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Energy absorption characteristics of thin-walled sinusoidal corrugated tube using RSM-CCD

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Abstract
The axial crushing behaviour of tubes of different section shapes has been extensively investigated as they have an excellent energy absorption, but the thin walled corrugated tube structures have been designed to further improve their energy absorption performance. The study aims to analyze the effect of sinusoidal corrugations along cross section of the tube on peak force, energy absorption and specific energy absorption. In the present work the response surface methodology (RSM) using central composite design (CCD) has been used and simulation work is performed by using ANSYS workbench to explore the effects of geometrical parameters on the responses of constructing models.

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1. Introduction

Thin walled buildings are used as energy absorbers to protect citizens and large infrastructure in the situation of ground vehicle traffic collisions and emergent aircraft and spacecraft landings (Alghamdi, 2001). Over the past decade, various experimental, theoretical, and numerical means were used to investigate tubular structures, especially circular and square tubes under axial compression / impact (Alexander, 1960; Abramowicz et al., 1986; Lu et al., 2003; Kavi et al., 2006; Nia et al., 2011). Apart from conventional tubes, several other non-conventional cross-sectional tubes (Zhang et al., 2012; Seitzberger et al., 2000; Umeda et al., 2010; Mamalis et al., 2003; Mamalis et al., 1991; Sebaey et al., 2014) have also become the focus of study. All of the above tubes have their own features in progressive axial crushing, and it is difficult for engineers and designers to compare and assess which tube has the best output in energy absorption. Energy absorption device behaviour is nowadays a major goal for researchers. Thus, the influence of geometry, material type, direction of loading and arrangements was widely studied (Fan et al., 2013; Nia et al., 2010; Fan et al., 2013; Hong et al., 2013; Ebrahimi et al., 2015; Palanivelu et al., 2011; Ochelski et al., 2009; Paruka et al., 2013; Baroutaji et al., 2015).

Many authors researched the crushing behaviour and capacity of radial corrugated geometries (Abdewi et al., 2008; Xiong et al., 2016) among many others. The study indicates that (Alkhatib et al., 2020) in the corrugated metal tubes was less than the value in the circular tubes, the first point in the load – displacement curve. The deformation mode in corrugated metallic tubes was more stable, too. Most of the aforementioned studies have been done experimentally despite being expensive, as it will be challenging to simulate the exact mechanisms of failure. On the other hand, finite element modelling is an extremely attractive solution by changing the boundary conditions, the type of material, the failure parameters and the level of interaction between the interacting component, this will assure an acceptable result as compared to the experimental observations.

All the above studies have the following characteristics: "single factor variation method" which contributes to a lack of systematic research; quadratic term interaction and effect is neglected, which will decrease model accuracy. Response surface methodology (RSM) is a set of mathematical and computational techniques, helpful in fitting models and evaluating problems when a range of independent parameters influence the dependent function (Montgomery, 2017). The aim is to take the initiative to design the factors and level of simulation and testing, then to obtain the quantitative functional relationship between the factors and response. The model is applied with the interaction and quadratic concept, so the implementation of RSM will break the constraint of "single factor variation process".

In the present work a numerical study is carried out to find out the energy absorbing characteristics of sinusoidal corrugated thin-walled tube made of structural steel with sectional parameters (mean diameter, thickness, amplitude and frequency) by using RSM. The above literature review shows that there are many methods which help to improve the energy-absorbing performances. Every method has its own features and drawbacks. Designing an effective energy-absorbing device that has all the required specifications remains a challenge for designers.

1.1. Details of the finite element model

In Ansys workbench, the tubular extrusions were modelled using S4R 4-node shell elements, while the plates were constrained as rigid bodies and modelled using R3D4 4-node 3-D bilinear rigid elements. Models mesh size was held constant by an estimated global scale of 4.5. The use of a general contact algorithm between the tubular extrusion and both plates was simulated. By restricting all six degrees of freedom to zero, the bottom plate was fixed, while the upper plate was a restriction to travel only in the vertical direction, as seen in Fig 1.

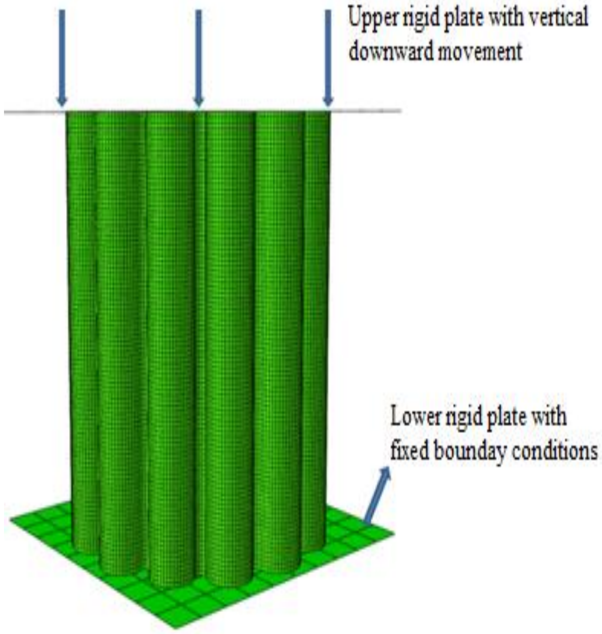

Fig. 1. Finite element numerical model

Subsequently, the upper plate was progressively displaced to crush the model. The analysis was performed with a step time of 40 ms for quasi-static loading condition. The extrusion length was taken 400 mm and kept constant, while the tubes were compressed throughout the analysis to one-fourth of its length. The structural steel material properties is shown in Table 1.

