DESIGN OPTIMIZATION OF FIBER GLASS FILLER CIRCULAR CRASH BOX UNDER FRONTAL LOADING MODEL

WIDJANARKO[1,2], MOCH. AGUS CHOIRON[3],ANINDITO PURNOWIDODO[3], YUDY SURYA IRAWAN[3]

[1]Doctoral Student of Mechanical Engineering Department, University of Brawijaya, Indonesia

[2]Mechanical Engineering, State Polytechnic of Malang, Indonesia

[3]Mechanical Engineering Department, University of Brawijaya, Indonesia

DOI: 10.17973/MMSJ.2025_03_2024132

E-mail: agus_choiron@ub.ac.id

This study aims to optimize the design parameters of a fiberglass filler circular crash box to enhance Energy Absorption (EA) capabilities under frontal loading conditions. Utilizing Response Surface Methodology (RSM) and a Box-Behnken Design (BBD), the research comprises 15 experiments to assess the impact of three primary parameters: foam diameter, foam height, and aluminum tube thickness. The optimal configuration achieved a maximum EA of 45.6002 kJ. The findings indicate that foam height significantly influences EA, and the interaction between foam height and tube thickness is crucial for optimizing crash box performance. This research also reveals significant interactions among design parameters, contributing to improved vehicle safety standards and crashworthiness. Consequently, the study underscores the importance of design optimization in enhancing vehicle safety, reducing the necessity for extensive physical testing, and ensuring effective energy dissipation during collisions. The results provide valuable insights for the future development of vehicle safety technologies.

KEYWORDS

Optimum design, fiber glass filler, circular crash box, frontal loading model, Response Surface Methodology

1 INTRODUCTION

To provide the urgent enhancement of crashworthiness, the challenge of improving EA is faced to fulfill more excellent crash box design. The field of crashworthiness is continuously evolving, with researchers exploring various materials and design strategies to enhance vehicle safety standards. Optimization and numerical modelling of crash boxes has been carried out, utilizing lightweight materials such as aluminum, PET foam and Glass Fiber Reinforced Polymer (GFRP) to improve crash performance while minimizing component weight (M. Costas et al., 2017). Studies have also focused on the Energy Absorption properties of composites made from natural and hybrid fibers, specifically focusing on jute, Kevlar, and glass fiber reinforced epoxy for automotive uses (Z. F. Albahash and M. N. M. Ansari, 2017). The utilization of alternative natural fibers, such as kenaf, offers notable advantages, including cost efficiency, lightweight properties, and biodegradability. These characteristics render them highly suitable for Energy Absorption structures in automotive applications (M. F. M. Alkbir et al, 2014**)**. The research analyzed the mechanical properties and Energy Absorption capabilities of composite materials, with a particular focus on Carbon Fiber Reinforced Polymer (CFRP) tubes, aluminum tubes, and steel tubes subjected to quasi-static compressive loads (Guangyong Sun et al, 2016). In addition, research has explored the experimental study and analysis of deformation, Energy Absorption, and crashworthiness of various foam-filled thin-walled structures, focusing on circular and square tubes, where that tubes filled with a hybrid of foam and honeycomb significantly increase the average crushing strength, EA, and Specific Energy Absorption (SEA) compared to hollow tubes (Zhibin Li et al, 2018; Rafea Dakhil Hussein et al, 2017). Prior research has explored the crushing behavior and Energy Absorption characteristics of GFRP composite tubes, emphasizing their potential application in automotive systems. These studies also assessed the crashworthiness of cylindrical tubes fabricated from aluminum, GFRP, and hybrid aluminum/GFRP materials under both quasi-static and dynamic axial loading scenarios (Khaled Yousif et al, 2024; Stavros S. A. Lykakos et al, 2021; Rosalia et al, 2020). Parametric studies are developed using optimizing vehicle crash boxes to improve crashworthiness through a nonlinear optimization approach. It utilizes a combination of uniform design for selecting sample points and RSM to develop a response surface model (Tatsuo Yoshino et al, 2010). To address large-scale design challenges in the automotive industry, response surface-based design optimization is employed. This method is applied to enhance vehicle crashworthiness or to achieve weight reduction without compromising crashworthiness performance. Additionally, it improves the mechanical behavior of various automotive components under impact loading conditions. Classical response surface methodology facilitates the efficient identification of design points that satisfy the specified constraints, thereby streamlining the optimization process (Lei Shi et al, 2013; M. Avalle et al, 2002; J. Forsberg and L. Nilsson, 2005). Building upon previous studies, an investigation was conducted on circular crash boxes filled with fiberglass to identify the optimal design parameters for maximizing Energy Absorption. This optimization process utilized the Response Surface Methodology (RSM) to systematically evaluate and refine the design.

