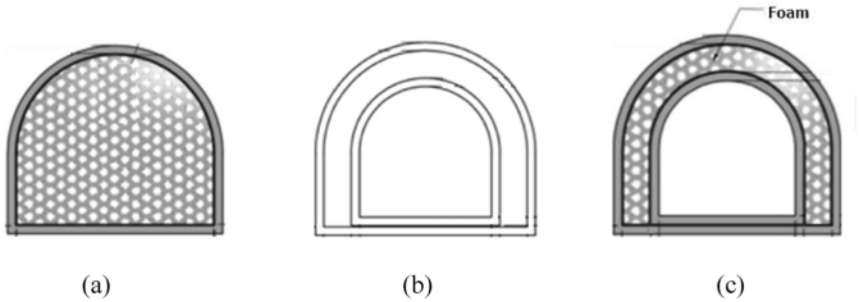

Fig. 3. Cross-section of the ship fender (a) as single foam fender (SFF), (b) empty double fender (EDF), and (c) foam-filled double fender (FDF).

integration technique were combined with the hourglass control to the model hull and rigid walls. Enhancement-based hourglass control and reduced integration were applied to avoid both artificial zero energy deformation modes and volumetric locking. Furthermore, a two mm element size was chosen based on a mesh convergence study of shells and foam elements. A mesh convergence was addressed to ensure a sufficient density and to capture the deformation process accurately. Less intense computational time was used to determine the contact interaction between all components and to avoid interpenetration of fender walls. Meanwhile, a finite sliding penalty-based contact algorithm with contact pairs between the foam and the fender walls was modeled. All contact surfaces were set at 0.3 as the friction coefficient value used in previous works (Guo and Yu, 2011a, 2011b). The Finite Element (FE) code ABAQUS –Explicit was used to develop the aluminum foam-filled tubular tube models and predict the response of thin-walled structures impacted by a free-falling impinging mass.

Fig. 4 shows that after crushing the fender structure for 0.2s, a deformed shape was formed. In a progressive fashion, the longitudinally reinforced stiffener was fully bent, and to take the impact energy, the top part of the structure bulged aside and folds.

2.3. *Material properties*

2.3.1. *Fender material*

The fender were made from aluminium alloy A6063 T6 (Yin et al., 2015; Fang et al., 2014a) with mechanical properties of density $\rho = 2700$ kg/m^3, Young's modulus $E = 60.2$ GPa, the Poisson's ratio $\nu = 0.3$, initial yield stress $\sigma_y = 184.4$ MPa, and ultimate stress $\sigma_u = 215.5$ MPa.

An elastic-plastic material model comprising Von Mises's isotropic plasticity algorithm was used to assess the constitutive behaviour of the tubes. Furthermore, the direction of aluminum foam, which caused the manufacturing process effect, was ignored. Piecewise lines were performed to define plastic hardening in the material's constitutive model. Moreover, the true stress and the plastic strain were experimentally found to determine the piecewise lines. The aluminum alloy A6063 T6 with different thicknesses was used to determine the uniaxial tension test results (Guo and Yu, 2011b). This model's effect of strain rate was omitted due to the insensitivity of the strain rate of aluminum alloy material (Langseth and Hopperstad, 1996). This was because the fracture of the aluminum alloy was not considered in the analysis.

2.3.2. *Aluminum foam-filled material*

The aluminium closed-cell foam filler was used to carry out this research, with material tests used to determine the average mechanical property value. The material's behaviour was obtained from experimental testing of the foam-filled material, while the uniaxial quasi-static compression test results with different foam apparent densities are given in references (Guo and Yu, 2011a, 2011b).

The constitutive behaviour was based on an isotropic uniform material of the foam model developed by Dehspande and Fleck (Deshpande and Fleck, 2000) using non-linear ABAQUS/Explicit software packages. However, this research failed to consider the effect of the manufacturing process on anisotropic behaviour of aluminum foam. Table 1 shows the details of the material's parameters used in the FE simulation experiments.

