Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	:2549-1999	No.	:5	Month	:October
p-ISSN	:1693-5462	Volume	:21	Year	: 2023

Article Processing Dates: Received on 2023-07-28, Reviewed on 2023-08-17, Revised on 2023-09-22, Accepted on 2023-10-04 and Available online on 2023-10-30

An investigation into the crashworthiness criteria of a top-hat structure with a dent-type crush initiator through numerical analysis

Harry Purnama[1*], **Joko Triwardono**[2], **Dwijaya Febriansyah**[1], **Hana Hermawan**[1]
[1]Research Centre for Process and Manufacturing Industry Technology, BRIN, Tangerang Selatan, 15314, Indonesia
[2]Research Centre for Metallurgy, BRIN, Tangerang Selatan, 15314, Indonesia
*Corresponding author: harr007@brin.go.id

Abstract

Ensuring the safety of passengers and the battery compartment in electric vehicles during frontal collisions is of utmost importance. This research aims to enhance the design of the top-hat structure used in car front rails by incorporating a crush initiator as the weakest section. The addition of a crush initiator optimizes the crashworthiness criteria by reducing peak force and increasing energy absorption. Numerical simulations were conducted using ABAQUS to validate the findings and compared against experimental results from references. The results demonstrate that the development of a top-hat structure with a dent-type crush initiator led to 27.5% decrease in peak force and 18.75% increase in energy absorption.The improvements in peak force and energy absorption could reduce the impact force and allow the crumple zone to completely absorb the kinetic energy during a collision, positively affecting the safety of passengers and battery compartments in electric vehicles.

Keywords:
Crashworthiness, top-hat structure, crush initiator, numerical analysis, electric vehicle.

1 Introduction

The automotive industry has prioritized developing crashworthy designs for the front-rail structure of electric vehicles to mitigate the impact of frontal collisions. In addition to ensuring occupant safety, it is also crucial to consider the safety of the battery, as even minor deformations can lead to explosions and fires [1]. Addressing environmental concerns such as energy consumption and efficient use of materials has made the weight of electric vehicles a key focus [2]. This knowledge is essential to achieve the objective of crashworthiness, which involves designing the electrical vehicle structure to absorb crash energy through controlled deformation while ensuring sufficient space for occupants and the battery.

The primary structures of a vehicle that absorb energy, including the bumper beam, crash box, front rail, shotgun, cab longitudinal, and firewall, are typically designed with great complexity. Among these components, the front rail plays the most significant role in absorbing energy in the crumple zone, potentially absorbing up to 34% to 39% of the kinetic energy during an impact of front collisions [3]. The front-rail is a complex pile of thin-walled structures that are joined using spot welds and can be specified as a top-hat section. The behavior of top-hat thin-walled structures in absorbing energy has been examined through quasi-static and dynamic experimental tests, as well as simulations. White et al. [4] for the first time through experimental tests derived a theoretical equation for the top-hat structure, a comparison of high-strength steel and mild steel top-hat structures tested quasi-statically and dynamically results in different effectiveness against crashworthiness criteria [5]. Sun et al. [6]performed experiments and simulations to investigate how the thickness distribution in top-hat structures affects their behavior in absorbing energy. The developed a theoretical model to predict the bending collapse and energy absorption of top-hat thin-walled structures, which was validated through three-point bending tests and finite element simulations [7]. Modifying the spot-welding pitch of the thin-walled structure with the top-hat section affects energy absorption and peak force [8], [9]. The top-hat structure varied using three variations of friction stir welding produces their respective advantages on crashworthiness criteria [10].

The material replacement and structural modifications could improve the crashworthiness criteria of the thin-walled structures with top-hat sections. However, material replacement can be a time-consuming process until the approval stage. Therefore, a possible solution is adding a crush initiator as a structural modification, the weakest section that can reduce peak force without damaging other parts of the vehicle and occupants [11]–[13].