2 MATERIAL AND METHODS

The frontal loading model is provided with a computer simulation model using ANSYS Version 2003 R2 software. Frontal loading model is set with impact speed 7.67 m/s [7]. This research is centered around the development of a frontal test model for a crash box, with Aluminum Alloy 6063 serving as the outer wall and Glass Fiber as the filling material as shown in Table 1. The glass fiber used materials commonly used on the market and tested using ASTM D695 compression test. The property is assumed in one direction properties due to all samples are built in similar direction.

Table. 1 Material properties

Material Propertis	Alumunium Alloy 6063	Fiber Glass
Density [kg/m³]	2700	2000
Young Modulus [MPa]	70000	10938
Poisson's ratio	0.3	0.2
Tangent Modulus [MPa]	580	2300
Yield Strenght [MPa]	180	230
Ultimate Strenght [MPa]	240	370

Integration of aluminum foam can bolster the structural integrity and EA performance of crash boxes, ultimately enhancing vehicle safety. Optimizing the length and shape of the foam can lead to improvement in Crushing Load Efficiency (CLE) without raising the

Peak Crushing Force (PCF), which is vital for minimizing the risk of overload on vehicle occupants. The design and geometric characteristics of the crash box such as the foam diameter, foam height, and aluminum tube thickness were evaluated to enhance EA efficiency (Wyne Maddever, 2005; Michal Rogala et al, 2021) The foam-filling configuration was implemented across three distinct models, as depicted in Figure 1. The crash box geometry consists of a length (L) of 150 mm, a diameter (D) of 76 mm, and a wall thickness (t) of 1.8 mm. The experimental setup utilized an impactor with a mass of 200 kg and 7.67 m/s speed to simulate frontal loading as presented in Figure 1. The crash box base was considered to have a fixed support condition, while the joining process was performed with a face dimension of 2 mm.

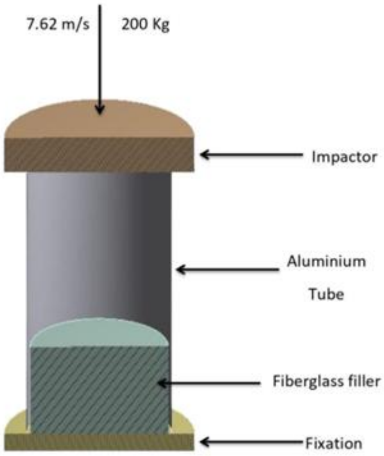


Figure 1. Crash Box Modeling

The RSM was utilized in this research to analyze parameters with the objective of maximizing EA. The specific levels assigned to each parameter in the crash box design are outlined in Table 2.

Table 2. Factors and level of experimental design

Notation	Factors	Levels		
		-1	0	1
A	foam diameter (mm)	68.4	70	71.6
B	foam height (mm)	60	70	80
C	Al tube thickness (mm)	1.8	2	2.2

RSM coupled with finite element analysis, was utilized to assess design variables, including segment diameter, thickness of the upper and lower segments, and joint positioning. This analysis was conducted to explore the parameters that optimize EA performance (M.A. Choiron and M. Ainul Yaqin, 2020). Table 3 shows the level value of each parameter of crash box design. The optimum response of performance is gained to find the maximum EA.

Table 3. Factors and level of experimental design

No	A	B	C	Foam Diameter (mm)	Foam Height (mm)	Aluminum Tube Thickness (mm)
1	1	0	-1	71.6	70	1.8
2	1	0	1	71.6	70	2.2
3	-1	1	0	68.4	80	2
4	0	-1	1	70	60	2.2
5	0	1	1	70	80	2.2
6	-1	0	-1	68.4	70	1.8
7	0	0	0	70	70	2
8	0	0	0	70	70	2
9	0	1	-1	70	80	1.8
10	0	-1	-1	70	60	1.8
11	0	0	0	70	70	2
12	-1	0	1	68.4	70	2.2
13	1	-1	0	71.6	60	2
14	1	1	0	71.6	80	2
15	-1	-1	0	68.4	60	2