2.4. *Design of experiment and meta-model technique*

A meta-model is a mathematical method created to produce an output from a simulation model based on an input data set. An example is a meta-model suitable for estimating the fundamentals of physics with

Table 1
The parameters of the materials (Guo and Yu, 2011a, 2011b).

	ρ(g/cm^3)	E (Gpa)	N	νp	K
Foam	0.45	0.625	0.1	0	1.732
Tube	2.7	60.2	0.3		

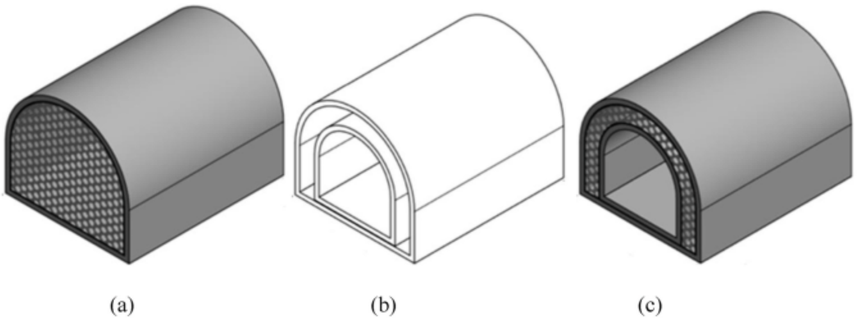

Fig. 4. The Finite Element (FE) models of fender structure (a) SFF, (b) DEF, and (c) DFF.

different data sets used to perform varying meta-models. Experimental design is the process of placing points on an area, such as input settings for a data set (Fang et al., 2005). Meta-models were developed from sample data collected from physical experiments or computer simulations using finite element analysis. Data were taken from the design space by determining the variables range, which is further designed according to points, where each represents a combination of variables at different levels. DOE is used to reduce the number of input data in meta-model development. It is also a statistical technique used to obtain information using a number of simulations with different variables used to determine the behaviour (Yin et al., 2014c). RBF is used for the adjustment of irregular topographic contours for geographic data. RBF has been used for many situations, such as for objective function approximation (Gao et al., 2016b).

Fang et al. (2005) used the RBF meta-model for the optimization of various vehicle body objectives in frontal accidents, which were validated by finite element simulations to determine the overall vehicle model. The results showed that RBF produced a better model than RSM based on the same number of reaction samples, with the identification of multiple quadric functions indicating the most stable and more accurate RBF. Furthermore, the accident absorption capacity was estimated using a minimum number of analytical elements to construct an RBF system. Surface reactions are coupled with genetic algorithms to produce single constraints and multi-objective optimization. The results proved that moderate eccentricity leads to a high-efficiency structure with stable forward, crushing characteristics and good absorption capacity with mass reduction of up to 7% and vertical impact effect of at least 20% for circular tubes (Zhang et al., 2015).

2.5. Multi-objective optimization

The design variables of sectional such as height h, the thickness of wall t, yield stress σ_y, foam density ρ_f, and constant tube length of 100 mm, were used to perform the multi-objective optimization. In addition, several preliminary studies (Fang et al., 2014c) investigated two indicators of crashworthiness that are optimized simultaneously to determine the maximum SEA and the minimum CFE subjected to transverse impact loadings.

Genetic Algorithm (GA) is a popular optimization tool because it avoids the trapping capability for searching for an optimum in local optima (Lanzi et al., 2004). The Non-dominated Sorting GA (NSGA) algorithm, such as NSGA version I and II, are a more effective and efficient algorithm for ranking solutions, assigning ranking fitness, and benchmarking number problems (Salehghaffari et al., 2011). The flowchart details for the crashworthiness optimization of double fender under impact loadings are shown in Fig. 4. In the first phase, the DoE method was used to define the design space and generate sampling points for different angle loadings. In the second phase, FEA was used to acquire the design responses for the initial D-optimal models of the design objectives. Finally, in the third phase, Pareto solutions of structures under different loading conditions were determined using the NSGA II method (see Fig. 5).

