



Crashworthiness of AA6060-T4 crash boxes at different drop heights

M. Sabri ^{a,b,*}, J. Adjah ^{c,d}, R. Ichwani ^{a,e}, M. Nasution ^{a,b}, M.T.L. Gaol ^{a,b}

^a Department of Mechanical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, 20155, Indonesia

^b Computational and Experimental System Mechanics Research Centre, Department of Mechanical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, 20155, Indonesia

^c Department of Mechanical Engineering, Program in Materials Science and Engineering, Worcester Polytechnic Institute, Worcester, MA, 01609, USA

^d Department of Materials Science and Engineering, School of Engineering Sciences, College of Basic and Applied Sciences, University of Ghana, Legon, Accra, Ghana

^e Energy and Advanced Material Manufacturing (EAMM) Research Group, Faculty of Engineering, Universitas Sumatera Utara, Medan, 20155, Indonesia

* Corresponding e-mail address: m.sabri@usu.ac.id

ORCID identifier: <https://orcid.org/0009-0005-4218-034X> (M.S.);

<https://orcid.org/0000-0003-2427-6573> (J.A.); <https://orcid.org/0000-0003-2777-2601> (R.I.)

ABSTRACT

Purpose: The study investigates the crashworthiness of corrugated AA6060-T4 aluminium crash boxes under axial impact loading, focusing on the effect of drop height on their corresponding energy absorption and deformation behaviour.

Design/methodology/approach: Drop-weight impact experiments were conducted at heights of 1, 2, and 3 m to obtain force–displacement responses. In parallel, finite element simulations using ANSYS were performed to validate the experimental results. Key parameters, including mean crushing force, absorbed energy, and crush force efficiency, were evaluated. The corresponding deformation patterns from both experimental and simulations were compared.

Findings: Increasing the drop height led to higher impact velocities, resulting in greater absorbed energy, higher crushing forces, and more pronounced progressive folding patterns. The force–displacement (F-D) responses consistently exhibited an initial buckling (primary peak) stage followed by a progressive folding (plateau) stage; with the onset of densification observed only at the highest drop height (3 m), confirming the stable absorption behaviour of the AA6060-T4 crash boxes. Higher drop heights promoted larger deformation strokes and increased crush force energy, thereby enhancing overall crashworthiness performance. Numerical results show good agreement with experiments.

Research limitations/implications: The study is limited by geometric imperfections and simplified numerical assumptions. Future work should consider advanced material models and alternative structural designs.

Practical implications: The study offers important insights into how impact severity affects crash box performance and serves as a useful reference for the design and optimisation of lightweight structures for automotive applications.



Originality/value: The paper presents a combined experimental–numerical analysis of corrugated AA6060-T4 crash boxes across varying drop heights, offering new insights into crashworthy structure optimisation.

Keywords: Corrugated crash boxes, AA6060-T4, Crashworthiness, Energy absorption, Crush force efficiency

Reference to this paper should be given in the following way:

M. Sabri, J. Adjah, R. Ichwani, M. Nasution, M.T.L. Gaol, Crashworthiness of AA6060-T4 crash boxes at different drop heights, *Journal of Achievements in Materials and Manufacturing Engineering* 136/1 (2026) 5-13. DOI: <https://doi.org/10.5604/01.3001.0055.8577>

ANALYSIS AND MODELLING

1. Introduction

In the automotive industry, manufacturers compete to develop vehicles with improved performance and higher safety standards [1-3]. Consequently, crashworthiness has become a critical area of research, focusing on the design of vehicle structures that can effectively reduce occupant injury during collisions. Crashworthiness analysis primarily concerns the plastic deformation behaviour of structures subjected to collision loading and has been widely applied to critical load-bearing systems such as vehicle frames, helicopter subfloors, and highway safety barriers [4]. To manage impact energy, several vehicle components are intentionally designed as energy-absorbing structures. Among these, bumpers and crash boxes have received considerable attention in crashworthiness research due to their crucial role in dissipating collision energy [5,6].

