

# Optimization foam filled thin-walled structures for the crashworthiness capability: Review

F. Djamaluddin<sup>3</sup>, S. Abdullah<sup>12</sup>, A. K. Arrifin<sup>12</sup> and Z. M. Nopiah<sup>12</sup>

<sup>1</sup> Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia <sup>2</sup>Center of Automotive Research (CAR), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia <sup>3</sup>Department of Mechanical Engineering, Universitas Hasanuddin, Makassar, Indonesia.

## Abstract

In automotive industry, foam-filled structures have aroused increasing interest because of lightweight and capacity of energy absorption. Two types of foam filled thin walled structures such as the uniform foam filled (UF) and the functionally graded foam (FGF). To improve crashworthiness performance, FGF are used to fill structures, unlike existing uniform foam materials. In addition, by seeking for an optimal design systematically, some computational optimization signifies a more effective tool to find the best crashworthiness design of structures. This paper will an exhaustive review of the previous studies of simulation-based optimization such as metamodells, objective functions, design variables, design of experiments, optimization techniques of crashworthiness of tubes.

**Keywords:** *Foam filled, Optimization, Crashworthiness, Thin walled structures, Uniform structure*

## 1. Introduction

The structure of modern vehicles are expected to absorb more energy and at the same time minimizing mass. To achieve this design, foam material has shown outstanding ability in absorbing energy because of large deformations in loading nearly constant [1]. To improve the stability of collision and deformation modes of the structure thereby enhancing the overall crashworthiness, so foam filler material are used. The experiment of thin-walled tubes were investigated, it was found that the foam deformation mode with different of foam density [2]. Zhang et al [3] has been exploring of the structural designs of thin-walled room filled with aluminum foam. For the reason reducing not too much weight and increasing the crashworthiness capability, aluminum foam is the best criteria of material for automotive structures.

Conventional optimization requires a large number of iterations for an optimum form of limited practical value may, for example simulations of crash structure requires high computational cost. To address this problem, one of the most effective ways is to create a metamodel method based on finite element analysis [4]. Metamodel method can be derive the relationship objective function as output data from design variable as input data. It also expressions easier for optimization. Until now, there are some kind of metamodel that have been developed in

practical engineering. Different metamodel can provide the accuracy and the response is different [5].

Based on the brief introduction, this paper aims to review papers from reputable papers that study design optimization of crashworthiness for structures that filled by foam. Because of the capability in absorption energy, crashworthiness optimization design for Functionally Graded Foam (FGF) needs to more improve in future for in-stance its double structure under axial and oblique impact. The knowledge from review can be used to improve of the performance and utilization of structural materials using significant optimization in crashworthiness structures.

## 2. Crashworthiness of Foam Filled Structures

### 2.1 Uniform Foam (UF)

For collision and crash analysis, some crashworthiness structures study and compare to find the superior structures (Figure 1). Thus, the basic concept of this theory have been studied extensively before developing a system of energy absorption. Structures under axial impact were studied such as for foam filled square tubes, circular tubes, hat tube, rectangular tapered tube, conical tube were studied [6-10]. However, structure filled by foam under different load angle was analyzed for example the crash behavior of square, circular, conical tube [11-13] containing foam under oblique loading. The combination of tubes and foam filler that play a role

by changing the mode on the mode of failure is more effective for double tube [14-16].

## 2.2 Functionally Graded Foam (FGF)

In the previous study, the energy absorption performances of thin-walled structures having uniform thickness (UT) are extensively investigated. However, the UT tubes may not provide the best energy absorption capabilities. Indeed, the FGT enables to obtain variable stiffness along the structure [17]. As the new material, Functionally graded foam (FGF) depends on its density for its mechanical property. FGF proposes to absorb more energy and it is developed by density variation. However, in terms of design FGF more complex than UT. FGF has produced in laboratory by Kie-back et al. [18]. The crash capacity and characteristics of FGF was investigated [19] and it was concluded that the FGF can be perform more excellent than UT for the crashworthiness criteria. FGF filled tapered [20] as new type of foam was studied. It is limited published works discuss of FGF tube especially behavior using experimental and simulation solution under oblique impact [21].

## 3. Optimization of Crashworthiness Issues

Generally, engineering design involves many disciplines and one of them is multi-objective optimization associated with many types of disciplines. Problems of design commonly known as the optimization problem multiple objectives and need for simultaneous consideration of all the objective function to optimize a system. Many solutions and existing methodology for optimization especially optimization in component for the case related crashworthiness.

