Optimization of Graded Metallic Foam Subjected to Impulsive Loading through DOE Approach

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Abstract – The purpose of this study is to use Design of Experiment (DOE) method to optimize the design of graded metallic foam under impulsive loading. Using aluminum foams with different densities the configuration of the aluminum layers is changed whilst keeping the sandwich structure weight constant. The effects of thickness of steel face sheets and the distance of impulse source were considered. The finite element trial models were designed using the multi-level factorial Design of Experiment method and the results were studied using Analysis of Variance. The statistical models were able to predict the relationship between layer configuration as independent variable, and maximum permanent deflection and internal energy as response variables. The proximity of predicted results and finite element results provides evidence the success of the DOE method in deriving predictive models.

Keywords – Design of Experiment, dynamic response, Finite Element model, graded metallic foam

I. INTRODUCTION

Metallic composite structures are used widely in many engineering applications such as aviation industry, railway industry and naval engineering [1,2]. Lightweight properties, high specific strength and high specific energy absorption are the reason for using this kind of structure. Sandwich panel is a class of composite panel which is made of two thin and stiff skin plates and a thick softer core [3-6]. Many studies have been performed to investigate the effect of using different types of foam, such as soft foam, honeycomb or truss core [7-9]. Metal foam with high porosity, low density and high impact resistance is another type of core that is used in order to create functionally graded materials (FGM) [10]. Aluminium, steel, nickel, lead, titanium, copper, and magnesium foam are the most common metallic foams used in previous studies [11-13]. Aluminium foam has a good balance between mechanical properties, availability and cost. The impact resistance of different metallic sandwich structures was compared with the laminate plate and it has been reported that the sandwich structures with the same weight have higher impact resistance compared to solid plates [2,3].

Several studies have been carried out to develop analytical model for evaluating the dynamic responses of clamped sandwich structures under shock wave. They found three different stages of response, namely fluid-structure interaction, core crushing and stretching. Subsequently, a hierarchical structure was proposed to increase the impact resistance of the lightweight structures. Some studies have been performed on the development of analytical models for multiscale hierarchical materials [14,15]. FGMs are the typical materials to obtain hierarchical composite structures. The results of previous studies show that the benefit of the FGMs when subjected to impulsive load is the introduction of a time delay for propagation the shock wave and this delay leads to higher dynamic energy absorption [16,17].

In many studies, the FGM structure has been designed for some particular tests, however, the FGM configuration does not essentially guarantee the best performance and there is a need to develop the optimal design of a FGM structure [13]. Optimization techniques through computational design can ensure the best composition and structure, resulting in the best functioning FGM sandwich plate [18]. The optimal design of FGM requires defining the main design variables and determining their possible interactions, which cannot be simply evaluated by conventional methods. Design of Experiment (DOE) method is a well-known optimization technique to design a set of experiments that requires a minimal number of runs to be performed and still be able to obtain all the necessary information. It can determine the factor levels that will simultaneously satisfy a set of desired specifications [19]. In this study, a FGM sandwich plate having constant weight with a different relative density of foam as the core and different skin thickness was fabricated. In order to characterize the significant parameters of the structure under impulsive loading, a multi-objective optimization DOE approach was performed and the best design is recognized. The DOE approach identifies the best configuration of the particular FGM structure.

II. METHODS AND MATERIAL

A. *Finite Element Model*

The finite element model (FEM) in the current study operates in two different media. The first medium is air and the blast will occur in the air domain. The shock wave can move freely within the domain. The second medium is made up of continuum Lagrangian elements which are applied to the aluminum foams and face sheets. The air domain is meshed using Eulerian 8-node solid elements. The flat cubic charge is surrounded by air meshed by elements which match node-to-node at the boundary between the charge and air. Lagrange elements and Euler elements are coupled through Arbitrary Lagrange Euler (ALE) approach which is suitable while the high speed deformation of elements is considered [20]. After performing a mesh convergence analysis, a feature mesh size of 5 mm was determined to be optimal for both the shell and solid elements. The size also provides a balance between numerical stability requirement, the accuracy of the FEA results and the computational efficiency [21]. The fine mesh resulted in the number of elements for structure being 12800 while the surrounding air has 251850 elements. Figure 1 shows the FE model with applied boundary condition and surrounding air medium.