A crash box is a thin-walled structural component, typically manufactured from metallic materials (such as high-strength steel, aluminium, magnesium, and lightweight alloys) or advanced composite materials, and mounted at the front of a vehicle [7,8]. In metallic Energy-absorbing tubes—typically made of mild steel or aluminium—energy dissipation occurs primarily through plastic deformation [9]. Its primary purpose is to absorb impact energy during a collision, thereby reducing the forces transmitted to the main vehicle structure. The crash box is expected to collapse during the crash event, thereby minimising damage to the vehicle's main frame [10]. Crash energy absorption, often referred to as impact energy absorption, is the ability of a vehicle's structural and safety systems to dissipate and manage kinetic energy during a collision. The capability is strongly governed by material selection in vehicle design, as materials exhibiting controlled, progressive deformation behaviour can significantly improve occupant protection by redistributing impact forces [11].

Numerous studies have investigated crash box structures using a wide range of approaches and design parameters. From a design perspective, previous research has examined and compared various crash box geometries, including cylindrical, square or polygonal, conical or tapered, and hat-

sectional beam, elucidating their plastic deformation mechanisms and effectiveness as energy-absorbing components [7]. Other studies have focused on the influence of geometric dimensions on crash response characteristics [12]. For instance, thick-walled structures of the crash box have attracted increasing research interest to determine whether they can provide enhanced energy absorption capabilities compared with thin-walled designs [13]. The studies reported that the crashworthiness behaviour of the double-arrowed auxetic structure is more sensitive to variations in the long-inclined beam parameters than that of the short-inclined beam. In addition, several investigations have evaluated crash box performance under different design strategies, such as the incorporation of fillers [7] and the application of hybrid and multi-cell structures [12,14]. Citra Asti Rosalia et al. [15] experimentally studied crash boxes made of pure aluminium tubular structures and aluminium tubes reinforced with glass fibre-reinforced polymer (GFRP) using drop-weight impact tests. Their results demonstrated that adding composite layers to aluminium columns enhances energy absorption capacity due to the synergistic interaction between aluminium and the composite materials. In the drop-weight impact test, increasing the drop height results in higher impact velocities, and the resulting variation in maximum impact force can therefore be directly attributed to the drop height [16].

Several studies have examined the effect of drop height in drop-weight impact tests on glass fibre (GF)–reinforced concrete beams, demonstrating that increasing drop height positively influences the total absorbed energy [17]. However, investigations into the role of drop height in crash box applications are limited. AA6060-T4 is attractive for a crash box application due to its extrudability, moderate yield strength, and energy absorption capacity. Therefore, systematic drop weight impact investigations of AA6060-T4 profiles across multiple drop weights are needed. Accordingly, this study presents combined experimental and numerical investigations of the crashworthiness of corrugated AA6060-T4 crash boxes subjected to different drop heights. Drop-weight impact experiments were conducted on the crash boxes, and finite element analysis

was employed to gain deeper insight into the crash process. The results elucidate the energy absorption behaviour and deformation mechanisms, providing valuable guidance for the future design and optimisation of high-performance crash box structures.

2. Description of the approach, work methodology, materials for research, assumptions, experiments, etc.

Crash boxes serve as absorption energy elements in vehicles by dissipating impact energy during frontal accidents; accordingly, they are mounted at the frontmost part of the body-in-white structural frame as seen in Figure 1(a). This study investigated a crash box model fabricated from commercial AA6060-T4 aluminium alloy. Data on the crash box material, aluminium alloy AA6060-T4, are summarised in Table 1. A representative crash box specimen is illustrated in Figure 1(b), while detailed geometric specifications are provided in Figure 1(c) with 85 mm in length, 55 mm in width, and 150 mm in height. For repeatability, three samples were tested for all the cases.

