Energy Absorption Analysis of Circular Tube of The Foam for High-Speed Train

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Abstract: - This paper discusses the outcomes concerning the crushing properties of aluminum foam–filled tubes with a circular cross-section. The review assessed the impact of placing aluminum foam in single- and double-walled circular. A parametric evaluation was performed concerning the circular with the single- and double-walled variants. Validation results were contrasted against the documented experimental data, and a noteworthy alignment was observed. The foam strain rate is vital in regulating the crushing properties of the foam-loaded circular, and this factor must be considered. The outcomes also indicate the interaction between the circular wall and foam core has a varying deformation category and specific energy absorption. Foam loading had a similar effect concerning double-walled circular loads with foam. Moreover, evaluations were performed to determine the impact of core thickness and impact velocity on the crashworthiness performance. Further, it was discovered that a rise in core thickness for double-walled foam-loaded circular enhances crushing characteristics until the walls still interact. Subsequently, any rise in core thickness leads to the response aligning more with the single-walled circular energy absorber of a high-speed train

Key-Words: - Circular tube, foam, crashworthiness, impact, high-speed train, strain rate

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1 Introduction

There has been a global interest in railway collision studies due to the rising railway use for transportation. High-speed collisions typically lead to several deaths. The objective of evaluating such collisions is to ensure passenger safety (Figure 1) by improving design aspects to enhance train crashworthiness. Positive results can be achieved by evaluating dynamic structural properties like acceleration, force on impact, deformation, and energy absorption, [1], [2], [3], [4]. The most accurate technique to examine a railway accident is a full-scale train test, but its uses are few because of its high cost and lack of suitable facilities. Furthermore, accident scenarios in the actual world would be different from laboratory prototype tests. As a result, it is frequently beneficial to conduct testing using miniature trains. To analyze the dynamic response of train multi-body coupled collision, the decrease in train collision incidents, and the verification of the design parameters of train crashworthiness, it is essential to create an efficient train scaled model.

It is well-established that there are issues with structure scaling for dynamic impact events, which have made it difficult to use subsidized samples to explain a variety of phenomena in engineering structures under dynamic loads. In addition, computational methods and outcome verification by contrasting against experimental outcomes is a common technique to evaluate railway vehicle crashworthiness, [5], [6], [7], [8], [9]. Simulation techniques are inadequate to assess the unavoidable uncertainty due to input parameter dynamics; furthermore, numerous complex limits concerning structures cannot be exhibited, [10], [11]. Mathematical simulations can typically provide effective outcomes; however, they differ from the fundamental aspects of accidents, [12], [13].

Fig. 1: Energy absorber of high-speed train

Vehicle impact safety has attracted more attention as railway vehicles have developed. The collisions between trains across the world result in significant injury or death to passengers as well as significant property loss. Thin-walled tubes, which have been used in various applications, are particularly effective at absorbing energy and have been used to guard against car and train collisions. Alghamdi assessed typical energy absorption structures having varying cross sections and presented deformation categories using numerous literature reviews, [14]. In the study, [15], asserted that extreme plastic deformations soak up most kinetic energy from the impact. Further, studies on corner cross sections suggested that 90° to 120° angles are the most preferred for application studies. Moreover, research, [16], [17], indicates that energy absorption systems with multiple cells perform superior to simple tubes. Further, cross sections having octagonal or hexagonal shapes perform best. Studies, [18], [19], [20], [21], [22], attempted to optimise a structure's energy absorption by changing cross-corner angles and including shell sheets.

Nevertheless, most of the referred works concerning energy-absorbing structures are related to automobiles rather than railways. Improving metro vehicle crashworthiness requires novel designs comprising gradual energy absorption, as suggested by, [23]. The optimization was based on response surface frameworks. In the study, [24], designed circular tubes were incorporated with foam to perform axial deformation studies. Their work established efficient crash ability outcomes concerning the devised structures. In the study, [25], proposed a cutting-style structure to absorb energy, and its mathematical and practical correlations concerning the design variables and impact outcomes were assessed. Lastly, optimization outcomes indicated that the suggested structure exhibited an appreciable crashworthiness improvement.

Recent decades have witnessed the development of extremely lightweight engineering materials like aluminum foam. It has distinct mechanical characteristics like retaining low constant stress under extensive strain deformation before it densifies. Energy absorption is a primary application of this material. Incorporating the circular with aluminum foam enhances energy absorption properties, stabilizing the circular's buckling properties. In the study, [26], [27], [28], mathematically evaluated metal foam core-based thin-walled members and suggested extraordinary weight efficiency. In the study, [29], contrasted energy absorption for double- and single-walled circular having distinct cross sections and axial load-crushing aspects. The outcomes indicated that a circular double–walled foam–filled circular exhibited superior energy absorption ability regardless of loading properties. Another reseacher [30], evaluated foam–filled circular in single-, double-, and multi-wall configurations, including circular forms. The multi-walled foam-loaded circular exhibited noticeable differences in energy absorption and deformation characteristics.

Numerous studies and reports discuss aluminum foam and its strain rate sensitivity, such as, [31], asserting that closed foam cells are independent of strain rate primarily due to gas dispersal across the cells after the wall cracks. The study, [32], indicated a remarkable impact of strain rate concerning peak stress and densification strain. Moreover, a mathematical assessment performed by, [33], indicated that the cell geometry of aluminum foams affects strain properties for higher strain values. Recently, [34], assessed the dynamic and quasi–static compressive crushing properties of circular in–situ aluminum foam–filled circular. The outcomes suggested that strain rate impacts circular crushing characteristics. Therefore, to better comprehend how single- and double-walled foam–filled circulars respond to low-speed impact, this work conducted a parametric assessment of such structures where the foam core and impact velocity are affected due to strain rate.

