

Research Paper

Crashworthiness Evaluation of a Parallel 5-Tube Circular Multi-Segment Crash Box with Cutting Die Trigger for Railway Safety

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Abstract

This study presents a crashworthiness evaluation of a Parallel 5-Tube Circular Multi-Segment Crash Box with a cutting die trigger, designed to promote controlled progressive folding for high-speed railway applications. The crash box integrates four primary tubes and one secondary tube in a parallel configuration, featuring multi-segment wall thickness and a die-trigger mechanism designed to initiate controlled folding from the tube's end. The die acts as a deformation initiator, guiding the folding sequence to occur progressively, thereby improving energy dissipation and reducing peak impact forces. Two impact models, namely the Cutting Die Model (CDM) and the Flat Model (FM), were employed to investigate the combined effects of trigger mechanism, multi-segment wall thickness, and impact direction using validated finite element simulations supported by quasi-static and drop-test experiments. Finite Element Analysis (FEA) simulations using ANSYS LS-DYNA were conducted to assess key crashworthiness indicators, including maximum crushing force (F_{max}), energy absorption (EA), specific energy absorption (SEA), mean crushing force (F_{mean}), and crushing force efficiency (CFE). Experimental validation through quasi-static and drop tests confirmed the reliability of the simulation results. The findings reveal that the CDM configuration significantly outperforms the FM model, exhibiting lower F_{max} and higher EA, SEA, and CFE values. Progressive folding initiated by the die mechanism enables more stable and efficient energy dissipation. Additionally, the impact direction influences deformation behavior, with the t_1 - t_2 configuration yielding superior performance. These results demonstrate the effectiveness of the proposed crash box design in meeting the stringent safety and spatial requirements of modern railway systems.

Keywords: Ramie fiber; PLA composite; Electric vehicle; Lightweight structure; Flexural strength; Three-point bending

1. Introduction

Passive safety in high-speed railway systems relies heavily on the capacity of structural components to absorb impact energy during collisions [1], [2], [3]. Crash boxes are essential for mitigating impact forces transmitted to the main frame and protecting passengers [4], [5]. A major challenge in railway crash box design is the limited space available within the cabin [6], [7], which demands a compact structure capable of

delivering high crashworthiness performance [8], [9], [10].

To overcome this challenge, previous studies have explored several strategies, including multi-cell [11], [12], [13], [14] and multi-tube configurations to increase energy absorption capacity [15], [16], [17], the application of multi-segment thickness to control deformation [18], [19], [20], and the integration of folding triggers to reduce peak force [21], [22], [23]. These approaches have shown



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significant improvements in crashworthiness indicators, particularly Specific Energy Absorption (SEA) and Crushing Force Efficiency (CFE). Although these strategies have improved crashworthiness indicators, significant gaps remain. Most research has focused on single-tube or multi-cell crash boxes with conventional triggers [24], [25], [26], often under simplified loading conditions [27], [28], [29]. Previous studies that employed die-based triggers often reported splitting deformation [30]. This study introduces a die-based trigger specifically engineered to promote progressive folding, thereby improving EA and overall crashworthiness.

Despite these advancements, limited attention has been devoted to multi-segment crash boxes incorporating five parallel tubes and die-based triggers. The combined effect of multi-segment wall thickness and impact direction on deformation behavior remains insufficiently studied, particularly for high-speed rail applications where spatial constraints and safety requirements are critical. This gap underscores the need for innovative designs that enable controlled, progressive folding while maintaining compact dimensions.

To address these gaps, this study proposes a multi-segment crash box design comprising five parallel circular tubes, each equipped with a die-based folding trigger. Unlike earlier designs that caused splitting [31]. The proposed concept aims to initiate folding at the tube's end and promote progressive deformation. The configuration consists of four primary tubes and one secondary tube arranged in parallel, tested using two impact models: the Cutting Die Model (CDM) and the Flat Model (FM). The CDM employs a die to initiate controlled folding from the tube's end, while the FM operates without a die. The die mechanism aims to achieve progressive deformation, enhancing energy dissipation and minimizing peak impact forces. The design incorporates variations in multi-segment configurations and impact directions, with tubes featuring two levels of wall thickness (t_1 and t_2). This study investigates how these variations affect key crashworthiness indicators. Numerical simulations using finite element analysis (ANSYS LS-DYNA) are complemented by experimental validation through quasi-static and drop tests.

Building on this approach, the primary objective of this work is to provide a comprehensive evaluation of the proposed design and to offer practical recommendations for passive safety systems in high-speed railway vehicles. By addressing the identified gaps, this study contributes to the development of lightweight, compact crash boxes and advances understanding of controlled deformation mechanisms in thin-walled structures.

2. Methods

This research was conducted through simulation methods utilizing ANSYS LS-DYNA software. Experimental procedures were carried out to validate the deformation patterns and crashworthiness performances observed in the simulations. The experiments involved both drop tests and quasi-static testing to ensure comprehensive validation.

2.1. Experimental

Two experimental methods were employed in this study: a drop test and a quasi-static compression test. Both tests were designed to verify the reliability of the numerical model by comparing deformation patterns and key parameters. The drop test was used to observe deformation behavior under dynamic loading, while the quasi-static test provided quantitative crashworthiness data, such as force–displacement response and energy absorption, serving as a reference for simulation validation. This approach ensures consistency between physical and numerical models, enabling accurate correlation for subsequent analysis and design optimization. **Figure 1** illustrates the schematic arrangements for both setups, with panel (a) showing the drop test configuration and panel (b) depicting the quasi-static compression configuration.

The full-scale crash box design (400 × 400 mm) exceeded the capacity of the available laboratory equipment, therefore, a half-scale specimen was fabricated for testing. Although the diameter was reduced by half while the wall thickness remained constant, resulting in a change in the t/D ratio, the specimen still falls within the thin-walled domain ($t/D < 0.1$), where progressive folding mechanisms remain consistent [32], [33]. According to established thin-walled tube theory, crashworthiness indicators such as F_{mean} and EA

depend primarily on dimensionless ratios (t/D , L/D) and material properties rather than absolute size. Thus, scaled tests are widely accepted for validating deformation patterns and crashworthiness trends when normalized parameters are applied [34]. Due to equipment limitations, the experimental program focused on a single multi-segment tube as the test specimen rather than the full five-tube configuration, ensuring that the folding mechanism and crashworthiness characteristics could still be observed and validated effectively.

The primary objective of the experiment was to evaluate the influence of using a die as a folding trigger (CDM) compared to a model without a die (FM), thereby confirming differences in deformation patterns and crashworthiness performance between the two configurations. This trend is predictable and validated through both simulation and physical testing [35], [36]. Figure 2 shows the single multi-segment crash box tube and the cutting die specimen, both fabricated at half-scale, used as test objects in the drop test and quasi-static compression test for model validation.

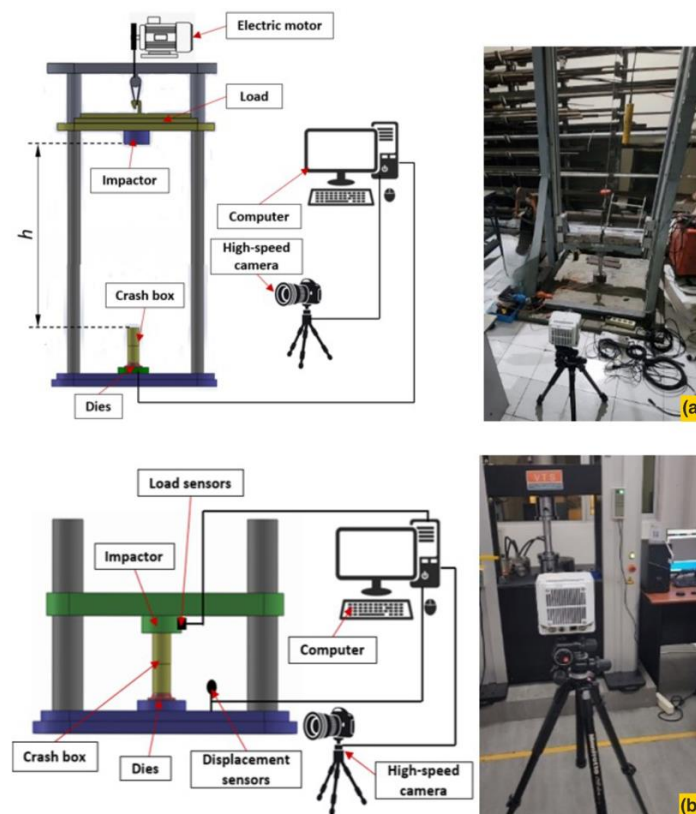


Figure 1. Experimental setup schematics: (a) Drop test; (b) Quasi-static test

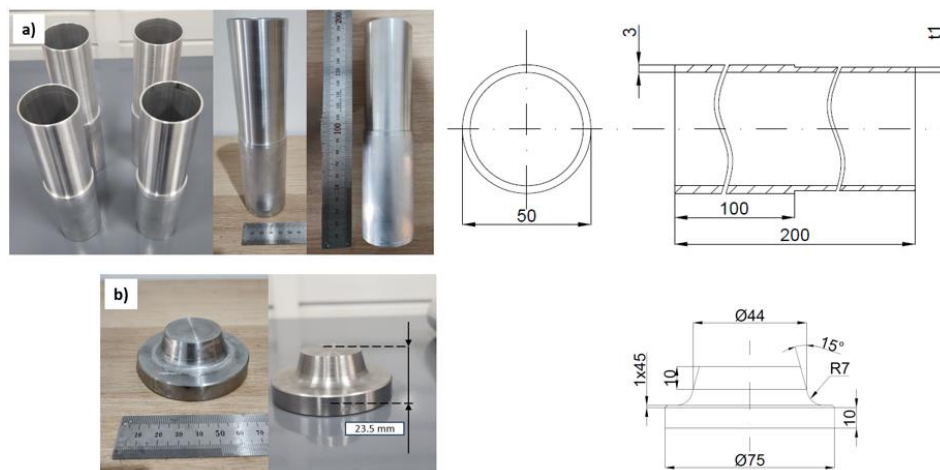


Figure 2. Experimental test specimen and its geometry: (a) Single multi-segment crash box tube; (b) Die

The experimental tests were conducted on two model configurations, CDM and FM. In the CDM configuration, the specimen included a die component, whereas the FM configuration was tested without a die.

