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Optimization of Foam-Filled Square Thin-Walled Aluminium Structures

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Abstract. Crash box are the structural part designed to absorb energy during crash and minimize the injury to passengers. Various design of energy absorbers has been introduced to unleash design with the best crashworthiness behavior. Foam-filled structures are one of the promising designs. In this study, foam-filled structure was investigated to increase the energy absorption capability and reduce the initial peak force simultaneously. Since most foam-filled structures tend to absorb more energy with high peak force, optimization of the energy absorbers is significant in obtaining the optimum design. Response surface methodology (RSM) has been dominant technique in crashworthiness optimization mainly because of it provides efficient and accurate solution. This paper focused on the optimization foam-filled columns with respect to thickness of the tube and length of foam to enhance energy absorptions and reduce initial peak force. The optimization results suggested by Design Expert software for impact test is 515.9 J for EA and 134.94kN for IPF value with the column thickness of 2.0mm and foam length of 185mm. For quasi-static test, the optimum solution value for EA and IPF are 864.5J and 88.33kN respectively with column thickness of 1.87mm and foam length of 200mm.

Keywords ***: optimization, energy absorption, initial peak force, foam-filled column***

I. INTRODUCTION

Aluminium thin-walled structure has been used as a crash box as it can dissipate energy excellently. This paper was divided into 4 major part. Part 1 gives an overview of the design of empty and foam-filled structures and the energy absorption capability of the design. Part 2 describes the design and experimental procedure, consists of specimen preparation and optimization method of foam-filled structure under quasi-static and dynamic loading. Later, part 3 presents and discusses the experimental results of the structures together with the optimization results and finally the conclusion was describing in part 4

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The energy absorption capability must be high and initial peak force should be sufficiently low and the fluctuation should be in controlled manner to avoid the impact from causing injury to the passenger[1]. Uma Devi et al have conducted a simulation study to find an optimum cross sectional shape of a crash box to ensure high capability for energy absorption without crash beads [2]. There are few research papers that compared the performance of structures in different cross-sections such as circle [3], square [4] and polygonal [5] under different impacting velocities. Haorongbam et al. found that energy absorption capacity of all the double hat-section is better than the single hat-section[6]. Moreover, the carbon fiber reinforced plastics (CFRP) has gain much attention due to remarkable structure and performance.[7]

Instead of varies in cross-section, a few design have been introduced to enchance the performance of crashworthiness structure such as multi-cells structures, functionally graded thickness structures and corrugated tubes [8]. Alavi Nia and Parsapour [9] compared experimental and simulation results of multi-cell with triangular, square, hexagonal and octagonal sections. Results shown that all the multi-cell had greater specific energy absorption (SEA) in comparison with the simple structure. Xie et al developed 5 structures with different arrangement of the interior tube walls and connectivity with the exterior tube walls [10] and concluded that the crushing force and energy absorption influenced by the sectional form of the structure. The study was extended by Fang et al [11] by introducing the functionally graded thickness to multi-cell tubes. The simulation results shown that the functionally graded thickness tubes have higher energy absorption capability than the uniform tubes. Figure 1 shows the design of multi-cell and corrugated tubes introduced to enhance the energy absorption capability of the structure.

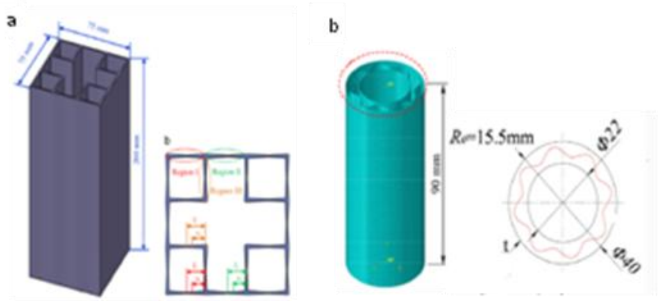


Fig. 1.Configuration of the (a) functionally graded multi-cell tube [11]and (b) the sandwich sinusoidal lateral corrugated tube [25]

Then An et al [12] found that under axial crushing condition, specific energy absorption of functionally lateral graded thickness tubes are always greater than those of uniform tubes. Apart from that, a quasi-static axial crushing experiments conducted by Zheng et al.[13] has similar conclusion that laterally variable thickness multi-cell tubes is better compared to the uniform tubes. Later, a study conducted by Sun et al.[14] proven that tubular structures with graded thickness was remarkable compared to uniform counterparts under axial loading. Besides multi-objective optimization shown that graded thickness structure achieves high SEA and low initial peak force (IPF).