2 Materials and Methods

2.1 Finite Element Models of the Structures

To model energy absorbing structures, the aluminum foam-filled double tubes of the length of L = 210 mm and outer diameter d_o = 90 mm. Moreover, a stroke efficiency of 0.5 as described thus for all tubes was assumed a maximum crash distance of 100 mm.

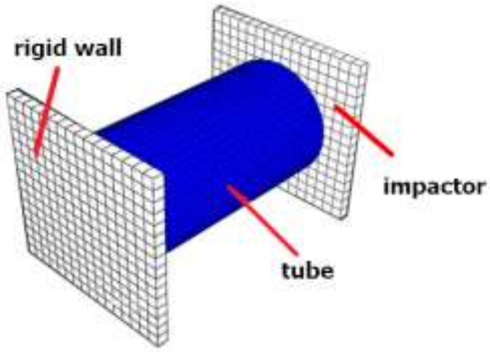
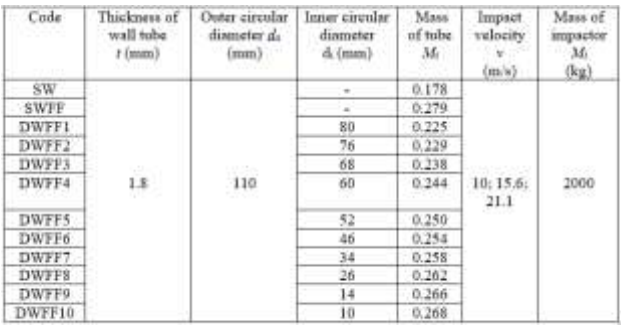


Fig. 2: The schematic of the double circular tubes

The rigid wall impacted the top of the tubes at an initial velocity of v = 10, 15.6, and 21.1 m/s which is the speed obtained from the Railway Assessment Program (Figure 2). The rigid body as the mass block was modeled, all other translational and rotational degrees of freedom were fixed then only one allowable is translational displacement. The mass block of 2000 kg is attached to the top free end. This material structure has a yield stress of aluminum thin-walled tubes σ_y and density of foam filler ρ_f.. The cross-section of the bitubal circular tubes were shown in Figure 3. The outer diameter d_o and inner diameter d_i of each tube, respectively. Moreover, the outer and inner thickness (t) of the double tube wall is 1.8 mm. The Parameters of the Geometrical and impactor of the tube are presented in Table 1.

Table 1. Parameters of Geometrical and impactor of the tube



Code	Thickness of wall tube t (mm)	Outer circular diameter d_o (mm)	Inner circular diameter d_i (mm)	Mass of tube M_t	Impact velocity v (m/s)	Mass of impactor M_i (kg)
SW	1.8	110	-	0.178	10; 15.6; 21.1	2000
SWFF			-	0.279		
DWFF1			80	0.225		
DWFF2			76	0.229		
DWFF3			68	0.238		
DWFF4			60	0.244		
DWFF5			52	0.250		
DWFF6			46	0.254		
DWFF7			34	0.258		
DWFF8			26	0.262		
DWFF9			14	0.266		
DWFF10			10	0.268		

To develop the models of aluminum foam-filled tubular tubes and to predict the response of thin-walled structures impacted by free-falling impinging mass, the finite element (FE) code FE software was used.

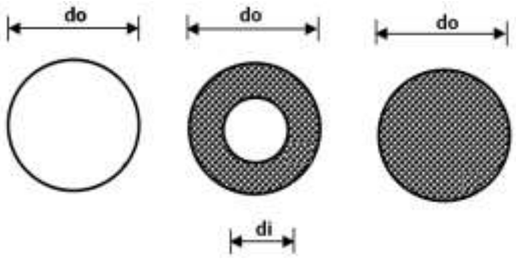


Fig. 3: Cross section of double circular tubes (a) empty single-walled tube (SW), (b) foam-filled double-walled tube (DWFF), and (c) foam-filled single-walled tube (SWFF)

Four node shell continuum elements with five integration points in the element thickness direction were used to simulate the wall of tubular tubes. Furthermore, the foam filled was modeled utilizing eight-node continuum components, decreased integration approaches, and the hourglass control. Enhancement-based hourglass control and decreased integration were used to prevent fake zero energy deformation states and keep volumetric locking at a distance. 2 mm element sizes were determined based on mesh convergence research for the shells and foam components. Mesh convergence is addressed to achieve enough mesh density and correct recording of the deformation process.

2.2 Material Properties

Extruded aluminum alloy circular tube (AA 6063 T1) packed with a closed-cell aluminum foam (ALPORAS) block was employed in this research. The mechanical characteristics of ALPORAS were determined from, [24], [25], for different strain rates, as shown in Figure 4a. According to, [24], [25], ALPORAS with more than 15% relative density will have a more pronounced strain-rate impact. The kinetics of gas flow through the cell structure is to blame for this. However, since, [24], [25], did not include the densification section of the stress-strain curves needed for numerical analysis, some extra data were incorporated in this study based on typical ALPORAS characteristics, as can be seen in Figure 4(b). Young's modulus of solid aluminum (E) was chosen as the second tangent modulus. Since the aluminum foam would compact and behave like solid aluminum during densification, the final modified stress-strain curves at a relative density of 16% are shown in Figure 4(c).

