# ENERGY ABSORPTION CHARACTERISTICS AND DEFORMATION PATTERNS IN FIBERGLASS FILLED CRASH BOX UNDER QUASI STATIC LOADING

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This study investigates the crashworthiness of fiberglass filled crash box under quasi-static loading by varying filler height and central hole diameter. The crash box specimens consisted of 1.8 and 2.2 mm thick aluminum tubes with an outer diameter of 76 mm, filled with fiberglass. The fiberglass fillers were prepared in four height configurations: 30 mm, 60 mm, 90 mm, and 120 mm. To investigate the effect of crush initiators, a central axial hole was drilled through the fillers in three diameters: 24 mm, 28 mm, and 32 mm. Compression tests were conducted to evaluate energy absorption (EA), and specific energy absorption (SEA). Increasing filler height improved EA from 6.39 to 36.92 kJ. Central perforations acted as buckling initiators: a 24 mm hole offered the best performance, maintaining the highest EA (23.63 kJ). In contrast, a 32 mm hole triggered early collapse, reducing energy absorption. The results show that optimal combinations of filler geometry improve both energy absorption and structural stability. These findings offer a practical, cost-efficient design strategy for lightweight, crashworthy components, with potential application in sustainable automotive structures.

**KEYWORDS**

Fiberglass filled crash box, specific energy absorption, filler height, perforation diameter, quasi static, crashworthiness

## 1 INTRODUCTION

Lightweight energy-absorbing structures play a critical role in enhancing vehicle safety while reducing fuel consumption and environmental impact. Among advanced materials used for such applications, glass-fiber-reinforced polymer (GFRP) has received considerable attention due to its high strength-to-weight ratio, corrosion resistance, and superior energy absorption capabilities compared to traditional metals such as aluminum and steel [C. A. Rosalia et al., 2020], [K. Hussain et al., 2015]. Based on the structure's ability to protect vehicle occupants in a crash, impact resistance has been developed. One such passive safety system is the crash box. To reduce energy absorption to an acceptable level, the crash box is designed [M. A. Choiron 2020]. The characteristics above make GFRP ideal for crash box applications, where absorbing impact energy and maintaining structural integrity are vital to protecting occupants during collisions. Studies have shown that crash boxes filled with GFRP offer improved energy absorption under axial loading, especially wall thickness, stacking sequence, and fiber orientation parameter are optimized [[C. A. Rosalia et al., 2020], [K. Hussain et al., 2015]. Beyond static strength, GFRP's performance across varying strain rates and its adaptability to different geometries make it a reliable alternative to metallic-only designs [K. Y. Chethana 2023]. Even sustainable fillers such as seashell powder in GFRP matrices have been proposed to maintain structural integrity while improving environmental impact [A. W. Al Zand 2021]. Comparative analyses suggest that GFRP often provides a well-balanced compromise between cost, manufacturability, and crashworthiness, particularly when compared to more expensive alternatives such as CFRP [G. Fortin et al., 2020]. Its versatility in different cross-sectional designs further supports its role in modern structural crash energy absorbers [M. Costas et al., 2017]. Despite these benefits, one of the ongoing challenges in crash box design is managing peak crushing force (PCF), which can transfer dangerously high loads to the passenger cabin if not properly mitigated. Hybrid structures that combine aluminum tubes with GFRP reinforcements have been shown to reduce PCF and enhance deformation stability under impact. Such hybrids exhibit better energy dissipation and post-peak behavior compared to monolithic tubes. Honeycomb hybrid structures, especially from the geometric cross-section, it is shown that the honeycomb-filled structure helps the folding process of the crash box, where the honeycomb structure will fill the folds of the outer wall and increases energy absorption without damaging the outer wall [S. S. A. Lykakos et al., 2021], [A. P. Kumar 2018], [Fina Andika F.A. et al., 2023]. Fiber orientation and filler geometry also influence failure modes and deformation control [J. L. Yang 2025], [V. A. Natarajan et al., 2022]. Another effective strategy is using foam or internal fillers to control buckling patterns and energy dissipation. Foam-filled tubes, for instance, show improved performance by stabilizing deformation and delaying catastrophic failure [E. Durif et al., 2007], [W. Yan et al., 2007]. The addition of a re-entrant auxetic structure significantly improves the impact resistance performance of square tubes compared to empty tubes [Arif Rochman F. et al., 2025]. Advanced configurations with double-tube systems [Y. Zhao et al., 2023] and GFRP skeletons with PET foam highlight how hybrid fillers can synergistically improve crash behavior [M. Costas et al., 2017]. In addition to fillers, engineered perforations—known as crush initiators—are used to trigger controlled folding and reduce PCF. Studies have demonstrated that strategically placed holes can lower peak forces and initiate progressive folding in thin-walled tubes [S. Subramaniyan et al., 2014], [J. Istiyanto et al., 2014], [H. Alshahrani et al., 2022]. Optimization studies also indicate that hole diameter and placement play a key role in balancing energy absorption with structural weakening [M. Hafid et al., 2023], [M. Malawat et al., 2019]. Recent research further identifies filler height as a significant factor in crash performance. Varying the length of internal fillers can influence the onset of folding, the extent of energy absorbed, and the stability of deformation. The study showed that adjusting fiberglass filler height led to substantial improvements in energy absorption [Widjanarko et al., 2025]. Other researchers support this observation through investigations using honeycomb cores, bio-composite geometries, and origami patterns [F. Geng et al., 2024], [J. H. Ang et al., 2015], [W. Zhou et al., 2023]. Despite these advances, most existing studies examine filler height and hole diameter separately. There is limited experimental data exploring the combined influence of these two parameters on crash box performance. Without such data, it is difficult to optimize crash box design holistically for both energy absorption and structural safety. This study addresses that gap by investigating the crash behavior of aluminum tubes filled with fiberglass of varying heights and central hole diameters. The goal is to determine how these two factors influence energy absorption, and deformation mechanism. Novelty lies in the combined experimental mapping of filler height and perforation size in a single design matrix, using standardized testing procedures to generate reliable data for future optimization efforts. The findings offer practical implications for lightweight vehicle crash safety systems and composite structure design.

