Crashworthiness Enhancement: The Optimization of Vehicle Crash Box Performance by Utilizing Bionic-Albuca Spiralis Thin-Walled Structure

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Crashworthiness Enhancement: The Optimization of Vehicle Crash Box Performance by Utilizing Bionic-Albuca Spiralis Thin-Walled Structure

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Abstract: This paper presents a comprehensive investigation utilizing simulations to analyze the peak force and energy absorption characteristics of cylindrical configurations, as well as a novel spiral crash box design inspired by the albuca spiralis form. The study aims to evaluate the behavior of these designs in low-speed collisions by utilizing aluminum and steel as two different materials. Four primary forms of thin-walled structures, including concentric circles, tangent circles, half-balanced circles, and spiral circles, were thoroughly examined using finite element analysis. Mesh-independent tests were conducted to ensure the accuracy of the simulation results, and various crumple displacements were compared to determine the optimal mesh sizing. The numerical results demonstrate a significant reduction in peak force for the aluminum crash box, with a remarkable 60% decrease compared to the steel crash box. Furthermore, the spiral shape, identified as an optimized design, exhibits a low peak force of only 118.42 kN and offers superior energy absorption of 9.15 kJ per kilogram compared to the other designs. Consequently, employing nature-inspired designs provides substantial benefits for enhancing crashworthiness in energy-absorbing devices.

Keywords: Bionic inspired; energy absorption; crash box; thin walled, peak force, crashworthiness

1. Introduction

Thin-walled structures are widely utilized in automotive engineering due to their favorable energy absorption and low mass characteristics[1-2]. Implementing this structure in such conditions is beneficial for both energy efficiency and safety perspective. The thin-walled structure provides a lightweight, related to the low energy consumption, and gives better safety with its incredible energy absorption simultaneously. On the vehicle configuration, the crumple zone is the most common area in a vehicle that utilizes thin-walled technology. This is the zone where the structure of a car should be crumpled during the crash to minimize the injuries both for the driver and pedestrians[3].

A Crumple zone is typically placed in two areas, the front, and the back of a vehicle, and both are supposed to reduce the impact energy during the crash. This section has many components, such as a fascia, bumper, crash boxes, subframes, longitudinal beams, upper rails, etc. Compared to the other parts, the crash box plays a substantial role as the structure is dedicated to being an energy-absorbing member of the vehicle due to collision in the event of a crash[4]. The crash box structure as a vehicle passive safety system is expected to absorb kinetic energy in frontal crashes, maintain the vehicle deceleration at a safe limit, and decrease the chance of injury to the vehicle's passenger during collision[5].

The crash box structure study encompasses many aspects and approaches but mainly contributes to crashworthiness. One The crash box design is one of the most concerning topics[6]. Bathe et al.[7] analyzed advances in crash investigation, specifically in crash box design. Strengthened by the inquiry by Liu[8] on crash box design optimization and crashworthiness analysis has reinforced the importance of enabling crash box designs to effectively absorb impact forces through a crumpled structure, highlighting the significant contribution of various designs to the performance of energy-absorbing devices.

Various thin-wall structures, such as cylindrical, square, conical, and hat-sectional beams, have been observed and compared to understand the plastic deformation behavior and how good their performance as an energy-absorbing device in a vehicle[4, 9]. Some of the previous research has scrutinized the roles of dimension and thickness of thin-wall structure in crash behavior[9, 10], and others observed the crash box design configurations under different parameters, such as fillers[11, 12], multi-cell, and hybrid [9, 10]. One of the most popular shapes with various forms is a circular-inspired design. The circular shape is believed to have a suitable energy absorption property as it has been investigated in its material[13] and its design[14].

According to the literature, a cylindrical crash box structure offers a significant result as it has a better crashworthiness property, thereby possessing the considerable potential to be an energy-absorbing structure in vehicle engineering. While substantial works have been performed to design novel tubal configurations, these previous studies were still incomplete without analyzing the effect of the position of each circular tube and other closest potential designs, such as spiral shape, as the optimized design from these circular tubes, especially in low-speed parameters. When using more than one thin cylindrical wall, each tube's position and connection can generate different patterns and or mechanical properties. This is crucial to be observed since the thin-walled design notably impacts the energy-absorbing ability[15-17].