2.1.1. Drop test

The drop test was carried out to observe the final deformation pattern of the specimen under dynamic impact loading. A 65 kg mass was released in free fall from a height (h) of 2 meters, directly impacting the crash box. Here, h represents the vertical distance between the impactor and the top surface of the crash box (see [Figure 1a](#)). Two specimens were tested for each configuration to ensure repeatability and capture potential variability in deformation behavior. This approach provides qualitative insight into the structural response under dynamic conditions while addressing consistency concerns.

The test was conducted solely to validate the deformation pattern, not to evaluate overall crashworthiness performance, due to laboratory equipment limitations. A high-speed camera recorded the progressive folding process during impact at approximately 1,000 fps. Test photos were used to confirm the consistency of the deformation pattern with the dynamic simulation.

2.1.2. Quasi-static experimental

The quasi-static compression test was performed to obtain complete crashworthiness data, including force–displacement behavior, due to limitations of the drop test. Although quasi-static loading does not replicate real dynamic impact conditions, it provides reliable quantitative data for validation.

Four specimens were tested for each configuration ($n = 4$) to capture manufacturing variability and ensure repeatability. The specimen was compressed at an impactor speed of 1 mm/s until complete failure, while force and displacement were continuously recorded using integrated sensors. A high-speed camera recorded the deformation sequence for qualitative observation only.

The Quasi-static tests were conducted using a VTS electromechanical Universal Testing Machine (model WDW-300E) with a load capacity of 300 kN. The load cell accuracy was $\pm 0.5\%$ of the applied force, and displacement was measured

via an internal encoder with $\pm 0.5\%$ accuracy and a resolution of 0.01 mm. The machine was calibrated according to ISO 7500-1 and ASTM E4 standards. That has been provided by the Integrated Research Laboratory (LRT) of Brawijaya University.

Data were processed to generate force–displacement curves and calculate crashworthiness parameters such as EA, $F_{\max}$, SEA, F_{mean} , and CFE. Variability was quantified using mean, standard deviation (SD), coefficient of variation (CV), and 95% confidence interval (CI) based on the t -distribution ($df = 3$). SD was computed using the sample standard deviation ($ddof = 1$), and CV was calculated as SD divided by the mean multiplied by 100%. This statistical approach provides a clear measure of repeatability.

2.2. Numerical Simulation Setup

Numerical simulations were performed by computer using ANSYS LS-DYNA software to evaluate the performance of all crash box specimens investigated in this study. The crash box tubes were made of Al 6063 material, while ST 37 steel was used for the dies. Based on previous research, the mechanical properties of Al 6063 were determined through tensile testing by ASTM E8M standards [26] and the material properties of ST 37 [37], as shown in [Table 1](#) and the engineering stress–strain curve shown in [Figure 3](#). Mechanical properties of Al 6063 obtained from tensile testing of Al6063 (ASTM E8/E8M flat specimen, thickness = 1.5 mm). Young's modulus (E) was determined from the initial linear elastic region, while the yield stress (σ_y) was calculated using the 0.2% offset method. The tangent modulus (E_t) was obtained from the slope of the second linear segment in the plastic region before necking. These parameters were used to define the bilinear isotropic hardening model (MAT_024) in LS-DYNA. The bilinear isotropic hardening model

Table 1. Properties of Al 6063 and ST 37

Parameters	Al 6063	ST 37
Density (kg/m ³)	2,700	7,850
Young's modulus (Gpa)	70	200
Poisson's ratio	0.33	0.3
Yield stress (MPa)	240	315
Ultimate stress (MPa)	265	450
Tangent modulus (GPa)	5.30	--

was selected because it efficiently represents elastic-plastic behavior using tensile test parameters and is widely adopted in similar crashworthiness studies.

The crash box geometry was modeled in ANSYS SpaceClaim and analyzed using LS-DYNA. An explicit dynamic solver was used with an end time of 0.1 s and a time step safety factor of 0.9, and all simulations for the parallel multi-segment crash box models were performed using this dynamic solver as the primary focus of the study. Tubes were meshed with 3 mm elements, while the impactor and die used 5 mm. Al 6063 was modeled as elastic-plastic with bilinear isotropic hardening, where plasticity was represented by a yield stress of 240 MPa and a tangent modulus of 5.30 GPa. The stress-strain curve obtained from ASTM E8M tensile tests was implemented in the material card to capture nonlinear behavior. Contact between components applied a surface-to-

surface penalty method with a friction coefficient of 0.1. Tubes were fully deformable, while the die was assumed rigid to reduce computational cost, justified by its significantly higher stiffness (ST37 steel) compared to the aluminum tubes. Two simulation sets were conducted: validation against drop and quasi-static tests, and parametric analysis of multi-segment crash box performance. Outputs included force, displacement, internal energy, and deformation patterns, which were processed to compute EA, F_{mean} , F_{max} , CFE, and SEA. Figure 4 to Figure 4c illustrate the full-scale geometry of the crash box and die, which served as the reference design for obtaining the primary dataset in this study.

The Parallel 5-Tube Circular Multi-Segment Crash Box comprises four primary tubes and one secondary tube. Primary tubes have two wall thicknesses: t_1 (1, 1.5, 2, 2.5, and 3 mm) and t_2 (constant at 3 mm). The full-scale design measures

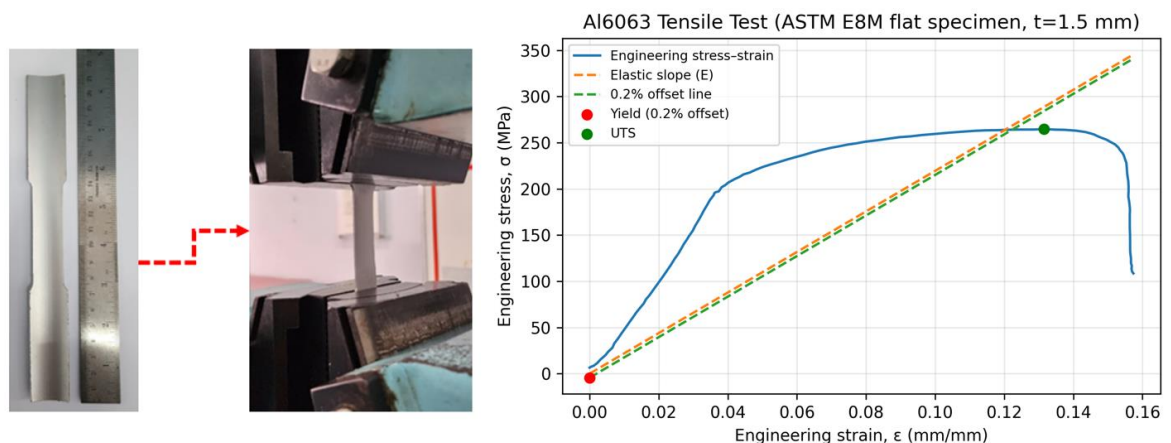


Figure 3. Engineering Stress-Strain Curve of Al6063 from Tensile Test (ASTM E8M)

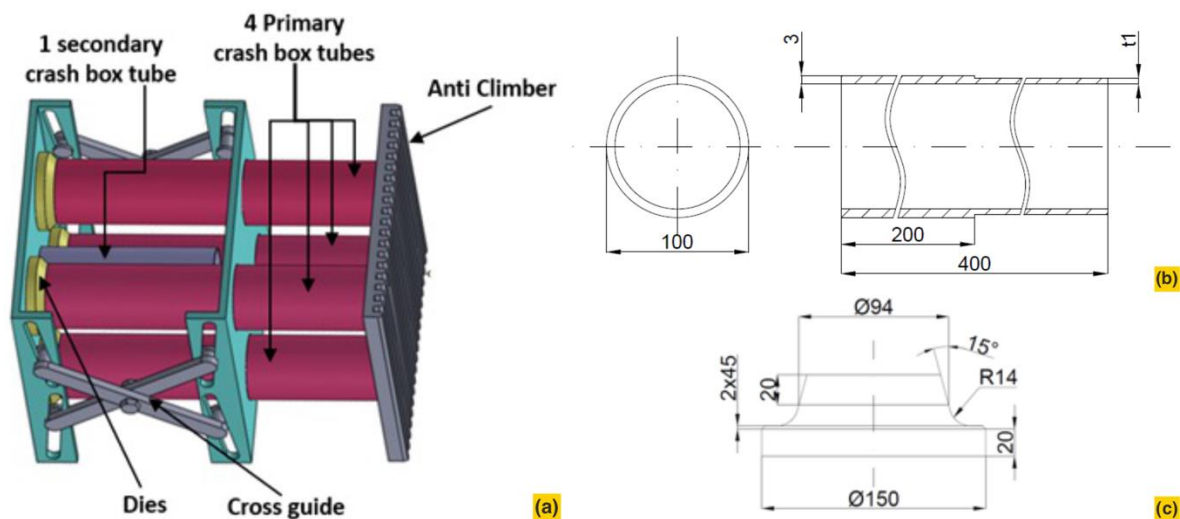


Figure 4. Design 3-dimensional and geometry of a parallel 5-tube circular multi-segment crash box: (a) the crash box assembly; (b) Full-scale geometry of the tube; (c) Full-scale geometry of the die