The study on corrugated tubes demonstrated that the energy absorption capacity of structures could be increased by using the corrugation design. Corrugation design is development folds in rows of wavelike or basically formed into a series of regular folds that appears like waves[15]. Experimental study by Eyvazian et al [16] proven that deformation mode of the corrugated metal tubes are more stable and controllable. Besides, the corrugation has succeeded in reducing the initial peak force of the metal tube. Deng and Liu [17] carried out the crashworthiness study on sandwich sinusoidal lateral corrugated (SSLC) tubes and optimization showed that the maximum crushing force and SEA can be reduced compared to that of the single tubes. The truncated conical sandwich shell with corrugated was fabricated and optimized by Yang et al [18] has shown great potential to be applied as crashworthiness structure. Deformation mode of the TCSS shown an additional plastic hinges due to strong interaction effect of the face sheet and the core which relates with the excellent energy absorption capacity

However application of thin-walled structures as crash box have led to existence of undesirable IPF and the fluctuation in force-displacement curve when subjected to non-axial loadings[19]. The instability problem in a thin-walled structure has evoked the application of polyurethane as a filler in the structural member. Polyurethane are unique polymer material with wide range of physical and chemical properties that is widely used in energy absorption's application such as in passive safety mechanism in automotive industries. It has the ability to absorb energy while deforming due to the mechanics of cell crushing[20] Polyurethane foam-filled structure may compensate irregular overall buckling and the unstable effect during crushing process[21]. Besides, foam-filled thin-walled tubes were introduced to enhanced the energy absorption while maintaining the mass of the vehicle. This is because the foam helps to support the energy absorption capability of the structure [22]. It was supported by a study conducted by Hussien et al that found the specific energy absorption of foam-filled structure was higher compared to hollow one [1]. Similar results gained by Yan et al in the study on lateral crushing of polyurethane foam-filled natural flax fabric reinforced epoxy composite tubes [23].

Hanssen et al [24] has proven that insertion of foam inside the foam-filled structure significantly increases the energy absorption capability of the thin-walled column but concurrently increases the initial peak force. This was supported by Song et al. [25] that concluded that the energy absorption of foam-filled structure is higher than the sum of energy for the foam and the hollow structure individually. The foam is functioned as an elastic foundation for the tube walls to minimize the local buckling distance and allow extra progressive folds to be generated[26]. Furthermore, Yan et al [27] has proven that foam-filled corrugated sandwich can increased substantially the mean crushing strength and energy absorption capacity of the beam. Other than that, this design has altered the failure mode and increased the bending resistance of the metallic beams. Similar results obtained by Mahbod and Asgari [28] shown that foam-filled corrugated tubes has improved the energy absorption capacity in axial and oblique loading condition. The study also proven that by increasing the foam density, the SEA of the tubes has increased simultaneously while crushing force efficiency decreased. The crushing behavior of polygonal structures were optimized using RSM by Liu [29]. Thickness of the tubes and cross-section edge length were chosen as input factor for the response of maximum SEA. In other paper, the optimization of a square crash box with multi-cell design to maximize the energy absorption and minimize the peak force conducted using RSM [30]. Several objective functions have been evaluated including linear, quadratic, cubic, quartic and quintic polynomial and the quartic polynomial function produces the best fit RS model. Study conducted by Fang et al [31] found that response surface methodology (RSM) is capable in producing fit approximation models for energy absorption and the suitability of the model can be predicted using ANOVA. The objective of this study was to optimize foam-filled structures in term of thickness of the tube and length of foam to increase energy absorptions and reduce initial peak force. This study proposes foam-filled tubes with 5 different configurations of foam length and two different thicknesses of tube in order to offer better energy absorption and lower initial peak force compared to the full-filled tubes. Quasi-static and impact test were conducted for all the specimen. The experimental data were optimized using response surface model to achieve maximum energy absorption with minimum initial peak force.