The variation of circle design should be carefully observed; one of the most popular cylindrical-related designs is a spiral-based design inspired by nature life, albuca spiralis plant, as seen in Figure 1. Biological structures have matured remarkable properties and innovative designs through millions of years of evolution and natural selection[18]. Spiral-based design is believed to be one of the most promising designs for energy-absorbing devices. Several studies showed that using spiral-based thin-walled structures could improve energy-absorbing performance[19, 20].

Fig. 1: Albuca spiralis plant.

In this paper, a simulation study of the crash box in axial loading conditions is observed using F.E.M. (Finite Element Method) software as this study aimed to provide the crash box performance of three different circular configuration forms and then optimized by bionic spiral-based structures. F.E.M. is commonly used for many applications to discover the behavior of a system and structure[21] and offers a straightforward approach at almost no cost[22]. This simulation approach is also able to validate the structural design integrity[23], to calculate the stress-strain distribution easier than the experimental [24], and to increase the accuracy of the result[25]. Therefore, an F.E.M. analysis is used in this work to predict the performance of the crash box design. For achieving better performance, peak force reduction and buckling behavior analysis are the primary concerns of this work. The S.E.A. (Specific Energy Absorption) and the P.F. (Peak Force) are considered in this study as the top-notch standard for topology enhancement. The numerical simulation focuses on comparing the response of various circle configuration forms, which are concentric circle, tangent circle, and half-balanced circle thin-walled, compared to the spiral-based thin-walled structure as an optimization of the previous designs under quasi-static axial loading situations.

2. Material Properties and Crashworthiness Criteria

Steel and aluminum are the most common materials employed as a crash box since both offer a considerable performance to absorb the impact energy during the crash. The mechanical properties of both materials can be found in Table 1. This impact-absorbing ability is pivotal for a crash box to absorb the kinetic energy during the collision to avoid fatal injuries for occupants and pedestrians. This qualification is known as crashworthiness. Almost every transportation mode uses this technology for optimizing their safety design, i.e., aircraft[26, 27], railways[28-30], and automobiles[3, 31-33]. To meet the crashworthiness criteria, intense studies and analyses must be carried out carefully. Both computerized simulation and actual tests are commonly used in crashworthiness analysis. Critical points such as the deformation behavior of vehicle structure, vehicle acceleration before and at the moment of a crash, and the ability to prevent further injuries using a dummy human body are the pivot criteria in crashworthiness study[34]. In mechanical analysis, speed, mass, design, and material properties of vehicles and components are among the important parameters that need to be observed profoundly. These following criteria are utilized to formulate not only optimum design but also testing methods as well as to create an ideal condition of the safety transportation.

Table 1. Mechanical properties of aluminum and steel.

	Aluminum	**Steel**
Density (kg/m^3)	2700	7830
Elastic Modulus (MPa)	70.3	210
Yield Stress (MPa)	125	250
Ultimate Strength (Mpa)	275	360
Poisson's ratio	0.3	0.3

2.1 Energy Absorption (E.A.)

Energy absorption is the area below the load-displacement curve which comprehend and asses the structure crushing conditions during the collision, which may be expressed as:

$$EA(d) = \int_o^d f(x)dx \qquad (1)$$

Axial impact force is defined by $f(x)$ Which rely on displacement (x) At the time of the collision, d represents the net deformation distance of the structure used in this work.

2.2 Specific Energy Absorption (S.E.A.)

S.E.A. is the total energy absorbed per structure mass; its unit is kJ/kg. This is important to compare the structure's ability to absorb energy, given as:

$$SEA(d) = \frac{EA(d)}{m} = \frac{\int_o^d f(x)dx}{m} \quad (2)$$

2.3 Mean Crushing Force (M.C.F.)

M.C.F. is gained by dividing the energy absorbed by the total effective deformation and expressed as:

$$MCF = \frac{EA(d)}{d} = \frac{\int_o^d f(x)dx}{d} \qquad (3)$$

2.4 Initial Peak Crushing Force (I.P.C.F.)

When crash box tubes at the beginning reach a peak point, known as I.P.C.F., then a drop is seen, and after that, waves are shaped in the bottom level under axial compression loading until densification. As an essential factor, it may trigger a danger when the initial peak force is exorbitantly maximum[35]. Hence, this I.P.C.F. should be kept in a safe area for safety purposes.