Young's modulus, plateau stress, first tangent modulus, densification strain, and second tangent modulus are typical characteristics that reflect the behavior of aluminum foam. The material utilized for the circular wall in this study is the 6063 T1 densification strain. The constitutive behavior of the foam model proposed by, [35], utilizing non-linear FE software packages is based on an isotropic uniform material. This study did not take into account the effect of the manufacturing process on the anisotropic behavior of aluminum foam.

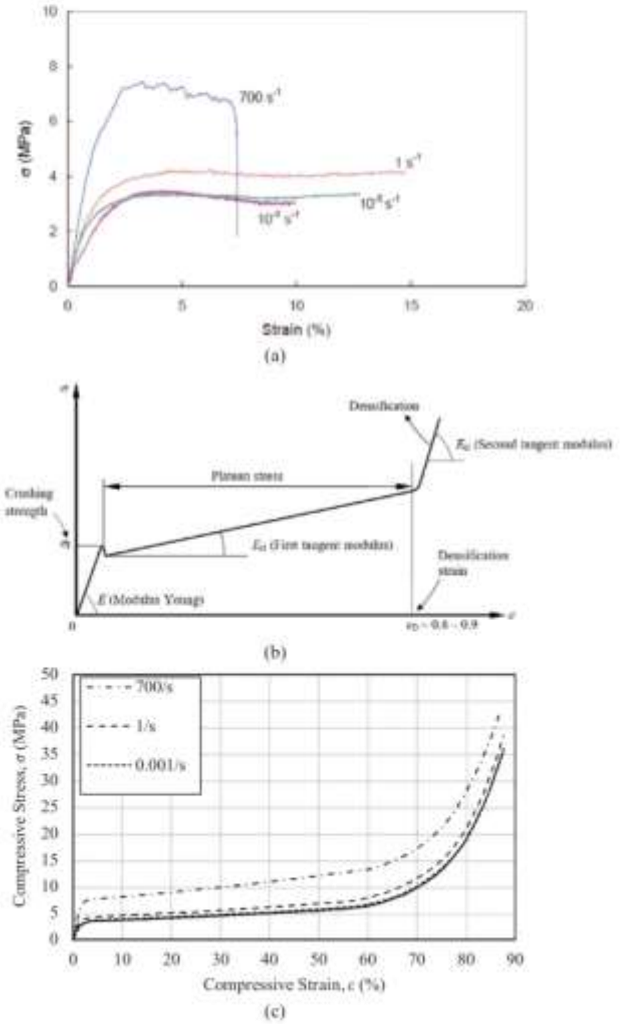


Fig. 4: ALPORAS stress-strain curve with a relative density of 16% at various strain rates, including (a) original experimental data, (b) a typical ALPORAS stress-strain curve used as a baseline for modification, and (c) modified stress-strain curves utilized in the current study, [36]

To gather precise material information and to specify the input for material modeling in the numerical simulations, two types of tensile tests were performed: quasi-static (0.001 /s) and dynamic (0.1, 1, 10, 100 /s). It was discovered that the engineering stress-strain curve of aluminum alloys is insensitive to strain rate, hence strain rate effects do not need to be included in the material model. Figure 3 depicts the true stress - true plastic strain curve, [36]. AA6063-T1 true stress - true plastic strain curve is presented in Figure 5.

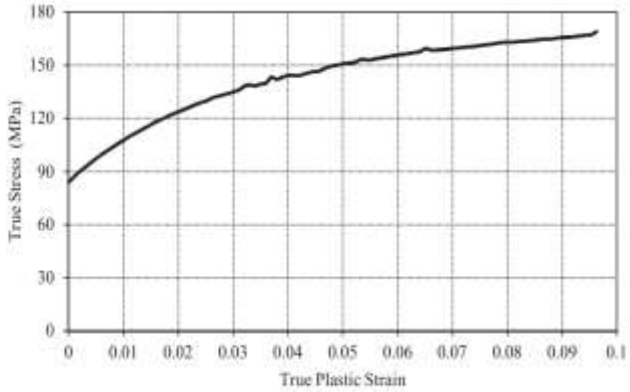


Fig. 5: AA6063-T1 true stress - true plastic strain curve, [36]

3 Result and Disscusion

3.1 Validation Data

To ensure finite element models are sufficiently accurate for design structure, they should be compared to experimental data, [37]. The difference in the maximal crushing force between the experiment test and the simulation is 1.42% (Table 2). The deformation patterns also indicate that the model was quite similar (excellent agreement) between the simulation and the test, as illustrated in Figure 6.