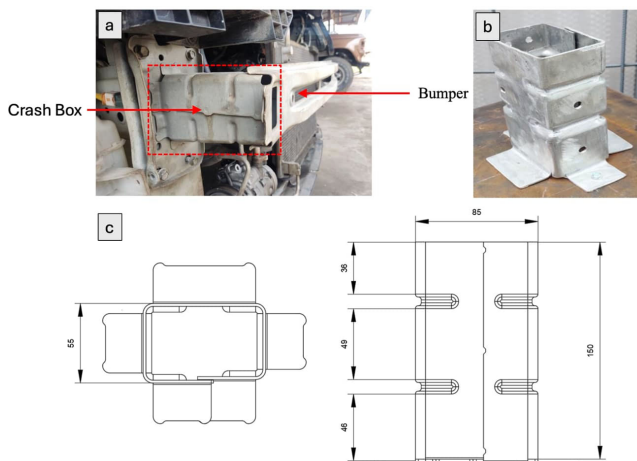


Fig. 1. (a) Crash box attached to a bumper car, (b) crash box specimen made of AA6060-T4 aluminium alloy, and (c) geometry details of the crash box specimens

Table 1.

Material properties of AA6060-T4

Material Properties, units	Values
Density, kg/m ³	2700
Young modulus, MPa	68200
Poisson's ratio	0.33
Yield strength, MPa	82
Tangent modulus, MPa	515.6
Ultimate tensile strength, MPa	500
Thickness, m	0.0015

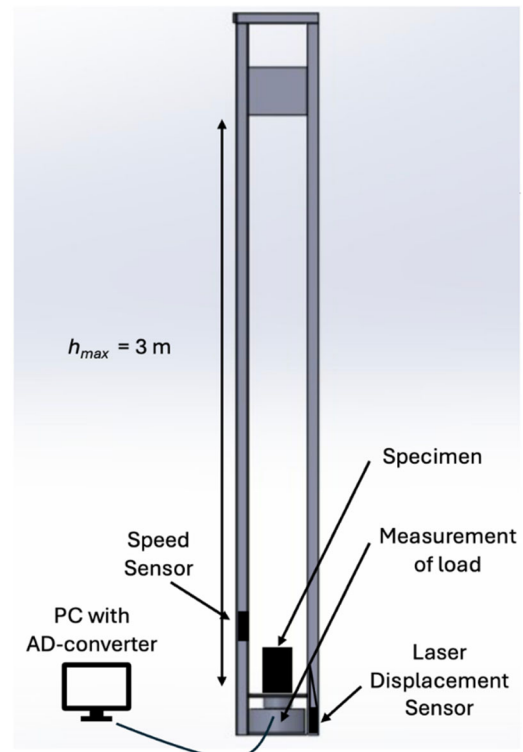


Fig. 2. Schematic of the test setup

Axial dynamic impact experiments were performed on AA6060-T4 crash box specimens using a drop-weight testing apparatus, as presented in Figure 2. In the present study, a constant impact mass of 55 kg was employed. The force and displacement (F - D) data were acquired through a PC-based data acquisition system using an AD converter. The impact force was measured using strain gauges and a laser displacement sensor, which provided the axial deformation of the boxes. The samples were mounted on the steel plate to hold the specimen during the drop-weight impact testing. Drop heights of 1, 2, and 3 m were used in this study. The initial impact energy was determined prior to the weight striking the crash box by calculating the velocity corresponding to each drop height, which was then used to compute the kinetic energy at impact. The corresponding impact velocities for drop heights of 1, 2, and 3 m were determined based on theoretical free-fall conditions, yielding values of 4.43 m/s, 6.26 m/s, and 7.67 m/s, respectively. The measured velocities from the speed sensor in the test rig for the same drop heights are 4.13 m/s, 6.12 m/s, and 7.05 m/s, respectively. The measured values are in close agreement with the theoretical predictions, with minor deviations attributed to frictional and system losses. The crash boxes were impacted under gravitational free fall; accordingly, the impact velocity at the instant of contact was obtained from $v = \sqrt{2gh}$, where $g = 9.81 \text{ m/s}^2$ and h is the

drop height. For drop heights of 1, 2, and 3 m, the corresponding impact kinetic energies are 0.54, 1.08, and 1.62 kJ for a 55 kg drop mass, respectively.