450 × 400 × 400 mm to fit train cabin constraints. A novel cutting die (Figure 4c) was introduced as a folding trigger. Two models were analyzed, CDM and FM, combined with variations in t_1 and impact direction (t_1-t_2 vs t_2-t_1), totaling 20 simulations. Figure 5a to Figure 5d illustrate these scenarios. A frontal axial load of 9 tons, assumed to represent the weight of one train carriage, was applied, with an impact velocity of 6,900 mm/s per EN15227 crashworthiness standards, to ensure consistency and safety in testing [38].

2.3. Mesh Convergence and Solver Stability

Mesh convergence was assessed by testing three element sizes: 7 mm, 5 mm, and 3 mm. The evaluation considered crashworthiness indicators and global energy balance to ensure numerical accuracy. Solver stability was verified through energy conservation checks and compliance with the Courant time step criterion. Based on these procedures, the mesh size selected for all subsequent simulations was determined after confirming independence from further refinement.

2.4. Crashworthiness Indicators

Prior to analyzing the impact resistance characteristics of a crash box structure, it is imperative to establish the impact resistance index. This process involves a comprehensive evaluation of crashworthiness parameters, including the F_{max} , F_{mean} , EA, SEA, CFE, and the associated crushing deformation modes.

Energy Absorption (EA) is a quantity that quantifies the total energy dissipated by a thin-

walled tube subjected to axial loading. A higher EA value signifies superior energy absorption capability, which is a critical attribute for enhancing the structural performance during impact scenarios.

$$EA = \int_0^{xn} f(x)dx \quad (1)$$

The parameter xn denotes the effective crushing displacement, which typically ranges from 70% to 75% of the total length of the crash box tube [9]. The function $f(x)$ represents the instantaneous axial compressive force exerted during deformation.

Specific Energy Absorption (SEA) is defined as the total energy absorbed per unit mass of the crash box tube. A higher SEA value indicates enhanced energy absorption efficiency, which is desirable for improving the crashworthiness of the structure.

$$SEA = EA / m \quad (2)$$

where, m denotes the total mass of the crash box tube.

Maximum Crushing Force (F_{max}) refers to the peak force observed at the initial stage of deformation, which initiates the folding of the crash box structure. A lower F_{max} value is generally preferred, as it reduces the severity of the initial impact transmitted to the surrounding structure.

Mean Crushing Force (F_{mean}) represents the average axial force exerted during the crushing process. It provides a measure of the overall load-bearing capacity of the crash box throughout deformation. The mean crushing force can be calculated using the following expression:

$$F_{mean} = EA/s \text{ or } F_{mean} = \int_0^{xn} f(x)dx / xn \quad (3)$$

where, s represent the crushing distance, which corresponds to the axial displacement experienced by the crash box during impact.

Crushing Force Efficiency (CFE) is a key indicator used to evaluate the consistency of load transmission throughout the crushing process. It is defined as the ratio of the F_{mean} to the F_{max} . A higher CFE value indicates a more stable and efficient energy absorption behavior, which is favorable for improving the crashworthiness performance of the structure.

$$CFE = F_{mean} / F_{max} \quad (4)$$

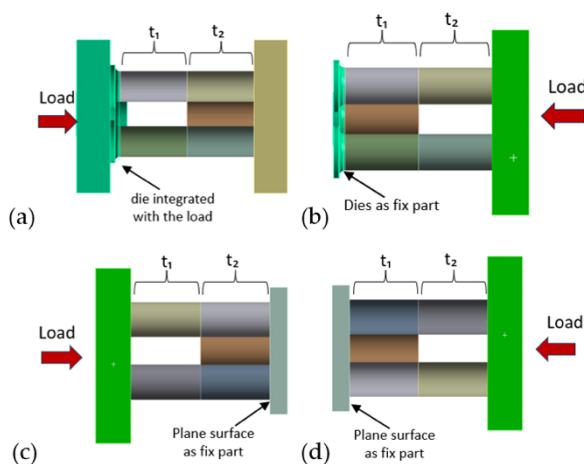


Figure 5. The crash box impact scenarios: (a) CDM- t_1-t_2 ; (b) CDM- t_2-t_1 ; (c) FM- t_1-t_2 and; (d) FM- t_2-t_1 .

3. Results and Discussion

3.1. Model Validation and Verification

Validation ensures the reliability of crashworthiness simulations by confirming that numerical models accurately replicate physical behavior. This section addresses three key aspects: comparison of experimental results from drop tests with dynamic simulations, quasi-static compression tests with quasi-static simulations, and numerical verification through mesh convergence and energy balance analysis. All experimental tests were conducted on half-scale specimens to accommodate equipment limitations while maintaining geometric similarity and thin-walled behavior, ensuring that the validation reflects the actual deformation mechanisms of the full-scale design.

3.1.1. Drop test vs dynamic simulation

Figure 6 presents the deformation patterns from drop tests and dynamic simulations for two configurations, FM and CDM. Panels (a) and (b) show FM results, while panels (c) and (d) show CDM results. The drop test was performed on two specimens for each configuration to ensure repeatability and capture potential variability in deformation behavior.

For FM, both experiment and simulation indicate initial folding at the interface between thin and thick walls, followed by localized buckling zones. In CDM, the die effectively triggers deformation at the tube end, producing controlled folding that propagates upward.

However, folding does not extend along the entire tube or only partially due to limitations in the drop test setup, including restricted height and limited impactor mass. Despite these constraints, both experimental and simulated results consistently indicate the same collapse initiation points: mid-section for FM and tube end for CDM. This confirms that the dynamic simulation accurately replicates the physical deformation mechanism under impact conditions.

3.1.2. Quasi-static experimental results vs numerical simulation

Figure 7 illustrates the comparison of force–displacement curves obtained from four quasi-static test specimens and one quasi-static numerical simulation for each model (CDM and FM). The four experimental specimens were included to capture manufacturing variability and provide a representative average, while a single calibrated simulation was used for numerical validation.

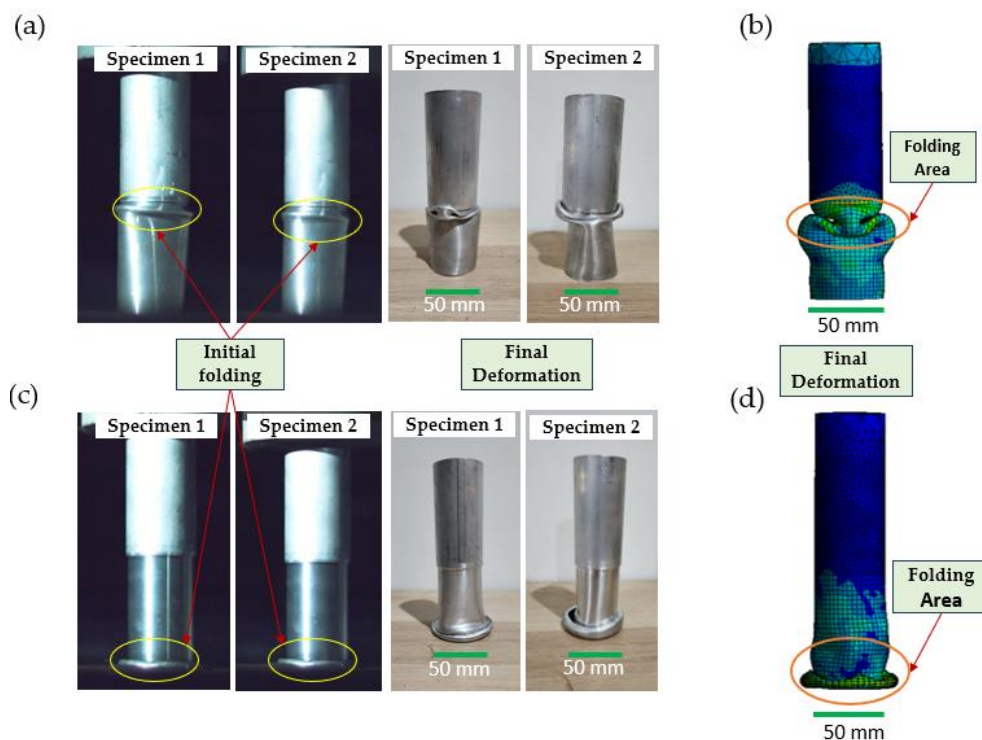


Figure 6. Deformation comparison between the drop test and the dynamic simulation for FM and CDM: (a) FM – drop test; (b) FM – dynamic simulation; (c) CDM – drop test; (d) CDM – dynamic simulation