Table 1. Structural steel material properties

Material Properties	Value
Density (kg/m^3)	7865
Young's modulus (GPa)	200
Poisson's ratio	0.27
Yield strength (GPa)	0.31

2. Methodology

Generally, CCD consists of a 2^n factorial runs with 2n axial runs, and the experimental error is measured by center runs (nc). This experimental design is composed of 2^n factorial with coded by ±1 notation augmented by 2n axial points (±α, 0, 0. . .0), (0, ± α, 0. . .0) . . . (0, 0, ± α . . .0) and center points n_c (0, 0, 0 . . . 0). Each variable is investigated at five levels while as the number of variables (n) increases, the number of runs for a complete replicate of the design increases rapidly (here ±α is ±2). CCD was used for quadratic effect since the individual effect of second order cannot be calculated separately by 2n factorial designs. In this paper, there are five design levels for each factor: ±α, 0, ±1. Independent variables and their coded levels for the central composite design are shown in Table 2. All the results obtained from simulation are presented in Table 3.

Thus, four considered significant factors including mean diameter, thickness, amplitude and frequency of corrugation listed in Table 2. Total runs at 30 trials for P_{peak}, $E_{absorbed}$ and $E_{specific}$ were presented in Table 3. The multiple regression analysis on the resulting response has yields with major factors and interactions to the following second-order polynomial equations. The validity of the models was controlled using the ANOVA with F and P-values being two significant factors in the study.

Table 2. Independent variables and their levels for the central composite design

Levels of variables	Factor			
	Independent variables			
	A- Mean Diameter (mm)	*B-* Thickness (mm)	*C-* Amplitude (mm)	*D-* Frequency
-2	228.6	4.8	0.25	5
-1	247.65	6.1	5.0625	7
0	266.7	7.4	9.875	9
+1	285.75	8.7	14.6875	11
+2	304.8	10	19.5	13

Table 3. Independent parameters and theirs output responses

S. No.	*A*- Mean Diameter (mm)	*B*- Thickness (mm)	*C*-Amplitude (mm)	*D*-Frequency	Mass (kg)	$E_{absorbed}$ (kJ)	P_{peak} (kN)	$E_{specific}$ (kJ/kg)
1	285.75	8.7	5.0625	7	184.25	1548	2689	8.401
2	247.65	8.7	5.0625	11	164.95	1475	2903	8.94
3	247.65	6.1	5.0625	11	116.9	560.2	1509	4.792
4	285.75	6.1	14.6875	11	161.39	543.9	1914	3.37
5	266.7	7.4	9.875	9	161.39	637.7	2186	3.951
6	285.75	6.1	5.0625	7	130.38	445.6	1737	3.418
7	266.7	7.4	9.875	9	161.39	637.7	2186	3.951
8	285.75	6.1	14.6875	7	145.77	777.6	2390	5.334
9	247.65	8.7	5.0625	7	159.8	1580	2631	9.885
10	285.75	8.7	5.0625	11	188.74	1409	2913	7.463
11	285.75	8.7	14.6875	7	206.19	1431	3380	6.942
12	285.75	6.1	5.0625	11	133.53	528.9	1836	3.961
13	247.65	6.1	14.6875	7	130.76	412.7	1685	3.156
14	247.65	6.1	5.0625	7	113.24	368.1	1464	3.25
15	266.7	7.4	9.875	9	161.39	637.7	2186	3.951
16	266.7	7.4	9.875	9	161.39	637.7	2186	3.951
17	247.65	6.1	14.6875	11	157.28	419.7	1865	2.668
18	247.65	8.7	14.6875	11	222.62	616.3	2460	2.768
19	285.75	8.7	14.6875	11	240.13	769.8	2658	3.206
20	247.65	8.7	14.6875	7	184.79	1797	2944	9.722
21	266.7	7.4	9.875	5	149.6	879.6	2266	5.88
22	266.7	7.4	9.875	13	179.12	478	1890	2.669
23	304.8	7.4	9.875	9	180.55	903.3	2411	5.003
24	266.7	7.4	9.875	9	161.39	637.7	2186	3.951
25	266.7	7.4	9.875	9	161.39	637.7	2186	3.951
26	266.7	10	9.875	9	216.14	1767	3535	8.176
27	228.6	7.4	9.875	9	142.55	922.9	2274	6.474
28	266.7	4.8	9.875	9	105.61	388.5	1392	3.678
29	266.7	7.4	0.25	9	144.25	853	1829	5.913
30	266.7	7.4	19.5	9	205.94	1083	2471	5.259

3. Results and discussion

Energy absorption characteristic parameters peak load (P_{peak}), energy absorbed ($E_{absorbed}$), and specific energy absorbed ($E_{specific}$) are determined based on the quasi static behaviour from the numerical simulation results for the sinusoidal corrugated tube, see Table 2 and 3.

3.1 Effect of geometric parameters on peak force responses under axial compression:

The statistical "Design expert" software was used to study the simulation data regression analysis and to draw the response surface plot. ANOVA is used to estimate the statistical parameters. For the peak force study, the required range and coded level of variables are given in Table 2 and 3. F value of 30.53 shows that the model is significant.