II. METHODOLOGY

The flow of the research works has been simplified in the flow chart in Figure 2

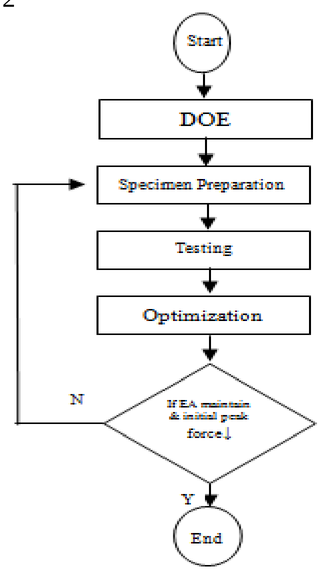


Fig. 2. Methodology flow chart

A. Preparation of specimen

Square column with dimension 80mm x 80mm x 200mm with 1.4 mm and 2.0mm thickness were prepared as energy absorber. Both types of these energy absorbers were filled with foam that have been prepared and cut into the desired length. Table 1 represents the configuration of each specimen. Thin-walled square structures were made of aluminium alloy AA6063. The specimens were test under quasi-static and dynamic loading condition to determine the EA and IPF achieved by each configuration.

Table- I: Notification of specimen

Notification	*Column thickness*	*Foam length*
A1.4P0	1.4	No foam
A1.4P185	1.4	185
A1.4P190	1.4	190
A1.4P195	1.4	195
A1.4P200	1.4	200
A2.0P0	2.0	No foam
A2.0P185	2.0	185
A2.0P190	2.0	190
A2.0P195	2.0	195

B. Index of crashworthiness

The crushing behaviour of the thin-walled square structures can be analysed regards to various parameter such as the IPF (initial peak force), MCF (mean crushing force), EA (energy absorption), and SEA (specific energy absorption). Some of these indices are described in Table II.

Table- II: Notification of specimen

Parameter	*Symbol*	*Description*
Initial peak force	IPF	relates to the first point at which force is highest for first fluctuation in load-displacement curve
Energy absorption	EA	area under the force-displacement curve.
Mean crushing force	MCF	is achieved by dividing the energy absorption with the displacement
Specific energy absorption	SEA	energy absorbed per unit mass

C. Experimental setup

The Universal Testing Machine apparatus was used to conduct quasi-static axial loading. The test was performed at a rate of 6 mm/ min. Specimens will be axially deformed between two parallel steel flat platens consists of fixed and moving platens. The fixed platen was connected with a load cell where the load signal was taken directly to the computer. The specimens were crushed up to 70% of the length. The impact test was performed using Dynatup drop weight impact tester.

III. RESULTS AND DISCUSSION

A. Optimization methodology

RSM has been dominant technique in crashworthiness optimization mainly because of it provides efficient and accurate solution. Besides, analysis of variance (ANOVA) can be used to predict model suitability before it can be implemented in design optimization[31]. As an energy absorber, the foam-filled structure is required to absorb maximum impact energy. Thus, the energy absorption should be an objective function and be maximized from the optimization perspective. While, the initial peak force of the structure is another significant parameter that relates to the safety of the passenger, which should be minimized.

The response surface model was formulated based on historical data method using two levels for two central points in Design Expert software. This research was focused on two parameters which is thickness of the thin-walled tube that were 1.4mm and 2.0 mm and length of foam that ranged from 185mm to 200mm.

Response surface model was conducted to the experimental data using statistical software named Design-Expert. The RSM prepared an effective method of formulating estimated functions for unknown responses using linear, quadratic, or higher-order polynomials. The commonly used response surface models are those using linear or quadratic polynomials.