## 3.1 Crashworthiness Optimization for Bitubal Tube

It is increasing attention from the researchers, the advantage of bitubal tubes under oblique impact. To compared the energy absorption capacity of bi-tubular and tri-tubular configurations filled by tube of circular and square tubes by using simulation methode [22]. Using experimental and numerical solution testing, the bitubal tubes under bending conditions was investigated and it was indicated the superiority of the ability absorbing the energy [23]. In addition, with different arrangements under quasi- static axial compression loading using experimental and finite element analyses, Kashani [24] studied bitubular square thin-walled tubes. Li et al. [25] investigated the energy absorption of single and bitubal tube filled by foam under oblique loading. The crash capacity of foam-filled bitubular tubes is better than that of the empty and the single tubes.

Computer optimizations are used to attain the best and the more effective performance of crashworthiness of structures. The optimum of squared bitubal tube was studied by Zhang [26]. They depeloped the design of the crashworthiness optimization. it can be concluded that bitubal structure has a better crashworthiness than the foam-filled monotubal. The structure of foam filled double tube has a better crashworthiness than a single structure for automotive applications are studied by multi objective optimization design. Fang [27] performs the multiobjective robust design optimization (MORDO) method to explore the design of bitubal structures filled by foam. Futhermore, the optimization of the tubes under axial [28] and oblique [29] load and this bitubular structures can be implemented for the automobile bumper system.

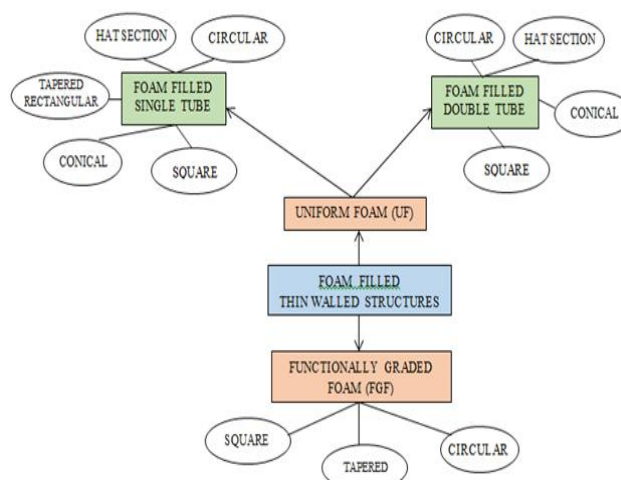


Fig1. Comparing of the UF and FGF structures

**Table 1.** The type of structures, materials, loading conditions and methods of crashworthiness tubes

Researchers	Structures	Materials	Loading Conditions	Design of Experiment	Meta model	Optimization Method
[38]	Square tubes	UF	Axial/Dynamic	D-optimal	Response surface method	Response surface method
[39]	squared columns	UF	Axial/Dynamic			Geometrical average method
[40]	Hexagonal columns	UF	Axial/Dynamic	polynomial functions	Response surface method	
[41]	Tapered circular tubes	UF	Axial/Dynamic	Factorial design Latin Hypercube Sampling	Response surface method	Particle swarm optimization
[42]	Tapered square tubes	UF	Oblique/Dynamic	Full factorial design	Response surface method	Particle swarm optimization
[26]	Double square column	UF	Axial/Dynamic	D-optimal	Kriging	
[37]	Square columns	UF	Oblique/Dynamic	D-optimal	Kriging	Non-dominated Sorting Genetic Algorithm II Particle swarm optimization
[43]	Square columns	FGF	Lateral/Dynamic	Full factorial design	polynomial functions	multiobjective particle swarm optimization
[44]	tapered tube	UF and FGF	Axial/Dynamic	Latin hypercube design	polynomial response surface	multiobjective particle swarm optimization
[46]	Square columns	FGF	Oblique/Dynamic	Full factorial design	radial basis function	Non-dominated Sorting Genetic Algorithm II multiobjective particle swarm optimization
[36]	conical tube	UF	Oblique/Dynamic	D-optimal	Kriging model	Non-dominated Sorting Genetic Algorithm II
[47]	Square columns	UF	Lateral/Dynamic	Latin Hypercube Sampling	Kriging model	Sequential quadratic programming
[48]	Square tube	UF	Axial/Dynamic	full factorial design	Response Surface Method	Non-dominated Sorting Genetic Algorithm II
[49]	Double circular tube	UF	Axial and Oblique/Dynamic	D-optimal	radial basis function	multiobjective particle swarm optimization
[50]	Double ellipse tube	UF	Axial and Oblique/Dynamic	D-optimal	Kriging Quartic polynomial functions	Non-dominated Sorting Genetic Algorithm II
[51]	ellipse tubes	UF	Oblique/Dynamic	D-optimal		