3. Finite Element Modeling

The finite element (F.E.) is among the most popular tools in crash analysis for transportation due to its ability to offer a less budget and a convenient approach to investigate any physical damage that occurs during the collision. Some studies used this numerical simulation for analyzing the vehicle frame[36, 37], engine hood[38], and crash box[39-42] of a vehicle. In crash box cases, F.E. is usually employed to investigate the peak force, structure behavior, and stress location during the crash. To generate an accurate and credible result, every parameter used in the simulation should be well-prepared and designed as near as possible to the actual conditions. Thus, this simulation's models and boundary conditions are based on the real application of a vehicle crash box as seen in Figure 2.

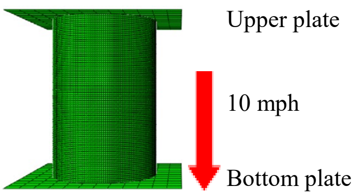

Fig. 2: Finite Element model and boundary conditions.

The crash box is positioned between two rigid plates; the bottom plate represents the vehicle bumper/ structure, and the upper plate is a movable plate that serves as a crash object. The lower part of the crash box was fixed to the bottom plate by employing ENCASTRE, and the upper plate, as the crash object was, kept moving only in the z direction to hit the crash box. A low-speed crash scenario was employed in this study, simulating a speed of 10 mph. According to the Florida Highway Safety and Motor Vehicles (FHSMV) low-speed car crashes are defined as crashes when all vehicles involved are traveling between 1 and 10 Mph. The material properties of steel and aluminum are adopted as the mechanical input data for the crash box in this study, as both are among the most common materials used for a crash box[43].

3.1 Mesh Convergence Test of Thin-walled Geometry

Mesh generation is the initial step in performing a simulation[44]. To produce an accurate simulation, mesh independent test is one of the most overlooked issues in computational mechanics to ensure that the simulation results are not affected by changes in the mesh size. It is also pivotal to determine the best mesh condition to be used in study[45]. Five different mesh sizes are performed in this work which are 6 x 6mm, 3 x 3mm, 1.5 x1.5mm, 0.75 x 0.75mm, and 0.375 x 0.375mm. In this case, to perform the mesh convergence test, displacement versus time was performed to find out the preferable mesh size can be used in this study, as shown in Figure 3.

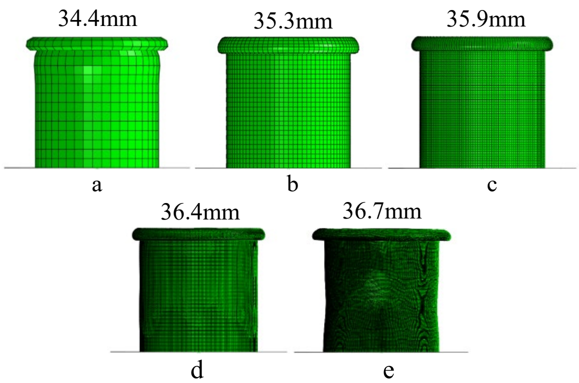

Fig. 3: Mesh independence test results for various meshing sizes, (a) 6x6mm, (b) 3x3mm, (c) 1.5x1.5mm, (d) 0.75x0.75mm, (e) 0.375x0.375mm.

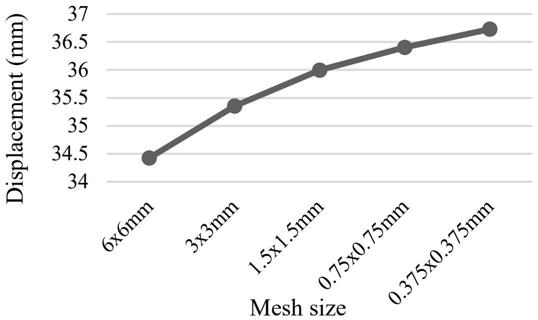

Fig. 4: Displacement vs time of various mesh sizing.