Generally, it is a bit challenging to formulate the mathematical relationship between SEA and IPCF by taking into account the material properties, nonlinearities geometry, and contact-impact nonlinearities [32]. A few techniques are suggested for example the RSM to considered those effects of suitable parameters in designing energy absorbers [28]. The design parameters are stated mathematically as below.

$$y(x) = \sum_{i=1}^{p} \beta_i \varphi_i(x) \quad (1)$$

where p indicates the quantity of basic functions, while β_i is the unknown coefficient to be measured. The coefficients $b = (\beta_1, \beta_2, \dots \beta_n)$ of the polynomial terms can be determine by employing the least-square method,

$$b = (\Phi^T \Phi)^{-1}(\Phi^T y) \quad (2)$$

where Φ is a matrix composed of basic functions $\varphi_i(x)$ assessed at these M design sampling points and can be presented as:

$$\Phi = \begin{bmatrix} \varphi_1(x^1) & \cdots & \varphi_n(x^1) \\ \vdots & \ddots & \vdots \\ \varphi_1(x^M) & \cdots & \varphi_n(x^M) \end{bmatrix} \quad (3)$$

By substituting Eq. (3) into Eq. (4), the coefficient vector $b = (\beta_1, \beta_2, \dots \beta_n)$ can be measured.

B. Analysis of variance (ANOVA)

In this study, ANOVA was conducted to identify the effect of length of foam and thickness of the thin-walled structure in numerical intensity to energy absorption capability and initial peak force. Each output response was analyzed individually for the for both input factors.

Table for ANOVA acquired by using Design-Expert software consists of value of sum of square which is a variables that emerges as part of a general approach to present outcomes of such analysis, mean square which is a measurement of the quality for an approximation, F-value is obtained with by dividing two mean squares and decides the ratio of explained variance to unexplained variance, P-value which is the level of significance limits within a statistic hypothesis test to present the probability of the of a studied case[28]. For the model to be significant, the P-value shall not more 0.05. The estimation of value EA and IPF acquired from the response functions and experimental results. The values of sum of square, mean square, R^2, R^2-adj, p-value and F-value can be observed in Table III for quasi-static test and Table IV for impact test. Suitability of the RS model can be measure by the larger values of R^2 and R^2-adj (almost 1).

Table- III: ANOVA table for quasi static test

Output response	Source	Sum of squares	Mean square	F-value	P-value	R^2	adj-R^2	pred-R^2	
QS-EA	Model	205500	68496	433.39	<0.0001	0.9969	0.9946	0.986	significant
	Length	51825.6	51825.6	327.91	<0.0001				
	Thickness	134900	134900	853.47	<0.0001				
	Residual	632.19	158.05						
	Std. Dev	12.57	C.V. %		1.95				
	Mean	643.8	PRESS		2885.6				
QS-IPF	Model	6765.5	3382.75	479.97	< 0.0001	0.9948	0.9927	0.9858	significant
	Length	198.92	198.92	28.22	0.0032				
	Thickness	6566.58	6566.58	931.72	< 0.0001				
	Residual	35.24	7.05						
	Std. Dev	2.65	C.V. %		4.08				
	Mean	65.08	PRESS		96.54				

Table- IV: ANOVA table for impact test

Output response	Source	Sum of squares	Mean square	F-value	P-value	R^2	adj-R^2	pred-R^2	
IMP-EA	Model	165900	82963.05	2739.86	< 0.0001	0.9991	0.9987	0.9974	significant
	Length	1188.1	1188.1	39.24	0.0015				
	Thickness	164700	164700	5440.49	< 0.0001				
	Residual	151.4	30.28						
	Std. Dev	5.5	C.V. %		1.42				
	Mean	388.75	PRESS		439.44				
IMP-IPF	Model	5614.62	2807.31	57.15	0.0004	0.9581	0.9413	0.8844	significant
	Length	910.12	910.12	18.53	0.0077				
	Thickness	4704.5	4704.5	95.77	0.0002				
	Residual	245.6	49.12						
	Std. Dev	165900	82963.05	2739.86	< 0.0001	0.9991	0.9987	0.9974	significant
	Mean	1188.1	1188.1	39.24	0.0015				

- **ANOVA of energy absorption responses for quasi-static and impact test.**

For quasi-static test, energy absorption obtained a linear model solution. The p-value is smaller than 0.05 indicates that the model term is significant. Value of R^2 shown the outcome of any input factor studied in the model, that influence the effect in the output responses. While value of R^2-adj specify the actual outcome of the model input factor on the output responses. The higher value of R^2-adj and its accuracy to the R^2 value suggest the desirability of the output model projection. Value of R^2 is 0.9969 is in reasonable agreement with the R^2-adj which is 0.9946. The higher value of R^2 relates to the higher accuracy of the RS model. Therefore, for EA, two factor interaction (2FI) is found to be the best approximation compared to other response functions.