Despite numerous studies on the impact response of top-hat structures and crush initiators, there is still a research gap concerning the number, spacing, and type of crush initiators. This study aims to perform a numerical analysis using ABAQUS 6.10, based on the experiments conducted by Tarigopula et al. [14], who examined the behavior of the top-hat section of DP800 under axial impact. According to Cho et al. [11] dent-type crush initiators are better in crashworthiness criteria compared to hole-type. Departing from those findings, the authors would like to determine the effect of a dent-type crush initiator as a structural modification and investigate itson Energy Absorption (EA), Peak Force (Fmax), Mean Force (Fmean), Specific Energy Absorption (SEA), and Crush Force Efficiency (CFE). Adding a dent-type crush initiator is a possible solution from references with experimental results to improve the crashworthiness criteria of the top-hat section. The outcomes of this research will aid in the advancement of superior crashworthiness criteria for the front rail's top-hat section.

2 Research Method

2.1 Material and Numerical Setup

The present study involved conducting a numerical analysis to investigate the behavior of a top-hat structure based on the reference study by Tarigopula et al. [14], as shown in Fig. 1. The top-hat structure was developed a thickness of t = 1.8 mm and mass of the top-hat structure is m = 1.3 kg, outer dimensions of a = 60.5 mm and b = 59.5 mm, with corner radius of R1 = 3 mm and R2 = 2 mm. The structure was made up of two parts joined by spot welding with a constant weld pitch of 25 mm and a diameter of 5 mm. The top-hat structure had a length of 410 mm, with the lower 100 mm constrained by the bottom rigid part, which was impacted by a 600 kg rigid mass impactor at an initial velocity of 15 m/s from the upper structures.

The numerical simulations were performed using explicit time integration in ABAQUS. The mesh density was 3mm× 3mm and coefficient of friction 0.3. The element type was S4R, with 15956 elements and 16390 nodes. The modeling of high-strength steel DP 800 for dynamic simulation, following the reference by Tarigopula et al. [14] and Zafer et al. [15], employed the empirical constitutive equation for effective stress at yield, $\bar{\sigma}$ (Eq. 1).

$$\bar{\sigma} = \left(\sigma_0 + \sum_{i=1}^{2} Q_i\left(1-\exp(-C_i\bar{\varepsilon})\right)\right)\left(1+\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0}\right)^{q} \qquad (1)$$

Where σ_0 is the initial yield stress, Q_i and C_i represent strain hardening coefficients,and $\dot{\varepsilon}_0$ is a user-defined reference strain rate, and q denotes a material constant, with values 495 N/mm^2, 200 N/mm^2, 76, 0.001 1/s , and 0.00116, respectively. The yield stress undergoes an increase of about 15% when the strain rate is raised from roughly 10^{-3} to 500/s during material flow.

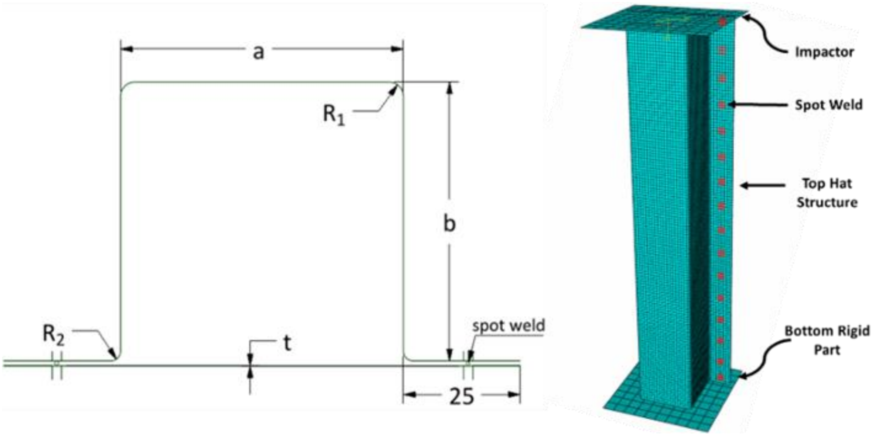

Fig. 1. Schematic of the geometry and numerical setup.

In addition to answering the objectives of this paper, the detailed dimensions of the crush initiator were developed on three sides of the top-hat structure to investigate the effect of a dent-type crush initiator as a structural modification, as shown in Fig. 2. The first model was a Top-Hat (TH) without a dent, while the second to sixth models were Top-Hat Dent (THD) models that used one to five dents, named THD-1, THD-2, THD-3, THD-4, and THD-5, respectively.