The primary parameters evaluated in this study were the mean crash force (MCF, F_m) and the absorption energy (U) that can be calculated according to the force-displacement (F - D) curve of crashing test, defined by:

$$U = \int_0^s F(x) ds \quad (1)$$

$$F_m = \frac{\int_0^s F(x) ds}{s} \quad (2)$$

where $F(x)$ is the function of the F - D curve of the crashing test, and s is the displacement resulted from the crash. The drop height was varied between 1-3 m. During the impact tests, the deformation behaviour of each crash box was continuously monitored. Each specimen was tested three times to ensure repeatability.

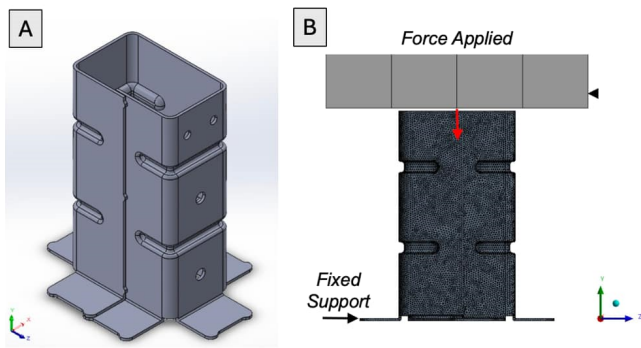


Fig. 3. (a) Crash box design, and (b) the associated meshing and boundary condition

The absorption energy and the resulted deformation patterns of crash boxes after collision were further evaluated with a software based on the finite element method (FEM) ANSYS Explicit Dynamics by bilinear isotropic hardening model. The crash box geometry was illustrated in Figure 3(a). The crash box (1.5 mm wall thickness) was meshed using linear-order solid elements with a uniform element size of 4 mm (curvature-based refinement down to 2 mm, growth rate 1.5). The impactor was modelled as a rigid body striking the crash box at a velocity of 4.13 m/s, 6.12 m/s, and 7.05 m/s, corresponding to different drop-height with a gravitational acceleration of 9.8 m/s². The procedure has been done in previous reports by Astuti et.al. [18]. The specimen was secured to the base of the test rig using a steel fixture and then subjected to axial compression loading (Fig. 3(b)). In the simulations, the impactor was dropped from various heights to evaluate the crash response. The impactor and the fixed support were modelled as a rigid body (structural

steel), while the crash box was modelled as a deformable, elasto-plastic body. Contact between the impactor and crash box was modelled using a penalty-based, frictionless contact formulation with trajectory-based contact detection. The explicit time integration used a program-controlled time step with a safety factor of 0.9, solved to an end time of 1.5 ms. A mesh convergence study, strain-rate sensitivity effects, and experimental or literature-based validation of the model were not incorporated in the current study and are acknowledged as limitations of the work.

3. Description of achieved results of own research

Axial impact tests on corrugated crash boxes of AA6060-T4 have been conducted with the various drop height. In the experimental work, the dynamic crash load and displacement (F - D) were measured to provide detailed insight into the crushing behaviour of the crash boxes under impact loading. The structural models are identical in both simulation and experimental tests. Figure 4(a) presents the representative of F - D responses of the crash box at different drop heights. The results show that there was a variation in force level with the respect to the deformation mode of the crash boxes. Upon collision, the force-displacement curves of the crash boxes generally exhibit three distinct stages: an initial buckling stage characterized by a primary peak force (F_{cr}), a plateau stage with fluctuating force associated with progressive buckling, and a densification stage [16]. In this result show that there are two main stages including initial buckling stages and a plateau stage with a pronounced densification stage was not fully developed within the available crushing stroke, its onset appearing only at the 3 m drop height. The primary peak force (F_{cr}) was increased rapidly within a short compression displacement. Higher values of F_{cr} generally indicated the improved energy absorption characteristics of crash box [19]. However, an excessively high F_{cr} is undesirable in crashworthiness applications, as it transmits larger loads and decelerations to the occupants and surrounding structure. A favourable response is therefore characterised by a high crush force efficiency ($CFE = F_m/F_{peak}$), in which the mean crushing forces approaches the peak force, rather than by a high F_{cr} alone [19]. Among the drop height tested, the F_{cr} did not increase monotonically with drop height; the 3 m drop height produced instead produced the highest mean crushing force and the highest absorbed energy of 1.294 ± 0.125 kJ.