The equation in terms of actual factor obtained for the energy absorption response in quasi-static test is stated in Eq. (4).

$$EA^{qs} = 6589.53 - 34.71L - 5127.85t + 28.89Lt \quad (4)$$

While in impact test, value of R^2 is 0.9991 is in reasonable agreement with the R^2-adj which is 0.9987. Similar to Tran[33] study ,linear function is found to be the best approximation for EA. The equation in terms of actual factor obtained for the energy absorption response in impact test is stated in Eq. (5)

$$EA^{imp} = -844.07 + 2.18L + 478.33t \quad (5)$$

- **ANOVA of initial peak force responses for quasi-static and impact test.**

The results for the IPF response of both quasi-static and impact test led to a linear model with a relationship between length of foam, L and thickness, t. Value of R^2 for quasi-static test is 0.9948 is in reasonable agreement with the R^2-adj which is 0.9927. It indicates the output model ability to predict the response behavior. Model is defined as significance condition when value of $p< 0.05$. While for IPF in quasi-static test, the linear function should be used for the optimum design. The equation in terms of actual factor was obtained as Eq. (6)

While in impact test, value of R2 is 0.9581 is in reasonable agreement with the R^2-adj which is 0.9413. Linear function is found to be the best approximation compared to other response functions. The equation in terms of actual factor obtained for the energy absorption response in impact test is stated in Eq. (7)

$$IPF^{qs} = -268 + 0.89L + 95.55t \quad (6)$$

$$IPF^{imp} = -379.71 - 1.91L + 80.83t \quad (7)$$

C. Validation of the RS models

Figure 3 shown a scatter diagrams for the distribution of the actual values acquired from the experiment vs the predicted values from output model for each output response. From the diagram, the distribution of the point that located near the diagonal line reflects the model ability to predict the response trends

D. Crashworthiness optimization for quasi-static test

The experimental data used in this study can be observed clearer in Figure 3 that shows the variation in EA and IPF respectively with thickness and length. It shown that that both EA and IPF increase with the increment in thickness. Moreover, the EA and IPF displays the decrease trends with decreasing of length of foam. As for in this study, the structure is optimized with the length and thickness as the input factor and EA and IPF as the output response formulated in Equation 1. EA and IPF are modeled by the linear polynomials. RS approximation approach as in [35] has been adopt to obtain the better responses. The optimum solutions for quasi-static test are shown in Table-V, there are 4 design solution were suggested. But according to the desirability value, the first solution with 200mm length of foam and 1.87mm thickness were selected to obtain 864.5 J of EA and 88.3 kN of IPF. The optimum results for EA and IPF for quasi-static test can be observed in in Figure 4.