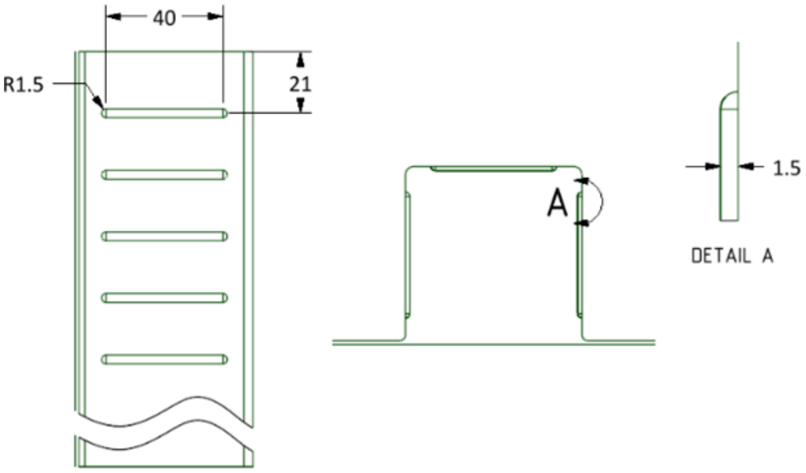

Fig. 2. Schematic of the geometry of additional dent type crush initiator.

2.2 General Equations of Crashworthiness

The equations used to determine crashworthiness criteria are based on the force-displacement curve, which is described in various references [16]–[18] (Eq. 2 – Eq. 5).

1. Energy Absorption (EA)

$$EA = \int_0^{\delta_{max}} F(\delta)d\delta \qquad (2)$$

Where F is instantaneous crushing force, δ is vertical displacement of impactor mass.

2. Mean Force (F_m)

$$F_m = \frac{EA}{\delta_{max}} \qquad (3)$$

3. Specific Energy Absorption (SEA)

$$\text{SAE} = \frac{EA}{\text{m}} \qquad (4)$$

Where m is thin-walled structure mass.

4. Crush Force Efficiency CFE)

$$\text{CFE} = \frac{F_m}{F_{max}} \qquad (5)$$

Where F_{max} is peak force that resulted by impact between impactor and thin-walled structure first buckling.

The ranks the crashworthiness criteria using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), this is one of the methods for solving multicriteria problems that refer to taking the best alternative with logical consistency and ease of use. The method was first introduced by Hwang and Yoon in 1981 [19], [20].

Several steps are taken by specifying the decision-making matrix, which is then converted to a normalized decision matrix. Next is to Calculate the weighted normalized decision matrix, obtain the ideal and negative ideal choice, obtain the separation measures for each mode, and specify the relative proximity to the ideal option, where the option with the highest value is determined to be the best model.

2.3 Numerical Simulation Validation

The energy curve of the finite element model is shown in Fig. 3. The total energy is 6.75E-7 J, the initial kinetic energy is 6.75E-7 J, and the hourglass energy is negligible. As time passes, the kinetic energy decreases while the internal energy increasesat t = 0.22 ms, the system's kinetic energy aligns with its internal energy. Generally, the axial impact converts most kinetic energy into internal energy, resulting in relatively conserved energy. To conclude, the numerical simulation indicates good alignment in terms of energy transfer.

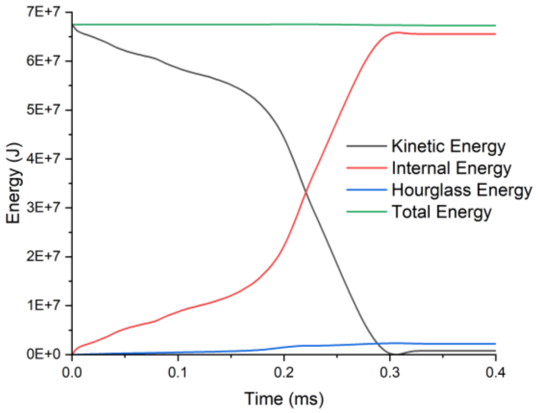

Fig. 3. Various energy-time curves in numerical simulation.

The numerical simulation conducted in this research engineering paper has been rigorously validated against experimental data obtained by Tarigopula [14]. The validation process involved comparing the presence force-deformation curve, as depicted in Fig. 4, and analyzing the qualitative data of EA, Fmax and Fmean, as presented in Table 1.