The design matrix factors are set as 15 experiments based on Box-Behnken. The BBD is an incomplete three-level factorial design method utilized in conjunction with RSM to identify optimal factors in experimental studies. A primary advantage of the BBD lies in its ability to minimize the number of design points required, significantly reducing the total number of experimental sets without compromising the accuracy of the optimization process. This approach allows for the acquisition of sufficient information to establish optimal operating conditions, thereby lowering experimental costs (Lotfi B. S. et al, 2024, Ikenna C.E. and Bilal P., 2024, Pengpeng Qiu et al, 2014, Cimen Demirel et al, 2022). The impact of the chosen parameters for the fiberglass-filled circular crash box on EA can be forecasted using this model across the analyzed range. To facilitate the interpretation of the findings, the influence of each design parameter will be displayed individually, followed by a comprehensive analysis of the overall plots. The effect of design parameters on EA is presented as 3D surface and contour plots.

3 RESULT

Figure 2 illustrates the response surface of EA for the crash box, analyzing the effects of foam diameter and foam height. The highest EA values occur at specific parameter combinations, marked by the dark red regions. The color scale on the right indicates EA values in kJ, increasing progressively from the lowest (purple) to the highest (dark red).

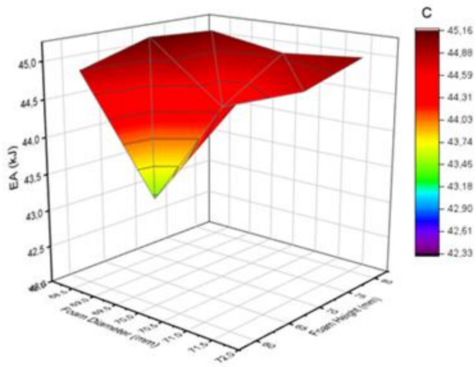


Figure 2. The effects of foam diameter and foam height on the EA

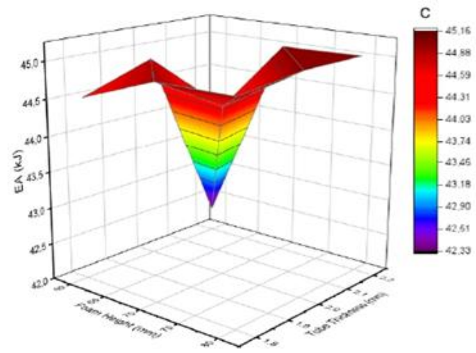


Figure 3. The effects of foam diameter and tube thickness on the EA

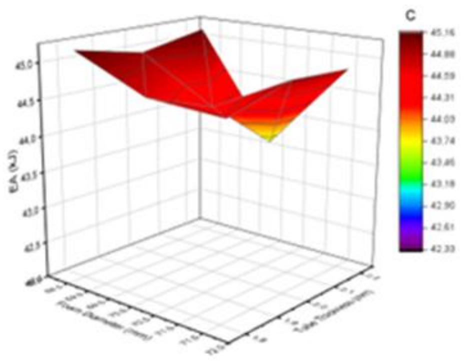


Figure 4. The effects of foam height and tube thickness on the EA

Figure 3 also displays the response surface of EA relative to variations in foam diameter and foam height. The EA values, ranging between 42.33 kJ and 45.16 kJ, are represented by a color gradient on the right. The dark red regions signify maximum EA, while the green and blue regions denote lower values. The surface plot reflects how variations in these two parameters influence the EA performance. In contrast, Figure 4 shows the response surface of EA for foam height and tube thickness. A pronounced drop in EA is observed at specific parameter combinations, indicated by blue and purple regions. The color scale on the right, ranging from 42.33 kJ to 45.16 kJ, demonstrates an upward progression from blue to dark red. This pattern highlights the substantial impact of foam height and tube thickness on the crash box's EA behavior. The EA observation of fiber glass filler circular crash box was acquired and filled in the design matrix as shown in Table 4.