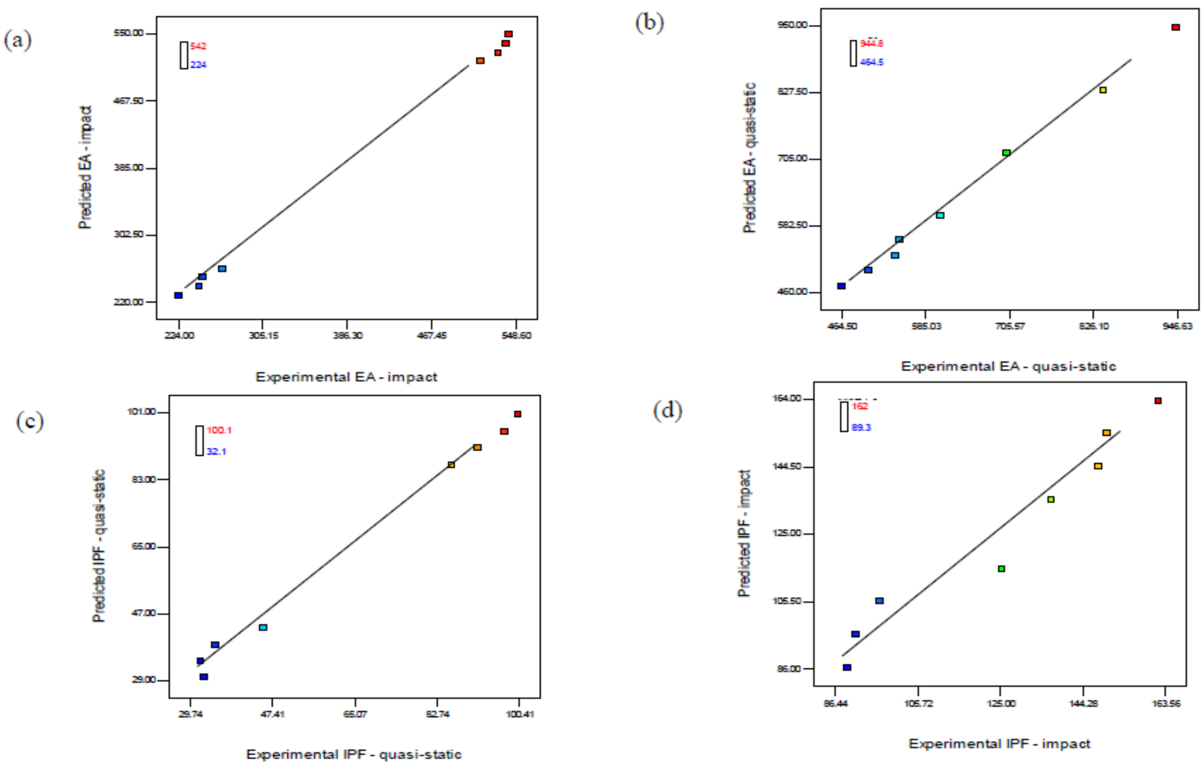


Fig. 3. Predicted versus experimental graph (a) Energy absorption response (quasi-static), (b) Energy absorption response (impact), (c) Initial Peak Force response (quasi-static), (d) Initial Peak Force response (impact)

Table- V: Design solution given by Design Expert software for quasi-static test

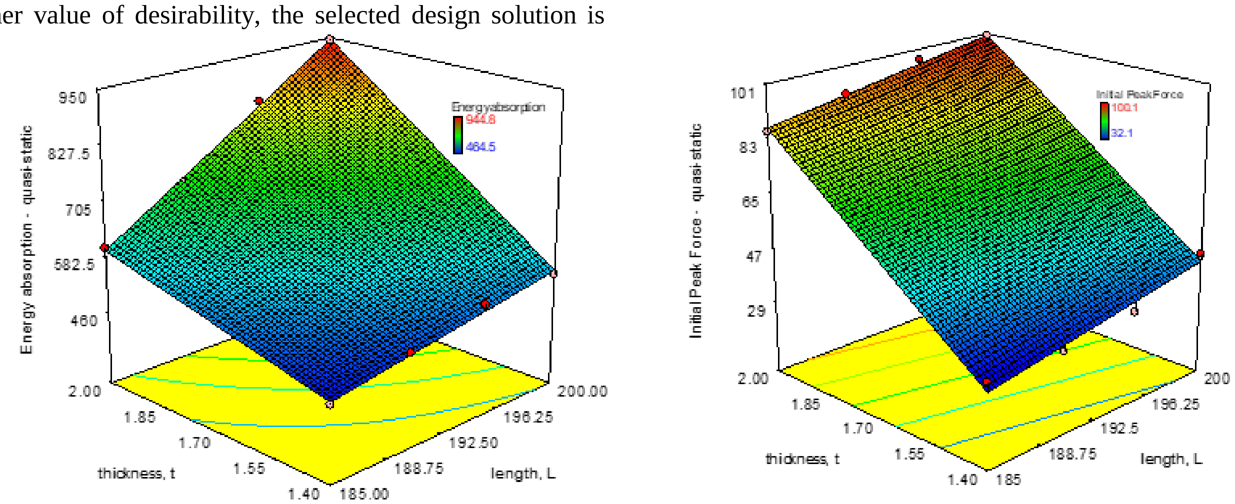
Solution	Length (mm)	Thickness (mm)	EA (J)	IPF (kN)	Desirability
1	200	1.87	864.47	88.33	0.641
2	200	1.88	865.85	88.54	0.641
3	200	1.87	862.69	88.08	0.641
4	200	1.88	868.60	88.94	0.641