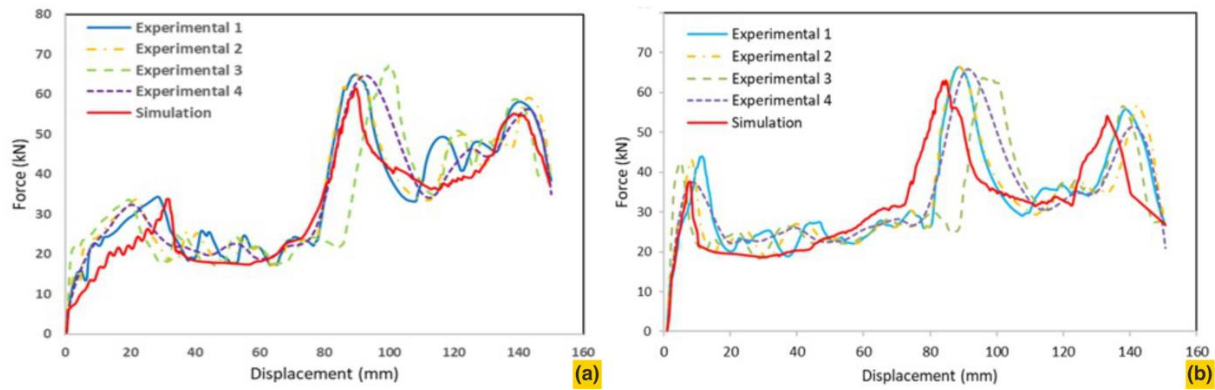


Figure 7. Comparison of quasi-static force-displacement graphs from experimental and numerical simulation results: (a) CDM; (b) FM

Both experimental and simulation curves exhibit consistent trends. For both models, a noticeable increase in force occurs at a displacement of approximately 80–100 mm, corresponding to the engagement of the thicker segment (t_2). The compression stroke was set to 150 mm to ensure folding progressed close to full collapse.

This validation approach aligns with crashworthiness standards, where an error margin of $\leq 10\%$ between experimental averages and simulation results is considered acceptable [39]. Table 2 confirms that EA, F_{mean} , and SEA fall within this range, indicating good agreement. Larger deviations in F_{max} and CFE are primarily attributed to geometric imperfections during fabrication, which affect the initial peak force.

Statistical analysis shows that EA, SEA, and F_{mean} exhibit low variability, with coefficients of variation (CV) generally between 1.5% and 2.2%, reflecting strong consistency among specimens. F_{max} demonstrates higher variability (CV up to

6%), which is expected due to its sensitivity to initial geometric imperfections and alignment during the onset of folding. CFE remains relatively stable, with CV values below 5%, supporting the reliability of the folding mechanism. The 95% confidence intervals for all parameters are narrow, confirming that the experimental data are statistically robust and repeatable. These findings provide clear evidence of measurement consistency and uncertainty quantification.

Figure 8 illustrates the folding sequence during deformation. CDM initiates folding at the tube end near the die and propagates upward with a progressive concertina pattern, whereas FM begins folding at the midsection with an axial folding mode. In FM, the first fold forms at the center due to stress concentration at the t_1 – t_2 interface, then develops upward and downward. Both models exhibit symmetric folds that stack sequentially.

Table 2. Comparison of the crashworthiness performance between experimental and simulation

CDM													
Parameters	Sim.	Experimental 1		Experimental 2		Experimental 3		Experimental 4		Mean	SD	CV (%)	CI 95% (lower-upper)
		Results	Error (%)	Results	Error (%)	Results	Error (%)	Results	Error (%)				
EA (kJ)	4.85	5.01	3.30	5.02	3.54	4.90	1.12	4.79	1.27	4.93	0.11	2.21	4.75 – 5.10
F _{max} (kN)	33.89	35.95	6.08	34.72	2.45	34.19	0.89	32.85	3.06	34.43	1.28	3.73	32.38 – 36.47
F _{mean} (kN)	32.33	33.40	3.30	33.48	3.54	32.70	1.12	31.92	1.27	32.87	0.73	2.21	31.71 – 34.02
CFE	0.95	0.93	2.62	0.96	1.07	0.96	0.23	0.97	1.84	0.96	0.02	1.95	0.92 – 0.98
SEA (kJ/kg)	28.87	29.82	3.30	29.89	3.54	29.19	1.12	28.50	1.27	29.35	0.65	2.21	28.32 – 30.38
FM													
Parameters	Sim.	Experimental 1		Experimental 2		Experimental 3		Experimental 4		Mean	SD	CV (%)	CI 95% (lower-upper)
		Results	Error (%)	Results	Error (%)	Results	Error (%)	Results	Error (%)				
EA (kJ)	4.75	4.93	3.86	4.79	0.81	4.96	4.44	4.90	3.26	4.8938	0.08	1.55	4.77 – 5.01
F _{max} (kN)	39.63	42.13	6.30	37.56	5.22	42.62	7.54	42.73	7.83	41.26	2.48	6.01	37.31– 45.20
F _{mean} (kN)	31.65	32.87	3.86	31.90	0.81	33.05	4.44	32.68	3.26	32.625	0.5	1.55	31.82 – 33.42
CFE	0.80	0.78	2.30	0.85	6.37	0.78	2.88	0.76	-4.24	0.7925	0.04	4.86	0.73 – 0.85
SEA (kJ/kg)	28.26	29.35	3.86	28.49	0.81	29.51	4.44	29.18	3.26	29.13	0.45	1.55	28.41 – 29.84

Figure 9 shows the final deformation of both models. The simulation accurately replicates the fold locations, sequence, and shapes, including stacked folds at the lower end of the tube. This similarity confirms the predictive capability of the numerical model in capturing complex folding mechanisms under quasi-static loading.

3.1.3. Validation of Numerical Model

Table 3 summarizes the mesh convergence analysis. Mesh convergence was assessed using element sizes of 7 mm, 5 mm, and 3 mm on the representative CDM- t_1 - t_2 configuration ($t_1 = 1$ mm) under dynamic impact conditions. The comparison of crashworthiness indicators

revealed that reducing the mesh size from 7 mm to 3 mm resulted in only minor variations: $F_{\max}$ changed by approximately 1.3%, crushing displacement by 1.6%, and EA by 3.1%, while SEA and CFE remained practically unchanged. Differences between 5 mm and 3 mm were even smaller ($<1.4\%$ for EA and $<0.5\%$ for $F_{\max}$), confirming mesh independence. Therefore, a 3 mm mesh was selected as the optimal balance between accuracy and computational efficiency. This approach is consistent with best practices for explicit dynamic simulations, as recommended by LS-DYNA technical guidelines and ASME standards for verification and validation in computational modeling [40], [41].

