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Research Article

Optimization of Crashworthiness Parameters of Thin-Walled Conoidal Structures

K. Vinayagar,[1] P. Ganeshan,[2] P. Nelson Raja,[1] M. S. Zakir Hussain,[3] P. Vengala Kumar,[4] P. Ramshankar,[5] V. Mohanavel,[6,7,8] N. Mathankumar,[9] K. Raja,[10] and Tesfaye Tefera Bezabih[11]

[1]*Department of Mechanical Engineering, Fatima Michael College of Engineering & Technology, Madurai, India*
[2]*Department of Mechanical Engineering, Sri Eshwar College of Engineering, Coimbatore 641202, Tamil Nadu, India*
[3]*Department of Mechanical Engineering, AAA College of Engineering & Technology, Sivakasi, Tamil Nadu, India*
[4]*Department of Mechanical Engineering, University VOC College of Engineering, Thoothukudi, Tamil Nadu, India*
[5]*Department of Civil Engineering, University College of Engineering Dindigul, Dindigul 624622, Tamil Nadu, India*
[6]*Centre for Materials Engineering and Regenerative Medicine, Bharath Institute of Higher Education and Research, Chennai 600073, Tamil Nadu, India*
[7]*Department of Mechanical Engineering, School of Technology, Glocal University, Delhi-Yamunotri Marg, Saharanpur, Uttar Pradesh 247121, India*
[8]*Department of Mechanical Engineering, Chandigarh University, Mohali 140413, Punjab, India*
[9]*Department of Mechanical Engineering, NPR College of Engineering and Technology, Natham, Dindigul 624401, Tamil Nadu, India*
[10]*Department of Mechanical Engineering, University College of Engineering Dindigul, Dindigul 624622, Tamil Nadu, India*
[11]*Department of Mechanical Engineering, Ambo University, Ambo, Ethiopia*

Correspondence should be addressed to Tesfaye Tefera Bezabih; tesfaye.tefera@ambou.edu.et

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This paper aims to identify the optimum level of factors or parameters that affect the energy absorption of conoidal structures by grey relational examination. To optimize crashworthiness parameters of conical structures, the L9 orthogonal array has been adopted to design the experiments. The tailor-made thin-walled conical structures were fabricated by three most important factors, such as base diameter, height, and thickness, as design variables, and they were subjected to axial compression in a quasi-static method. The important responses of crashworthiness indicators such as the mean crushing force and specific energy absorption (SEA) were calculated with the help of a load-displacement curve. Experimental results showed that the crushing behaviours of conical structures were fairly significant. Grey relational analysis (GRA) and analysis of variance are used toobtain the optimal levels of parameters. From the results, the optimum levels of parameters are found to be a base diameter of 180 mm, a height of 120 mm, and a thickness of 1.5 mm.

1. Introduction

Energy absorbers with lightweight are widely used to develop the crashworthiness of vehicles at the time of collisions. The thin-walled formations or structure are normally used as energy absorbers in all types of transport systems owing to their properties like very less weight and the capacity to absorb more impact energy. By determining the mean crushing power, the energy lost until the substance or material was compressed-honeycomb structures' ability to absorb energy is assessed. Several studies have been carried out to develop theoretical models to forecast the mean or average crushing force for thin-walled structures. Significant analysis has been carried out by the authors in [1] intended for out-of-plane axial crushing confrontation of hexagonal honeycomb. The wall thickness and diameter of hexagonal wall structures were compared to the crushing strength and folding wave's wavelength and the submitted solutions were based on the design's convenience. Crushing strength, flow stress, curvature effects, and wavelength are considered and evaluated in the model. This folding model was again improved by considering more detailed structures and changing the structural loading in that deformation [2]. For honeycomb structures, analytical and experimental results are compared with each other [3–6].

In the past decade, the hexagonal structure has been modified by other structures like square and circular structures. It has been investigated by numerical, theoretical, and experimental methods under axial compression or impact [7–12]. To improve the energy absorber performance, a number of researchers have modified several odd and even numbers of polygonal sections and star sections. The tubes offered their own performance in axial loading, and the results were compared [13–18]. Several researchers have identified several alternative approaches, including single cell various cross-sectional tubes, multicell tubular sections, and filler materials [19, 20]. Single and multi-cell hollow columns' capacities for absorbing energy were compared analytically and quantitatively, and it was determined that the multi-cell available columns outperformed the single columns [21, 22]. The experimental findings, the circular cylinder's capacity to absorb energy, and the development of empirical relationships for concertina or axisymmetric structures [23]. Multicell square columns compressed axially using analytical and numerical techniques [24]. In hexagonal honeycombs and circular honeycombs, the influence of the central angle and the boundary effect is found to be an important factor in the crushing strength of the structure when the number of cells is very small [25, 26]. Analysis was carried out to develop the crashworthiness of thin-walled sections, and the circular honeycombs with the square package and hexagonal package were examined numerically and experimentally [27, 28].