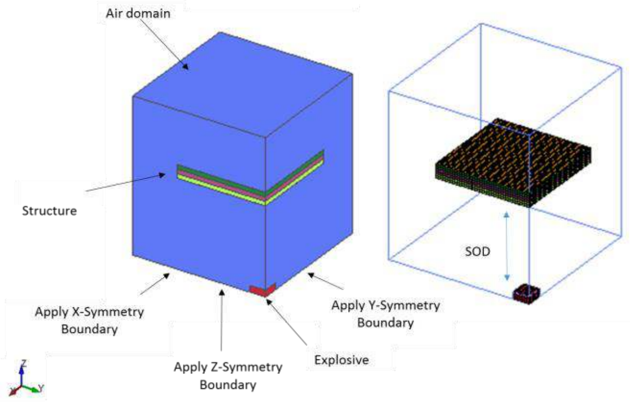

Fig 1. (a) FEM model with constraints. (b) Surrounded air mesh masked for a better view of structure

Due to the symmetry of the structure and loading only a quarter of the sandwich panel is considered (see figure 1). The size of each core plate is 200×200×10 mm (one-quarter of real size) and the size of skin plates is the same as the core foams, however, the thickness of skin is to be varied for different cases. The thicknesses of top and bottom face sheet skin plates are 0.5, 1 and 1.5 mm and the combination of these thicknesses make different case studies. In this study three different aluminium foam cores are used. The relative density of these foams are 10%, 15% and 20%. Figure 2 shows the aluminium foam and face sheets that are used in this study. The face sheets and cores are modelled by Belyschko-Tasy shell elements and 8-node solid elements respectively. The mechanical behavior of TNT and air are governed by LS-DYNA *Mat_High_Explosive_Burn and *Mat_Null modules respectively. In this study 250 gr TNT was assigned to model the source of impulse. The applied equations of state for TNT and air are Jones-Wilkins-Lee (JWL) and Linear polynomial respectively. The parameters used were chosen from Reference [22]. To model the material properties of steel skin plates the elasto-plastic model from a previous work was implemented [23]. From compression test of different aluminum foams, the stress strain curves are extracted and implemented in the crushable foam model.

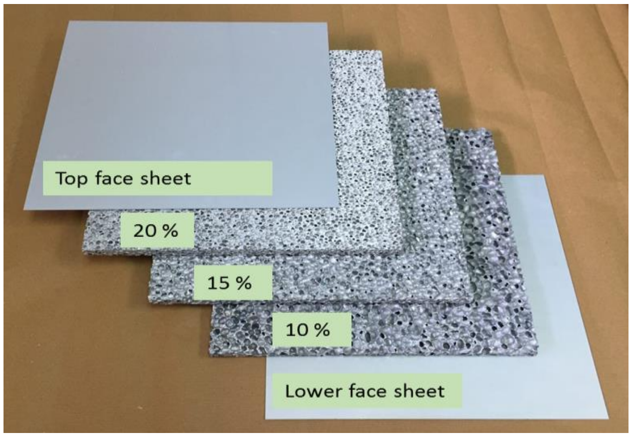

Fig 2. Aluminium foam core with different relative densities.

B. *Design of experiment model*

In this study three factors or control parameters were selected, namely, relative foam density, face sheet thickness and standoff distance (SOD). Three relative densities of foam core were considered. In each sample, three foam layers with different relative densities were used. It means that in every core, each foam density was only used once. Table 1 shows the effective parameters and their levels that are considered in this study. Based on multi-level full factorial design, a number of 24 trials (4×3×2) should be performed to complete the response output of all experiments. The test trial results are presented in Table 2.

