MODELING AND OPTIMIZATION OF ALUMINUM FOAM CYLINDRICAL DOUBLE TUBES UNDER AXIAL IMPACT

F. Djamaluddin, S. Abdullah*, A.K. Arrifin and Z.M. Nopiah

Faculty of Engineering and Built Environment
Universiti Kebangsaan Malaysia
43600 UKM Bangi, Selangor, Malaysia
*Email : shahrum@eng.ukm.my
Tel: +60-3-89118411, Fax: +60-3-89259659

ABSTRACT

Due to their high energy absorption and lightweight material, foam-filled metallic tubes are used for vehicle structures to improve occupant safety and to reduce weight for fuel consumption efficiency. This paper presents the optimization of the empty and foam-filled double circular tubes under axial impact loading. In this work, both ends of a circular tube were clamped, at the bottom as a boundary condition and at the top to apply quasi-static force with respect to the longitudinal direction. The finite element model was validated with experimental tests taken from the literature. Finite element analysis and optimization design were combined to observe the crashworthiness of the double tubes. The geometric dimensions, such as the diameter and thickness of the tubes, were chosen as the design variables. The crush parameters, namely minimum peak crushing force and maximum specific energy absorption, were calculated using the non-dominated sorting genetic algorithm II to obtain the Pareto optimal solution. The radial basis function and factorial were calculated to formulate the objective and variable functions. The results show that aluminum foam-filled double circular tubes have more crashworthiness capability than empty tubes. The optimum values of the foam-filled tubes were higher than the empty double cylindrical tubes (3.5%). Finally, foam-filled double circular tubes can be recommended as the energy absorber in automobiles.

Keywords: Aluminum foam; crashworthiness; circular tube; radial basis function; axial impact.

INTRODUCTION

Several researchers have studied the behavior of thin-walled tubes, considering the geometry, size, cross section and the loading condition of the tubes to improve energy absorption [1, 2]. For instance, the progressive buckling, inversion and splitting of circular tubes have been discussed previously [3]. Furthermore, the collapsible energy absorbers of different tube structures, i.e. circular and square tubes, have been explored [4] and it was found that the energy absorbing capability of circular tubes is better than that of square. To improve the crashworthiness capability of thin-walled tubes, some researchers [5-9] used cellular materials, such as foam. Similarly, empty and foam-filled circular tubes with a double-cell profile have also been studied [10, 11]. Due to faster computers and better algorithms, some optimization techniques have been applied in structure design, particularly to optimize the configurations of foam-filled tubes. The

maximum energy absorption and the minimum weight of foam-filled aluminum tubes under axial load were investigated [12]. Moreover, maximizing the specific energy absorption and minimizing the peak crash force using multi-objective optimization has been researched. For example, the maximum crush force efficiency (CFE) and the maximum specific energy absorption (SEA) of tapered circular thin-walled tubes using multi-objective crashworthiness optimization have been identified [13]. Moreover, different mathematical programming, such as genetic algorithms (GA) [14, 15] and particle swarm optimization (PSO) [16], has been used to seek optimal solutions.

In this paper, multi-objective optimization of tubular cylindrical aluminum tubes under axial impact loading is undertaken using the non-dominated sorting genetic algorithm II (NSGA II). Furthermore, this method is a fast and elitist GA [17]. The parameters of the structures, such as the inner diameter, outer diameter and thickness of the double tubes, were optimized. Previously, the crush behavior of tubes has been simulated in finite element software ABAQUS/Explicit. The results of the simulations were validated against the relevant experimental tests in the literature. The radial basis function (RBF) was used to construct the approximating design sub-problem. Finally, this research presents Pareto solution sets.