Although many researchers and series of experiments mainly concentrated on polygonal sections (square, pentagon, hexagon, octagon, and circular) as energy absorbers, in this work, conical structures have been used as energy absorbers. The thin-walled conical ribs are fabricated in sheet metal in various types, and then, we study the performance of energy absorption of tubes type wise using the crashworthiness indicators. The study and investigation of energy absorption capabilities of conical ribs were experimentally performed, and the Taguchi method with the grey relational method was used to find out the optimal parameters for multiresponse such as the mean crushing force and specific energy absorption. This proposed work is useful for the design of engineering structures, which are used as energy absorbers.

2. Parameters of the Crashworthiness Study

In crashworthiness, basic parameters such as total energy absorption (TEA), specific energy absorption (SEA), and average or mean crushing force (F_{mean}) are delineated underneath with numerical equations. This study aims to determine the optimal level of factors or operating parameters for the maximum of (output) objectives of SEA and F_{mean}. Specific energy absorption (SEA) is portrayed as held vitality per unit mass. This is a basic criterion for looking at the vitality retention limit with particular mass, which is expressed as follows:

$$SEA = \frac{EA}{m}, \tag{1}$$

where m refers to the mass of the specimen and EA is the total energy absorption of crushing force. EA evaluated with the help of the load/force-displacement curve by applying direct integration is expressed as follows:

$$EA = \int_0^{\delta} F(\delta) d\delta. \tag{2}$$

F_{mean} is the average or mean crushing force which is calculated as follows:

$$F_{\text{mean}} = \frac{EA}{\delta}. \tag{3}$$

2.1. Taguchi Method with Grey Relational Analysis (GRA). The Taguchi method is one of the simplest and most popular methods to obtain the optimum set/level of factors or parameters for a single objective optimization problem To solve and analyze a multiresponse problem, Taguchi-based grey relational analysis is identified as a suitable method.

The main objective of crashworthiness analysis is the maximization of SEA and CFE. To evaluate the quality of experimental results, in Taguchi analysis, the signal to noise (S/N) ratio is considered larger than the best characteristic response, which is calculated as follows:

$$\frac{S}{N} \text{Ratio } x_i(k) = -10 \log_{10}\left(\frac{1}{j}\right) \sum_{i=1}^{j} \left(\frac{1}{y_i^2(k)}\right), \tag{4}$$

where $y_i(k)$ is the observed response value for the k^{th} response in the I^{th} trial, $x_i(k)$ is the S/N ratio value for the k^{th} response in the I^{th} trial, and j is the number of experiments.

Optimum parameters can be obtained from Taguchi's method after obtaining discrete datasets from experimental results. The responses are normalized across the range from 0 to 1. The normalized S/N ratios can be obtained as follows:

$$x_i'(k) = \frac{x_i(k) - \min x(k)}{\max x(k) - \min x(k)} \text{For better response}, \tag{5}$$

where $k = 1$ to n, n is the performance characteristic kth response at all trials, and $i = 1$ to 9.

After calculating the normalized S/N values, the grey relational coefficient can be calculated as follows:

$$\xi_i(k) = \frac{\left(\min_k \min_i \left\| x_i(0) - x_i'(k) \right\|\right) + \psi\left(\max_k \max_i \left\| x_i(0) - x_i'(k) \right\|\right)}{\left| x_i(0) - x_i'(k) \right| + \psi\left(\max_k \max_i \left\| x_i(0) - x_i'(k) \right\|\right)}, \tag{6}$$

where ψ is the resolution coefficient, and its value is taken as 0.5.

Table 1: Factors and levels of parameters.

Notation of factor	Factors (mm)	Levels		
		1	2	3
A	Base diameter	160	170	180
B	Height	120	130	140
C	Thickness	0.5	1	1.5

Table 2: Chemical composition of Al5052.

Composition	Percentage
Al	96.35
Mg	2.2
Si	0.25
Mn	0.1
Fe	0.4
Cu	0.1
Zn	0.1
Residuals	0.5

Grey relational grade can be obtained as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=i}^{n}\xi_i(k). \tag{7}$$

2.2. Analysis of Variance. GRA is simple and easy to understand, and it is based on range analysis. However, the range analysis cannot distinguish experimental errors and data fluctuations caused by level changes in parameters or factors. For this problem, ANOVA is used to design the optimized levels of parameters, which significantly affect the characteristics. The predicted optimum condition of grey relational grade using crashworthiness can be evaluated as follows:

$$\hat{\gamma} = \gamma_{\text{avg}}(m) + \sum_{i=1}^{n}\left(\gamma_i(m) - \gamma_{\text{avg}}(m)\right), \tag{8}$$

where n is the number of experiments, $\gamma_{\text{avg}}(m)$ is the mean of grey relational grade, and $\gamma_i(m)$ is the mean of grey relational grade at optimum level.