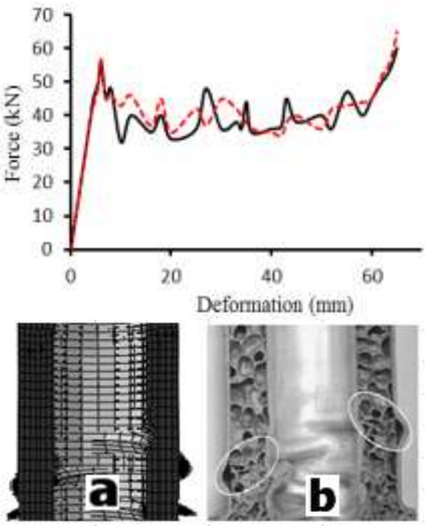
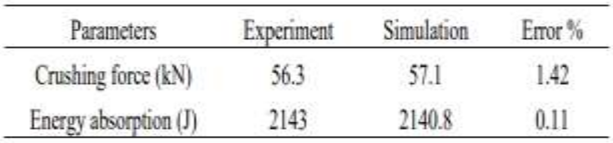


Fig. 6a: Force displacement of simulation and experiment test, [37]. 6b: Deformation mode (a) simulation and (b) experiment test of DWFF

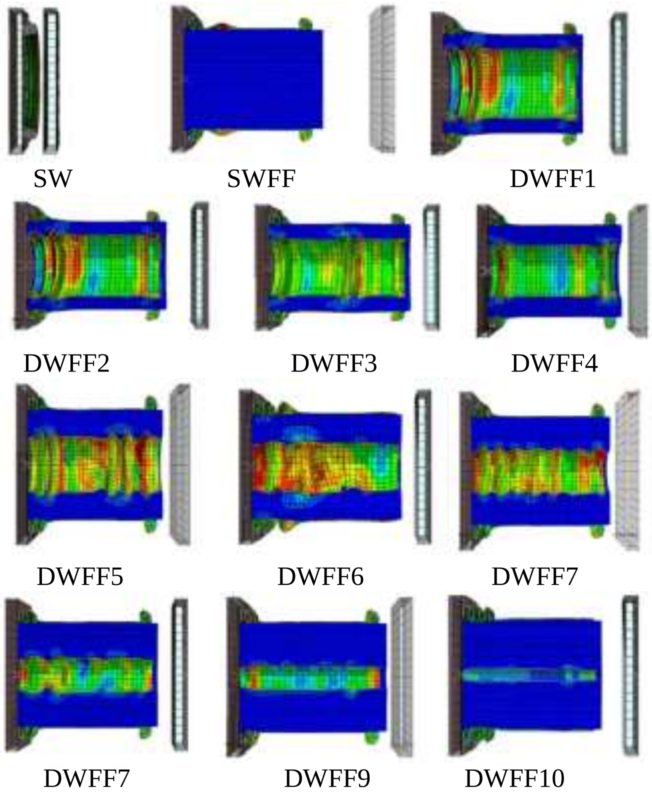
Table 2. Difference between FEA and experiment results, [37]



Parameters	Experiment	Simulation	Error %
Crushing force (kN)	56.3	57.1	1.42
Energy absorption (J)	2143	2140.8	0.11

3.2 Plastic Deformation Modes

The SW1, SWFF, and DWFF1-DWFF10 circular tubes undergo plastic folding distortions. It is observed that frameworks that account for strain rate align better with practical outcomes than those that disregard it. Figure 7 depicts the initial extensional folding of DWFF, which transitions to in-extensional modes. It indicates that the fold count concerning DWFF5 aligns well with the practical outcomes. The DWFF5 foam core absorbed more energy owing to superior peak stress at a higher strain rate, as depicted in Figure 6. Strain rate impact enhances corner-specific energy absorption by enhancing local deformation in the circular of aluminum. Consequently, there is a minor increase in overall crushing force. Therefore, it can be concluded that the foam core's strain rate has a meaningful impact on the crushing characteristics of the foam-incorporated circular.