NUMERICAL SIMULATION

Finite element (FE) simulation is part of crashworthiness optimization. In this work, computer simulation of double circular tubes under quasi-static axial impact loading using the FE code with ABAQUS software was undertaken. The tubular circular tubes were placed between two rigid walls. Figure 1 shows all of the tubes fixed at the bottom with the other end impacted by a moving rigid wall with constant velocity of 0.9 m/s. Empty and aluminum foam-filled thin-walled double circular tubes 200 mm long (*l*) were considered. The variable design parameters of the tubes are the inner diameter (*d*) 45 mm, the outer diameter *2d*, and the thickness (*t*) 2.5 mm.
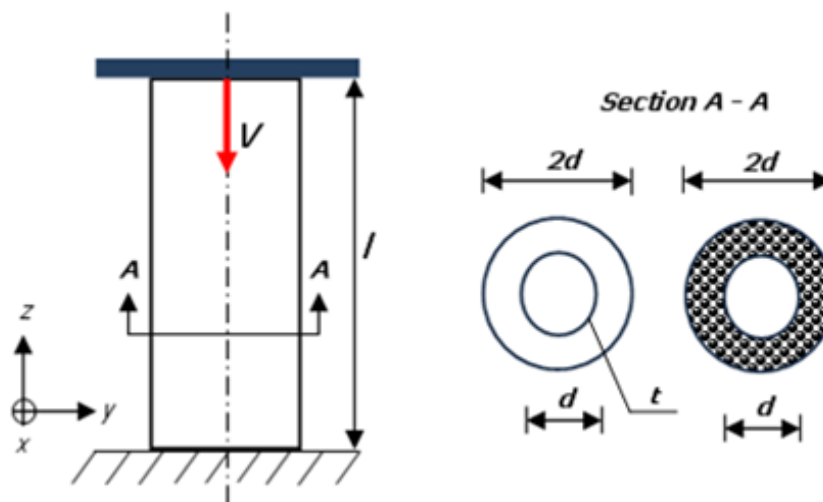

Figure 1. Dimensions, boundary, and loading condition of the aluminum foam-filled double tube.

The walls of the inner and outer tubes were made from aluminum alloy A6063 T6 with density $\rho = 2700 \, \text{kg/m}^3$, Young's modulus $E = 60.2$ GPa, Poisson's ratio $\nu = 0.3$, initial yield stress $\sigma_y = 184.4$ MPa, and ultimate stress $\sigma_u = 215.5$ MPa with

engineering stress-strain, as in Figure 2. In addition, the aluminum foam filler was produced by liquid state processing using TiH2 as the foaming agent, giving average mechanical property values of nominal density $\rho_f = 0.45$ g/cm^3, Young's modulus $E = 625$ MPa, compression strength $\sigma_c = 9.74$ MPa, and plateau stress $\sigma_p = 8.12$ MPa [18].
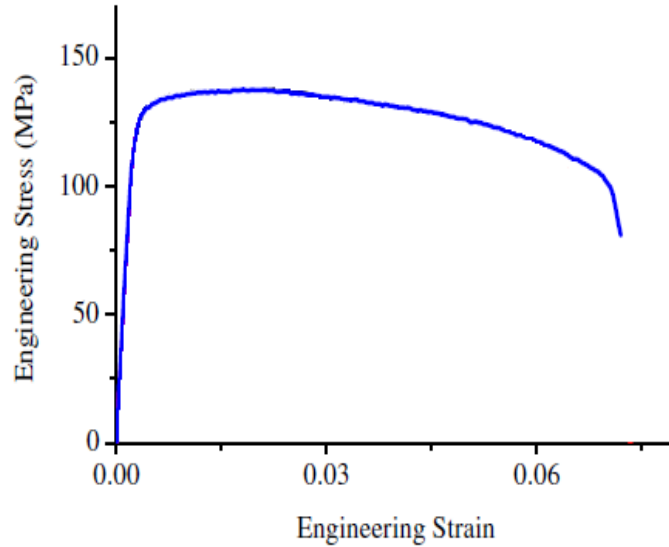

Figure 2. Engineering strain–stress curve of the A6063 T6 [18].