Following the primary peak, the force then decrease as the first folding unit is completed, followed by repeated increases and decreases, resulting in a fluctuating force-displacement response until the crash test is completed. This region was identified as the secondary peak forces,

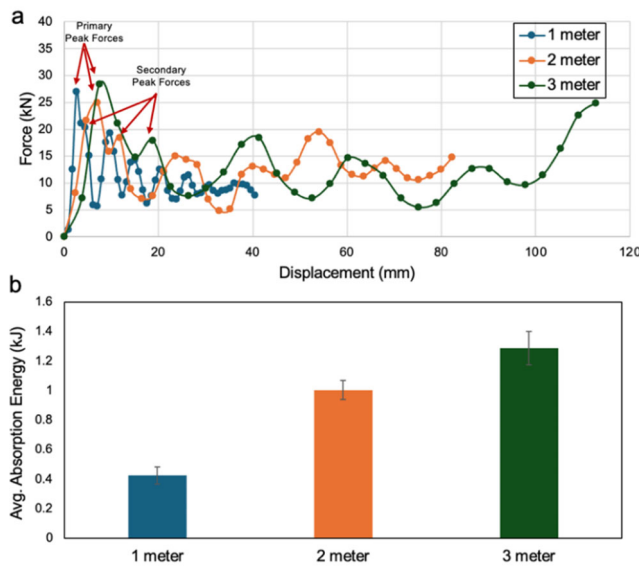


Fig. 4. (a) Force-displacement (F-D) curve for AA6060-T4 crash boxes with different drop height, and (B) the corresponding absorption energy (kJ) values

representing the continued resistance of the structure throughout the deformation process [20,21]. The higher drop height led to larger deformation strokes in the crash boxes compared to lower drop height, which in turn resulted in greater energy absorption [19]. It is consistent with the higher impact velocity supplying more kinetic energy to drive additional folding lobes and larger plastic strains per unit displacement. Because the crushing strokes differed between cases, the absorbed energies were also compared at a common crushing length and normalised through the mean crushing force (F_m) and the crush force efficiency ($CFE = F_m/F_{peak}$), so that the influence of drop height could be separated from that of stroke length. On this basis, the higher absorbed energy at larger drop height is likely to be partly attributed by the longer deformation stroke. The resulting

absorbed energy values for all drop heights are summarised in Figure 4(b) and Table 2. The crash box samples labelled (A1-A3), (B1-B3), and (C1-C3) were subjected to impact loads from drop height of 1m, 2m, and 3m, respectively.

To validate the experimental findings, the crashworthiness performance of the AA6060-T4 crash boxes was further analysed with simulation. Figure 5(a) presents force-displacement (F - D) curves for the 1, 2, and 3 m drop height cases from simulation, illustrating the crash box response under impact condition: a sharp initial peak corresponding to onset of the first plastic fold, a drop into a folding plateau, a secondary peak marking the formation of a second major fold, and a gradually rising tail as the folded walls begin to interact toward densification.

To further quantify the agreement between numerical and experimental results, four key crashworthiness parameters- peak force, average absorption energy, mean crushing force, and displacement stroke- are compared across the three drop heights in Figure 5(b-e), respectively. While the simulation results demonstrated good agreement with experimental data in terms of overall trends, a consistent underprediction of peak force and mean crushing force was observed across all drop height conditions. The discrepancy is attributed to the absence of strain-rate dependent material modelling in the finite element analysis, as higher drop heights introduce greater impact velocities that amplify dynamic strain-rate hardening effects. The discrepancies were also likely due to the geometric imperfections in specimen fabrications. The frictionless contact assumptions used in numerical approach may also underestimate the resistive forces present in the physical test, contributing to the observed underprediction in FEM simulation [19,22]. Nevertheless, the simulation successfully reproduced the progressive deformation mechanism and energy absorption trend, validating its applicability for comparative crashworthiness assessment. Overall, the findings confirm that increasing drop height positively enhances the crashworthiness performance of the crash box