From Figure 4, it can be concluded that the mesh size of 0.75x0.75mm has a slight difference of only 0.89% (lower than 1%) from the mesh size of 0.375x0.75mm. Thus, we can assume that the mesh size of 0.75x0.75mm is relevant for all models in this simulation study.

3.2 Material Comparison

In this study, four cylindrical configurations were examined: concentric circle, tangent circle, half-balanced circle, and a spiral-based circle. Each configuration consisted of four circle tubes with varying dimensions, while the spiral circle featured four loops. The primary focus was on comparing the performance of steel and aluminum materials in the concentric circle design, considering factors such as weight, peak force, and energy absorption ability. Figure 5 illustrates the design of the concentric circle, which served as the base design for this investigation.

In Figure 6, CCST (Concentric Circle Steel) and CCAL (Concentric Circle Aluminum) were investigated under the same boundary conditions.

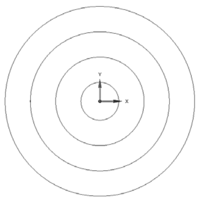

Fig. 5: Concentric circle shape

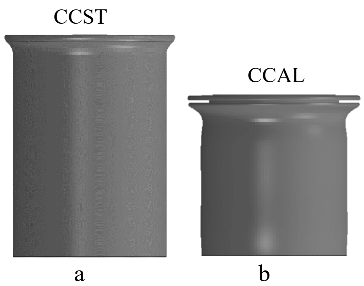

Fig. 6: Concentric circle after low-speed crash; (a) steel, (b) aluminum.

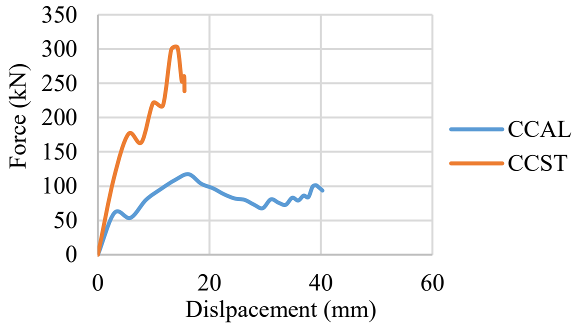

Fig. 7: Force-displacement graph of CCST and CCAL.

Figure 7 illustrates that the aluminum-based crash box exhibits a significant reduction in peak force compared to the steel crash box, with a remarkable difference of over 60%. Moreover, the concentric circle configuration with aluminum material (CCAL) demonstrates superior energy-absorbing performance, absorbing 3.11 kJ of energy, whereas the other variations can only absorb 2.45 kJ during low-speed collisions. In terms of weight, CCAL stands out with a mere total weight of 0.36 kg. Conversely, the steel-based crash box weighs three times as much as CCAL, exceeding 1 kg in total. Based on these findings, aluminum was selected as the primary material for further investigation in this study.

3.3 Design Optimization

The performance of a crash box heavily relies on its design, making it a crucial aspect to optimize [46]. In this study, the base concentric circle design was the focal point, with an exploration of tangent circles, half-balanced circles, and spiral circles. The tangent circle (T.C.) design took inspiration from a straight line intersecting the circle at a single point, leading to the configuration of each circle accordingly. The half-balanced circle (H.C.) design involved arranging the outer circle (C1) and the third inner circle (C3) concentrically, while positioning the second circle (C2) and fourth circle (C4) tangentially, as illustrated in Figure 8b. The final design, the spiral circle (S.C.), showcased in Figure 8c, retained the dimensional inspiration from the concentric base circle but introduced connected circles arranged in loops (L1-L4). Optimization through these different circle configurations aimed to enhance the crash box's overall performance.