3. Results and discussion

3.1. Model validation

Finite element models using the ABAQUS model were compared to LS DYNA model data to ensure that they were sufficiently accurate for design optimization in accordance with the research carried out by (Jiang and Gu, 2010). MinF(x) = $i_{I^1(x),f_2(x),\ldots}$ The fender impacted on a rigid wall with an initial velocity of 1 m/s (approximately 2 knots), and the weight of the 1200 T tube model was validated subjected to transverse load. Furthermore, simulation research was carried out by (Jiang and Gu, 2010) with a length of 600 mm taken from one frame spacing of a medium-sized vessel and height of the side frames 100 mm to determine the under the axial impact (0°) for fender (in Fig. 6), found a good agreement (see Table 2).

A radial basis functions meta-model was constructed to determine the sample points accurately. Furthermore, five extra random points

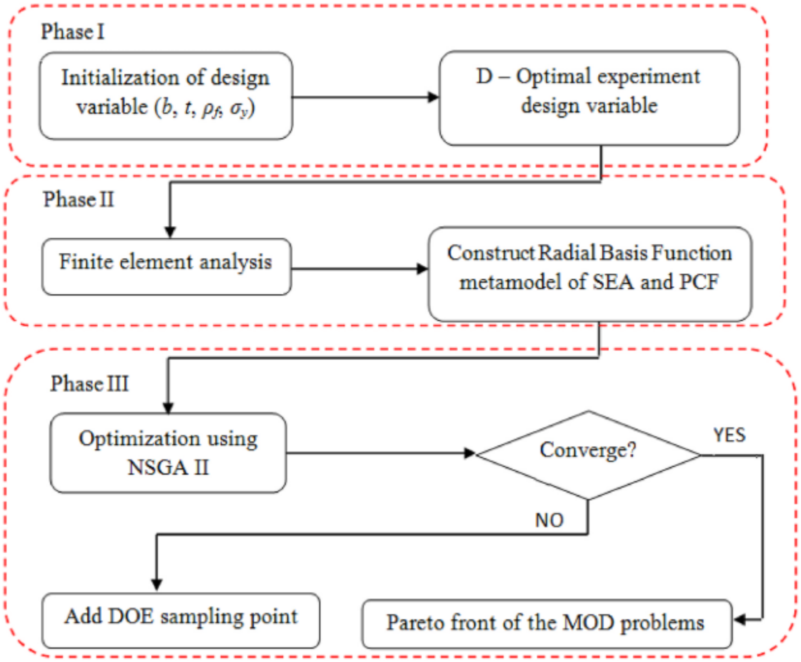

Fig. 5. Flowchart of crashworthiness multi-objective optimization for tubes [(Djamaluddin et al., Nopiah)-79].

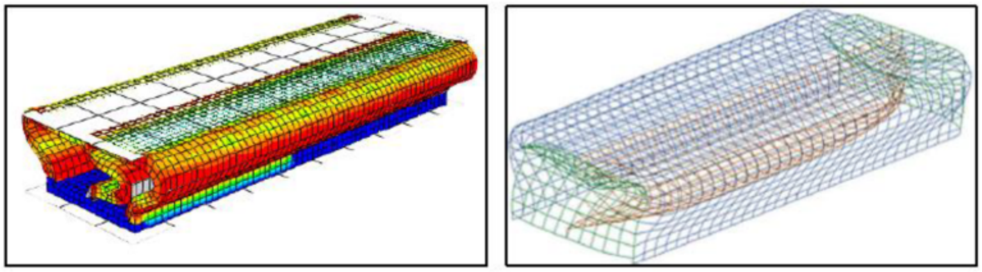

Fig. 6. Simulation using ABAQUS and reference (Jiang and Gu, 2010).

Table 2
Difference between FE LS DYNA and FE ABAQUS.