Table 2.
Summary of the experimental results

Sample	Distance load-specimen in testing, m	Peak forces (F_{peak}), kN	Mean crushing force (F_m), kN	Absorption energy (U), kJ	CFE (F_m/F_{peak}), %
A1	1	28.420	11.414	0.392	40.163
A2	1	30.499	10.531	0.491	34.530
A3	1	30.291	10.732	0.390	35.429
B1	2	24.992	12.628	1.038	50.529
B2	2	23.008	12.928	1.044	56.188
B3	2	24.891	12.759	0.928	51.259
C1	3	28.4207	12.558	1.438	44.142
C2	3	29.0123	14.257	1.228	59.143
C3	3	29.134	15.237	1.216	52.299

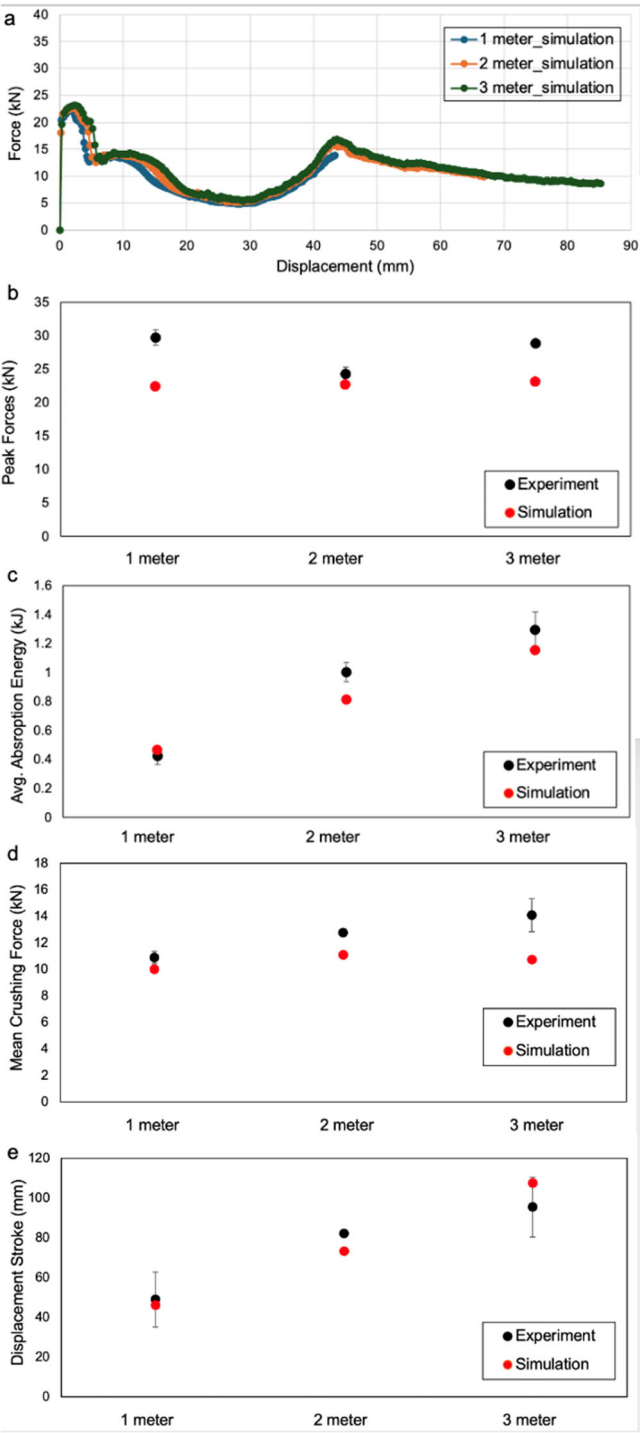


Fig. 5. (a) Force-displacement (F-D) curve for AA6060-T4 Crash Boxes with different drop height obtained from numerical simulation of finite element method (FEM). The comparison of peak force (b), absorption energy (c), mean crushing force (d), and displacement stroke (e) values between experiment and FEM

by improving energy absorption and crushing stroke, while also highlighting the necessity of incorporating strain-rate sensitivity in future numerical models to improve predictive accuracy under high-velocity impact conditions. The error metrics between experimental and simulation are introduced in Table 3.