The results obtained for the P_{peak} response is a quadratic model, in which thickness (t) with the maximum F value of 351.18 can be considered as the most important factor when compared to others parameters. The final empirical model in terms of coded factors for peak force is shown in Eq. (1), where negative signs signify inhibitory effect, whereas positive signs signify synergistic effects.

$$P_{peak}(kN) = 2185.90 + 194.39A + 1038.44B + 241.61C - 134.47D - 163.08AB + 179.83AC - 222.08AD - 50.47BC - 139.28BD - 535.88CD + 191.45A^2 + 312.30B^2 - 0.5958C^2 - 72.95D^2 \quad (1)$$

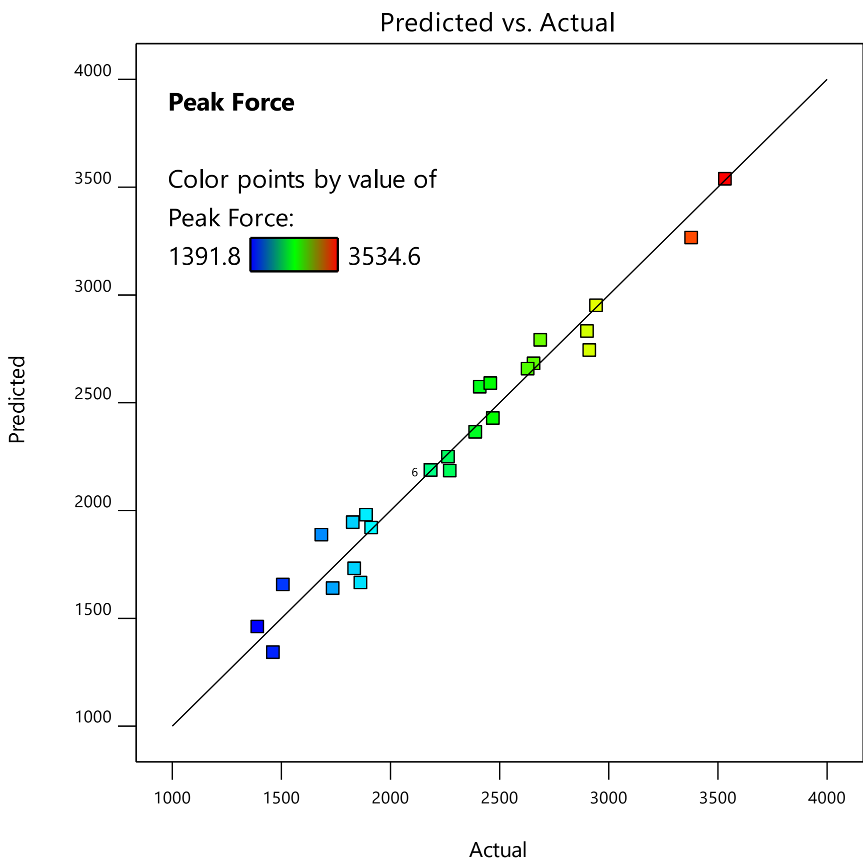

Fig. 2. Actual and predicted peak force 'kN'

The validity of the developed model was the key component in verification of the simulation's data analysis. The relationship between the actual peak force and the predicted value is accurate, as shown in Fig 2. The response surface methodology was used to analyse the individual and interaction effect of the three-factor on mean diameter, width, amplitude and frequency on peak force, these figures indicate that the developed RS models are almost adequate, because the residuals in the prediction of each response are in acceptable range since most of the peak force values lie near to best-fit line of the predicted results. It was revealed that the numerical data for peak force fitted in acceptable range with the predicted value of the model.

Based on ANOVA, the results were obtained, the effects of design factors on peak force, corresponding three-dimensional response surface plots were shown in Fig 3. A comparison can be seen clearly between the different parameters considered, in which thickness has the most significant effect.