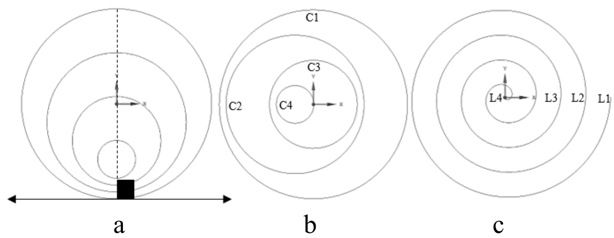

Fig. 8: Optimized crash box design; (a) tangent circle, (b) half-balanced circle, (c) spiral circle.

Table 2. Crushing characteristic of concentric, tangent, half-balanced, and spiral circle under low-speed crash.

Design	Weight (kg)	disp. (mm)	IPCF (kN)	MCF (kN)	EA (kJ)	SEA (kJ/kg)
Concentric circle	0.36	40.2	117.42	0.07	3.11	8.63
Tangent circle	0.36	39.9	118.63	0.07	3	8.6
Half-balanced circle	0.36	40.2	120	0.07	3.13	8.69
Spiral circle	0.36	38.7	118.42	0.08	3.33	9.15

Fig. 9: Optimized design after low-speed crash conditions of(a) T.C., (b) H.C., and (c) S.C.

The impact test results are depicted in Figure 9, showcasing the conditions of the top and side crash boxes. Table 2 presents notable findings, indicating that the spiral circle design outperforms other designs in terms of energy absorption, with an impressive rate of 9.15 kJ per 1 kg of the structure. Additionally, the spiral circle design exhibits a lower peak force compared to the tangent and half-balanced structures. It is only 0.1 kN higher than the concentric circle design but offers the same weight and higher energy absorption. Based on these compelling data, the spiral-based thin-walled design proves to be significantly superior to the other variants in terms of crashworthiness performance.

4. Conclusions

The primary objective of this paper was to identify an optimal material and design for a vehicle's crash box. In this pursuit, steel and aluminum, commonly used materials in the crash box industry, were tested in a concentric circle design to evaluate their respective performance. Comparing the results with a steel crash box, the aluminum-based crash box demonstrated a remarkable reduction of over 60% in peak force. Additionally, the Concentric Circle Aluminum (CCAL) design exhibited superior energy absorption capacity, absorbing 3.11 kJ during low-speed impacts, in contrast to the Concentric Circle Steel (CCST) design, which could only absorb 2.45 kJ. Furthermore, CCAL weighed a mere 0.36 kg, while the steel-based crash box was more than three times heavier, surpassing 1 kg. These findings led to the selection of aluminum as the material for further design optimization in this study.

Considering crashworthiness, material alone does not suffice as a determining factor. Thus, various circular variations were explored as part of an optimization approach. The investigation focused on tangent, half-balanced, and spiral circles as enhancement designs. The results revealed that the spiral circle design showcased superior energy absorption capabilities, absorbing 9.15 kJ per kilogram of the structure in low-speed impact tests conducted under identical dimensions and crash conditions. Moreover, the peak force of the spiral circle design was only 0.1 kN higher than that of the concentric circle design, despite having the same weight and exhibiting higher energy absorption. Based on these compelling findings, the bionic-inspired spiral structure, inspired by the albuca spiralis, emerged as the clear frontrunner among the available options.

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Sudirja is the main contributor to this study. The other authors are involved differently in smaller portions, such as in the design and data processing and in the discussion and analysis of the results. All authors acknowledged the content of this manuscript.

References

1) X. Sun, H. Zhang, W. Meng, R. Zhang, K. Li, and T. Peng, "Primary resonance analysis and vibration suppression for the harmonically excited nonlinear suspension system using a pair of symmetric viscoelastic buffers," Nonlinear Dyn., 94 (2) 1243–1265 (2018). doi:10.1007/s11071-018-4421-9.
2) Y. Zhang, Q. Liu, Z. He, Z. Zong, and J. Fang, "Dynamic impact response of aluminum honeycombs filled with expanded polypropylene foam," Compos. Part B Eng., 156 17–27 (2019). doi:10.1016/j.compositesb.2018.08.043.
3) Sudirja, A. Hapid, S. Kaleg, A.C. Budiman, and Amin, “The Crumple Zone Quality Enhancement of Electric

Cars Bumper Fascia using a Carbon Fiber Reinforced Vinyl Ester – Microsphere Composites," in: 2019 Int. Conf. Sustain. Energy Eng. Appl. ICSEEA, 2019: pp. 1–5. doi:10.1109/ICSEEA47812.2019.8938633.