Table 4. The design matrix and EA results

No.	A	B	C	EA (kJ)
1	0	1	1	44.907
2	0	0	0	44.367
3	0	-1	-1	44.516
4	0	1	-1	44.904
5	-1	0	1	45.138
6	-1	1	0	45.037
7	-1	-1	0	44.875
8	0	0	0	44.367
9	-1	0	-1	45.157
10	0	0	0	44.367
11	1	0	1	44.859
12	1	-1	0	44.822
13	0	-1	1	42.332
14	1	1	0	44.997
15	1	0	-1	44.646

The EA outcomes derived from the 15 experiments, as detailed in Table 4, reveal a spectrum of responses influenced by the various combinations of foam diameter, foam height, and aluminum tube thickness. The maximum EA recorded was 45.157 kJ, achieved with a configuration of reduced foam diameter (-1), medium foam height (0), and decreased aluminum tube thickness (-1). The results indicate that variations in foam height exert a more significant influence on EA compared to other parameters. Specifically, an increase in foam height generally correlates with enhanced EA. Furthermore, the interaction between foam height and aluminum tube thickness was identified as a crucial factor in optimizing the EA characteristics of the crash box. These findings underscore the necessity of balancing design parameters to attain optimal EA performance in crash box applications.

Table 5. Estimated regression coefficients for EA

Term	Coef	SE Coef	T	P
Constant	44.3670	0.3294	134.681	0.000
A	-0.1104	0.2017	-0.547	0.608
B	0.4125	0.2017	2.045	0.096
C	-0.2484	0.2017	-1.231	0.273
A*A	0.6755	0.2969	2.275	0.072
B*B	-0.1097	0.2969	-0.370	0.727
C*C	-0.0925	0.2969	-0.312	0.768
A*B	0.0032	0.2853	0.011	0.991
A*C	0.0580	0.2853	0.203	0.847
B*C	0.5467	0.2853	1.916	0.113

Based on Table 5, the friction time have the most significant effect on the EA of crash box design. All interaction effect between each parameter does not show strong dependence. ANOVA is calculated for the model regression evaluation as shown in the Table 6. Based on the table, it can be seen from the P-value that the linear is significant while the interaction and square components are not.

Table 6. The Analysis of Variance

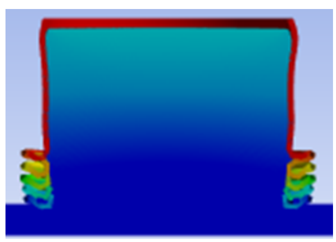
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	5.00935	5.00935	0.55659	1.71	0.288
Linear	3	1.95223	1.95223	0.65074	2.00	0.233
A	1	0.09746	0.09746	0.09746	0.30	0.608
B	1	1.36125	1.36125	1.36125	4.18	0.096
C	1	0.49352	0.49352	0.49352	1.52	0.273
Square	3	1.84788	1.84788	0.61596	1.89	0.249
A*A	1	1.77716	1.68480	1.68480	5.18	0.072
B*B	1	0.03913	0.04447	0.04447	0.14	0.727
C*C	1	0.03159	0.03159	0.03159	0.10	0.768
Interaction	3	1.20924	1.20924	0.40308	1.24	0.388
A*B	1	0.00004	0.00004	0.00004	0.00	0.991
A*C	1	0.01346	0.01346	0.01346	0.04	0.847
B*C	1	1.19574	1.19574	1.19574	3.67	0.113
Residual Error	5	1.62779	1.62779	0.32556		
Lack-of-Fit	3	1.62779	1.62779	0.54260		
Pure Error	2	0.00000	0.00000	0.00000		
Total	14	6.63714				

4 DISCUSSION

Table 5 denotes the fitted response surface analysis on the performance of model with acceptable residuals. To perform the optimization of EA, the verified model of the EA was in the form of the following equation:

$$EA = 44.367 - 0.110375 . FD + 0.4125 . FH - 0.248375 . TT + 0.6755 . FD^2 - 0.10975 . FH^2 - 0.0925 . TT^2 + 0.00325 . FD . FH + 0.058 FD . TT + 0.54675 FH . TT$$

where, FD is foam diameter, FH is foam height, and TT is tube thickness.



(a)

(b)

Figure 5. Deformation Pattern (a) Highest EA, (b) Lowest EA

The deformation pattern of the crash box exhibiting the highest EA value demonstrates a uniform and stable deformation across the tube structure, signifying an efficient EA process (Figure 5a). The even distribution of deformation facilitates the effective dissipation of impact energy. Conversely, the deformation pattern for the crash box with the lowest EA value shows an uneven distribution of deformation, localized in specific regions, leading to a diminished ability of the structure to absorb impact energy (Figure 5b). This pattern indicates a less optimal energy distribution mechanism.