A maximum crash distance of 100 mm was assumed, representing a stroke efficiency of 0.5. Moreover, the rigid wall was defined in the y – z plane and ABAQUS FE software was used to develop the FE models of the different cross-section double tubes in Figure 3. Four node-shell continuum elements, with five integration points along the thickness direction of the element modeled the thin wall structure. Furthermore, eight node continuum elements used the reduced integration technique to develop the foam. Based on a mesh convergence study, an element size of 5 mm was chosen for the shells and the foam [19].
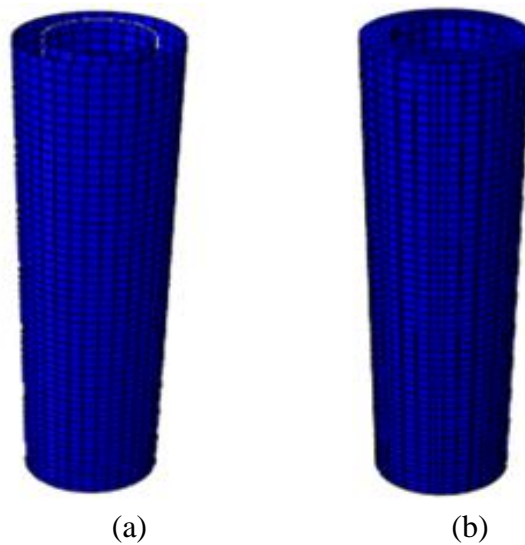

(a)   (b)

Figure 3. FE models of cylindrical double tubes (a) empty and (b) foam filled.

To simulate contact between all components the "general contact algorithm" was used with the contact algorithm. As finite sliding penalty based contact algorithm with contact pairs and hard contact to model the contact between the tube walls with and without foam. The friction coefficient was set at 0.2 for all contact surfaces [19].

VALIDATION

The FE results and the experimental data in the literature were studied to ensure that the developed models are accurate in order to be explored for design optimization, particularly in the simulation of double-cylinder aluminum-foam tubes. The experiment [20] studied the deformation and energy absorption of empty, aluminum-foam single- and double-cylinder tubes under oblique impact and the result explained that double tubes have more crashworthiness capability to absorb energy than other structures. Figure 4 shows the correlation graph between the results of the experiment and the numerical simulation of aluminum-foam double-cylinder tubes with respect to displacement and crushing force. Table 1 shows the difference between the experiment and numerical simulation, which is similar to references [21-23]. From these results, it can be assumed that the developed FE models are competent for design optimization exploration.
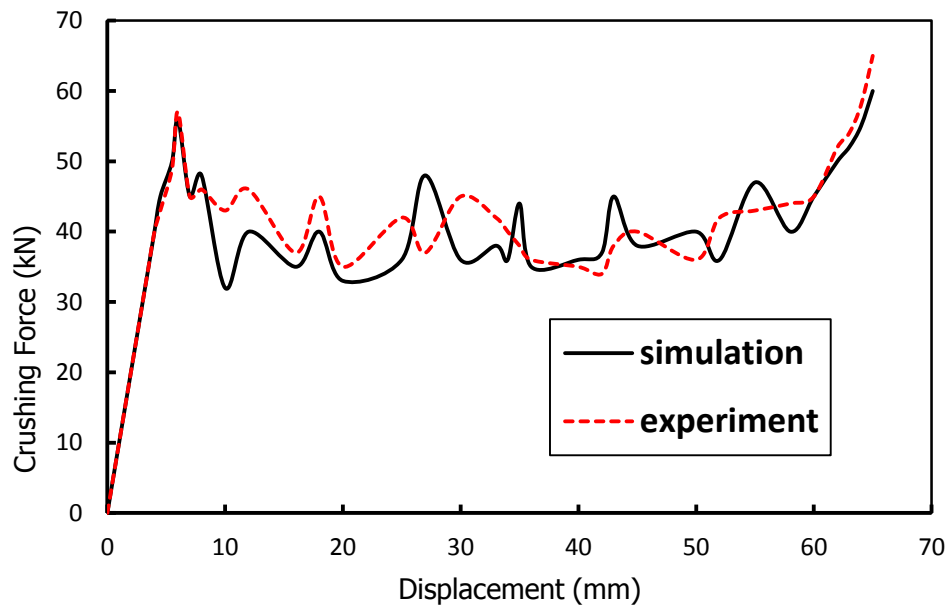

Figure 4. Comparison between (a) the experimental test [20] and (b) the numerical simulation.

Table 1. Difference between experimental test [20] and numerical simulation.