4) N.N. Hussain, S.P. Regalla, and Y.V.D. Rao, "Comparative study of trigger configuration for enhancement of crashworthiness of automobile crash box subjected to axial impact loading," Procedia Eng., 173 1390–1398 (2017). doi:10.1016/j.proeng.2016.12.198.
5) A. Dimas, T. Dirgantara, L. Gunawan, A. Jusuf, and I.S. Putra, "The effects of spot weld pitch to the axial crushing characteristics of top-hat crash box," Appl. Mech. Mater., 660 578–582 (2014). doi:10.4028/www.scientific.net/AMM.660.578.
6) N.A.Z. Abdullah, M.S.M. Sani, M.S. Salwani, and N.A. Husain, "A review on crashworthiness studies of crash box structure," Thin-Walled Struct., 153 106795 (2020). doi:10.1016/j.tws.2020.106795.
7) K.-J. Bathe, J. Walczak, O. Guillermin, P.A. Bouzinov, and H.-Y. Chen, "Advances in crush analysis," Comput. Struct., 72 (1) 31–47 (1999). doi:10.1016/S0045-7949(99)00041-3.
8) Y. Liu, "Optimum design of straight thin-walled box section beams for crashworthiness analysis," Finite Elem. Anal. Des., 44 (3) 139–147 (2008). doi:10.1016/j.finel.2007.11.003.
9) J. Wang, Y. Zhang, N. He, and C.H. Wang, "Crashworthiness behavior of koch fractal structures," Mater. Des., 144 229–244 (2018). doi:10.1016/j.matdes.2018.02.035.
10) X. Xu, Y. Zhang, J. Wang, F. Jiang, and C.H. Wang, "Crashworthiness design of novel hierarchical hexagonal columns," Compos. Struct., 194 36–48 (2018). doi:10.1016/j.compstruct.2018.03.099.
11) A.K. Toksoy, and M. Güden, "The optimisation of the energy absorption of partially al foam-filled commercial 1050h14 and 6061t4 al crash boxes," Int. J. Crashworthiness, 16 (1) 97–109 (2011). doi:10.1080/13588265.2010.514774.
12) F. Wu, T. Liu, X. Xiao, Z. Zhang, and J. Hou, "Static and dynamic crushing of novel porous crochet-sintered metal and its filled composite tube," Compos. Struct., 209 830–843 (2019). doi:10.1016/j.compstruct.2018.11.022.
13) M. Quanjin, M.S.A. Salim, M.R.M. Rejab, O.-E. Bernhardi, and A.Y. Nasution, "Quasi-static crushing response of square hybrid carbon/aramid tube for automotive crash box application," Mater. Today Proc., 27 683–690 (2020). doi:10.1016/j.matpr.2019.10.161.
14) W. Lee, Y. Jeong, J. Yoo, H. Huh, S.-J. Park, S.H. Park, and J. Yoon, "Effect of auxetic structures on crash behavior of cylindrical tube," Compos. Struct., 208 836–846 (2019). doi:10.1016/j.compstruct.2018.10.068.
15) Y. Nakazawa, K. Tamura, M. Yoshida, K. Takagi, and M. Kano, "Development of crash-box for passenger car with high capability for energy absorption," in: VIII International Conference on Computation Plasticity (COMPLAS VIII), Barcelona, 2005.
16) T. Wang, Z. Li, L. Wang, and G.M. Hulbert, "Crashworthiness analysis and collaborative optimization design for a novel crash-box with re-entrant auxetic core," Struct. Multidiscip. Optim., 62 (4) 2167–2179 (2020). doi:10.1007/s00158-020-02568-6.
17) Q. Ma, Y. Zha, B. Dong, and X. Gan, "Structure design and multiobjective optimization of cfrp/aluminum hybrid crash box," Polym. Compos., 41 (10) 4202–4220 (2020). doi:10.1002/pc.25705.
18) S. Sharifi, M. Shakeri, H.E. Fakhari, and M. Bodaghi, "Experimental investigation of bitubal circular energy absorbers under quasi-static axial load," Thin-Walled Struct., 89 42–53 (2015). doi:10.1016/j.tws.2014.12.008.
19) Q. Zuo, F. Zhang, and K. He, "A new type of energy absorbing structural component: spiral thin-walled tube," I.O.P. Conf. Ser. Mater. Sci. Eng., 576 (1) 012009 (2019). doi:10.1088/1757-899X/576/1/012009.
20) P.K. Kostazos, S.S.A. Lykakos, P.-A.E. Kyritsis, and D.E. Manolakos, "Quasi-static axial crushing of multi-walled (spiral) aluminium tubes fabricated by roll bending: experimental and numerical investigation," Thin-Walled Structures, 159 107237 (2021).
21) A. Kumar, A.K. Chanda, and S. Angra, "Numerical modelling of a composite sandwich structure having non metallic honeycomb core," EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 8(4) 759 -767 (2020). https://doi.org/10.5109/4742119
22) S. Ibrahim, B. Alkali, A. Oyewole, S.B. Alhaji, and A.A. Abdullahi, "Structural integrity study for a quadcopter frame to be deployed for pest control," EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 8(3) 667-672 (2021). https://doi.org/10.5109/4491843
23) V. Shrivastava, V. Diwakar, M. Sehgal, M. Verma, and E. Neha, "Modelling and analysis of hexapod walking robot," EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 9(2) 378-388 (2022). https://doi.org/10.5109/4794162
24) A. Jha, M. Soni, and M. Suhaib, "Non-invasive invitro modelling and finite elemental analysis of a uniquely designed prosthetic hand," EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 9(3) 729-736 (2022). https://doi.org/10.5109/4843106
25) A.S. Baskoro, M.A. Amat, and M.F. Arifardi, "Investigation effect of ecr's thickness and initial value of resistance spot welding simulation using 2-