## 2 MATERIAL AND METHODS

This study was designed to investigate the crashworthiness performance of fiberglass filled circular aluminum crash box under quasi-static axial compression, with a focus on how two parameters—filler height and central hole diameter—influence energy absorption (EA) and specific energy absorption (SEA). All testing procedures followed the ASTM D695 standard for compressive properties of rigid plastics and composites, which provides guidelines for specimen preparation, loading rate, and failure mode assessment [G. Suresh 2020], [R. F. Faidallah et al., 2025], [C. M. Miriţoiu et al., 2022]. The crash box specimens consisted of 1.8 mm thick aluminum tubes with an outer diameter of 76 mm, filled with fiberglass. The fiberglass fillers were prepared in four height configurations: 30 mm, 60 mm, 90 mm, and 120 mm. To investigate the effect of crush initiators, a central axial hole was drilled through the fillers in three diameters: 24 mm, 28 mm, and 32 mm. A baseline group with solid (non-perforated) fillers was also included. This two-factor design, which varies both internal geometry and initiator characteristics, mirrors experimental strategies employed who explored hole diameters and structural interactions in crash tubes [H. Alshahrani et al., 2022]. Sample preparation was carried out according to ASTM D695 standards. Fiberglass cores were fabricated using a resin-casting process and machined to size. Each sample was visually inspected to ensure smooth surfaces, accurate geometry, and proper fit into the aluminum tubes. The drilled holes were positioned at the longitudinal centerline, and all samples were conditioned at room temperature for 24 hours prior to testing to ensure thermal and moisture equilibrium [G. Suresh 2020]. Visual representations of the specimen configurations can be found in Figure 1 (assembled crash box), and Figure 2 (perforated fiberglass cores).