**Table 2** The type of optimization, objective functions and design variables of crashworthiness tubes

[47]	√		specific energy absorption initial peak force	thickness gradient thickness ranges
[48]	√	√	specific energy absorption mean crushing forces	Poisson's ratios
[49]	√		specific energy absorption peak crushing force	wall thickness
[50]	√		specific energy absorption peak crushing force	wall material yield stress variables of radial rate
[51]	√		specific energy absorption peak crushing force	foam density variables of radial rate
				foam density

**2 Crashworthiness Optimization of Tube under Oblique impact**

The vehicle collision happens in a combination of oblique (or off-axis) impacting direction in real world not only axial or transverse loads. The deformation mode of the tubes have been analyzed and some novel structures are proposed under the oblique loading has been analyzed and some novel structures. The Structure deformation as studied [30] It was found that a critical load angle in the transition place from the axial to the bending collapse mode. The foam-filled structures under different angle of load conditions. There was decreasing of the energy absorption as increasing loading angle [31-33]. Also the other structures such as tapered thin-walled rectangular tubes [34-35] and found it is better stability than the straight tube under oblique impact. In addition, foam-filled conical tubes as energy absorbers under oblique loads was analyzed [36]. The optimal foam-filled tube may have better crashworthiness under pure axial loading compare to the empty tube, but the optimal empty tube has more space to enhance the crashworthiness under oblique loading [37].

The optimization design especially the type of methods can be in table 1 and it continues to main

finding in table 2 for crashworthiness optimization issue on thin-walled structures.

**3. Conclusions**

The recent research trend concerning to the use of optimization of structures were provided an overview in this paper. The number of research papers that use optimization methods to solve impact and crashworthiness problems has increased dramatically in recent years and some researchers have solved multi-objective problems related to crashworthiness using some metamodel and optimization techniques for uniform functionally graded thickness foam filled structures especially for double structures under axial and oblique impact. Finally the crashworthiness design optimization of FGF filled double structure under axial and oblique impact will be explored in future work.