Table 3.
Error metrics between experiment and numerical simulation

Metrics	Values, %
F peak	6.4-24.6
F mean	8.04-23.76
Absorption Energy	9.1-19.2
Displacement Stroke	5.6-12.66

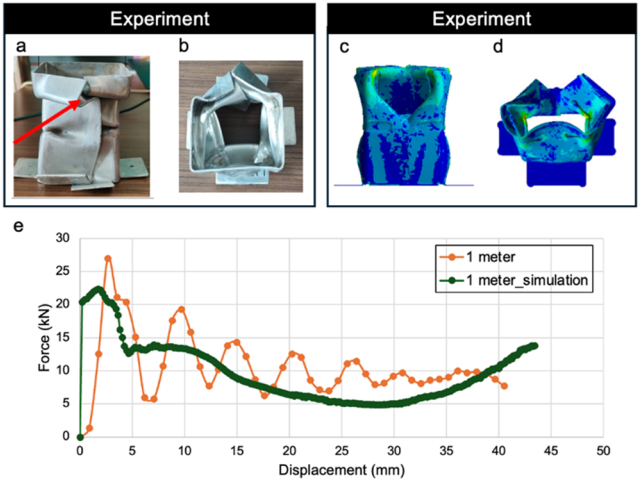


Fig. 6. Comparison between the experimental and simulation results on (a-d) deformation behaviour, and (e) force-displacement curves of AA6060-T4 crash box subjected to 1 m drop height load

The deformation pattern of AA6060-T4 crash boxes with drop height of 1 meter between experimental and simulation tests are illustrated in Figure 6(a-d). Based on the experimental result, the folds and deformation appearing in the top region which was in contact with the compactor was in the same as in the numerical simulation. Among three primary deformation patterns (axisymmetric, diamond, and mixed axisymmetric–diamond modes) of crash box [22], the deformed crash boxes under 1 meter drop height developed axisymmetric folding mode, in which lobes formed concentrically about the loading axis. The mode is favoured at lower impact velocities/energies, where the structure has sufficient time to redistribute stress symmetrically before each successive fold initiates, consistent with classical axisymmetric (concertina-type) collapse behaviour of corrugated thin-walled tubes [22]. The close agreement

between the experimental and simulated F - D curves in the primary peak region (Fig. 6(e)) confirms that the FE model correctly captures the elastic-plastic transition and the geometry-driven onset of the first fold. The slightly larger secondary-peak area in the simulation is attributed to the idealized geometry used in the FE model, which does not capture the local material and dimensional imperfections introduced during fabrication – imperfections that are known to lower the effective folding resistance in real specimens by triggering earlier or asymmetric local buckling [23].

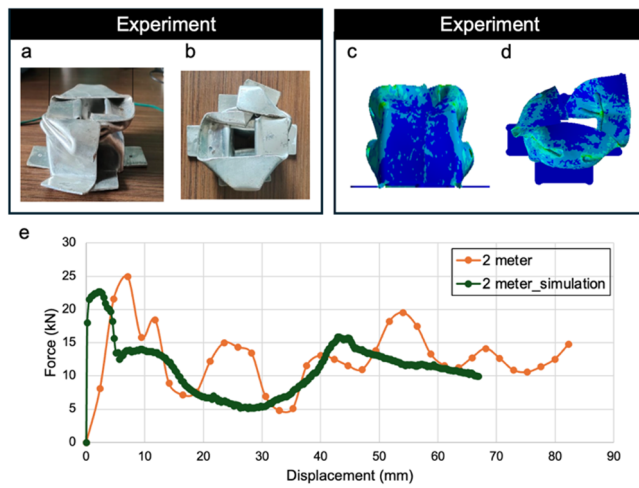


Fig. 7. Comparison between the experimental and simulation results on (a-d) deformation behaviour, and (e) force-displacement curves of AA6060-T4 crash box subjected to 2 m drop height load