dimensional thermo-electric coupled," EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 8(4) 821-828, (2021). https://doi.org/10.5109/4742127

26) S.E. Sadiq, S.H. Bakhy, and M.J. Jweeg, "Crashworthiness behavior of aircraft sandwich structure with honeycomb core under bending load.," I.O.P. Conf. Ser. Mater. Sci. Eng., 881 (1) 012046 (2020). doi:10.1088/1757-899X/881/1/012046.

27) Y. Ren, J. Xiang, J. Zheng, and Z. Luo, "Crashworthiness analysis of aircraft fuselage with sine-wave beam structure," Chin. J. Aeronaut., 29 (2) 403–410 (2016). doi:10.1016/j.cja.2016.02.002.

28) "Multibody analysis of longitudinal train dynamics on the passenger ride performance due to brake application - sunil kumar sharma, 2019," (n.d.). https://journals.sagepub.com/doi/abs/10.1177/1464419318788775 (accessed July 20, 2022).

29) S.K. Sharma, U. Saini, and A. Kumar, "Semi-active control to reduce lateral vibration of passenger rail vehicle using disturbance rejection and continuous state damper controllers," J. Vib. Eng. Technol., 7 (2) 117–129 (2019). doi:10.1007/s42417-019-00088-2.

30) T. Zhu, S. Xiao, C. Lei, X. Wang, J. Zhang, B. Yang, G. Yang, and Y. Li, "Rail vehicle crashworthiness based on collision energy management: an overview," Int. J. Rail Transp., 9 (2) 101–131 (2021). doi:10.1080/23248378.2020.1777908.

31) F. Xiong, D. Wang, S. Chen, Q. Gao, and S. Tian, "Multi-objective lightweight and crashworthiness optimization for the side structure of an automobile body," Struct. Multidiscip. Optim., 58 (4) 1823–1843 (2018). doi:10.1007/s00158-018-1986-3.