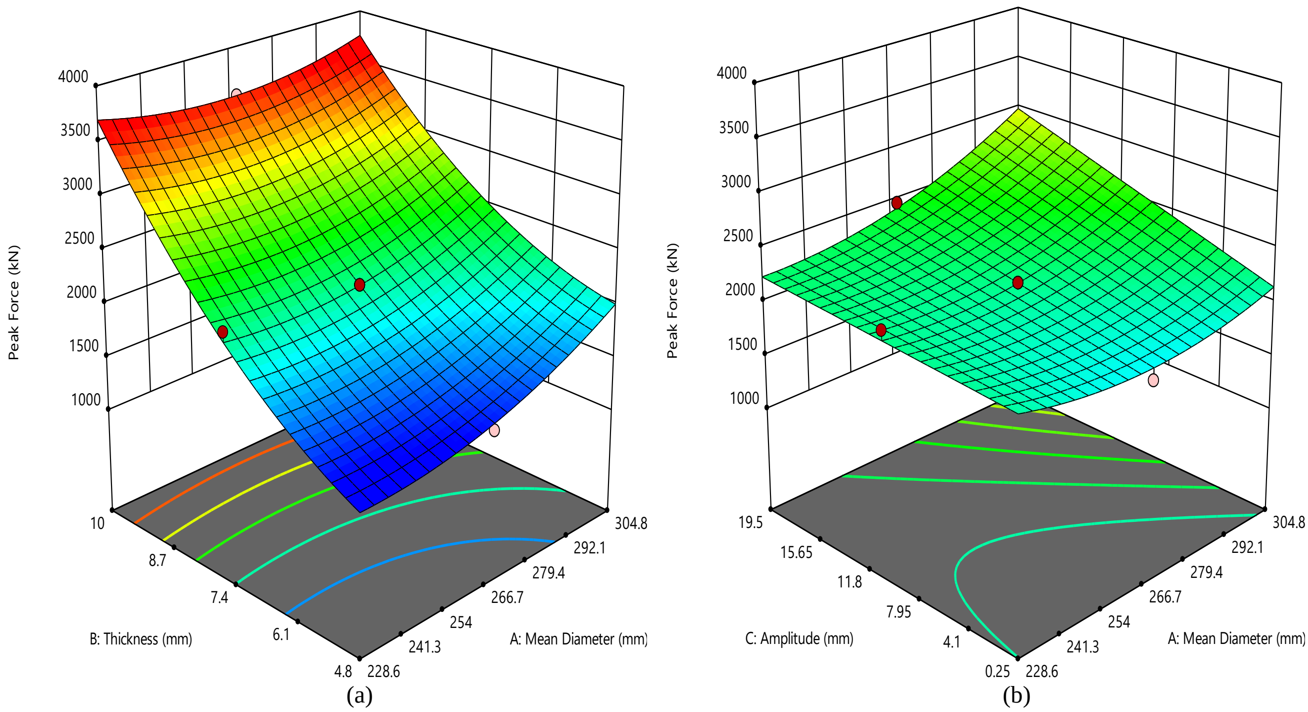

Fig. 3. a, b Response surface graph for the proposed sinusoidal corrugated tube for peak force; (a) effect of mean diameter and thickness (b) effect of mean diameter and amplitude

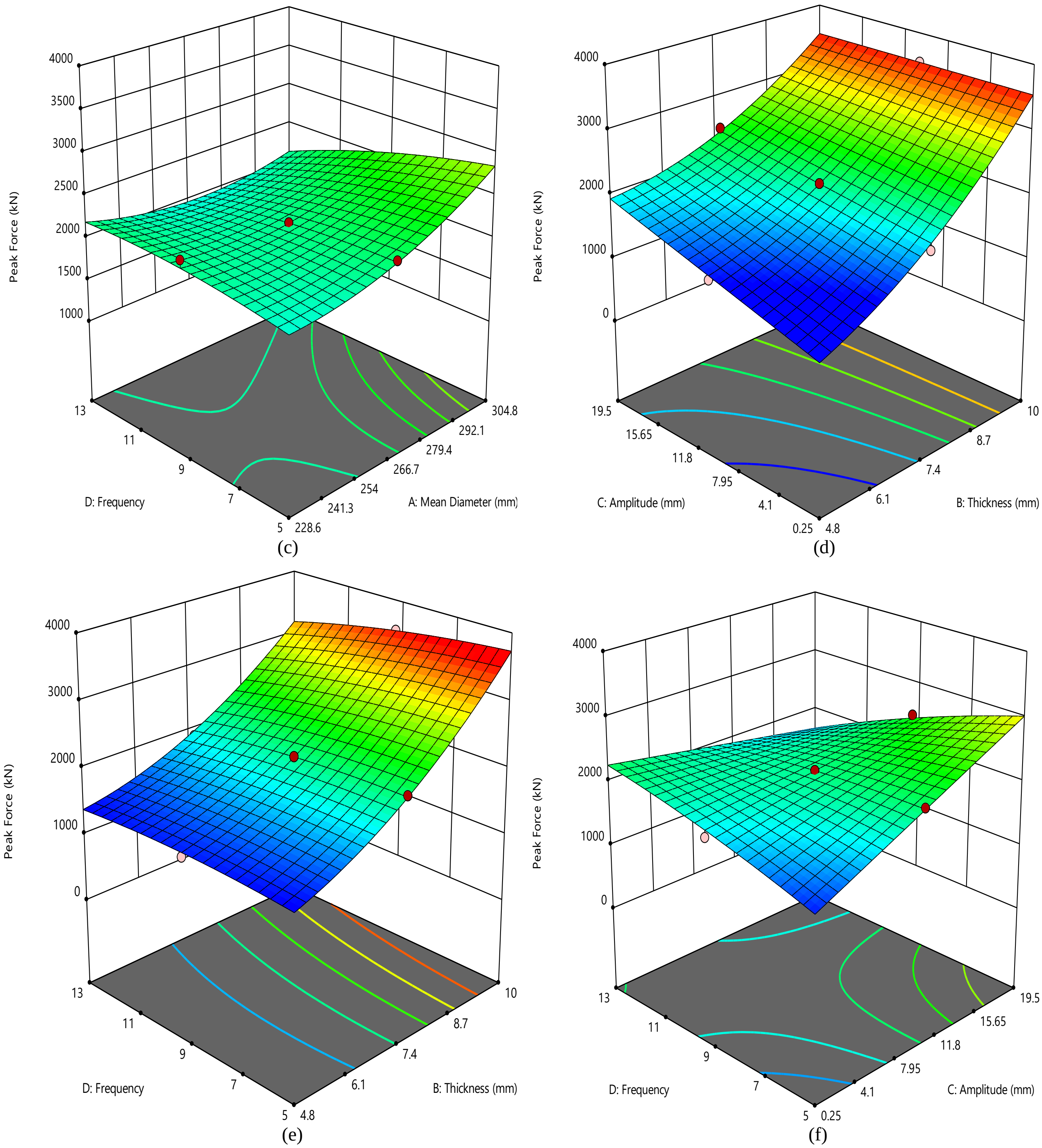

Fig. 3. c, d, e, f Response surface graph for the proposed sinusoidal corrugated tube for peak force; (c) effect of mean diameter and frequency, (d) effect of thickness and amplitude, (e) effect of thickness and frequency, (f) effect of amplitude and frequency.