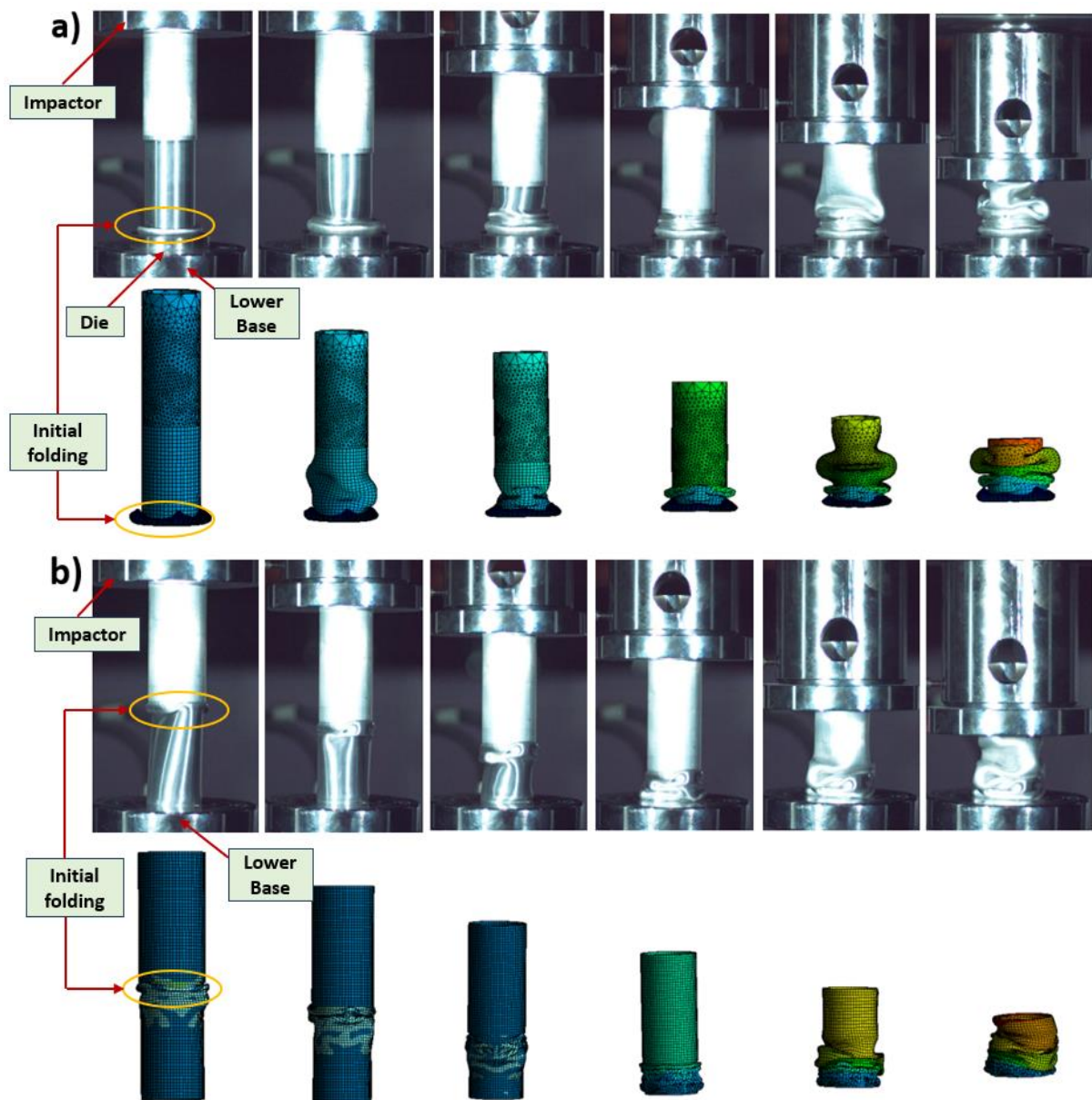


Figure 8. Deformation comparison between the simulation and the quasi-static compression test: (a) CDM; (b) FM

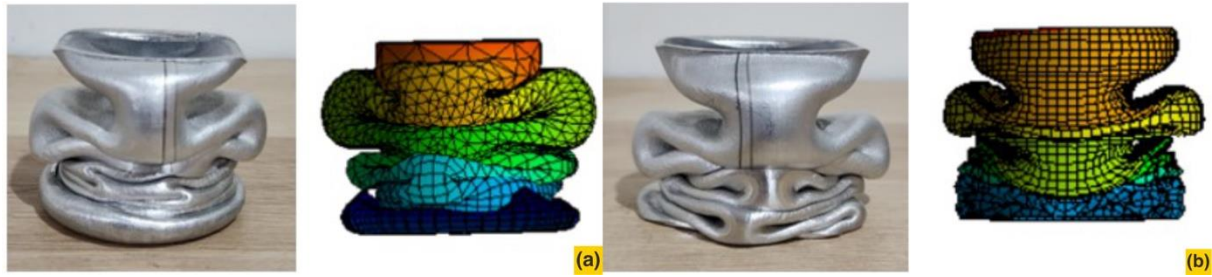


Figure 9. Final deformation of quasi-static test and simulation: (a) CDM; (b) FM

Table 3. The mesh convergence results

Crashworthiness Parameters	Mesh sizes (mm)		
	3	5	7
Mass (kg)	3.22	3.22	3.22
Disp (mm)	355.09	353.54	349.23
EA (kJ)	152.53	150.44	147.74
F _{max} (kN)	445.25	443.34	439.34
F _{mean} (kN)	429.55	425.52	423.04
CFE	0.96	0.96	0.96
SEA (kJ/kg)	47.37	46.72	45.88

Figure 10 presents the energy balance history of internal, kinetic, and total energy, demonstrating solver stability throughout the crash box loading. Solver stability was verified through global energy balance during the explicit dynamic integration process. Energy drift was calculated as the relative deviation of total energy from its initial value using:

$$\text{Energy drift} = \frac{E_{\text{max}} - E_{\text{initial}}}{E_{\text{initial}}} \times 100\% \quad (5)$$

The maximum deviation observed was approximately 7.1% during the initial transient

phase, after which the drift decreased to less than 0.23% at the end of the simulation. Furthermore, the ratio of kinetic to internal energy dropped below 1% (median $\approx 0.61\%$) in the final stage, indicating a stable dynamic response without spurious oscillations. According to LS-DYNA guidelines and ASME V&V standards, an energy drift of $\leq 10\%$ is generally considered acceptable for explicit dynamic crash simulations, provided that the trend stabilizes and returns near the initial level at the end of the run [39], [40], [41], [42]. Therefore, the observed drift of 7.1% falls within the recommended threshold, confirming that the numerical model is sufficiently validated for crashworthiness analysis and design optimization. The slight energy drift during the initial transient phase is mainly due to contact initialization and the explicit solver's numerical integration. These deviations are typical in LS-DYNA because of penalty-based contact and hourglass control, and remain within ASME V&V acceptable limits.

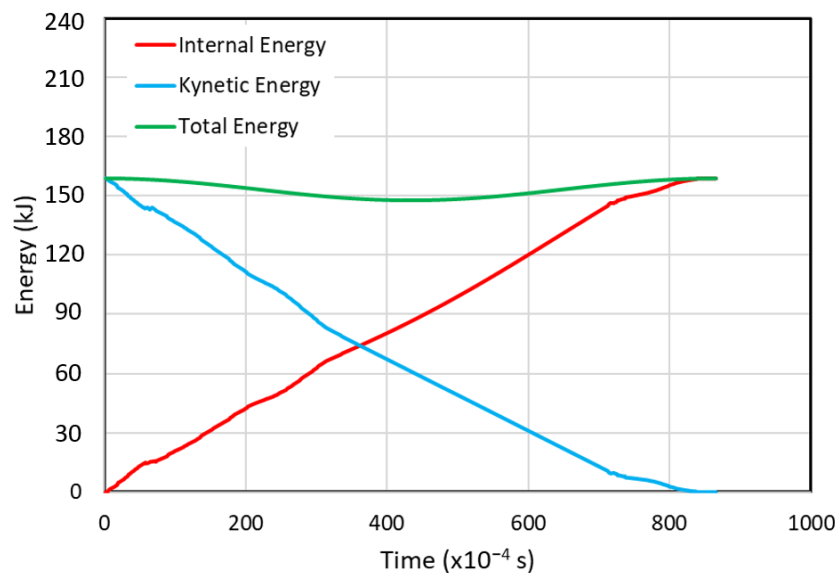


Figure 10. The energy balance history of internal, kinetic, and total energy for CDM-t1-t2 (t1=1mm)

3.2. Crashworthiness Evaluation of Multi-Segment Parallel Five-Tube Crash Box

This section examines the influence of three key variables on crash box performance: the die trigger mechanism (CDM vs. FM), wall thickness configuration (multi-segment vs. uniform), and impact direction (t_1 - t_2 vs. t_2 - t_1). Unlike previous studies that primarily focused on single-tube crash boxes [26]. This research introduces a parallel five-tube configuration designed to enhance EA, which is critical for high-speed rail applications. Theoretical principles suggest that, under ideal conditions, adding identical tubes in parallel can proportionally increase EA, provided that deformation occurs simultaneously without adverse interactions [36].

Numerical simulations generated force-displacement data, internal energy, and deformation patterns, which were processed to calculate crashworthiness indicators based on Eq. (1) to Eq. (4). The simulation results are summarized in Table 4, serving as the basis for the subsequent analysis.

3.2.1. Effect of crash box model (CDM vs FM) on performance

Table 4 shows that CDM consistently outperforms FM in crashworthiness indicators. The lowest peak force ($F_{\max}$) was recorded for CDM- t_1 - t_2 with $t_1 = 1$ mm (445.25 kN), while FM with uniform thickness ($t_1 = t_2 = 3$ mm) reached the highest $F_{\max}$ (746.31 kN). EA increased with wall thickness, peaking at 159.42 kJ for CDM- t_1 - t_2 with $t_1 = 2.5$ mm. However, SEA and CFE were highest for thinner walls ($t_1 = 1$ mm), with CDM achieving SEA of 47.33 kJ/kg and CFE of 0.96.

Figure 11 illustrates force-displacement curves, where CDM exhibits a smoother force response and longer crush stroke (355 mm) compared to FM (340 mm), indicating more gradual energy dissipation. Meanwhile, Figure 12 confirms that CDM consistently achieves higher EA and SEA and lower $F_{\max}$ across all thickness variations and impact directions. Then, Figure 13 shows deformation patterns. CDM initiates folding at the tube end and progresses systematically, while FM starts at the midsection, resulting in less controlled collapse.