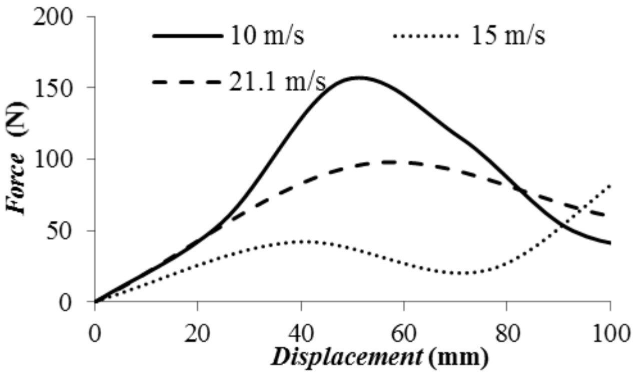


SW SWFF DWFF1
DWFF2 DWFF3 DWFF4
DWFF5 DWFF6 DWFF7
DWFF7 DWFF9 DWFF10

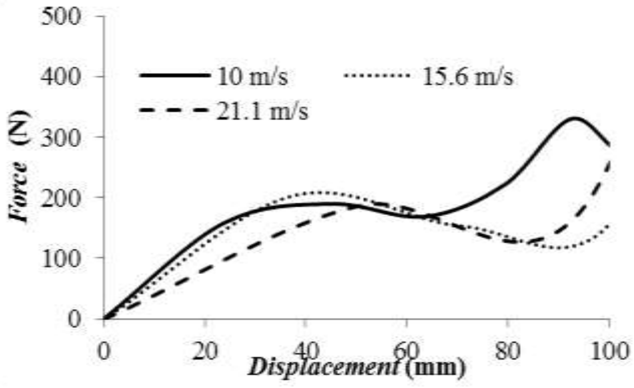
Fig. 7: Deformation mode of structures

3.3 Crushing Force Curve

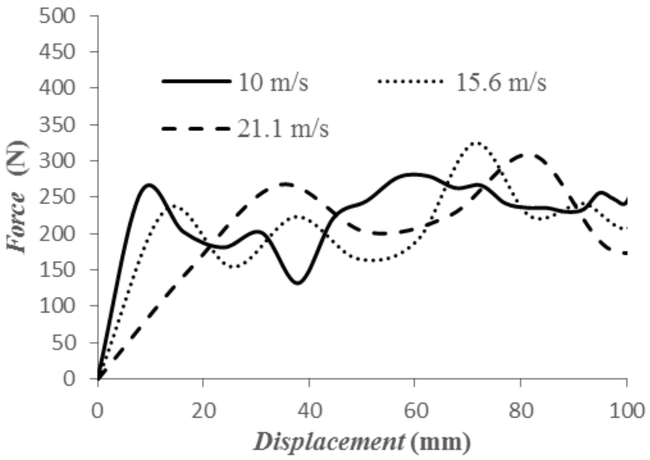
Figure 8 depicts curves corresponding to SW, SWFF1, and DWFF1-10 circular and presents the instantaneous crushing force vs crushing length. It is understood that the strain rate effect must be accounted for in the material framework for finite element simulations of the foam. Hence, a proper and accurate estimate can be obtained concerning the true physical and crushing characteristics of axial dynamical loads placed on the circular. It can also be seen that single-walled foam-filled circular (SWFF) outperforms the responses of only circular walls (SW) when loaded individually (Figure 8). The interaction between the circular wall and the foam will greatly improve the crushing resistance. The response of DWFF is found to be much better than the sum of the circular walls and the foam-filled circular tube. For double-walled foam-filled circular, indicating that in this model, the interaction between the column walls and the foam also has a significant effect on the crushing behavior of the column, as shown in Figure 8. It can be seen also that peak force increases significantly when increasing the impact velocity of an impactor.