Parameters	Experiment	Simulation	Error %
Crushing force (kN)	56.3	57.1	1.42
Energy absorption (J)	2143	2140.8	0.11

CRASHWORTHINESS OPTIMIZATION

RBF is a surrogate model that represents the relationships between the individual objective functions and the design variable vector. Given the design variable vector and the response values at *n* arbitrary design (training) points, the RBF approximation of the response function $f'(x)$ was derived from an FE simulation, as the following expression:

$$f'(x) = \sum_{i=1}^{n} \lambda_i \emptyset(||x - x_i||) \tag{1}$$

where, *x* is the vector of the normalized design (input) variables with x_i representing the normalized coordinates of the i_{th} training point, $ri = ||x - x_i|| = \sqrt{((x - x_i)^T(x - x_i))}$, $\emptyset$ is a radial symmetric basis function, and $i = 1$ is the unknown interpolation coefficient.
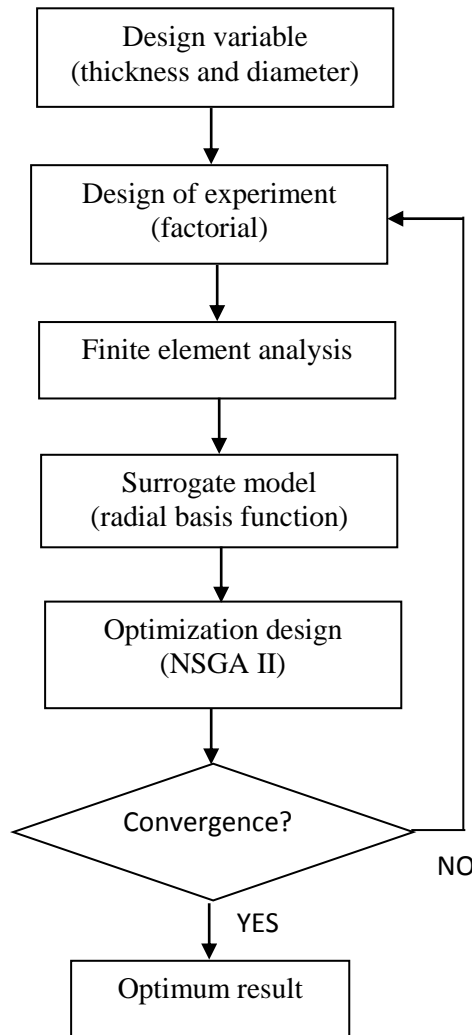

Figure 5. Flowchart of the multi-objective optimization of double cylindrical tubes

The GA is a popular optimization tool, because it avoids the trapping capability of searching for an optimum in local optima. The non-dominated sorting GA (NSGA) is a more effective and efficient algorithm in ranking solutions, assigning ranking fitness, and benchmarking number problems. Figure 5 shows the implementation of multi-objective optimization for the empty and foam-filled double-cylinder tubes. The flow chart clarifies the whole crashworthiness multi-objective optimization using finite element analysis (FEA) and produces the code for RBF and NSGA II using MATLAB. However, NSGA II, based on a fast non-dominated sorting principle, was used herein to calculate the formulas for multi-objective optimization in Equation (2). Several researchers have investigated simultaneous optimization of two-criteria crashworthiness. This is a multi-objective optimization scheme. In general, the mathematics of multi-objectives can be expressed as:

$$\begin{cases} Min\ F(x) = [f_1(x), f_2(x), ..., f_n(x)]^T \\ \quad s.t.\ x \in R^m\ and\ x^L\ \leq x \leq x^u \\ \qquad g_u(x) \geq 0, u = 1, ..., s \\ \qquad h_v(x) = 0, v = 1, ..., p \end{cases} \tag{2}$$

where, x is the design variable vector, n is the objective function number, $f_n(x)$ is the objective function of the objective, $x^L = (x^L_1, x^L_2, ... x^L_1)$ denotes the lower bound, *and* $x^U = (x^U_1, x^U_2, ... x^U_1)$ the upper bound of the m design variables, and s and p are the numbers of the unequal and equal constraints, respectively.

RESULTS AND DISCUSSION

In the quasi-static loading condition, the axial impact of empty and foam-filled aluminum double circular tubes was modeled. Figure 6 shows the different height reductions of empty and foam-filled circular tubes. At the same time, the collapse mode of the aluminum foam-filled tubes is higher than the empty double circular tubes due to the frictional interaction between the foam filler and the inner/outer tubes [21]. Similarly, the ability of the circular foam-filled tubes to absorb energy is greater than that of the empty tubes, as shown in Figure 7.