Table 4. Performance data on the crashworthiness of the Parallel Multi-segment crash box

Model		t_1 (mm)	Mass (kg)	Disp. (mm)	EA (kJ)	$F_{\max}$ (kN)	F_{mean} (kN)	CFE	SEA (kJ/kg)
FM	t_1 - t_2	1	3.22	350.64	142.42	539.42	406.17	0.75	44.19
		1.5	3.56	340.19	144.51	543.33	424.79	0.78	40.58
		2	3.90	321.92	148.86	638.88	462.41	0.72	38.17
		2.5	4.24	308.97	150.10	688.28	485.81	0.71	35.38
		3	4.58	293.15	131.31	746.31	447.93	0.60	28.67
		Mean	--	322.97	143.44	631.24	445.42	0.71	37.40
	t_2 - t_1	1	3.22	340.20	123.44	544.96	362.85	0.67	38.30
		1.5	3.56	335.81	132.68	594.32	395.10	0.66	37.26
		2	3.90	323.40	137.51	672.80	425.20	0.63	35.26
		2.5	4.24	309.19	136.81	722.01	442.48	0.61	32.25
		3	4.58	293.15	131.31	746.31	447.93	0.60	28.67
		Mean	--	320.35	132.35	656.08	414.71	0.64	34.35
CDM	t_1 - t_2	1	3.22	355.09	152.53	445.25	429.50	0.96	47.33
		1.5	3.56	349.17	153.49	504.74	439.59	0.87	43.10
		2	3.90	346.17	156.20	590.49	451.22	0.76	40.05
		2.5	4.24	340.91	159.42	664.25	467.63	0.70	37.58
		3	4.58	314.38	135.23	696.82	430.15	0.62	29.53
		Mean	--	341.15	151.37	580.31	443.62	0.78	39.52
	t_2 - t_1	1	3.22	355.13	147.78	448.87	416.13	0.93	45.85
		1.5	3.56	354.81	150.69	525.00	424.71	0.81	42.32
		2	3.90	353.32	154.78	590.34	438.07	0.74	39.69
		2.5	4.24	323.32	148.72	648.03	459.98	0.71	35.06
		3	4.58	302.56	143.02	702.06	472.70	0.67	31.23
		Mean	--	337.83	149.00	582.86	442.32	0.77	38.83

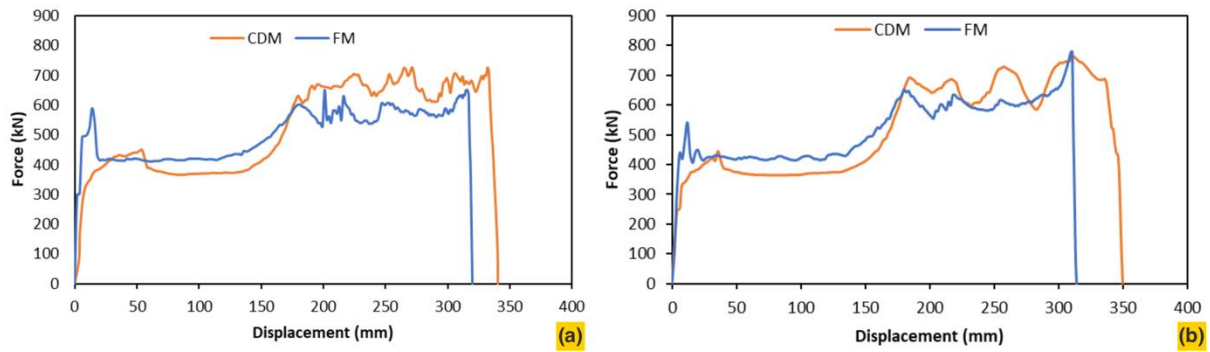


Figure 11. Force-Displacement graph of cdm ($t_1 = 1$ mm) vs FM ($t_1 = 1$ mm) : (a) Impact direction t_1 - t_2 ; (b) Impact direction t_2 - t_1

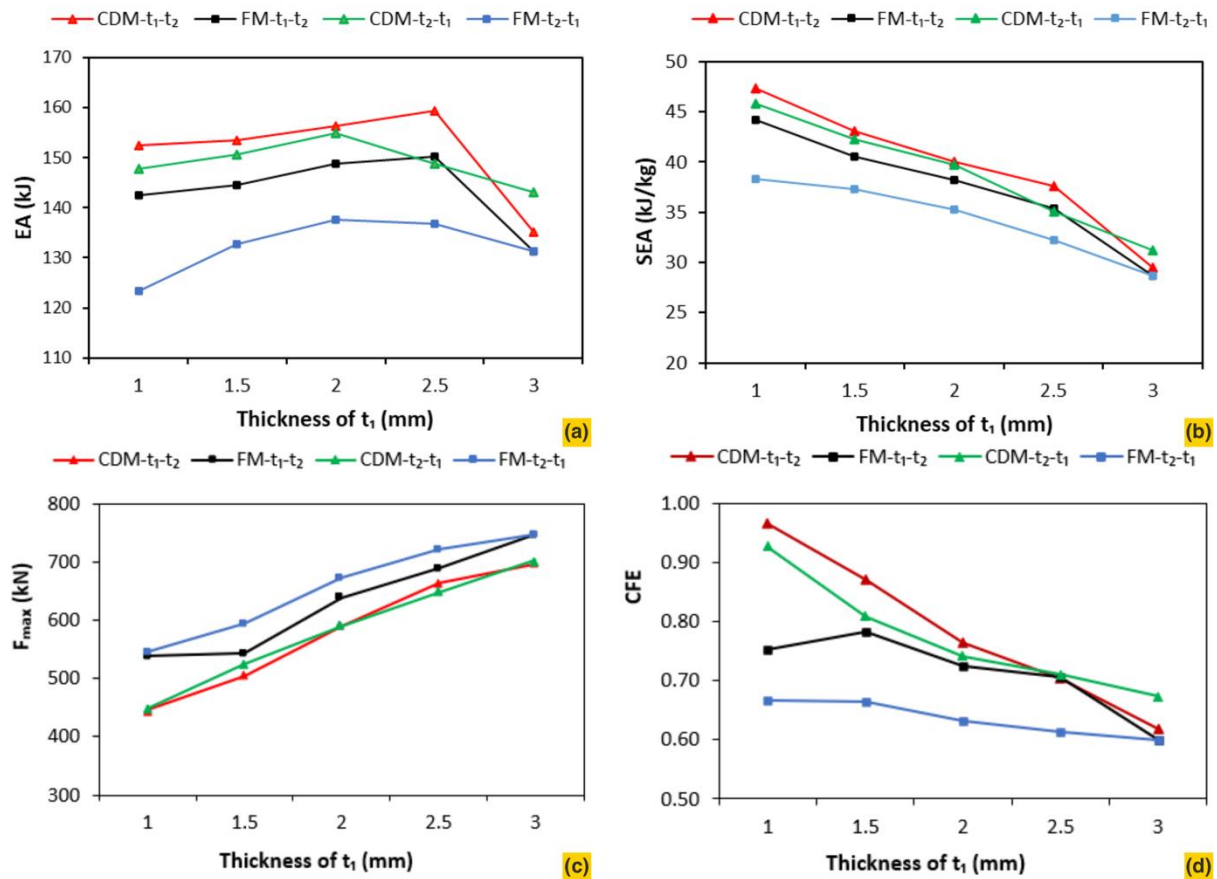


Figure 12. Performance comparison chart of crash box CDM vs FM: (a) EA; (b) SEA; (c) F_{max} ; (d) CFE

3.2.2. Effect of wall thickness configuration

Figure 14 shows the force-displacement curves for all models. During the initial deformation phase (0 – 150 mm), thinner walls ($t_1 = 1$ mm) exhibit the lowest force trend, while thicker walls show higher forces. This relationship is linear: as t_1 increases, F_{max} also rises. According to Table 4, F_{max} for CDM- t_1 - t_2 increases from 445.25 kN ($t_1 = 1$ mm) to 696.82 kN ($t_1 = 3$ mm). EA also increases with thickness, peaking at 159.42 kJ for $t_1 = 2.5$ mm, but SEA and CFE decrease as thickness grows.

Displacement length varies significantly. Uniform-thickness models show the shortest stroke (293 mm), while multi-segment models with $t_1 = 1$ mm reach up to 355 mm. Longer deformation allows more gradual energy absorption, reducing F_{max} . Figure 14a confirms that EA rises with thickness, while Figure 14b and Figure 14d show that SEA and CFE are highest for thin walls.

3.2.3. Effect of Impact Direction (t_1 - t_2 vs t_2 - t_1)

Two impact orientations were analyzed: thin-to-thick (t_1 - t_2) and thick-to-thin (t_2 - t_1). Figure 15

shows that deformation always begins in the thin section and then progresses to the thick section, regardless of impact direction. However,

performance indicators differ. Table 3 and Figure 14a reveal that EA is higher in the t_1 - t_2 configuration: CDM averages 151.37 kJ versus