	Impact angle (°)	FE ABAQUS	FE LS DYNA (Jiang and Gu, 2010)	Error (%)
Energy Absorption (J)	0	3427.34	3524	2.74
Specific Energy Absorption (J/g)		25.93	26.7	2.88

(Langseth et al., 2003; Hanssen et al., 2000a) were generated within the design domains of the six types of tubes subjected to the axial load. To validate these models at a reasonable cost, responses of SEA and PCF at validation points of FE and RBF models were used. The Relative Error (RE) (Guo and Yu, 2011b) is evaluated to determine the degree of approximation of the radial basis functions meta-model to the FEA results as follows:

$$RE = \left| \frac{y(x) - \widetilde{y}(x)}{y(x)} \right| \tag{4}$$

where, $\widetilde{y}(x)$ is the radial basis functions models and $y(x)$ is the finite element result.

The initial sample points for the FEA and the RBF in five random sample points. The RE for these RBF meta-model approximations was less than 4% in SFF, DEF, and DFF, as shown in Figs. 7–9. Therefore, it is assumed that the RBF model for the objective functions (SEA and PCF) provided sufficient accuracy for design optimization.

3.2. *Crashworthiness optimization design*

The multi-objective optimization of aluminum foam double tube equations was derived by considering several parameters. Furthermore, in the presence of trade-offs between two or more conflicting objectives, multi-objectives were applied. New objectives and constraint functions, with respect to design variables, such as *h, t, σy, ρf* and objective functions, namely SEA and CFE for double circular tubes, were constructed.

Case one, the foam-filled single Fender (SFF). The design problem of optimization was defined as:

$$\begin{cases} \{SEA(h,t,\rho_f,\sigma_y),\ CFE(h,t,\rho_f,\sigma_y)\} \\ 1.6\ mm\ \le t \le 3.0\,mm \\ 80\ mm\ \le h\ \le 100\ mm \\ 150\ MPa\ \le \sigma_y \le 230\ MPa \\ 110\ kg/m^3 \le \rho_f \le 270\ kg/m^3 \end{cases} \tag{5}$$

Case two, the Empty double Fender (EDF) were formulated as follows:

$$\begin{cases} \{SEA(h,t,\ \sigma_y),\ CFE(h,t,\sigma_y)\} \\ 1.6\ mm\ \le t \le 3.0\,mm \\ 80\ mm\ \le h\ \le 100\ mm \\ 150\ MPa\ \le \sigma_y \le 230\ MPa \end{cases} \tag{6}$$

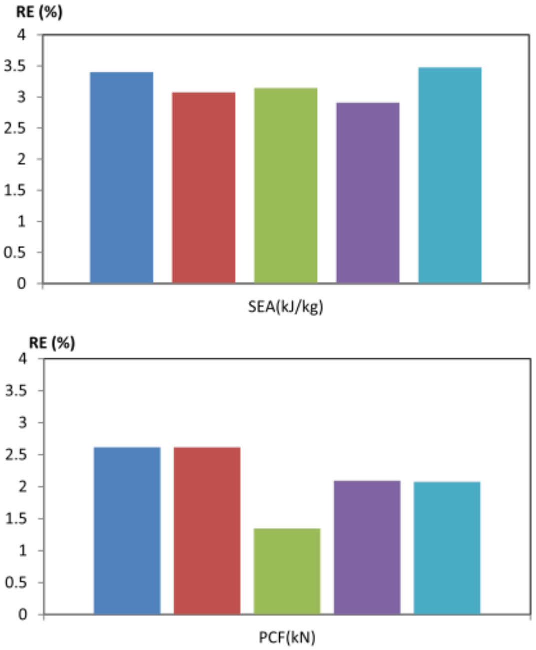

Fig. 7. Relative errors of design objectives of SFF.

Case three, the foam-filled double Fender (FDF), the formula is mathematically shown as:

$$\begin{cases} \{SEA(h,t,\rho_f,\sigma_y),\ CFE(h,t,\rho_f,\sigma_y)\} \\ 1.6\ mm\ \le t \le 3.0\ mm \\ 80\ mm\ \le h\ \le 100\ mm \\ 150\ MPa\ \le \sigma_y \le 230\,MPa \\ 110\ kg/m^3 \le \rho_f \le 270\ kg/m^3 \end{cases} \tag{7}$$

MOD problems are calculated to obtain the Pareto fronts, as shown in Equations (5)–(7). Based on radial basis functions meta-models, the NSGA-II algorithm was adopted to investigate the design space. Furthermore, the DoE method was used to create an initial 200 design point population for all cases of MOD. By considering the convergence of optimizations iterating for 20 generations, CFE vs. SEA Pareto fronts graphs were generated using NSGA-II for SEF, DEF, and DFF tube structures.