Similar to the crash boxes tested at 1 m of drop height, the simulation captured well the deformation pattern of the specimen subjected to a 2 m of drop height, illustrated in Figure 7(a-d). The transition reflects the imperfection sensitivity of thin-walled corrugated structures: at higher impact energy, small initial geometric or loading imperfections are amplified more strongly during collapse, producing the buckling instability toward one side and producing a mixed axisymmetric–diamond mode rather than a uniform concertina pattern. The asymmetry is also reflected in the F - D response (Fig. 7e), where the initial peak remains well predicted by the simulation, but the experimental curve shows more localised force oscillations and an extended deformation length, consistent with the additional energy dissipated through non-uniform, localised folding rather than uniformly distributed lobes. Moreover, at the higher drop height of 3 m, greater folding-in was observed in the crashed specimen, as shown in Figure 8(a-b), which was consistent with the crush force efficiency (CFE) values reported in Table 2. CFE (F_m/F_{peak}) reflects how

uniformly the crushing force is sustained, a higher value indicating a mean crushing force closer to the peak force. Therefore, higher CFE values at higher drop height correspond to a more favourable, energy-efficient collapse mode, since a smaller gap between the peak and mean crushing force reduces the risk of a high initial force spike being transmitted to the protected structure. Overall, the numerical model shows reasonable agreement with the experiments and captures the dominant crushing and energy-absorption trends, although the quantitative discrepancies discussed above (summarised in Table 3) should be noted.

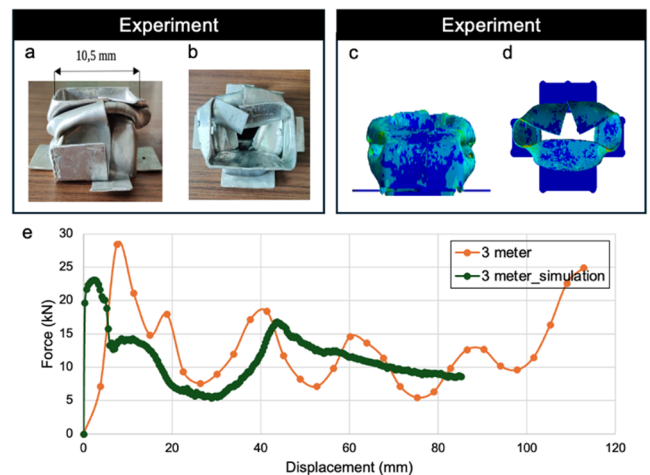


Fig. 8. Comparison between the experimental and simulation results on (a-d) deformation behaviour, and (e) force-displacement curves of AA6060-T4 crash box subjected to 3 m drop height load

4. Conclusions

The study investigated the crashworthiness behaviour of thin-walled corrugated AA6060-T4 aluminium alloy crash boxes subjected to axial impact loading at drop heights of 1, 2, and 3 m, using a combination of experimental drop-weight tests and finite element simulations. Increasing drop height increased impact velocity, with a shift from axisymmetric to asymmetric folding at higher impact severities. The force-displacement (F - D) responses shows an initial buckling stage followed by progressive folding, with densification onset only at the highest drop height and the FE model reproduced the experimental trends with reasonable but non-negligible error (6.4-24.6% in peak force, 8.0-23.8% in mean force, 9.1-19.2% in absorbed energy, 5.6-12.7% in displacement stroke), attributed to fabrication imperfections and modelling simplifications, including absence of a mesh convergence study, strain-rate effects, and broader experimental validation. The findings

provide practical guidance for the design and optimisation of corrugated crash boxes in lightweight automotive structures, while highlighting the need for refined numerical models in future work.

Acknowledgements

The authors gratefully acknowledge the support provided by the Department of Mechanical Engineering, Universitas Sumatera Utara, particularly for the computational resources utilised in the study.

Authors contribution

M. Sabri contributed to conceptualisation, data curation, and supervision; J. Adjah performed supervision of the work and validation of the overall results. R. Ichwani did formal analysis and writing – review and editing. M. Nasution and M.T.L. Gaol simulated the numerical analysis, performed the experimental investigation, and visualised the data. After all, all authors discussed the results and contributed to the final manuscript.

Research funding

This research was conducted using the authors' own resources and did not receive any external financial support.

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