Table 1. Design summary

	Factor Name	**Type**	**Level number and configuration**			
			1	2	3	4
A	Relative foam density (%)	numeric	10/ 15/ 20	20/ 15/ 10	15/ 10/ 20	15/ 20/ 10
B	Face sheet thickness (mm)	numeric	0.5/ 1.5	1.5/ 0.5	1.0/ 1.0	---
C	Standoff distance (mm)	numeric	150	200	---	---

Table 2. Response factors – results recorded from simulations.

No	Factors			response	
	A: Relative Foam Density%	B: Face Sheet Thickness (mm)	C: SOD (mm)	R1: Permanent Back Face Deflection	R2: Internal Dissipated Energy
1	10/15/20	0.5/1.5	150	45.9	232
2	10/15/20	1.5/0.5	150	39.9	143
3	10/15/20	1/1	150	42	175
4	20/15/10	0.5/1.5	150	39	141
5	20/15/10	1.5/0.5	150	38.7	121
6	20/15/10	1/1	150	38.6	128
7	15/10/20	0.5/1.5	150	41.5	168
8	15/10/20	1.5/0.5	150	38.9	124
9	15/10/20	1/1	150	39.6	136
10	15/20/10	0.5/1.5	150	39.5	135
11	15/20/10	1.5/0.5	150	35.8	109
12	15/20/10	1/1	150	37.4	137
13	10/15/20	0.5/1.5	200	41.5	178
14	10/15/20	1.5/0.5	200	35	104
15	10/15/20	1/1	200	37.2	134
16	20/15/10	0.5/1.5	200	36	106
17	20/15/10	1.5/0.5	200	34.6	90.01
18	20/15/10	1/1	200	34.8	93.1
19	15/10/20	0.5/1.5	200	37.5	151
20	15/10/20	1.5/0.5	200	34.1	112
21	15/10/20	1/1	200	35.1	122
22	15/20/10	0.5/1.5	200	36.4	121
23	15/20/10	1.5/0.5	200	32	98
24	15/20/10	1/1	200	33.7	123

III. RESULTS AND DISCUSSION

Figure 3 shows the deformed shape of the sandwich structure under impulsive loading within 1500 µs. Based on different DOE combinations, 24 simulations were carried out and the results of permanent deflection and maximum internal energy dissipation were recorded as responses of the DOE model.

A. *Statistical analysis*

The Analysis of Variance (ANOVA) is performed using Minitab17 to study the significance of the factors and their interactions. The significance level (α) is set at 0.05, which indicates the probability of the hypothesis. In other words, the probability of the hypothesis that an effect (main effect or second order interaction) is significant is 95% true. In the model (source) analysis, the sum of squares (SS) and mean sum of squares (MS) are calculated to evaluate the responses. F is the ratio of MS and MS Error and is compared with F distribution tables used in statistics. The P-value treatment combination is not significant. The values of P are obtained from F distribution tables. In the analysis, the coefficients (Coef) are used to build the mathematical model. The T is a test statistic with a student's t distribution and the P is associated with that test statistic. A P-value of 1 specifies that a factor is least significant and a P-value of 0 indicates maximum significance.

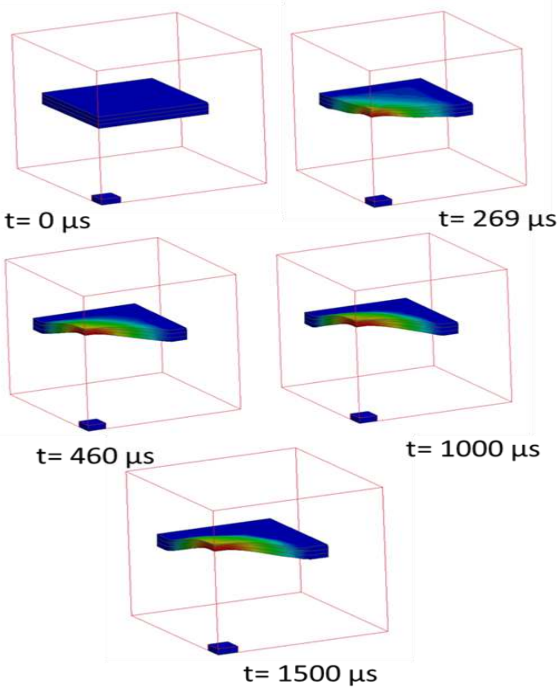

Fig 3. Representation of deformed shape of sandwich structure with time.