3. Experimental Procedures

3.1. Selection of Section Geometry and Parameters. In this work, the average or mean crushing force (F_{mean}) and specific energy absorption (SEA) were taken as output responses of crashworthiness with respect to the following parameters, such as base diameter, height, and thickness. Experiments were conducted on these three parameters/control factors (base diameter, height, and thickness) at three levels, and hence, the L9 orthogonal array (OA) was selected. The levels of factors for the experimental process are described in Table 1.

3.2. Materials. Aluminum alloy Al 5052 was selected for lightweight, high strength, cost-effectiveness, and greater formability. Chemical composition of aluminum alloy Al 5052 is listed in Table 2. Mechanical properties of materials are shown in Table 3. Experimental design using the L9 orthogonal array is mentioned in Table 4. Sample specimens are shown in Figure 1.

Table 3: Mechanical properties of Al 5052.

Property	Value
Young's modulus (E)	69.3 GPa
Ultimate tensile load	228 MPa
Elongation	15%
Density (ρ)	2.68 g/cm^3
Shear modulus (τ)	25.9 GPa
Poisson's ratio (μ)	0.33

Table 4: Experimental design using the L9 orthogonal array.

Test no	Base diameter (mm)		Height (mm)		Thickness (mm)	
	Level	Value	Level	Value	Level	Value
1	1	160	1	120	1	0.5
2	1	160	2	130	2	1
3	1	160	3	140	3	1.5
4	2	170	1	120	2	1
5	2	170	2	130	3	1.5
6	2	170	3	140	1	0.5
7	3	180	1	120	3	1.5
8	3	180	2	130	1	0.5
9	3	180	3	140	2	1

Figure 1: Samples of specimens before loading.

Figure 2: Crushed patterns of cones.

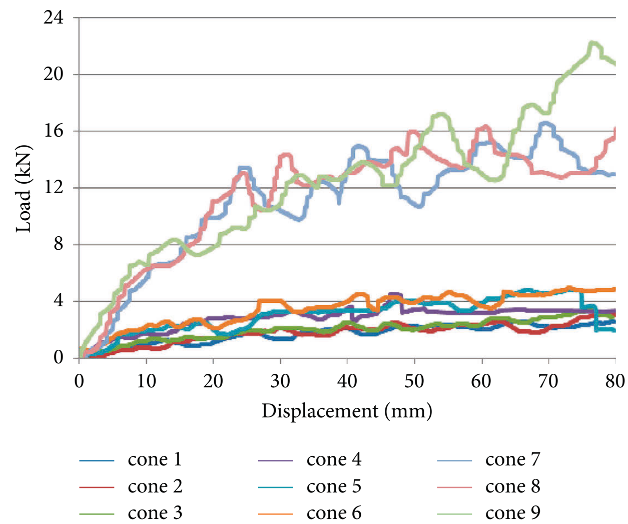

Figure 3: Load-displacement curves.

Table 5: Experimental results.

Code	Mass (kg)	Base diameter (mm)	Height (mm)	Thickness (mm)	F_{mean} (kN)	TEA (N-m) $F * d\delta$	SEA (kJ/kg) TEA (m)
Cone 1	0.046	160	120	0.5	1.48	118.4	2.574
Cone 2	0.1	160	130	1	3.51	280.8	2.808
Cone 3	0.16	160	140	1.5	7.98	638.4	3.990
Cone 4	0.104	170	120	1	4.86	388.8	3.738
Cone 5	0.16	170	130	1.5	8.65	692	4.325
Cone 6	0.065	170	140	0.5	2.76	220.8	3.397
Cone 7	0.175	180	120	1.5	9.59	767.2	4.384
Cone 8	0.074	180	130	0.5	3.45	276	3.730
Cone 9	0.146	180	140	1	6.15	492	3.370

3.3. Experimental Process. The compression test was carried out by using a computerized universal testing machine. The test specimen was vertically put between the lower movable table and the fixed cross head. The compressive axial force was applied to the samples, and the rate of compression was 10 mm/min. The crushed samples of specimens are shown in Figure 2. Specimens were compressed up to 80 mm displacement.