3.2 Effect of geometric parameters on energy absorption responses under axial compression

The regression analysis results from Table 3 for the $E_{absorbed}$ response led to a quadratic model. The empirical model equation for energy absorption is shown in Eq. (2). The F-value of 183.33 for thickness (t) is recorded as the most significant factor.

$$A_{absorbed}(kJ) = 637.70 + 15.56A + 777.14B - 236.71D + 211.20AB + 82.27AC + 33.70AD - 411.97BC - 33.72BD + 5151 - 524.95CD + 280.83A^2 + 445.58B^2 + 335.76C^2 + 46.53D^2 \quad (2)$$

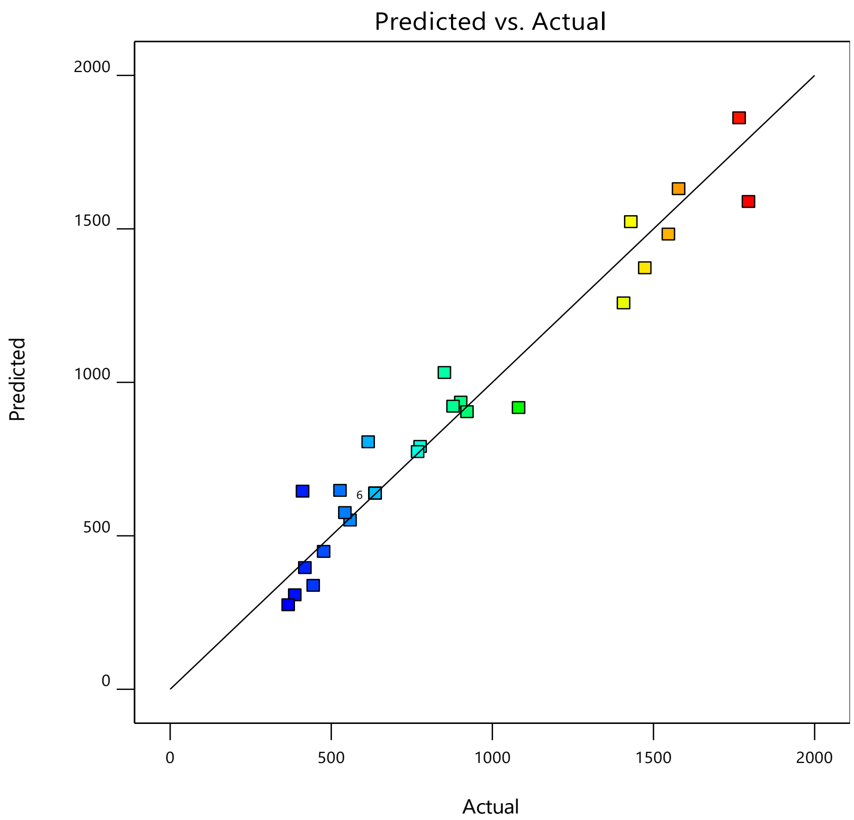

Fig. 4. Actual and predicted energy absorbed 'kJ'

Fig 4 shows the actual and predicted plot of energy absorbed. The result obtained as shown in Fig 5 that thickness effect plays important role as compared to other geometric parameters. The maximum energy absorbed value of 1796.6 kJ and the minimum value of energy absorbed among all the combinations was 368.07 kJ for all combinations considered in Table 3.

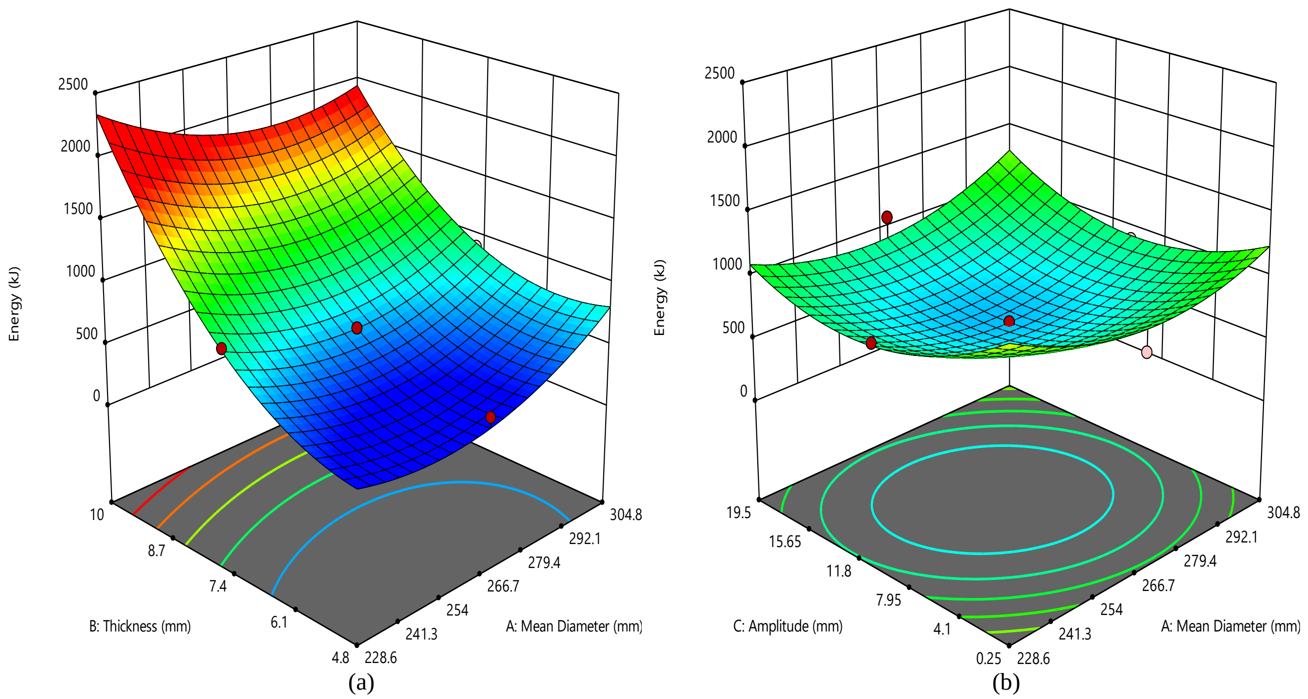

Fig. 5. a, b Response surface graph for the proposed sinusoidal corrugated tube for energy absorbed; (a) effect of mean diameter and thickness, (b) effect of mean diameter and amplitude