32) D. Wang, S. Li, and C. Xie, "Crashworthiness optimisation and lightweight for front-end safety parts of automobile body using a hybrid optimisation method," Int. J. Crashworthiness, 27 (4) 1193–1204 (2022). doi:10.1080/13588265.2021.1926809.

Sharma, "Crashworthiness analysis of foam filled star shape polygon of thin-walled structure," Thin-Walled Struct., 144 106312 (2019). doi:10.1016/j.tws.2019.106312.

33) D.K. Rajak, N.N. Mahajan, and E. Linul, "Crashworthiness performance and microstructural characteristics of foam-filled thin-walled tubes under diverse strain rate," J. Alloys Compd., 775 675–689 (2019). doi:10.1016/j.jallcom.2018.10.160.

34) S. Goyal, C.S. Anand, S.K. Sharma, and R.C. Sharma, "Crashworthiness analysis of foam filled star shape polygon of thin-walled structure," Thin-Walled Structures, 144 106312 (2019).

35) P. Manikandan, S. Balaji, S. Sukumar, and M. Sivakumar, "Experimental and numerical analysis of web stiffened cold-formed steel channel column with various types of edge stiffener," Int. J. Adv. Struct. Eng., 9 (2) 129–138 (2017). doi:10.1007/s40091-017-0153-1.

36) Y. Ren, Y. Yu, B. Zhao, C. Fan, and H. Li, "Finite element analysis and optimal design for the frame of sx360 dump trucks," Procedia Eng., 174 638–647 (2017). doi:10.1016/j.proeng.2017.01.201.

37) G.H. Kim, K.Z. Cho, I.B. Chyun, and G.S. Choi, "Dynamic stress analysis of vehicle frame using a nonlinear finite element method," KSME Int. J., 17 (10) 1450–1457 (2003). doi:10.1007/BF02982324.

38) A. Ahmed, and L. Wei, "Introducing cfrp as an alternative material for engine hood to achieve better pedestrian safety using finite element modeling," Thin-Walled Struct., 99 97–108 (2016). doi:10.1016/j.tws.2015.11.001.

39) Q. Li, Y. Liu, H. Wang, and S. Yan, "Finite Element Analysis and Shape Optimization of Automotive Crash-Box Subjected to Low Velocity Impact," in: 2009 Int. Conf. Meas. Technol. Mechatron. Autom., 2009: pp. 791–794. doi:10.1109/ICMTMA.2009.545.

40) H.R. Zarei, and M. Kröger, "Crashworthiness optimization of empty and filled aluminum crash boxes," Int. J. Crashworthiness, 12 (3) 255–264 (2007). doi:10.1080/13588260701441159.

41) B. Wang, and C. Zhou, "The imperfection-sensitivity of origami crash boxes," Int. J. Mech. Sci., 121 58–66 (2017). doi:10.1016/j.ijmecsci.2016.11.027.

42) L. Yuan, H. Shi, J. Ma, and Z. You, "Quasi-static impact of origami crash boxes with various profiles," Thin-Walled Struct., 141 435–446 (2019). doi:10.1016/j.tws.2019.04.028.

43) G.E.M. Su, "A study of using different crash box types in automobile frontal collision," Int. J. Simul. Syst. Sci. Technol., (2016). doi:10.5013/IJSSST.a.17.38.21.

44) H. Patil, and P.V. Jeyakarthikeyan, "Mesh convergence study and estimation of discretization error of hub in clutch disc with integration of ansys," I.O.P. Conf. Ser. Mater. Sci. Eng., 402 012065 (2018). doi:10.1088/1757-899X/402/1/012065.

45) Bahar, A.R. Andi, A.S. Yatim, and E.P. Wijaya. "C.F.D. Analysis of Universitas Indonesia Psychrometric Chamber Air Loop System." EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 9(2) 465-469 (2022). https://doi.org/10.5109/4794173

46) Alshahrani, H., Sebaey, T. A., Awd Allah, M. M., & Abd El-baky, M. A., "Multi-response optimization of crashworthy performance of perforated thin-walled tubes," Journal of Composite Materials (2023) 57(9) 1579-1597. doi: 10.1177/00219983231159508