Table 1. Qualitative data comparison between experimental and present simulation

	Experimental [14]	Present study	Error
EA	6.3 kJ	6.4 kJ	1.6 %
Fmax	208.1 kN	212.2 kN	1.9 %
Fmean	58.2 kN	58.8 kN	0.9 %

The results obtained from both the simulations and experiments, as illustrated in Fig. 4, indicate that the structure under investigation is a thin-walled structure with a top-hat section. When subjected to an impact with a velocity of 15 m/s and a weight of 600 kg, the structure exhibits progressive buckling. However, the fold along 115 mm does not conform to either an asymmetric mode or a symmetric mode. Furthermore, the middle part of the specimen also experiences global buckling.

Moreover, the comparison of the values for EA, Fmax, and Fmean between the experimental and simulation results reveals that the error is within 2%. This implies that there is a high degree of agreement between the experimental and simulated data. The relatively small error further indicates that the simulation model employed in this study is reliable and accurate.

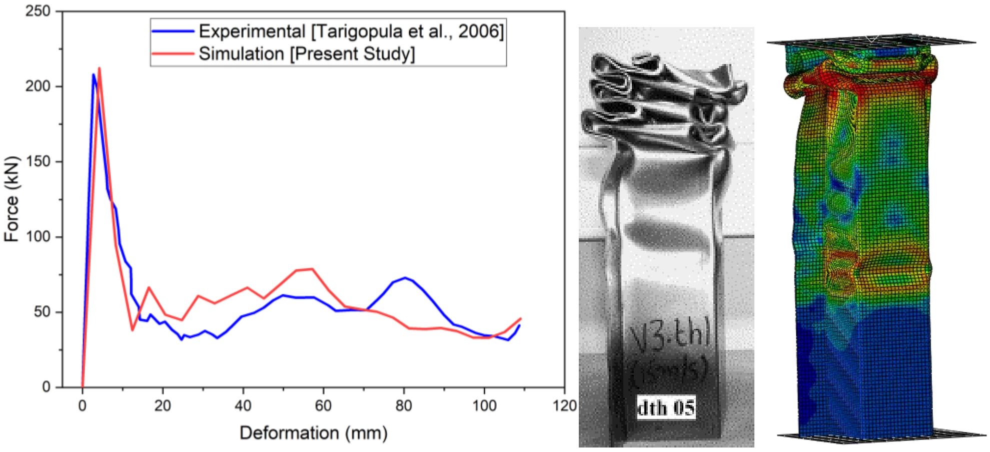

Fig. 4. Comparison of the force-deformation curve and deformation top-hat structure[14].

3 Result and Discussion

This section numerically analyses the influence of the number and spacing of crush initiators on the crashworthiness criteria of thin-walled top-hat structures. The main evaluation criteria EA, Fmax, Fmean, SEA and CFE are used to analyse the crashworthiness of top-hat structures using Eq. 2 – Eq. 5.

The force-deformation curve comparison of all top-hat models is presented in Fig. 5. The results indicate that the fluctuations in all top-hat structures are similar. However, THD-2 exhibits a longer initial distance between plastic hinges at the top and bottom of a basic folding element, approximately 30 mm after experiencing the peak force. This initial distance between plastic hinges of a basic folding element can impact the number of folds caused by axial impact as shown in Fig. 5.

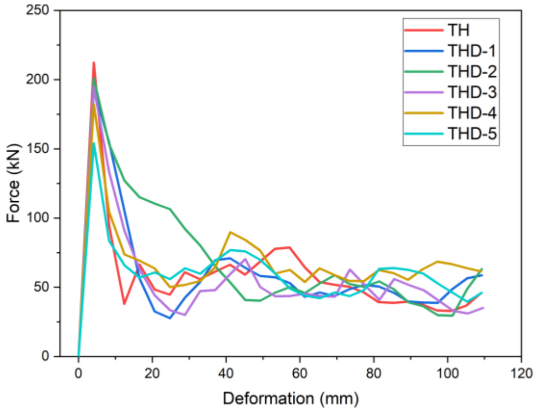

Fig. 5. Comparison of the force-deformation curve.

THD-2 has the least number of folds, while other top-hat models have six folds. The findings suggest that the initial distance between plastic hinges of a basic folding element is a critical factor in determining the number of folds in top-hat structures subjected to axial impact.