3.3. *Comparison of the fender structures subjected to transverse impact loadings*

A multi-objective optimization was used to compare the

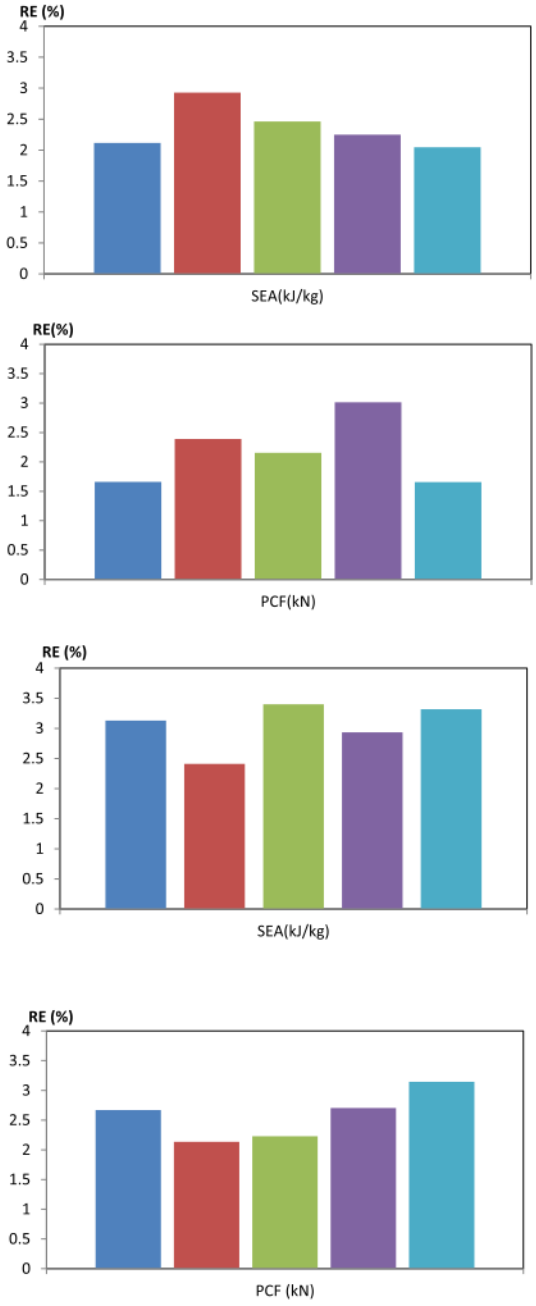

Fig. 8. Relative errors of design objectives of DEF.

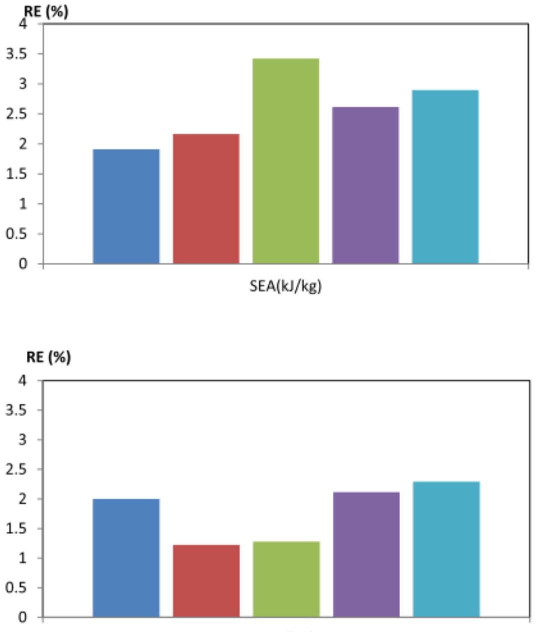

Fig. 9. Relative errors of design objectives of DFF.

crashworthiness of the structures, as shown in Equations (4)–(6). All structures had similar dimensions, boundary, and loading conditions, as those considering the design variable, as shown in Fig. 1. The comparison of deformation patterns from the different structures indicates progressive crease in DEF and EFF, while the DFF has a better energy absorber in loading conditions (see Fig. 10).