The optimization equations of the double tubes were derived by considering the parameters. The results were expected to determine the maximum SEA and the minimum peak crushing force (PCF). The optimization equation is shown below:

$$Min\{-SEA(t,d), PCF(t,d)\}$$
$$s.t.\ 1.5\ mm\ \leq t \leq 3\ mm$$
$$20\ mm\ \leq d\ \leq 25\ mm$$

SEA (t,d) = -0.00584454 + 0.53921 t + 0.66557d − 0.85593t^2 + 1.34975td
+ 0.67566d^2-0.97651t^3 + 2.75487t^2d + 0.08976td^2 + 0.09135d^3 + 0.58934t^4
-0.93167 td^3-1.89616 t^2d^2 + 0.07195 t^3d - 0.24987 d^4 (3)
PCF (t,d) = 0.0348443 + 0.87295 t + 0.92403 d − 0.32943t^2 + 1.78534td
+ 0.94024d^2-0.03453t^3 + 2.87353t^2d + 0.09340td^2 + 0.08349d^3 + 0.25564t^4
- 0.74594 td^3 - 1.03368 t^2d^2 + 0.08354 t^3d - 0.389456d^4 (4)
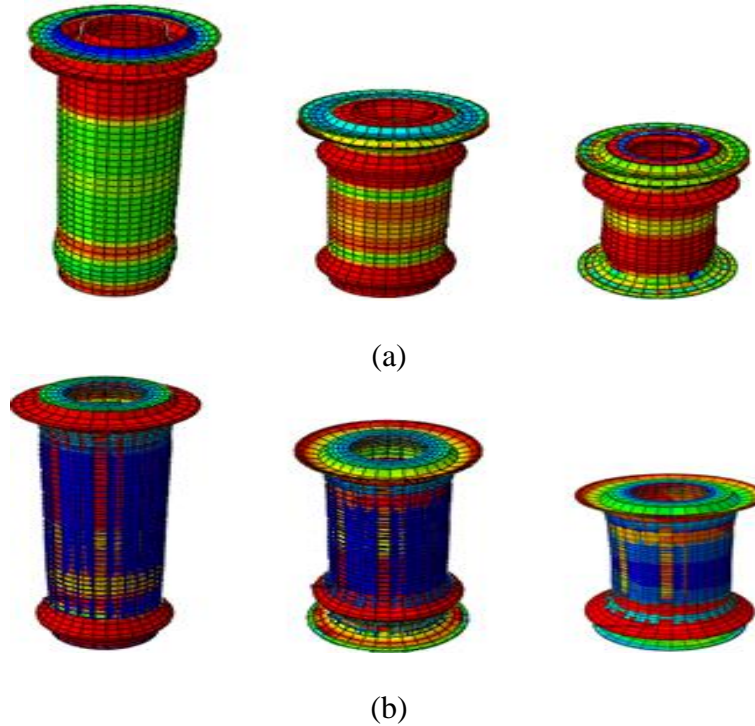
(a)

(b)

Figure 6. Deformation modes of (a) empty and (b) foam-filled circular tubes.
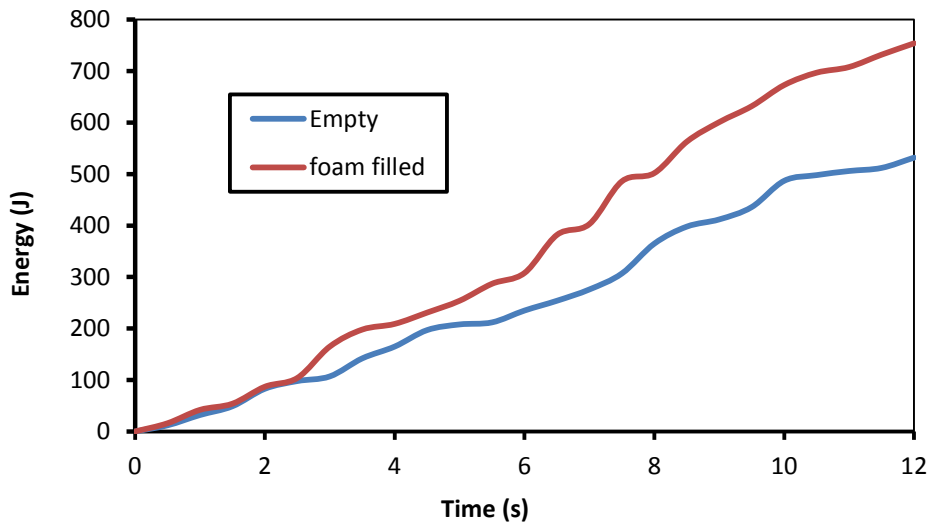

Figure 7. Energy vs time of the empty and foam-filled double circular tubes.