In Fig. 6, a detailed discussion of the top-hat models using a dent type crush initiator reveals that buckling occurs for the first time on the dent. Specifically, in THD-2, THD-3, THD-4, and THD-5, the first buckling occurs in the second row of the dent. This indicates that the weakest section experiences maximum stress and deformation before propagating axially. In contrast, TH and THD-4 exhibit extensional collapse modes because the extensive stress propagation is close to the fixed support, causing deformation in that section. These findings suggest that the location of the first buckling and the propagation of stress are critical factors in determining the collapse mode of top-hat structures using a dent type crush initiator.

As can be seen from Table 2, after calculating all the results, the most considerable energy absorption is THD-2, while the one with the least absorption energy is THD-3. Looking again at Table 2, between the absorption energy and the top hat structure model, the pattern of absorption energy values changes from increasing to returning to the usual value. This discussion shows that the additional use of a crush initiator only sometimes helps to increase the absorption energy. This is related to the buckling problem in the structure, mainly because this top-hat structure uses spot welding, where the welding pitch is one of the factors that can determine the buckling results, which then affect the energy absorption [21], [22].

Table 2. Qualitative data of crashworthiness criteria for all top-hat structure

Models	EA (kJ)	Fmax (kN)	Fmean (kN)	SEA (kJ/kg)	CFE (%)	Rank
TH	6.4	212.2	58.8	5.0	27.7	5
THD-1	6.6	193.3	60.3	5.2	31.2	4
THD-2	7.6	200.9	69.3	5.9	34.5	1
THD-3	6.2	194.7	56.4	4.8	29.0	6
THD-4	7.5	182.2	68.4	5.9	37.5	2
THD-5	6.6	153.9	60.8	5.2	39.5	3

The best peak force is THD-5, this time it turns out the more crush initiators will help to distribute the force throughout the top-hat structure evenly. Although there is an anomaly at THD-2, the results show that the peak force values continues to decrease between the top hat structure and the use of crushing initiators.

The simulation outcomes for the top hat configuration against crashworthiness standards yielded various values. Nevertheless, these values cannot determine the best model directly. For this purpose, the TOPSIS multi-criteria selection analysis has to be carried out. This study gives equal weight quality to crashworthiness criteria as each criterion is crucial and interdependent. Table 2 shows that the THD-2 model of the top-hat structure exhibits superior energy absorption and SEA, with a lower peak force than the top-hat structure without a crush initiator.