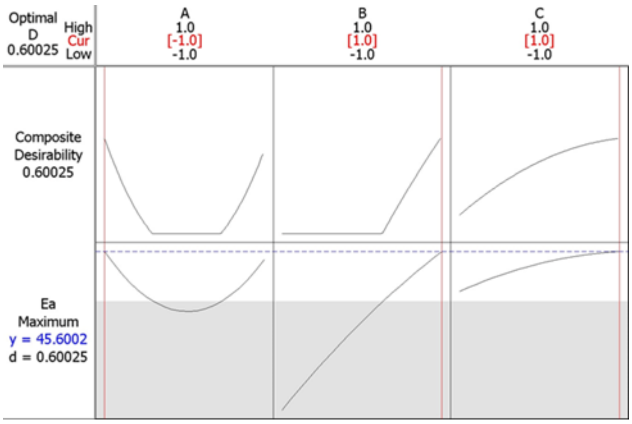


Figure 6. The optimal operational parameters chart of the crash box design for maximum EA

The simulation model was validated to check again the optimal parameters. The optimal operational parameters were as follows: foam diameter = 68.4 mm, foam height = 80 mm, and aluminum tube thickness = 2.2 mm, as shown in the Figure 6. The simulation model runs at optimal conditions were carried out to verify the the optimum design model accuracy. The model predicated the maximum EA could reach 45.6002 kJ on the optimal conditions. The mean value of maximum EA on the verification experiments was 45.131 kJ. Based on this value, the simulation model produces a good fit for this study. This optimum design can be connected from deformation pattern result as shown in the Figure 7. The number of folding is larger than other crash box models as phemonena on previous study. Additionally, this data is supported by a load-displacement graph which shows the appearance of folding towards the end of deformation; the curve rises significantly which will increase the value of EA (Figure 8). Therefore, Optimizing the operational parameters of the Fiber glass filler circular crash box parameters was successful for maximum EA and explaining the interactive effects between design parameter via response surface method. The deformation pattern of the crash box exhibiting the highest EA (EA) value demonstrates a uniform and stable deformation across the tube structure, signifying an efficient EA process. The even distribution of deformation facilitates the effective dissipation of impact energy. Conversely, the deformation pattern for the crash box with the lowest EA value shows an uneven distribution of deformation, localized in specific regions, leading to a diminished ability of the structure to absorb impact energy. This pattern indicates a less optimal energy distribution mechanism (Hafid M. et al, 2024).

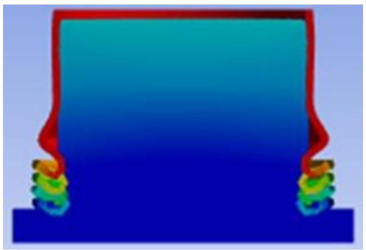


Figure 7. Deformation pattern results on the optimun design

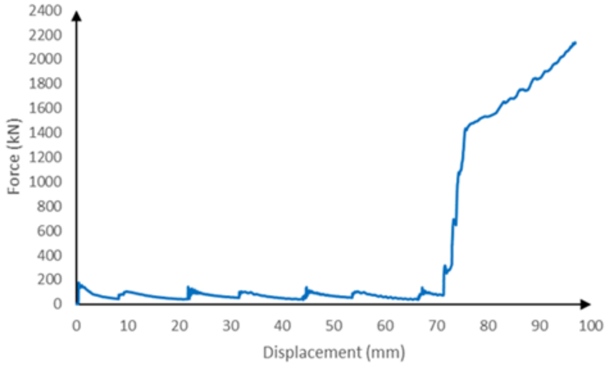


Figure 8. Load-Displacement curve on the optimum design crash box model

5 CONCLUSION

This study successfully demonstrates that the optimization of design parameters for fiberglass filler crash boxes can significantly enhance EA capabilities under frontal loading conditions. By employing RSM and the Box-Behnken design, the optimal configuration was identified with a foam diameter of 68.4 mm, foam height of 80 mm, and aluminum tube thickness of 2.2 mm, achieving a maximum EA of 45.6002 kJ. The findings indicate that friction time and the interaction between foam height and tube thickness significantly influence the performance of the crash box. Consequently, this research not only reduces the necessity for extensive physical testing but also plays a crucial role in improving vehicle safety during accidents. Furthermore, it highlights that the design optimization of crash boxes with fiberglass fillers can make a substantial contribution to vehicle safety, a primary concern for the general public. By enhancing EA capabilities in frontal loading scenarios, this optimized design mitigates the risk of injury to drivers and passengers during collisions while also decreasing the need for costly and time-consuming physical tests. The study's results, which achieved a maximum EA of 45.6002 kJ, underscore the significant potential for elevating vehicle safety standards on the roads, thereby providing a sense of security for vehicle users across society.