4. Results and Discussion

4.1. Experimental Results. A force/load-displacement curve is obtained during the test and is clearly shown in Figure 3. From the curves, all the patterns have more number of peaks. The number of peaks indicates the number of folds in each section. Based on the results, the crashworthiness effects of conical sections with base diameter, height, and thickness of thin-walled sections are studied, and the results are tabulated in Table 5.

4.2. Optimization Results. In the Taguchi method, the S/N ratios for better characteristics were chosen for the mean crushing force and specific energy absorption. Corresponding values of S/N ratios were calculated, and the results of multiple responses are tabulated in Table 5. Based on the S/N ratios, the normalized S/N ratios could be calculated for each parameter level.

Table 6 reveal that the test number 7 has the highest grey relational grade of the nine combinations, with the reference diameter 180 mm, height 120 mm, and thickness 1.5 mm.

The average grey relational grade and optimum level of controllable factors are calculated and tabulated in Table 7. Base diameter level 3, height level 1, thickness level 3, and the combination of the optimum process parameters are the optimum levels of the parameters. Optimum values of parameters at each level are indicated as stars in Table 7, and the variation of maximum to minimum is also indicated.

In multiperformance characteristics, the most affecting parameter has the maximum max-min value, and the highest value of max-min for thickness in response to the average grey relational grade is 0.456. The max-min value for base diameter is 0.195 and that for height is 0.02. The order of importance of factors in this study is listed as follows: factor C (thickness), factor A (base diameter), and factor B (height) such that $0.456 > 0.195 > 0.020$. Results of grey relational analysis (GRA) and importance of parameters were tested and listed by ANOVA, and the results are presented in Table 8. The analysis of variance also proved that the most significant and controllable factor is thickness, followed by base diameter and height of the conical structures.

Table 6: Taguchi and grey relational analysis results.

Specimen no.	Response I-F_{mean}			Response II-SEA			Grey rational grade	Rank
	S/N ratio	Normalized S/N ratio	Grey rational coefficient	S/N ratio	Normalized S/N ratio	Grey rational coefficient		
Cone 1	3.41	0.00	0.333	8.212	0	0.333	0.333	9
Cone 2	10.91	0.46	0.482	8.968	0.163	0.374	0.428	8
Cone 3	18.04	0.90	0.835	12.019	0.823	0.739	0.787	3
Cone 4	13.73	0.64	0.579	11.454	0.701	0.626	0.602	4
Cone 5	18.74	0.94	0.900	12.720	0.975	0.952	0.926	2
Cone 6	8.82	0.33	0.427	10.622	0.521	0.511	0.470	7
Cone 7	19.64	1.00	0.999	12.837	1.00	1	1.00	1
Cone 8	10.76	0.45	0.477	11.343	0.677	0.608	0.543	6
Cone 9	15.78	0.76	0.677	10.552	0.506	0.503	0.590	5

Table 7: Response of the average/mean grey relational grade.

Notation of factor	Control factors (mm)	Average grey relational grade			Max-min
		Level 1	Level 2	Level 3	
A	Base diameter	0.516	0.666	0.711*	0.195
B	Height	0.645*	0.632	0.625	0.020
C	Thickness	0.449	0.540	0.904*	0.456

The symbol * indicates optimum level of factors.

Table 8: ANOVA results.

Notation of factor	Control factor	DoF	Sum of squares	Mean squares	F value	% contribution
A	Base diameter (mm)	2	0.062	0.0312	21.996	15.055
B	Height (mm)	2	0.000626	0.000313	0.221	0.151
C	Thickness (mm)	2	0.349	0.1743	122.89	84.109
D	Error	2	0.00283	0.00142		0.684
Total		8	0.415	0.207		100

5. Conclusion

In this research, an optimization value of important crashworthiness parameters for conical structures was analyzed and presented by using the Taguchi-based grey relational method. Based on the grey relational approach, some key findings and conclusions were summarized:

(1) This analysis presents the significant effects of the base diameter, height, and thickness of a conical structure on crashworthiness.

(2) The optimum process parameters are a base diameter of 180 mm, a height of 120 mm, and a thickness of 1.5 mm, i.e, Test No. 7.

(3) Order of significance of various factors is as follows: thickness 84%, base diameter 15%, and height 0.15%, respectively.

(4) According to the influencing factor or parameter analysis, it was concluded that thickness and base diameter have a significant effect on the energy absorption/crashworthiness performance.

Obtained results can give some useful guidance to design thin-walled and lightweight structures for crashworthiness applications.

Experimental analysis described in this work would be useful for the development of energy absorption structural components in the field of aircraft, marine, and automobile applications.

Data Availability

The data used to support the findings of this study are included within the article, and the data can be made available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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