Fig. 11 show that the empty fender geometry had lower energy absorption than other configuration structures subjected to transverse loadings. However, due to the frictional interaction between the foam-filler and the inner/outer tubes (Langseth et al., 2003; Yin et al., 2014c) the combination structures i.e., SFF and DFF had more energy absorption capacity and lower peak crushing force. Therefore, these structures have the ability to improve the crashworthiness performance of thin-walled tubes, especially in ship fenders (see Fig. 12).

Table 3 shows the optimal configurations of SFF, DEF and DFF subjected to transverse loading conditions, and the ideal optimal values for two single objective functions of SEA and CFE. The maximum SEA was 19.98 kJ/kg when DFF was under pure axial impact. It is preferable when the wall has a thickness value of 2.230 mm and material yield stress of 203.89 MPa. There is a conflict between the two objective functions of the crashworthiness and the verification applied multi-objective optimization in such problems. Secondly, for maximum SEA, the optimal diameter of each double foam-filled fender is generally different under impact condition. For instance, DFF under pure axial impact for maximum SEA was the diameter of the optimal section of 85.61 mm. In these two cases, the corresponding optimal values for SEF were 87.54 mm and 88.92 mm, respectively. Apparently, with a constant tube length, the large diameter tube provided the effect of energy absorption. Therefore, tube material more susceptible to deform structures and more energy-efficient progressive collapse mode. Finally, the minimum PCF was close to a lower bond of 146.32 kg/m^3 foam-filler tubes, and the maximize SEA has had the highest foam density of 219.65 kg/m^3. However, the SEA maximization optimal foam density subjected to transverse impact is shown in reference (Altin et al., 2017; Hanssen et al., 2000a).

Multi-objective optimization was explored with respect to the design variables of sectional high of fender h, thickness t, yield stress σ_y, and foam density ρ_f to define the errors between the FEA and the radial basis functions models. Five random sample points (Hanssen et al., 2000a) were used to determine the Pareto fronts (see Fig. 13) using the radial basis functions and NSGA-II optimization method. The corresponding MOD problems and RBF models were implied and used to determine the entry of foam-filler in the crashworthiness simulation.

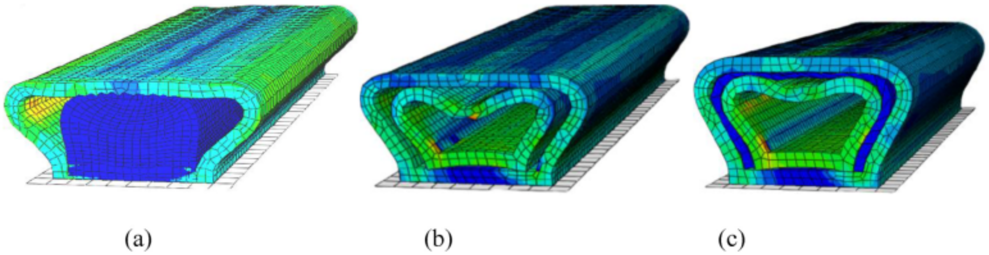

Fig. 10. Deformation pattern of three different structures: (a) SFF, (b) DEF, and (c) DFF.

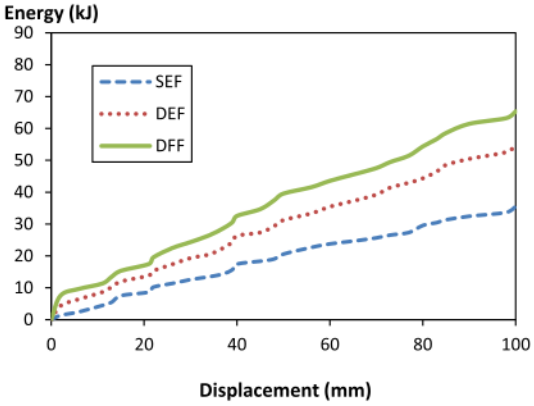

Fig. 11. Energy absorption capability for various structures.