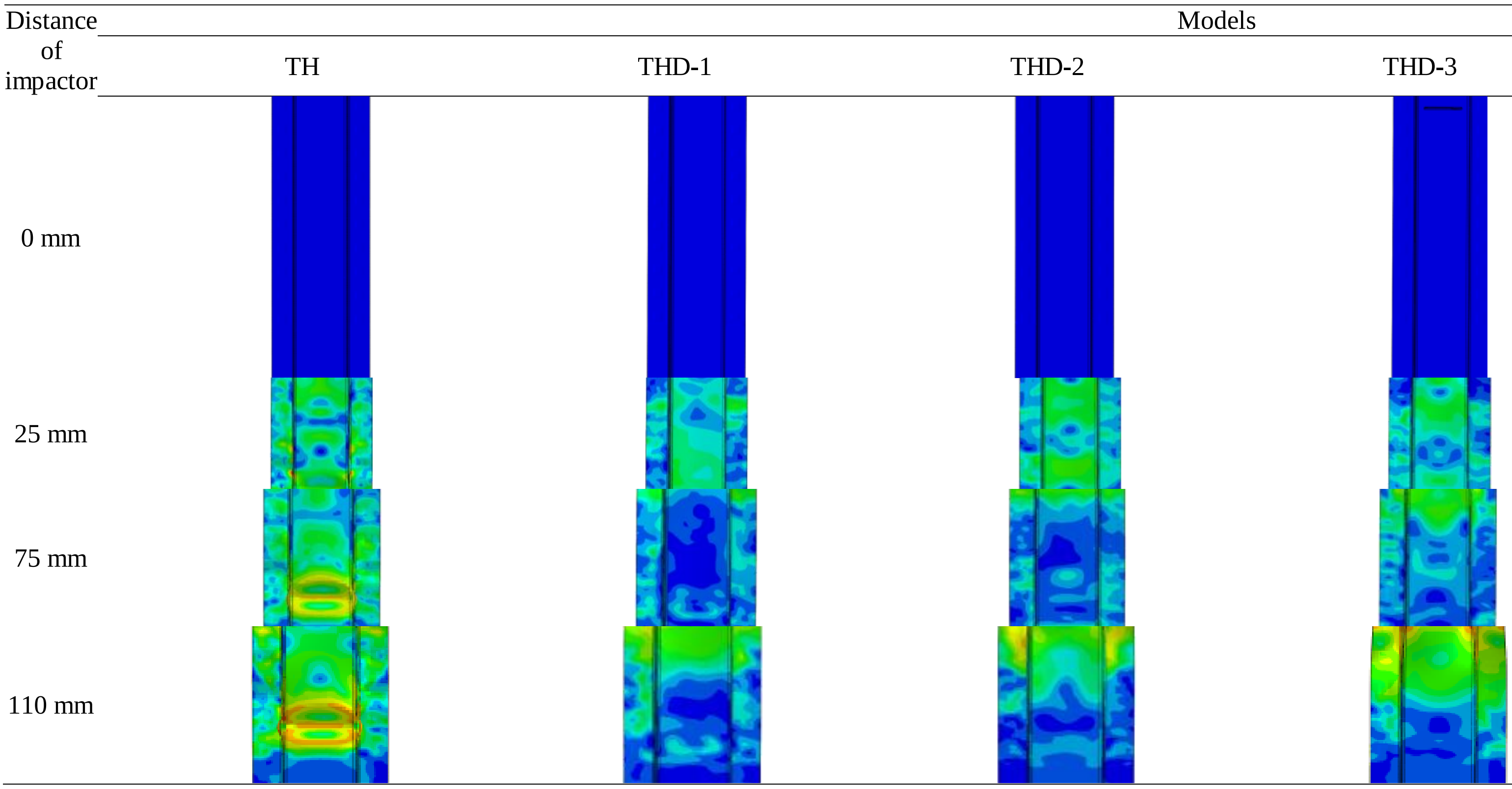

Fig. 1. Detail deformation all top-hat structure.

4 Conclusion

This research study focused on the evaluation and variation of an experimental top-hat structure based on numerical simulation. The results demonstrated good agreement with less than 10% difference for key parameters such as EA, Fmax, and Fmean when compared to the reference study.

A qualitative comparison between the top-hat and top-hat dent models revealed that THD-2 exhibited the highest EA at 7.6 kJ, equivalent to 18.75% improvement, while THD-5 showed the lowest Fmax at 153.9 kN, equivalent to 27.5% reduction. However, after employing multi-criteria decision methods, THD-2 was identified as the superior model. This suggests that simply adding more crush initiators does not necessarily lead to improved performance. Instead, modifying the geometry structure proves to be an effective approach for enhancing crashworthiness criteria.

For future research, it is recommended to investigate the optimal placement of crush initiators in relation to the geometry and material of the another structure like circular section, square section, double-hat section, etc. This will help achieve more optimal results, particularly for the application of these findings in electric-based vehicles under real-world conditions, where a robust design is crucial.

References

[1] Z. Biqiang, L. Xiaodong, and Z. Yajun, “The structure optimization analysis of electric vehicle in small offset rear end collision,” *Procedia Eng.*, vol. 137, pp. 103–108, 2016.

[2] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, “A Review on Electric Vehicles: Technologies and Challenges,” 2021, doi: 10.3390/smartcities4010022.

[3] Q. Q. Li, E. Li, T. Chen, L. Wu, G. Q. Wang, and Z. C. He, “Improve the frontal crashworthiness of vehicle through the design of front rail,” *Thin-Walled Struct.*, vol. 162, p. 107588, 2021, doi: https://doi.org/10.1016/j.tws.2021.107588.

[4] M. D. White and N. Jones, “Experimental study into the energy absorbing characteristics of top-hat and double-hat sections subjected to dynamic axial crushing,” *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 213, no. 3, pp. 259–278, 1999.

[5] F. Schneider and N. Jones, “Impact of thin-walled high-strength steel structural sections,” *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 218, no. 2, pp. 131–158, 2004, doi: 10.1243/095440704772913927.

[6] G. Sun, H. Zhang, J. Fang, G. Li, and Q. Li, “Multi-objective and multi-case reliability-based design optimization for tailor rolled blank (TRB) structures,” *Struct. Multidiscip. Optim.*, vol. 55, pp. 1899–1916, 2017.