Table 3. Variance analysis of maximum deflection.

term	coef	T	P		
Constant	303.8	4.58	0.000		
A	-41.1	-2.12	0.000		
B	-32	-1.25	0.000		
C	-59	-1.57	0.000		
A*B	7	1.18	0.003		
A*C	11.43	1.18	0.003		
B*C	2	0.15	0.088		
	SS=2.40621	R-sq 99.85%	R-sq (adj) 99.43%	PRESS 0.76	R-sq (pred) 97.60%
Source	DF	SS	MS	F	P
Regression	6	11224.4	1870.74	2.66	0.000
Linear	6	215.661	35.9435	4107.83	0.000
interactions	3.000	17.616	1.602	183.030	0.006
Residual error	17.000	0.0003	0.000		
Total	23.000	0.000			

Tables 3 and 4 show the variance analysis extracted from ANOVA table for maximum permanent deflection and internal dissipated energy. The results show that the P-value for the main factors and their linear interaction are less than 0.088. For both responses, the sum of square, R-square and adjusted R-square have acceptable values and shows that the analysis has good validity.

Table 4. Variance analysis based on internal energy.

Term	Coef	T	P		
Constant	50.390	10.490	0.000		
A	-2.030	-1.450	0.000		
B	-1.220	-0.650	0.000		
C	-4.170	-1.540	0.000		
A*B	0.188	0.440	0.006		
A*C	0.270	0.380	0.007		
B*C	-0.288	-0.300	0.075		
	SS 0.0935414	R-sq 99.98%	R-sq (adj) 99.91%	PRESS 0.84	R-sq (pred) 99.64%
Source	DF	SS	MS	F	P
Regression	6.000	170.540	28.423	7.700	0.000
Linear	6.000	19089.400	3181.560	549.510	0.000
interactions	3.000	4071.100	370.100	63.920	0.000
Residual error	17.000	0.004	0.0001		
Total	23.000	0.000			

The adjusted R-square of 99.4% indicates that 99.4% of variation in maximum deflection and internal energy are explained by the following un-coded empirical models:

*IE = 368.4 - 27.1 Foam Density - 134.0 Face thickness - 59.0 SOD + 29.88 Face thickness*Face thickness + 11.43 Foam Density*SOD + 2.0 Face thickness*SOD*

*Max deflection = 57.30 - 1.657 Foam Density - 10.17 Face thickness - 4.18 SOD + 2.356 Face thickness*Face thickness + 0.270 Foam Density*SOD - 0.287 Face thickness*SOD*

The normal distribution of residual maximum deflection and internal energy are shown in Figures 4(a) and 4(b). In this study the Confidence Interval was considered as 1 and the normal distribution with 95% accuracy is observed. Therefore, no transformation is being considered.

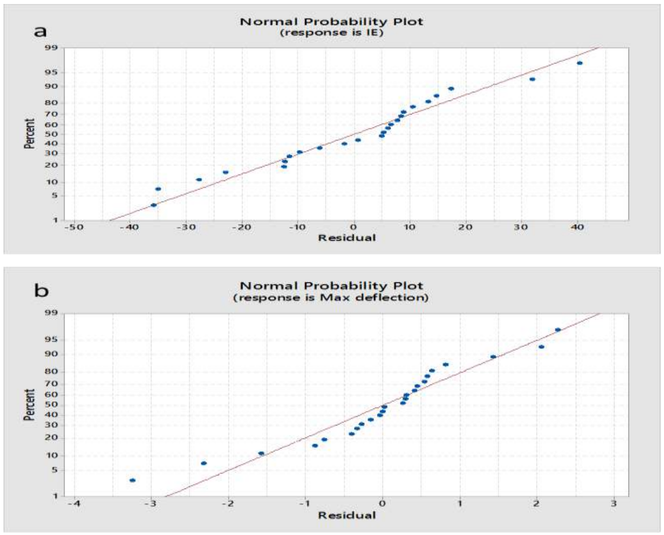

Fig4. Normal distribution of residual (a) internal energy (b) maximum deflection.