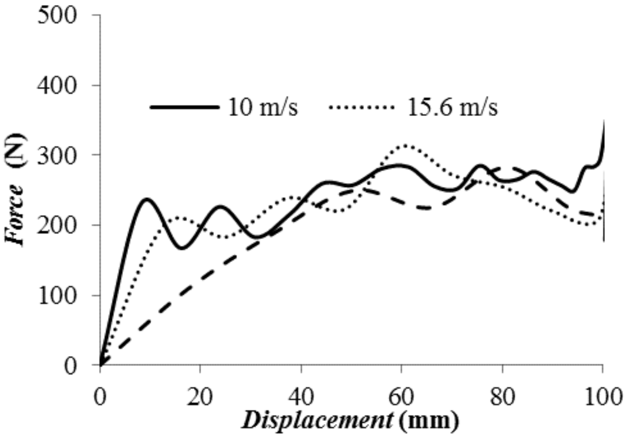
SW



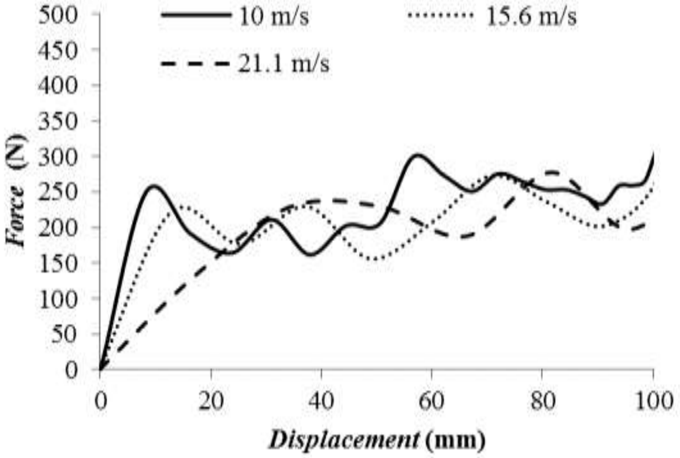
SWFF



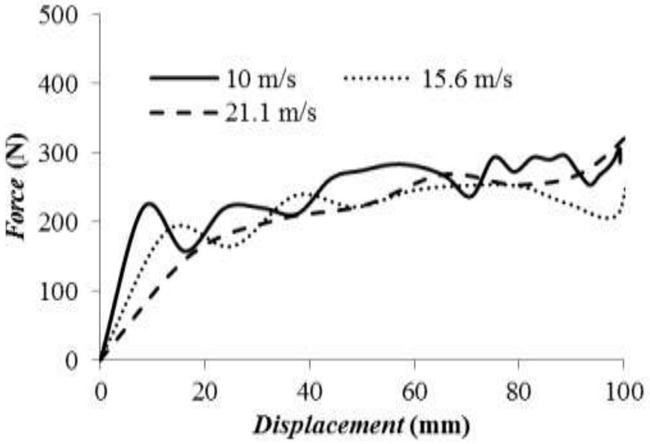
DWFF1



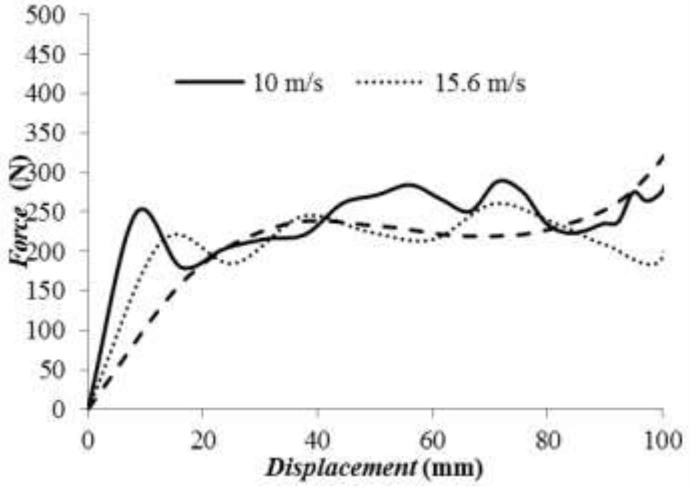
DWFF4



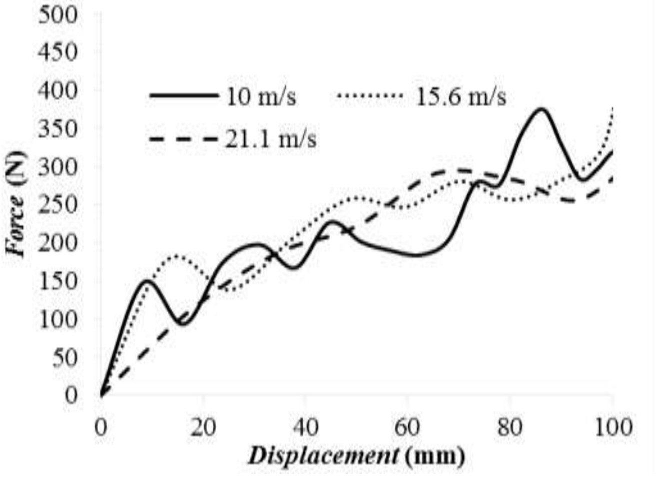
DWFF2



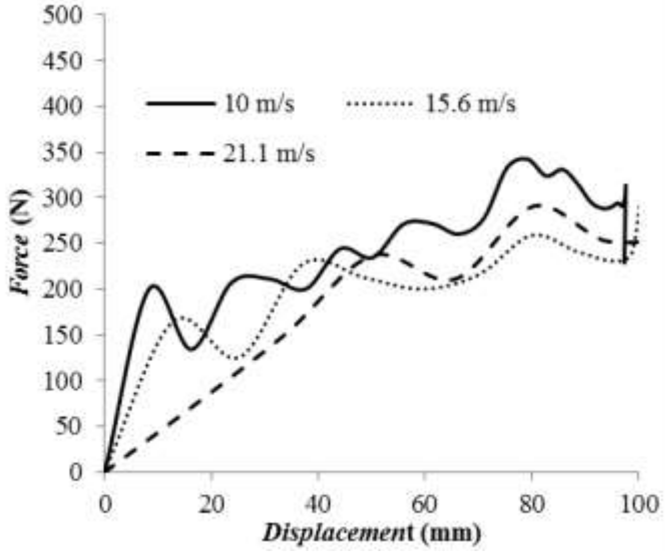
DWFF5



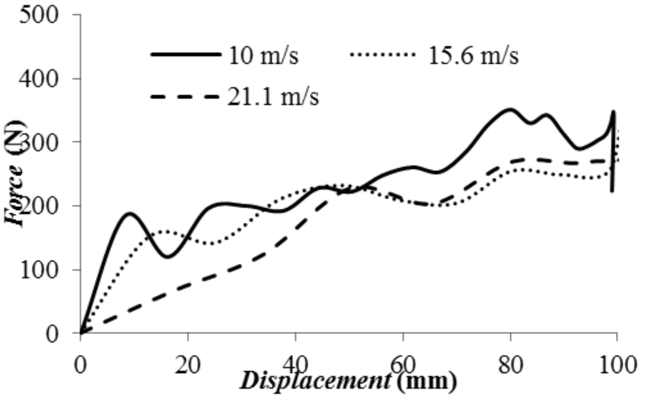
DWFF3



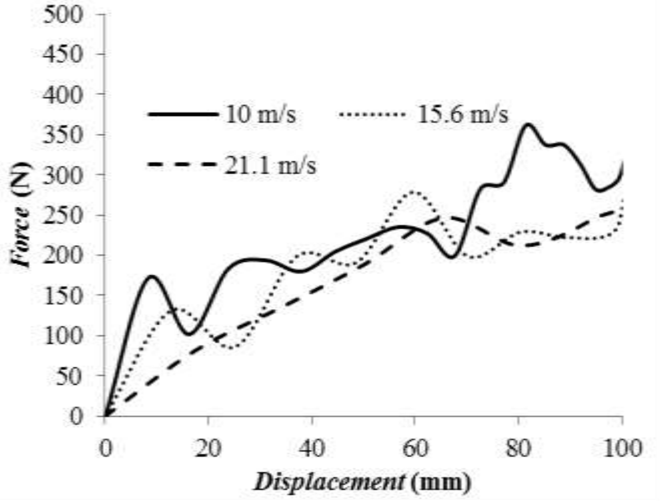
DWFF6



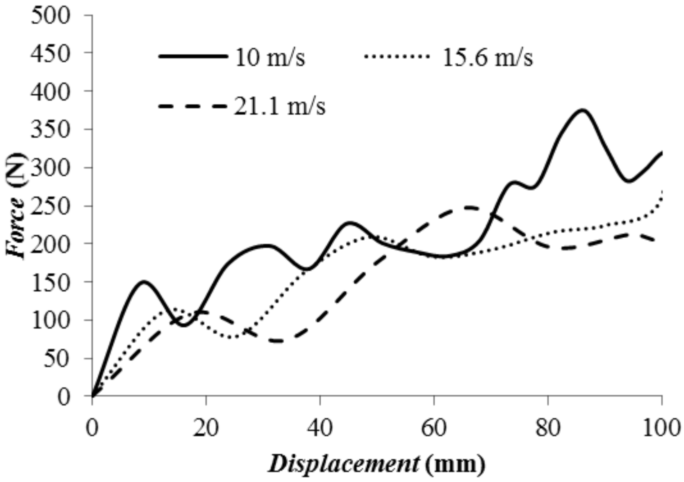
DWFF7



DWFF8



DWFF9

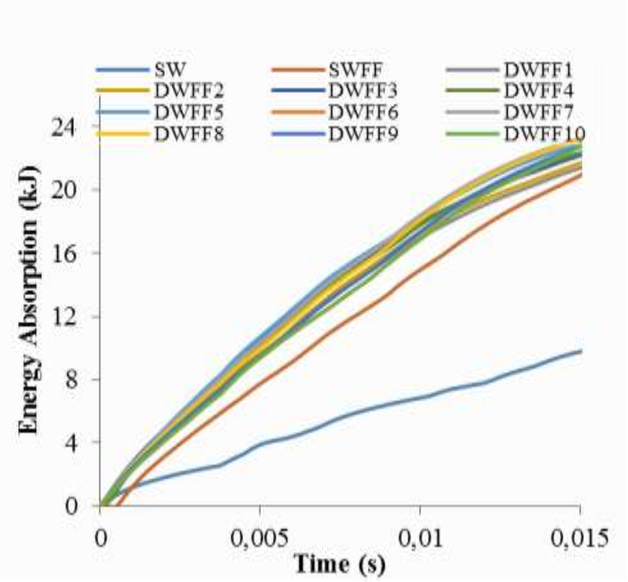


DWFF10

Fig. 8: Force response of structures with different impact velocity

3.3 Foam–filled Circular Analysis

This portion discusses foam-loaded circular crushing characteristics, energy absorption properties, and specific energy absorption in Figure 8 and Figure 9. Initially, single- and double–walled circular were evaluated concerning the impact of aluminum foam insertion. Subsequently, the impact of changing core thickness was evaluated. The material framework of the foam considers the effects of strain rate.



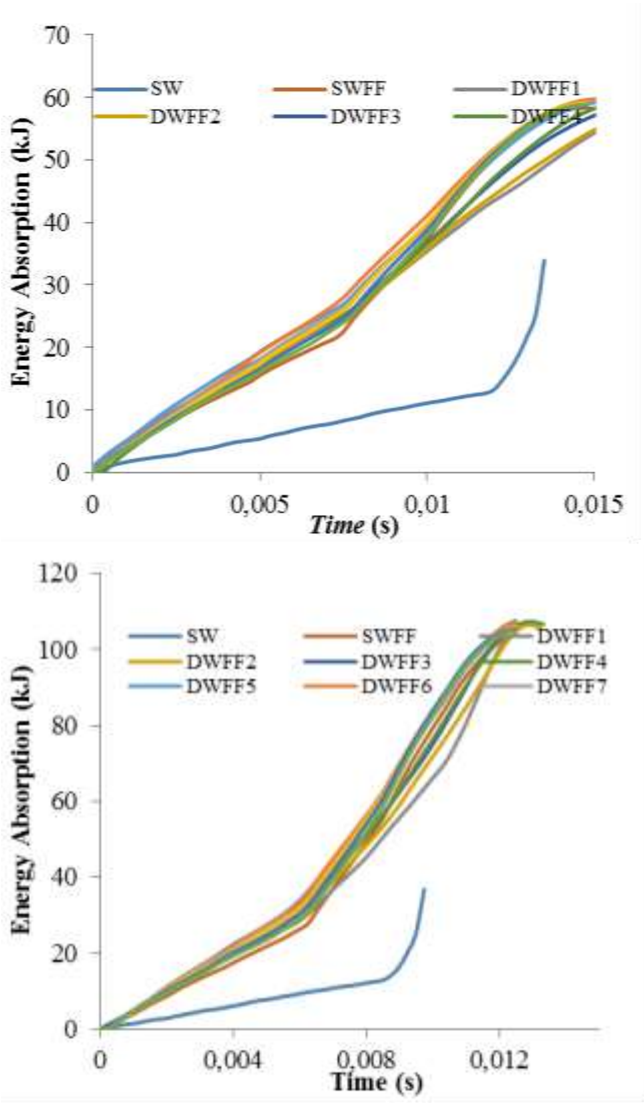


Fig. 9: Energy Absorption responses of structures with different impact velocity