## References

- [1]. G Zheng, S Wu, G Sun, G Li, Q Li, Crushing analysis of foam-filled single and bitubal polygonal thin-walled tubes, *International Journal of Mechanical Sciences* 87 (2014) 226–240.
- [2]. H Kavi, A. Kaan Toksoy, Mustafa Guden, Predicting energy absorption in a foam-filled thin-walled aluminum tube based on experimentally determined strengthening coefficient, *Materials and Design* 27 (2006) 263–269.
- [3]. Y Zhang, G Sun, G Li, Z Luo, Q Li, Optimization of foam-filled structures for crashworthiness criteria, *Materials and Design* 38 (2012) 99–109.
- [4]. Shujuan Hou, Qing Li, Shuyao Long, Xujing Yang, Wei Li, Multiobjective optimization of multi-cell sections for the (2008) 1355–1367.
- [5]. H Yin, G Wen And N Gan, Crashworthiness Design For Honeycomb Structures Under Axial Dynamic Loading, *International Journal of Computational Methods Vol Vol. 8, No. 4* (2011) 863–877
- [6]. A.G. Hanssen, M. Langseth, O.S. Hopperstad, Static and dynamic crushing of square aluminium, extrusions with aluminium foam filler, *International Journal of Impact Engineering* 24 (2000) 347–383
- [7]. S. Santosa, T Wierzbicki, Arve G. Hanssen, M Langseth, Experimental and numerical studies of foam filled sections, *International of Impact Engineering* 24 (2000) 509–534
- [8]. Halit Kavi a, A. Kaan Toksoy a, Mustafa Guden, Predicting energy absorption in a foam-filled thin-walled aluminum tube based on experimentally determined strengthening coefficie , *Materials and Design* 27 (2006) 263–269
- [9]. Qingchun Wang, Zijie Fan, Liangjin Gui Theoretical analysis for axial crushing behavior of aluminium foam-filled hat sections, *International Journal of Mechanical Sciences* 49 (2007) 515–521
- [10]. Ahmad Z, Thambiratnam DP. Dynamic computer simulation and energy absorption of foam-filled conical tubes under axial impact loading *Computers and Structures* 2009;87:186–97.
- [11]. A. Reyes, M. Langseth, O.S. Hopperstad, Crashworthiness of aluminum extrusions subjected to oblique loading: experiments and numerical analyses, *International Journal of Mechanical Sciences* 44 (2002) 1965–1984
- [12]. Borvik T, Hopperstad OS, Reyes A, Langseth M, Solomos G, Dyngeland T. Empty and foam-filled circular aluminium tubes subjected to axial and oblique quasi static loading. *Int J Crashworthiness* 2003;8(5):481–94.
- [13]. Z. Ahmad, D.P. Thambiratnam, A.C.C. Tan, Dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading, *International Journal of Impact Engineering* 37 (2010) 475–488
- [14]. Guo LW, Yu JL, Li ZB. Experimental studies on the quasi-static bending behavior of double square columns filled with aluminum foams. *Acta Mech* 2010;213:349–58.
- [15]. Djamaluddin F, Abdullah S, Ariffin AK, Nopiah ZM. Multi objective optimization of foam-filled tubular circular tubes for quasi-static and dynamic responses. *Latin Am J Solid Struct* 2015;12:1126–43.
- [16]. F. Djamaluddin, S. Abdullah, A.K. Ariffin, Z.M. Nopiah Non-linear finite element analysis of bitubal circular tubes for progressive and bending collapsesNon-linear finite element analysis of bitubal circular tubes for progressive and bending collapses, *International Journal of Mechanical Sciences* 99 (2015) 228–236.
- [17]. Li G, Zhang Z, Sun G, Huang X, Li Q. Comparison of functionally-graded structures under multiple loading angles. *Thin-Walled Structures* 2015;94:334–347.
- [18]. B. Kieback, A. Neubrand, H. Riedel, Structural materials properties micro- structure and processing, *Int. J. Mater. Sci. A* 362 (1–2) (2003) 81–105.
- [19]. Li G, Xu F, Sun G, Li Q. A comparative study on thin-walled structures with functionally graded thickness (FGT) and tapered tubes withstanding oblique impact loading. *International Journal of Impact Engineering* 2015;77:68–83.
- [20]. H. Yin, G. Wen, H. Fang, Q. Qing, X. Kong, J. Xiao, Zh Liu, Multiobjective crashworthiness optimization design of functionally graded foam-filled tapered tube based on dynamic ensemble metamodel, *Mater. Des.* 55 (2014) 747–757.
- [21]. [21]Xu F. Enhancing material efficiency of energy absorbers through graded thickness structures. *Thin-Walled Structures* 2015;97:250–265.
- [22]. Zhang Y, Sun GY, Li GY, Luo Z, Li Q. Optimization of foam-filled bitubal structures for crashworthiness criteria. *Mater Des* 2012;38:99–109.
- [23]. Goel MD . Deformation, energy absorption and crushing behavior of single-, double- and multi-wall foam filled square and circular tubes. *Thin Wall Struct* 2015;90:1–11 .
- [24]. Guo LW , Yu JL . Bending behavior of aluminum foam-filled double cylindrical tubes. *Acta Mech* 2011;222:233–44 .
- [25]. Haghi Kashani M , Shahsavari Alavijeh H , Akbarshahi H , Shakeri M . Bitubular square tubes with different arrangements under quasi-static axial compression loading. *Mater Des* 2013;51:1095–103
- [26]. Li ZB, Yu JL, Guo LW. Deformation and energy absorption of aluminum foam- filled tubes subjected to oblique loading. *Int J Mech Sci* 2012;48–56.
- [27]. Zhang Y, Sun GY, Li GY, Luo Z, Li Q. Optimization of foam-filled bitubal structures for crashworthiness criteria. *Mater Des* 2012;38:99–109.
- [28]. Jianguang Fang, Yunkai Gao,, Guangyong Sun, Yuting Zhang, Qing Li, Crashworthiness design of foam-filled bitubal structures with uncertainty