The model in the multi objective problem is analyzed to find the best condition and performance. In this study, the internal dissipated energy and maximum permanent deformation are the two objectives which should be minimized. The face thickness and foam density are taken into account as the design variables. Figure 5 shows the optimized condition for the graded structure subjected to the impulsive loading.

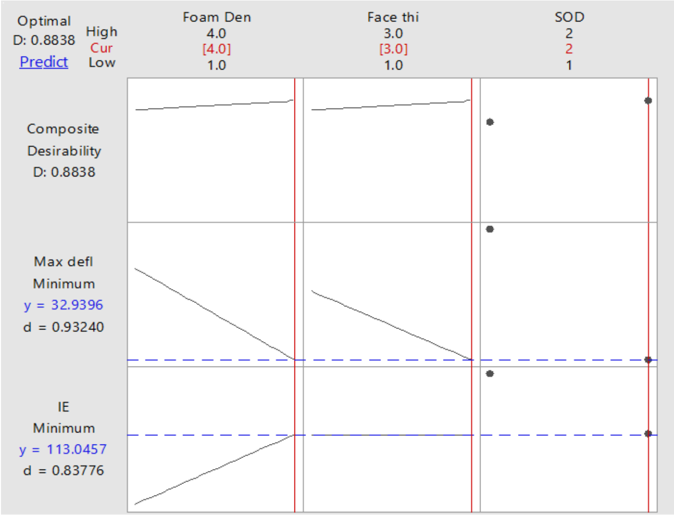

Fig5. The optimal condition for the graded structure with multi levels effective factors.

Figure 6 compares the permanent deflection of the best and worst configuration of sandwich panel. The results of FE simulation show that the optimized layer configuration decreases the permanent deflection around 23%.

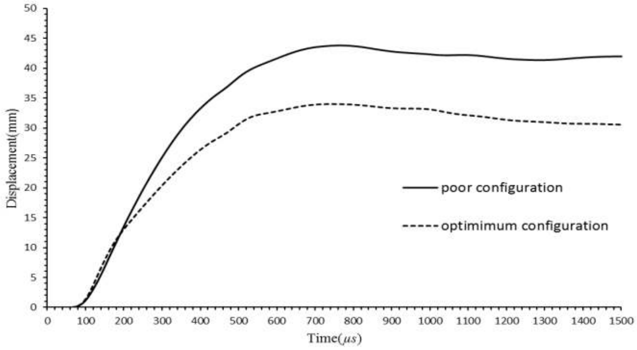

Fig 6. Comparison of the back face deflection between the best and the worst layer configuration over the time.

IV. CONCLUSION

The dynamic response and blast resistance of metallic sandwich plates with graded aluminium foam cores were investigated via FE simulation. The effective parameters of the structure were simultaneously considered for optimization of sandwich structure design, as a promising graded material, with respect to changes in three variables, relative foam density, face sheet thickness and SOD. Subsequently, a multi-objective optimization using FEA and DOE was performed in order to minimize the permanent deflection as well as internal energy. Based on ANOVA analysis on the responses, all variables have significant effect. Predictive models for permanent deflection and internal energy are statistically significant as the P-value is less than 0.05 at 95% confidence level. The results from optimization show that the best performance of the graded sandwich for both SOD conditions is the 15/20/10 % and 1.5/0.5 mm for relative foam density and face sheet thickness respectively. The current DOE method leads to obtaining the optimum performance of graded metallic foam with different design configurations.

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