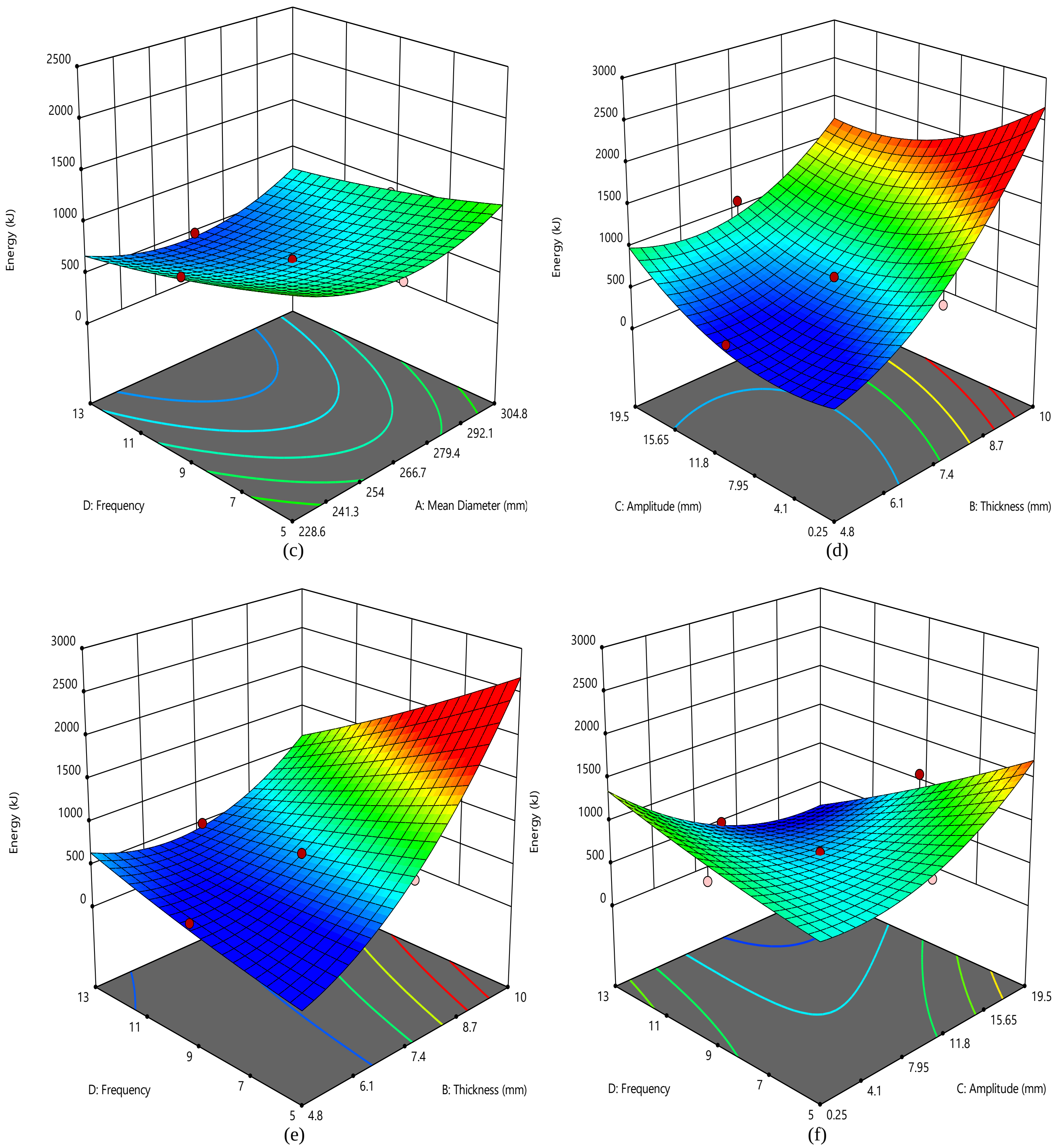

Fig 5. Response surface graph for the proposed sinusoidal corrugated tube for energy absorbed; (c) effect of mean diameter and frequency, (d) effect of thickness and amplitude, (e) effect of thickness and frequency on energy absorbed, (f) effect of amplitude and frequency.

3.3 Effect of geometric parameters on specific energy responses under axial compression

The final empirical equation for specific energy absorbed is shown in Eq. (3). F value of 74.73 shows the significance of model with thickness as dominating factor. It is clear seen from Fig. 7 that how all parameter effects the specific energy and the effect of each parameter can be well examined from the trend of the specific energy. Apart from all the wall thickness has shown much dominating effect and this trend is due to thick tubes having more material available for plastic deformation.

$$E_{specific}\left(\frac{kJ}{kg}\right) = +3.95 - 0.524A + 3.03B - 1.19C - 1.61D - 1.88AB + 1.04AC + 0.1873AD - 2.79BC - 3.05BD - 3.34CD + 1.84A^2 + 2.02B^2 + 1.68C^2 + 0.3717D^2 \quad (3)$$