This section assesses the crushing characteristics of the DWFF circular at several core thickness values (10 mm – 80 mm). The outcomes are contrasted against the single–walled foam–filled (SWF) circular. Instantaneous and mean-crushing responses are depicted in Figure 10. The outcomes indicate that the initial specific energy absorption increase for a single foam-filled tube (SWFF). For foam-filled double wall tubes (DWFF) it can be seen that SEA increases from DWFF1 to DWFF7 and then reduces as the core thickness rises (DWFF8-DWFF710), [37].

Fig. 10: Specific Energy Absorption responses of structures with different impact velocity

3.4 Normalised Mean Crushing Force and Structural Efficiency

Specific Energy Absorption (SEA) are critical crashworthiness aspects to determine the energy absorption efficiency of the elements, which are defined as Figure 11 provides SEA values for SW, DW, SWFF, and DWFF assessed in this portion. Figure 11 depicts the SEA circular normalized about the SW circular Therefore, the ability and efficacy of several circulars having distinct geometries can be contrasted directly concerning their energy absorption characteristics. Figure 11 depicts the normalized values of specific energy absorption observed. Rising foam thickness leads to foam-circular wall interactions, enhancing the circular's energy absorption ability until the inner wall is minimal, and the characteristics of the double–

walled foam–a filled circular approach that of the single-walled equivalent, [38], [39].