ACKNOWLEDMENTS

This research was supported by State Politechnic of Malang by the doctoral program scholarship funding. Many thanks to the Mechanical Engineering Department, Brawijaya University for their research support.

REFERENCES

[M. Costas 2017] M. Costas, D. Morin, M. Langseth, J. Diaz, I. Romera, "Static crushing of aluminium tubes filled with PET foam and a GFRP skeleton. Numerical modelling and multiobjective optimization", International Journal of Mechanical Sciences, 131–132 (2017) 205–217.

[Z. F. Albahash 2017] Z. F. Albahas, M. N. M. Ansari, "Investigation on Energy Absorption of natural and hybrid fiber under axial static crushing", Composites Science and Technology, DOI: 10.1016/j.compscitech.2017.07.028.

[M. F. M. Alkbir 2014] M. F. M. Alkbir, S. M. Sapuan, A. A. Nuraini, M. R. Ishak, "Effect of geometry on crashworthiness parameters of natural kenaf fibre reinforced composite hexagonal tubes", Materials and Design 60 (2014) 85–93.

[Guangyong Sun 2016] Guangyong Sun, Shunfeng Li, Qiang Liu, Guangyao Li, Qing Li, "Experimental study on crashworthiness of empty-aluminum foam-honeycomb–filled CFRP tubes", Composite Structures, http://dx.doi.org/10.1016/j.compstruct.2016.06.019.

[Zhibin Li 2018] Zhibin Li, Rong Chen, Fangyun Lu, "Comparative analysis of crashworthiness of empty and foam-filled thin-walled tubes", Thin-Walled Structures 124 (2018) 343–349.

[Rafea Dakhil Hussein 2017] Rafea Dakhil Hussein, Dong Ruan, Guoxing Lu, Stephen Guillow, Jeong Whan Yoon, "Crushing response of square aluminium tubes filled with polyurethane foam and aluminium honeycomb", Thin–Walled Structures 110 (2017) 140–154.

[Khaled Yousif 2024] Khaled Yousif, Aamir Dean, Elsadig Mahdi, "Crushing behavior of GFRP composite-reinforced PVC tubes. Experimental testing and numerical simulation, Composites Science and Technology 258 (2024) 110903.

[Stavros S. A. Lykakos 2021] Stavros S. A. Lykakos, Protesilaos K. Kostazos, Odysseas-Vasilios Venetsanos and Dimitrios E. Manolakos, "Crashworthiness Performance of Aluminium, GFRP and Hybrid Aluminium-GFRP Circular Tubes under Quasi-Static and Dynamic Axial Loading Conditions. A Comparative Experimental Study", Dynamics 2021, 1, 22–48. https://doi.org/10.3390/dynamics1010004.

[Citra Asti Rosalia 2020] Citra Asti Rosalia, Ichsan Setya Putra, Tatacipta Dirgantara, Annisa Jusuf and Bambang K. Hadi, "Experimental study on the crashworthiness response of hybrid Al-GFRP crash box structures under axial compression loading", Materials Science and Engineering, 1007 (2020) 012016 doi:10.1088/1757-899X/1007/1/012016.

[Tatsuo Yoshino 2010] Tatsuo Yoshino, Tao Xu, Tianshuang Xu, and Peng Cheng, "Crashworthiness Optimization Using Response Surface Method Based on Uniform Design", Applied Mechanics and Materials Vols. 34-35 (2010) pp 399-403.

[Lei Shi 2013] Lei Shi, Ren-JyeYang and Ping Zhu "An adaptive response surface method for crashworthiness optimization", Engineering Optimization iFirst, 2012, 1–13, http://dx.doi.org/10.1080/0305215X.2012.734815.