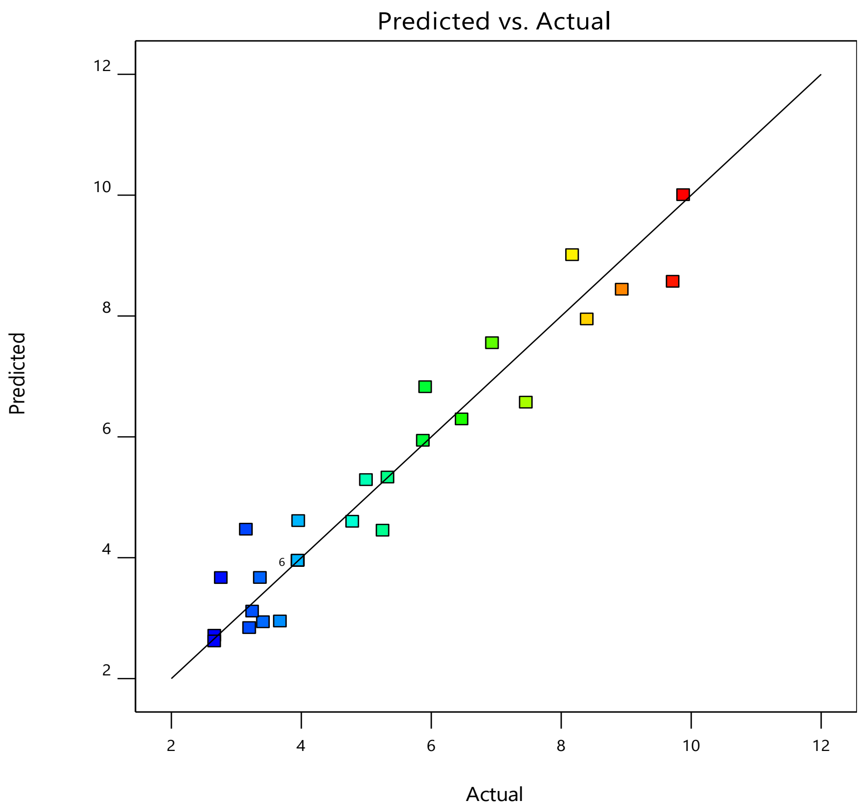

Fig. 6. Actual and predicted specific energy 'kJ'

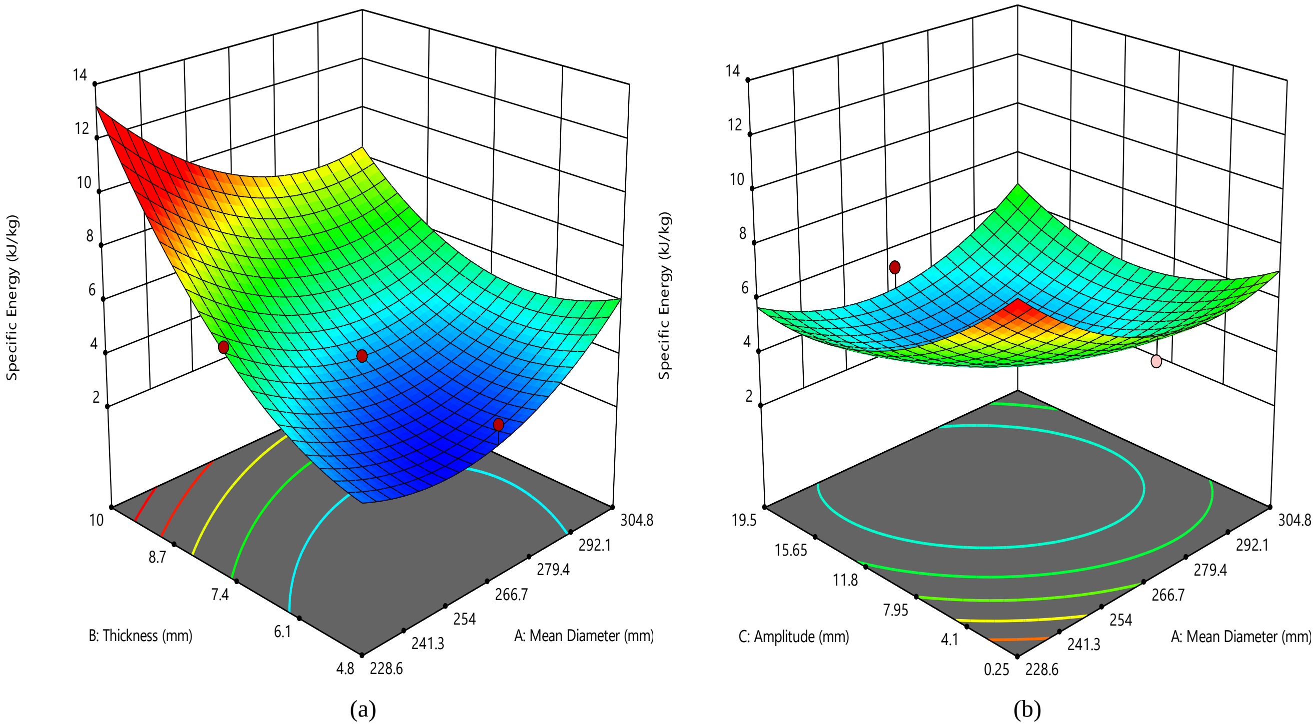

Fig. 7. a, b Response surface graph for the proposed sinusoidal corrugated tube for specific energy; (a) effect of mean diameter and thickness, (b) effect of mean diameter and amplitude