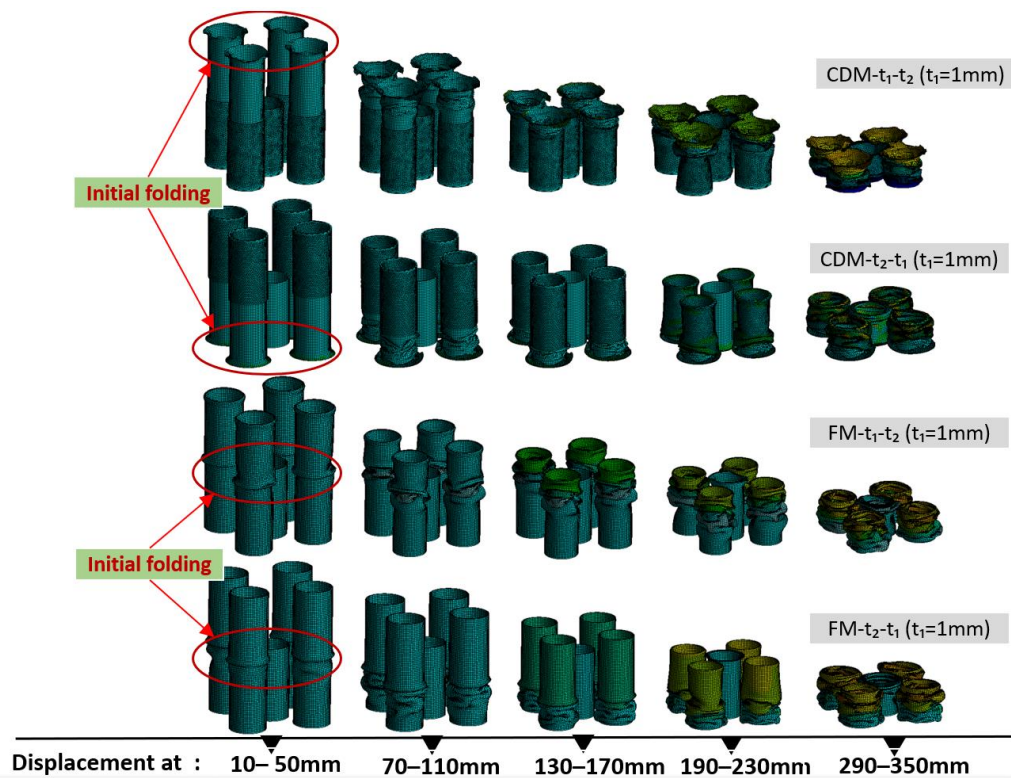


Figure 13. Sequence of crash box deformation at specific displacement intervals

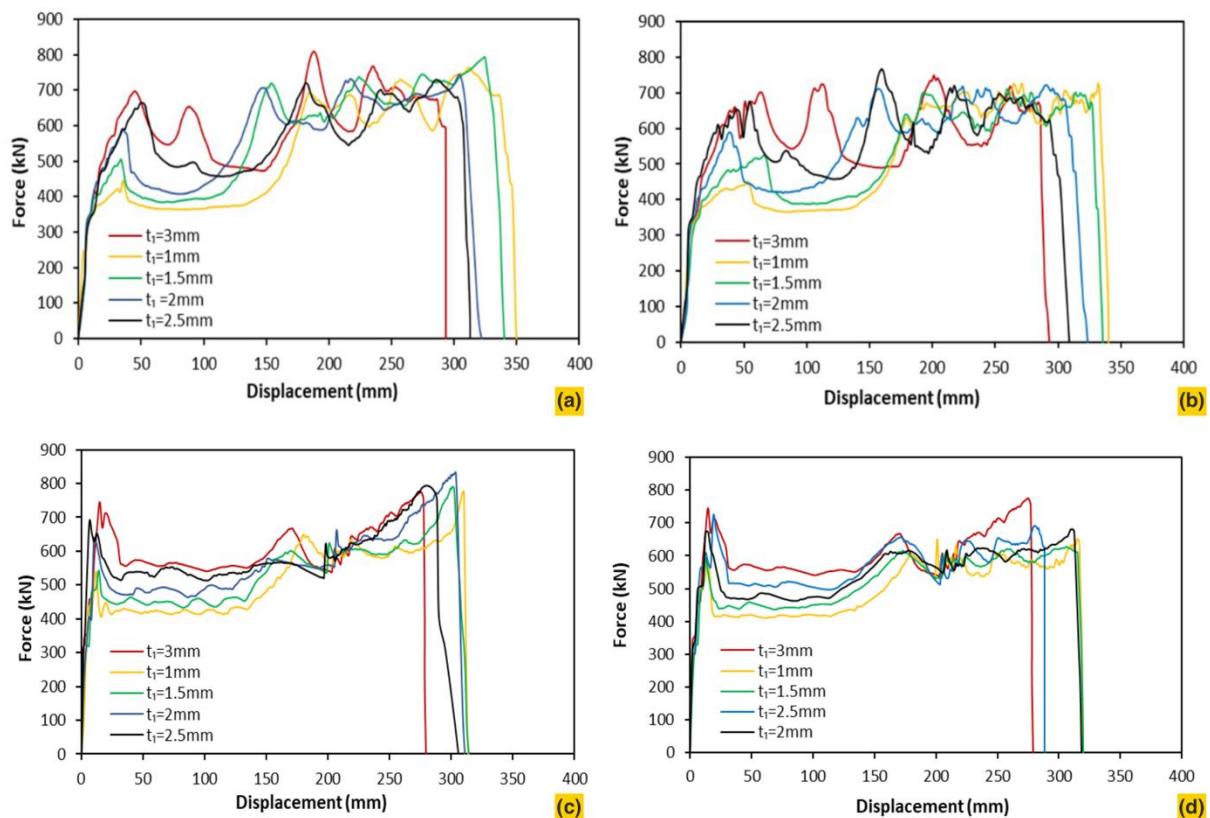


Figure 14. Force-displacement graph of all crash box models: (a) CDM- t_1 - t_2 ; (b) CDM- t_2 - t_1 ; (c) FM- t_1 - t_2 ; (d) FM- t_2 - t_1

149.00 kJ for t_2 - t_1 , while FM averages 143.44 kJ versus 132.35 kJ. Displacement is also longer for t_1 - t_2 (341 mm for CDM, 323 mm for FM) compared to t_2 - t_1 (338 mm and 320 mm). Longer stroke enables more gradual energy absorption. Peak force ($F_{\max}$) is lower when impact starts on the thin side: CDM averages 580.31 kN versus 582.86 kN for t_2 - t_1 , and FM averages 631.24 kN versus 656.08 kN. **Figure 14b** and **Figure 14d** confirm that SEA and CFE are higher for t_1 - t_2 , indicating better efficiency.

3.3. Discussion

The proposed multi-segment crash box comprising five parallel circular tubes and a cutting die as a folding initiator, delivers controlled, progressive deformation that enhances crashworthiness under space-constrained high-speed rail conditions. Consistently across configurations, the CDM outperforms the FM. End-initiated folding in CDM produces a concertina sequence that lowers $F_{\max}$, raises CFE, and increases both EA and SEA. Quantitatively, CDM improves EA by 8.9%, SEA by 9.2%, and CFE by 15.5%, while reducing $F_{\max}$ by 9.6% relative to FM (**Table 4**). These outcomes are reflected by smoother force responses and longer crush strokes (**Figure 11** and **Figure 14**), and align with thin-walled folding theory and prior evidence that geometric initiators reduce $F_{\max}$ without sacrificing EA [43], [44], [45], [46], [47].

The wall-thickness level (t_1) introduces a design trade-off. Increasing t_1 raises EA by storing more plastic work but also increases $F_{\max}$, while SEA and CFE decrease, consistent with the mechanics of thin-walled inextensional folding and limited extensional work [32]. Crucially, the apparent anomaly at $t_1 = 3$ mm (uniform thickness) is not merely uncontrolled deformation, it is a loss of staged collapse that truncates downstream engagement.

Segment-level energy analysis (**Figure 16**) shows that multi-segment tubes ($t_1 = 1$ mm, $t_2 = 3$ mm) redistribute plastic work from the entrance segment into the downstream thick segment and the secondary tube, increasing total EA by 12.8% in CDM and 8.5% in FM, with longer downstream displacement (155 mm CDM, 151 mm FM) than uniform counterparts (114 mm, 93 mm). By contrast, the uniform tube exhibits a shorter overall stroke (302–293 mm), earlier local/global buckling, and limited downstream participation, which reduces the area under the force–displacement curve and thus EA (**Table 4**, **Figure 14**). This mechanism also explains the decline in SEA and CFE as thickness grows. In practical terms, EA peaks around $t_1 \approx 2.5$ mm and then drops at 3 mm because uniform stiffness at the entrance impedes progressive engagement of downstream segments, selecting t_1 must balance system-level EA targets with acceptable $F_{\max}$ for frame integrity.

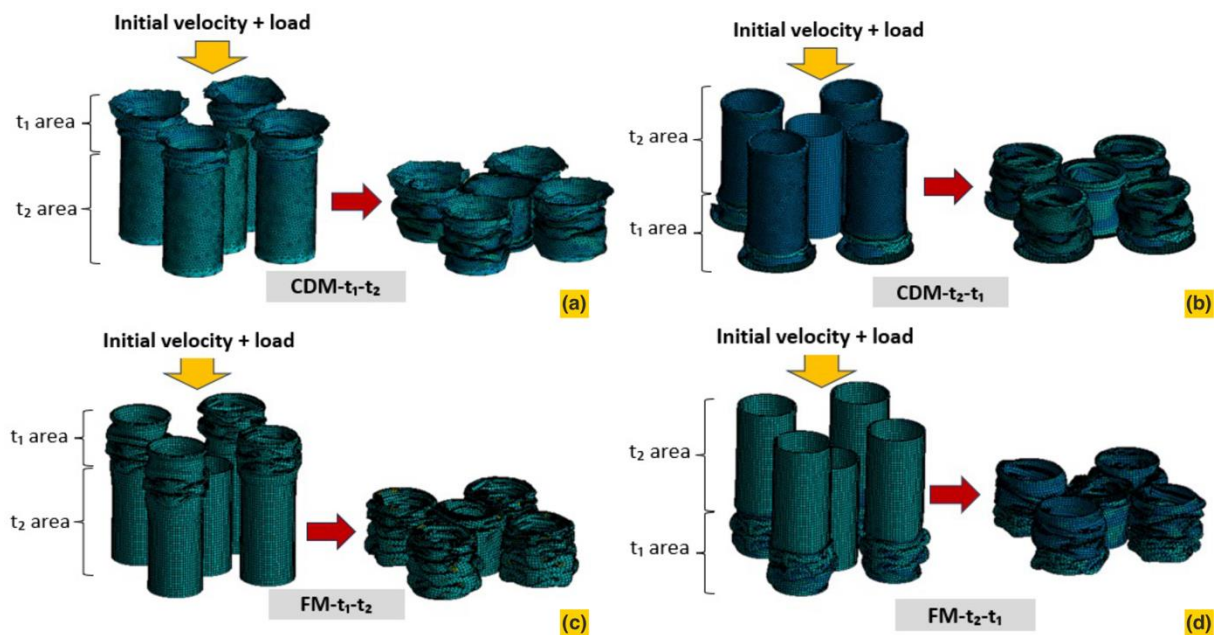


Figure 15. Crash box deformation under varying impact directions: (a) CDM- t_1 - t_2 ; (b) CDM- t_2 - t_1 ; (c) FM- t_1 - t_2 ; (d) FM- t_2 - t_1