[7] L. Duan, Z. Du, H. Jiang, W. Xu, and Z. Li, “Theoretical prediction and crashworthiness optimization of top-hat thin-walled structures under transverse loading,” *Thin-Walled Struct.*, vol. 144, p. 106261, Nov. 2019, doi: 10.1016/J.TWS.2019.106261.

[8] H. Purnama, J. I.-M. I. P. Industri, and undefined 2021, “Analysis Of Spot-Welding Pitch On Top Hat Structure Against Crashworthiness Criteria,” *ejurnal.bppt.go.id*, vol. 15, no. 1, pp. 28–33, 2021, Accessed: Apr. 09, 2023. [Online]. Available: https://ejurnal.bppt.go.id/index.php/MIPI/article/view/4628

[9] F. Xu and C. Wang, “Dynamic axial crashing of tailor-welded blanks (TWBs) thin-walled structures with top-hat shaped section,” *Adv. Eng. Softw.*, vol. 96, pp. 70–82, 2016.

[10] A. K. Lakshminarayanan and C. J. Daniel, “Influence of friction stir welding variants on crashworthiness of friction stir welded aluminium top hat sections,” *Mater. Sci. Forum*, vol. 979 MSF, pp. 97–101, 2020, doi: 10.4028/www.scientific.net/MSF.979.97.

[11] Y.-B. Cho, C.-H. Bae, M.-W. Suh, and H.-C. Sin, “A vehicle front frame crash design optimization using hole-type and dent-type crush initiator,” *Thin-Walled Struct.*, vol. 44, no. 4, pp. 415–428, 2006.

[12] M. Ferdynus, M. Kotełko, and M. Urbaniak, “Crashworthiness performance of thin-walled prismatic tubes with corner dents under axial impact-Numerical and experimental study,” *Thin-Walled Struct.*, vol. 144, p. 106239, 2019.

[13] M. Malawat, J. Istiyanto, and D. A. Sumarsono, “Effects of wall thickness and crush initiators position under experimental drop test on square tubes,” in *Applied Mechanics and Materials*, Trans Tech Publ, 2017, pp. 612–618.

[14] V. Tarigopula, M. Langseth, O. S. Hopperstad, and A. H. Clausen, “Axial crushing of thin-walled high-strength steel sections,” *Int. J. Impact Eng.*, vol. 32, no. 5, pp. 847–882, 2006.

[15] Z. Kazancı and K.-J. Bathe, “Crushing and crashing of tubes with implicit time integration,” *Int. J. Impact Eng.*, vol. 42, pp. 80–88, 2012.

[16] J. Istiyanto, H. Purnama, J. Triwardono, and J. Hendrawan, “The Effect of Corner Radius of Square Thin-Walled Structures on Crashworthiness Indicators,” *Maj. Ilm. Pengkaj. Ind.*, vol. 16, no. 2, pp. 81–86, 2022.

[17] S. Qin, X. Deng, and X. Liu, “Crashworthiness analysis of bioinspired hierarchical gradient multicell tubes under axial impact,” *Thin-Walled Struct.*, vol. 179, p. 109591, 2022.

[18] S. F. Abdulqadir, A. A. Abed, and A. Bassam, “Crashworthiness enhancement of thin-walled hexagonal tubes under flexural loads by using different stiffener geometries,” *Mater. Today Proc.*, vol. 42, pp. 2887–2895, 2021.

[19] E. Roszkowska, “Multi-criteria decision making models by applying the TOPSIS method to crisp and interval data,” *Mult. Criteria Decis. Making/University Econ. Katowice*, vol. 6, no. 1, pp. 200–230, 2011.

[20] Y. Lamrani Alaoui, *Introduction to Multi Criteria Decision Making: TOPSIS Method*. 2019. doi: 10.13140/RG.2.2.36465.22882.

[21] 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.*, vol. 660, pp. 578–582, 2014.

[22] A. Jusuf, L. Gunawan, T. Dirgantara, and F. Mubarhak, “Numerical Analysis of Double-Hat Multi-Corner Column Under Axial Loading,” in *Advances in Lightweight Materials and Structures: Select Proceedings of ICALMS 2020*, Springer, 2020, pp. 31–41.