Figure 8 shows that the outcome of the circular point optimization represents the Pareto front solutions, which explains the trade-off between SEA and PCF. From Figure 8 it can be seen that the foam-filled structure has a lower PCF and more energy absorption capacity than the empty double tube, as in reference [22]. Table 2 shows the influence of the foam on the crashworthiness optimization results for the aluminum foam double tube. The maximum SEA value, and on the other side the minimum PCF value on axial impact, were investigated and the results shown in Table 2.

Table 2. Ideal optimum objective function for the double tube under axial impact loading.

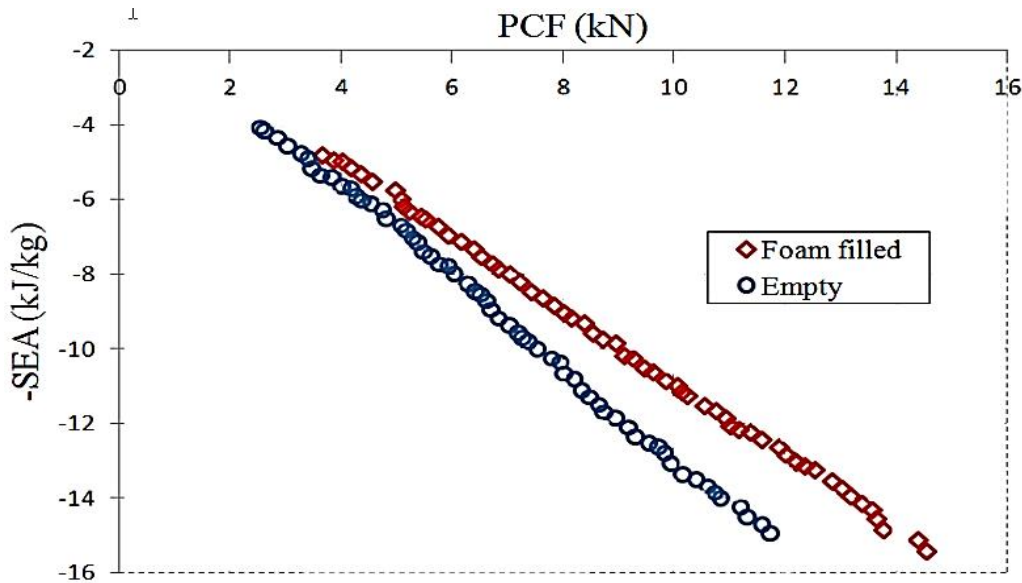| Double tube	Objective function	t [mm]	d [mm]	SEA[kJ/kg]	PCF[kN]
Empty	SEA	2.65	42.43	**14.97**	11.74
	PCF	2.64	40.67	4.07	**2.56**
Foam-filled	SEA	2.75	42.46	**15.43**	14.54
	PCF	2.19	40.15	4.83	**3.67**

Figure 8. Pareto fronts of PCF vs SEA for the double cylindrical tubes.

CONCLUSIONS

This paper presented the model and the optimization of aluminum foam cylindrical double tubes under axial impact loading by considering two tube structures. The FE model predicted the crashworthiness parameters of the tubes with great accuracy. The percentage difference in PCF and energy absorption between the experimental tests and the simulation were 1.42% and 0.11%. The multi-objective optimization equation was formulated to determine the maximum SEA and minimum PCF with different design variables, such as thickness and diameter of the tube walls. By using NSGA II, the optimum results showed that the crashworthiness capability of foam-filled double circular tubes (SEA = 15.43 kJ/kg) was better than empty (SEA = 4.97 kJ/kg). These results could be the foundation for designers to implement foam-filled double circular tubes, particularly as energy absorbers in automobile structures.

ACKNOWLEDGEMENTS

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