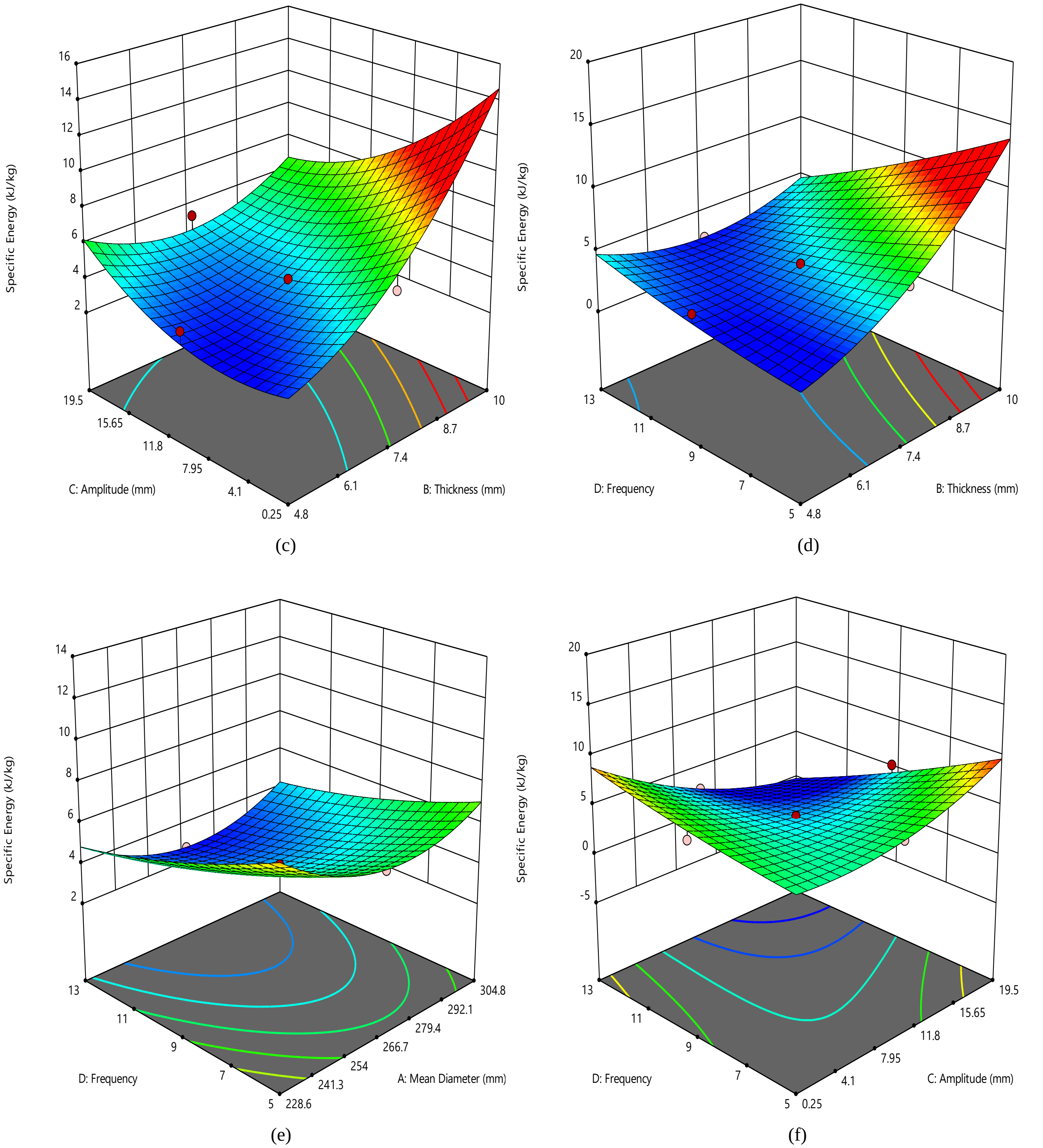

Fig. 7. Response surface graph for the proposed sinusoidal corrugated tube for specific energy; (c) effect of mean diameter and frequency, (d) effect of thickness and amplitude, (e) effect of thickness and frequency, (f) effect of amplitude and frequency.

4. Conclusion

The energy absorption characteristics of axially loaded sinusoidal corrugated thin walled tubes are investigated in this paper. Extensive simulation has been carried out, analysed and discussed. The numerical models presented were able to predict the parameters of crush-performance. The actual versus the predicted response variables for each output factors are shown in Fig 2, 4 and 6. As can be shown, the 45^0 line separated the data points equally. ANOVA was conducted to test the reliability of the regression models and to check the importance of the models for each term. The three-dimensional response surface was illustrated in Fig 3, 5, and 7 and used to display the interaction influences on the output for every pair of design variable. For all four response models, the quadratic terms are the most significant ones. After comparing the results of P_{peak}, $E_{absorbed}$ and $E_{specific}$, a corrugated sinusoidal with thicker wall should be adopted. A thicker tube increased $E_{absorbed}$ but the increased mass of the structure had a negative effect on SEA. It should be mentioned that there were less significant effect of amplitude and frequency of corrugation as compared to thickness for each output response. Thus, it can be shown that RSM may be commonly used as a kind of innovative modern form of experimental design in the development of the energy absorption system. In addition, the RSM based model may also apply to theoretical study, and has a promising prospect of implementation.

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基于RSM-CCD的薄壁正弦波纹管的能量吸收特性

關鍵詞
响应面法（RSM）
波纹管
能量吸收特性
有限元分析
薄壁结构最大值

摘要
由于截面截面形状的管材具有出色的能量吸收性能，因此已经对其进行了广泛的研究，但薄壁波纹管结构的设计旨在进一步提高其能量吸收性能。 该研究旨在分析沿管子横截面的正弦波纹对峰值力，能量吸收和比能量吸收的影响。 在本工作中，已经使用了使用中央复合设计（CCD）的响应面方法（RSM），并通过使用ANSYS工作台进行了仿真工作，以探索几何参数对构建模型响应的影响。