- International Journal of Non-Linear Mechanics 67 (2014) 120–132
- [29]. F. Djamaluddin, S. Abdullah, A. K. Arrifin and Z. M. Nopiah Modeling And Optimization Of Aluminum Foam Cylindrical Double Tubes Under Axial Impact, Journal of Mechanical and Science 2014
- [30]. Djamaluddin F, Abdullah S, Ariffin AK, Nopiah. ZM. Multi objective optimization of aluminum foam filled double tubes subjected to oblique impact loading for automobile bumper beam. Appl Mech Mater 2014;663:93–7
- [31]. Han DC, Park SH. Collapse behavior of square thin-walled columns subjected to oblique loads. Thin-walled Struct 1999;35:167–84.
- [32]. Reyes A. Square aluminum tubes subjected to oblique loading. Int J Impact Eng 2003;28:1077–106.
- [33]. Reyes A, Langseth M, Hopperstad OS. Crashworthiness of aluminum extrusions subjected to oblique loading experiments and numerical analyses. Int J Mech Sci 2002;44:1965–84.
- [34]. Nagel G, Thambiratnam D. Computer simulation and energy absorption of tapered thin-walled rectangular tubes. Thin-Wall Struct 2005;43:1225–42.
- [35]. Nagel G, Thambiratnam D. Dynamic simulation and energy absorption of tapered thin-walled tubes under oblique impact loading. Int J Impact Eng 2006;32:1595–620.
- [36]. Z. Ahmad, D.P. Thambiratnam, A.C.C. Tan, Dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading, Int. J. Impact Eng. 37 (2010) 475–488.
- [37]. Yang S, Qi C. Multiobjective optimization for empty and foam-filled square columns under oblique impact loading. Int J Impact Eng 2013:177–91.
- [38]. Zarei H, Kröger M. Optimum honeycomb filled crash absorber design. Mater Des 2008;29:193–204
- [39]. Hou SJ, Li Q, Long SY, Yang XJ, Li W. Crashworthiness design for foam filled thin-wall structures. Materials & Design 2009;30(6):2024–32.
- [40]. Hou SJ, Li Q, Long SY, Yang XJ, Li W. Crashworthiness design for foam filled thin-wall structures. Materials & Design 2009;30(6):2024–32.
- [41]. Bi, J., Fang, H., Wang, Q., and Ren, X. (2010a). “Modeling and optimization of foam-filled thin-walled columns for crashworthiness designs.” Finite Elements in Analysis and Design, 46(9), 398-709.
- [42]. Sun GY, Li GY, Hou SJ, Zhou SW, Li W, Li Q. Crashworthiness design for functionally graded foam-filled thin-walled structures. Mater Sci Eng A 2010;527:1911e9.
- [43]. Shujuan Houa, Xu Hana, Guangyong Suna,b, Shuyao Long a, Wei Li b, Xujing Yanga, Qing Li Multiobjective optimization for tapered circular tubes Thin-Walled Structures 49 (2011) 855–863
- [44]. Yong Zhang, Guangyong Sun, Guangyao Li, Zhen Luoc, Qing Li Optimization of foam-filled bitubal structures for crashworthiness criteria, Materials and Design 38 (2012) 99–109
- [45]. Hanfeng Yin a,b, Guilin Wena,b,†, Shujuan Houa,b, Qixiang Qing, Multiobjective crashworthiness optimization of functionally lateral graded foam-filled tubes Materials and Design 44 (2013) 414–428
- [46]. Hanfeng Yin, Guilin Wena, Zhibo Liu, Qixiang Qing, Crashworthiness optimization design for foam-filled multi-cell thin-walled structures Thin-Walled Structures 75 (2014) 8–17
- [47]. Hanfeng Yin, Youye Xiao, Guilin Wena, Qixiang Qing, Yufeng Deng, Multiobjective optimization for foam-filled multi-cell thin-walled structures under lateral impact, Thin-Walled Structures 94 (2015) 1–12
- [48]. Guangyao Li, Zheshuo Zhang, Guangyong Sun, Xiaodong Huang, Qing Li, Comparison of functionally-graded structures under multiple loading angles Thin-Walled Structures 94 (2015) 334–347
- [49]. Djamaluddin F, Abdullah S, Ariffin AK, Nopiah ZM. Optimization of foam-filled double circular tubes under axial and oblique impact loading conditions. Thin-walled Struct 2015;87:1–11.
- [50]. Qiang Gao, Liang Wang, Yuanlong Wang, Chenzhi Wang, Crushing analysis and multiobjective crashworthiness optimization of foam-filled ellipse tubes under oblique impact loading, Thin-Walled Structures 100 (2016) 105–112
- [51]. Qiang Gao, Liangmo Wang, Yuanlong Wang, Fuxiang Guo, Zunzhi Zhang, Optimization of foam-filled double ellipse tubes under multiple loading cases, Advances in Engineering Software 99 (2016) 27–35