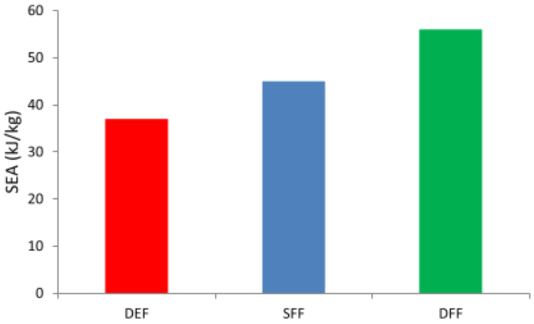

Fig. 12. Specific energy absorption for various structures of fenders.

Table 3
Optimal designs for three structures.

Fender Types	h (mm)	t (mm)	σ_y (Mpa)	ρ_f (kg/m^3)	SEA (kJ/kg)	CFE
SFF	87.43	2.451	197.54	206.74	**16.94**	158.87
	85.61	2.345	210.63	154.75	4.58	**63.84**
DEF	87.59	2.643	200.73	–	**18.77**	163.33
	86.78	2.943	199.32	–	5.78	**75.62**
DFF	90.21	2.230	198.97	203.89	**19.18**	172.39
	87.02	2.753	209.45	146.32	6.93	**83.23**

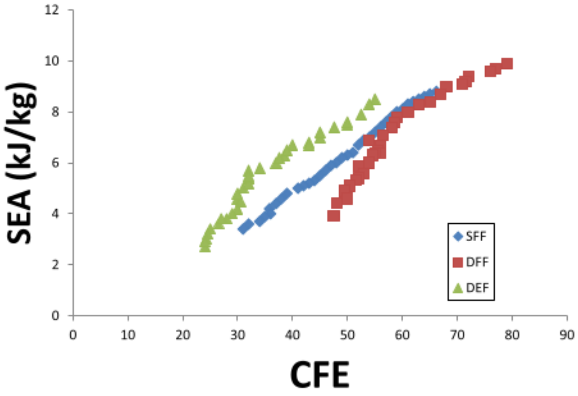

Fig. 13. Pareto fronts for various structures of fender.

4. Conclusions

In conclusion, this research explored the crashworthiness design for thin-walled structures made of aluminum foam-filled circular tubes. Furthermore, it also calculated the crashworthiness criteria, such as Specific Energy Absorption (SEA) and Crushing Force Efficiency (CFE) subjected to transverse. Multi-objective problems based on Radial Basis Functions (RBF) were constructed using Finite Element Analysis (FEA). The research showed that the maximum SEA and the minimum CFE under pure axial loading conditions were 19.98 kJ/kg and 63.54 kN, respectively. It was found that increasing the angle of loading on the double circular tubes led to a decrease in the values of [illegible] and CFE.

The main results are described as follows firstly, Non-dominated Sorting Genetic Algorithm-II (NSGA-II) was used for the multi-objective optimization of SEA and CFE for circular double tubes. Secondly, it was used to optimize the different structures, namely, Single foam-filled fender (SFF), Double foam-filled fender (DFF), and Double Empty Fender (DEF). Thirdly, DEF crashworthiness performed approximately 10% and 7% better than SFF and FET in terms of pure axial impact. The DFF were good potential candidates for energy-absorbing crashworthiness ship structure applications to protect during collisions.

CRediT authorship contribution statement

F. Djamaluddin: Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing, Conception and designof study, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, revising the manuscript, critically for important intellectual content, Approval of the version of the manuscript to be published (the names of all authors must be listed). **F. Mat:** Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing, Conception and designof study, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, revising the manuscript, critically for important intellectual content, Approval of the version of the manuscript to be published (the names of all authors must be listed).

Declaration of competing interest

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