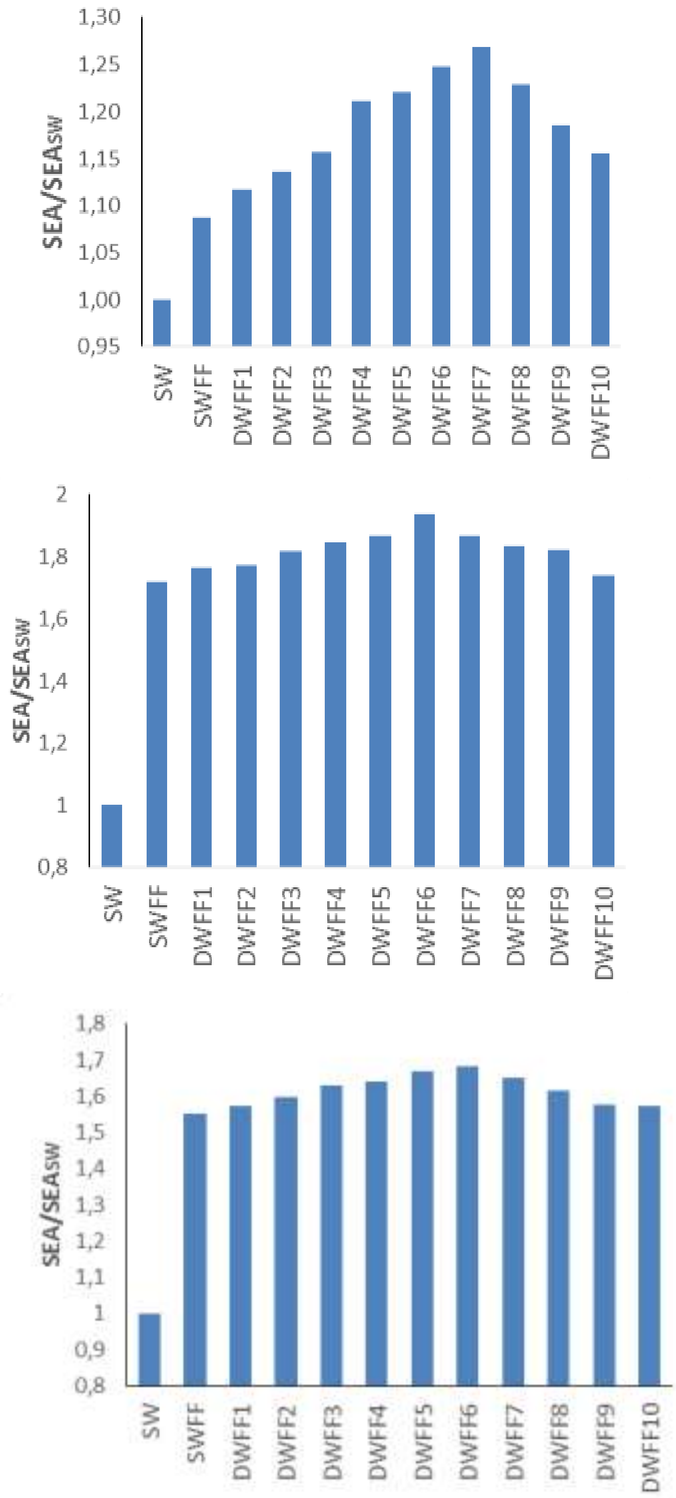


Fig. 11: Normalised specific energy absorption of structures with different impact velocity

4 Conclusions

This research presents a computational investigation of aluminum foam-filled circular under dynamic axial crushing force. The outcomes confirm that adding foam to a column will enhance its capacity to absorb energy. The outcome also demonstrates predictions of the crushing behavior that may be made using a numerical model that takes the strain rate effect into account.

The interaction of the foam core with the tube wall will change the mode of deformation from a single localized fold to several propagating folds and raise the column's mean total crushing force. In double-walled foam-filled tubes, similar effects of the filling are also seen. When compared to single-walled circular tubes, the mean crushing force of a foam-filled column is significantly enhanced, however, when compared to a double-walled circular tube, it is only slightly improved.

Increasing the core thickness will increase the crushing force up to an indication where the dimension of the inner wall tube is too small and the behavior of the double-walled foam-filled tube approaches that of the single-walled foam-filled tube, according to analysis results of the double-walled foam-filled tube with various core thicknesses of the same outer wall geometry. The findings demonstrate that the double-walled foam-filled tube has a greater mean crushing force than the single-walled foam-filled tube.

Based on the above presented approach of scaled train modeling, a similar scaled model of a train may be created to offer a quick and effective way to build the basic framework of a train in future research. A scaled-down train model is essential for understanding the development and energy distribution during railway crashes since it can accurately represent a full-size train collision and offer a practical and affordable way to replicate catastrophic incidents. The scaled modeling issues for thin-walled structures in high-speed trains could be effectively resolved by the scaled method presented here. It is also suitable for the scaled model design of other large prototypes composed of thin-walled structures in engineering.

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-Fauzan Djamaluddin carried out the simulation, the optimization and the methodology

-Daniel Susilo responsible for project administration and methodology

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Conflict of Interest

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