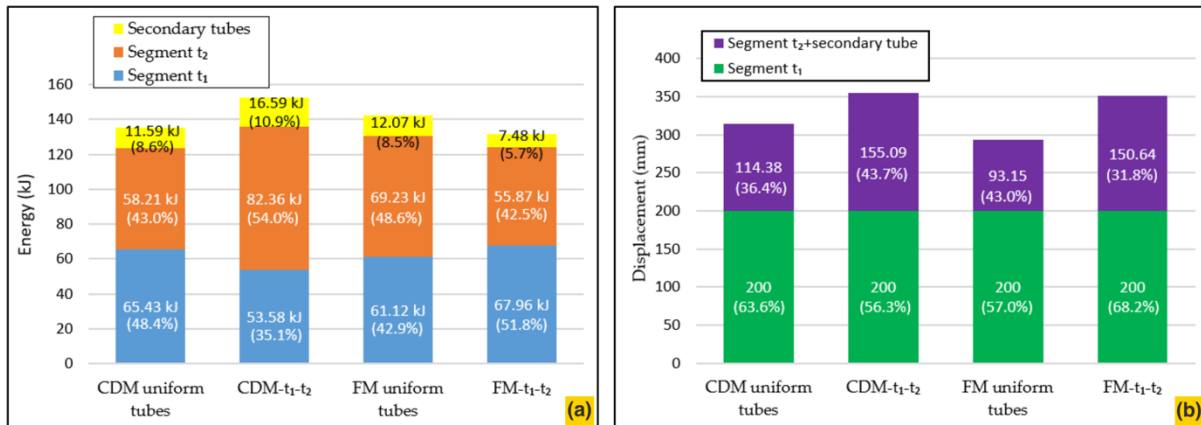


Figure 16. Redistribution of energy and displacement in tube segments: (a) energy distribution per segment; (b) crash displacement per segment

Impact direction further modulates performance even though folding always begins in the thin segment (**Figure 15**). Loading the thin side first (t_1-t_2) promotes earlier collapse, longer crush stroke (341 mm CDM, 323 mm FM), and higher efficiency. EA increases by 1.6% (CDM) and 8.4% (FM), while F_{max} decreases by 0.4% (CDM) and 3.8% (FM), accompanied by higher SEA and CFE (**Table 4**, **Figure 12**). These trends corroborate the design principle that orienting the thin-to-thick pathway toward the impact side yields more stable, efficient deformation [47], [48].

Consistent with the previous discussion on folding patterns, stress distribution provides additional evidence supporting this interpretation. **Figure 17a** and **Figure 17b**, taken from the simulation of the parallel multi-segment crash box models (CDM and FM, configuration t_1-t_2 with $t_1 = 1$ mm), display only one tube because its behavior represents the other tubes in the assembly. The model with the smallest t_1 was selected because it produces the sharpest folds and the most critical stress condition, representing the worst-case scenario for stress evaluation. The

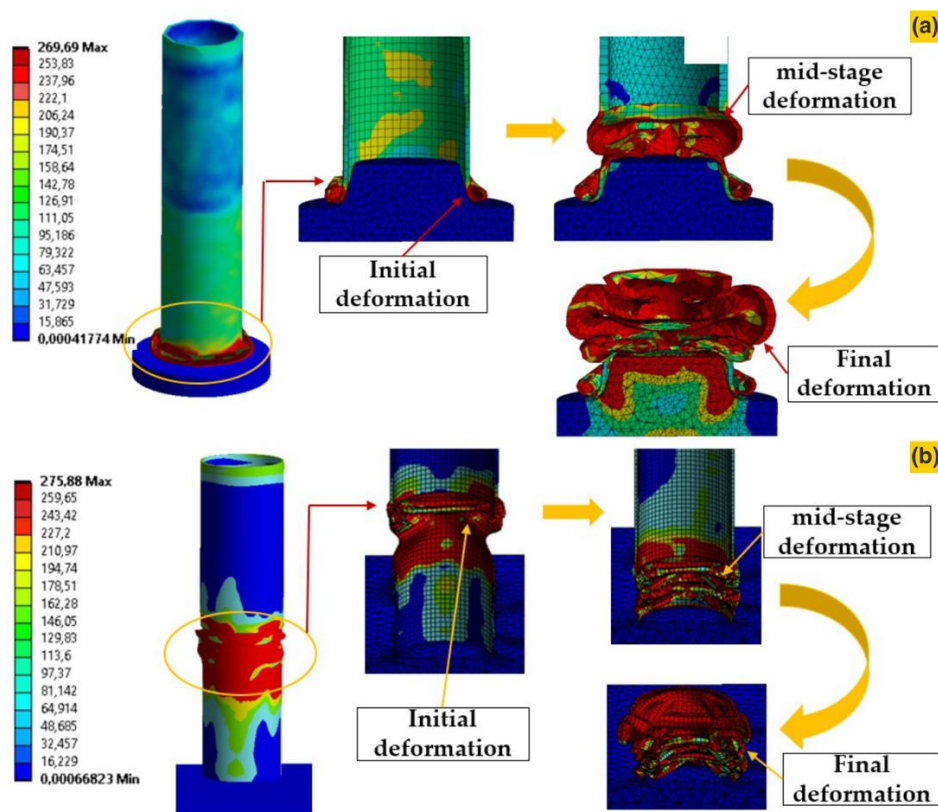


Figure 17. Deformation pattern & stress distribution: (a) CDM tube; (b) FM tube

die radius (R14) in CDM concentrates stress at the tube end and forms a larger, more uniform initial fold radius, which reduces extreme point concentrations and helps lower $F_{\max}$ while improving CFE. In contrast, FM initiates folding at the midsection with scattered high-stress zones, indicating uncontrolled buckling and less efficient energy absorption. The maximum Von Mises stress reaches 275.88 MPa in FM and 269.69 MPa in CDM, slightly exceeding the UTS of Al6063 (265 MPa). However, these values occur only at isolated points rather than spreading across critical folding areas. This explains why major structural failure is highly unlikely, as deformation remains governed by plastic folding. Physically, localized overstress may trigger micro-cracks, but such phenomena are not represented in the simulation because MAT_024 does not include damage modeling. Interpretation should therefore consider this limitation. Additional empirical and numerical snapshots (Figure 8, Figure 11, Figure 13) confirm end-initiated folding in CDM and midsection initiation in FM, consistent with differences in buckling stability and energy distribution.

4. Conclusion

This study comprehensively evaluated the crashworthiness performance of a Parallel 5-Tube Circular Multi-Segment Crash Box with a Cutting Die Trigger for high-speed railway applications. The integration of a die-based folding initiator in CDM significantly improved crash performance compared to the FM, consistently reducing $F_{\max}$ while increasing EA, SEA, and F_{mean} . These improvements indicate superior deformation control and more efficient energy dissipation.

Nevertheless, the validation was conducted in a simplified manner using half-scale specimens and single-tube tests, rather than the full five-tube configuration, which limits the generalizability of the results under real dynamic conditions. Additionally, the use of thin-walled sections with $t_1 = 1$ mm may pose practical risks, such as fatigue, manufacturing deviations, and sensitivity to geometric imperfections, which were not investigated in this study but are commonly associated with thin-walled structures in real-world applications.

The main contribution of this research lies in introducing a die-triggered progressive folding

mechanism combined with multi-segment wall thickness, offering a compact and lightweight solution for crash energy management in space-constrained railway systems. These findings advance the understanding of controlled folding in thin-walled structures and provide a promising direction for future crash box designs.

Future work should include full-scale dynamic validation of the five-tube configuration, fatigue and durability assessments, optimization of multi-segment geometry with alternative materials or energy absorbers, and evaluation under multi-directional impact scenarios in accordance with EN15227 standards.

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Author's Declaration

Authors' contributions and responsibilities

Conceived and designed the experiments and 3-D modelling (M.V.H, M.A.C), Performed the experiments and Numerical simulations (M.V.H.), Analyzed and interpreted the data (M.V.H, M.A.C, A.P., W.); Wrote the original paper (M.V.H); and Wrote the revised manuscript (M.V.H, M.A.C, A.P., W).

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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