E. Crashworthiness optimization for impact test

The same optimization process as in above section was conducted for impact test, the optimum design variables for the test are summarized in Table VI. There are 4 configurations of length and thickness are suggested for impact test for the optimum value of EA and IPF. But for the higher value of desirability, the selected design solution is 185mm of foam length with 2.0 mm thickness of the column to achieve the optimal value of EA and IPF which is 515.9J and 134.94kN respectively. Variation of thickness and length of foam with EA and IPF were shown in Figure 5

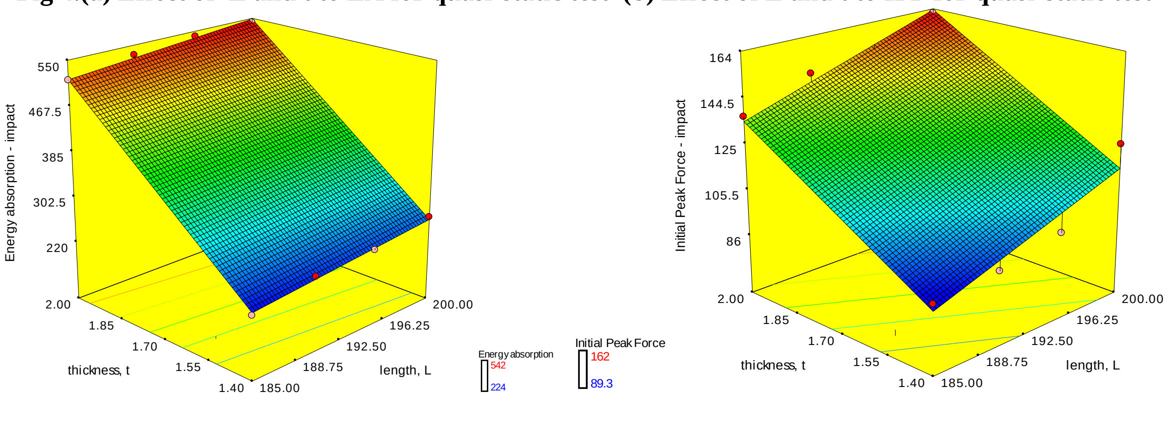
Table- VI: Design solution given by Design Expert software for impact test

Solution	Length (mm)	Thickness (mm)	EA (J)	IPF (kN)	Desirability
1	185	2	515.9	134.94	0.79
2	185.08	2	516.08	135.1	0.789
3	185	2	514.64	134.73	0.788
4	185	1.99	512.82	134.42	0.785



(a) (b)

Fig 4.(a) Effect of L and t to EA for quasi-static test (b) Effect of L and t to IPF for quasi-static test



(a) (b)

Fig 5.(a) Effect of L and t to EA for impact test (b) Effect of L and t to IPF for impact test

IV. CONCLUSION

This paper discussed optimization design for foam-filled square tubes subjected to quasi-static and impact test. The maximum of EA and minimum IPF are considered as the objective function. By using historical data design from experimental, it was found that the value of EA and IPF were much affected by the thickness of tubes and length of foam that filled in the tubes. Therefore, thickness and length of foam were selected as the input factor for the optimization.

Response surface method (RSM) was used to produce response functions of EA and IPF.
The optimization showed that the optimum EA and IPF for quasi-static was found to be 864.47J and 88.33kN respectively for foam length of 200mm and thickness of 1.87mm. While for impact test, the optimum value of EA is 515.9J with IPF of 134.94kN for foam length of 185mm and thickness of 2.0mm.

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