[M. Avalle 2002] M. Avalle, G. Chiandussi and G. Belingardi, "Design optimization by response surface methodology-application to crashworthiness design of vehicle structures", Struct Multidisc Optim 24, 325–332 © Springer-Verlag 2002, (DOI) 10.1007/s00158-002-0243-x.

[J. Forsberg 2005] J. Forsberg and L. Nilsson, "Evaluation of response surface methodologies used in crashworthiness optimization", International Journal of Impact Engineering 32 (2006) 759–777, doi: 10.1016/j.ijimpeng.2005.01.007.

[Wyne Maddever 2005] Wayne Maddever and Sebastien Guinehut, "Use Aluminum Foam to Increase Crash Box Efficiency, 2005 SAE World Congress Detroit, Michigan April 11-14, 2005, ISSN 0148-7191 Copyright © 2005 SAE International.

[Michal Rogala 2021] Michał Rogala, Mirosław Ferdynus, Katarzyna Gawdzinska and Paweł Kochmanski, "The Influence of Different Length Aluminum Foam Filling on Mechanical Behavior of a Square Thin-Walled Column", Materials 2021, 14, 3630. https://doi.org/10.3390/ma14133630.

[M.A. Choiron, 2020] M. A. Choiron and M. Ainul Yaqin, "Optimization of two segments crash box with rubber joint using response surface methodology", AIP Conference Proceedings 2278, 020012 (2020); https://doi.org/10.1063/5.001458.

[Lotfi B. S., 2024] Lotfi Ben Said, Shan Ali Khan, Umar Farooq, Haihu Liu, Muhammad Imran, Taseer Muhammad, Mesfer Ahmad Mesfer Alwadai, "Application of Box-Behnken design with RSM to predict the heat transfer performance of thermo-magnetic convection of hybrid nanofluid inside a novel oval-shaped annulus enclosure", Case Studies in Thermal Engineering 61 (2024) 105010, https://doi.org/10.1016/j.csite.2024.105010.

[Ikenna C.E., 2024] Ikenna C.E. and Bilal P., "Box-Behnken assisted RSM and ANN modelling for biodiesel production over titanium supported zinc-oxide catalyst", Energy 308 (2024) 132765, https://doi.org/10.1016/j.energy.2024.132765.

[Pengpeng Qiu, 2014] Pengpeng Qiu, Mingcan Cui, Kyounglim Kang, Beomguk Park, Yonggyu Son, Eunkyung Khim, Min Jang, Jeehyeong Khim, "Application of Box–Behnken design with response surface methodology for modeling and optimizing ultrasonic oxidation of arsenite with H2O2", Cent. Eur. J. Chem. • 12(2) • 2014 • 164-172, DOI: 10.2478/s11532-013-0360-y.

[Cimen Demirel, 2022] Cimen Demirel, Abraham Kabutey, David Herák, Ales Sedlacek, Cestmir Mizera and Oldrich Dajbych, "Using Box–Behnken Design Coupled with Response Surface Methodology for Optimizing Rapeseed Oil Expression Parameters under Heating and Freezing Conditions" Processes 2022, 10, 490. https://doi.org/10.3390/pr10030490.

[M. Hafid 2024] M. Hafid, Jos Istiyanto, and Nasruddin Nasruddin, "Multiobjective optimization of dimension and position of elliptical crush initiator on crashworthiness performance of square tube using response surface methodology", Front. Mech. Eng 9:1273447. doi: 10.3389/fmech.2023.1273447.

CONTACTS

Widjanarko, S.T., M.T State Polytechnic of Malang, Mechanical Engineering Jl. Soekarno Hatta No 9, Malang, 65141, Indonesia 0818647089, widjanarko@polinema.ac.id

Prof. Dr. Eng. Moch. Agus Choiron, S.T., M.T University of Brawijaya, Mechanical Engineering Jl. MT. Haryono 167, Malang, 65145, Indonesia 082139249937, agus_ choiron@ub.ac.id

Prof. Dr. Eng. Anindito Purnowidodo, S.T., M.Eng. University of Brawijaya, Mechanical Engineering Jl. MT. Haryono 167, Malang, 65145, Indonesia 085791489665, anindito@ub.ac.id

Dr. Eng. Yudy Surya Irawan, ST., M.Eng. University of Brawijaya, Mechanical Engineering Jl. MT. Haryono 167, Malang, 65145, Indonesia 085649776609, yudysir@ub.ac.id