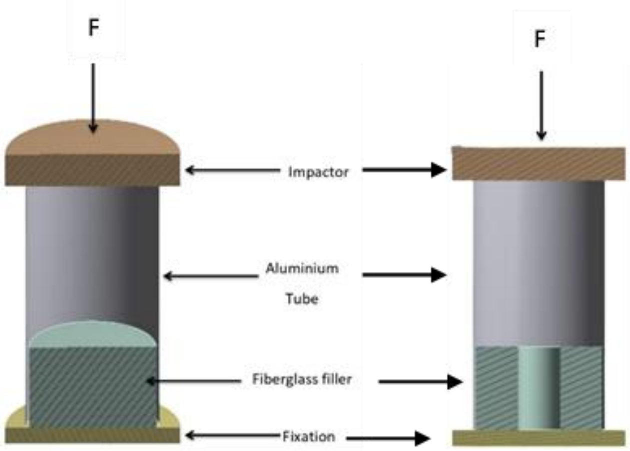


Figure 1. Fiberglass-filled circular crash box under frontal axial compression setup

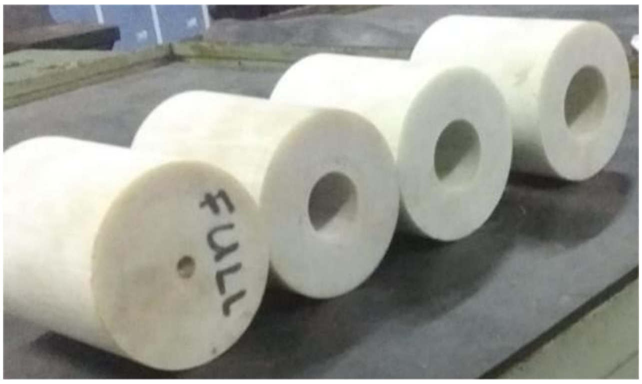


Figure 2. Fiberglass filler specimens: solid (0 mm) and with central holes of 24 mm, 28 mm, and 32 mm diameter

To verify compressive strength and consistency of the fiberglass material, reference tests were conducted using specimens prepared according to ASTM D695 geometries, shown in Figure 3. These tests provided baseline data for the compressive performance of the filler independent of the tube confinement.

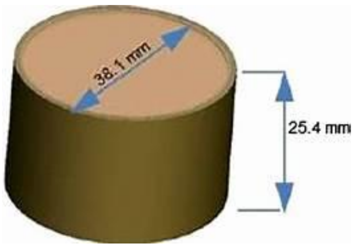


Figure 3. Standardized fiberglass specimen prepared for axial compression testing based on ASTM D695

All crash box testing was conducted using Universal Testing Machine (UTM) equipped with flat compression platens and force/displacement sensors. Figure 4 shows the full experimental setup. The tubes were compressed axially at a constant displacement rate of 10 mm/min to simulate quasi-static loading conditions in accordance with ASTM D695. The machine's fixtures ensured precise alignment to avoid stress concentrations or asymmetric deformation [ C. M. Miriţoiu et al., 2022].


Figure 4. Experimental test setup for axial compression testing using universal testing machine

Throughout the compression process, force and displacement data were recorded continuously, enabling the construction of force–displacement curves for each specimen. From these curves, key mechanical performance indicators were extracted: (i) Peak Crushing Force (PCF): the highest recorded force value. (ii) Energy Absorption (EA): the total area under the force–displacement curve up to a predefined displacement limit. (iii) Specific Energy Absorption (SEA): energy absorbed per unit mass of the specimen. The material properties of the three main components aluminum tube, fiberglass filler, and steel impactor are summarized in Table 1. The choice of 6063-T5 aluminum is based on its known strength and crash energy absorption characteristics, while the fiberglass core provides both structural integrity and damping through micro-fracture mechanisms and interfacial friction [ C. A. Rosalia et al., 2020].

*Table 1. Material Properties Aluminium, Fiberglass Filler and Impactor*

| Material | Density (kg/m³) | Yield Strength (MPa) | Modulus of Elasticity (GPa) |
|---|---|---|---|
| A 6063-T5 | 2700 | 180 | 68 |
| Fiberglass Filler | 2000 | 230 | 72 |
| Steel Impactor | 7850 | 350 | 200 |

Failure modes were documented and examined for each specimen. Observations focused on deformation sequences such as progressive folding, local buckling, shear cracking, and filler damage. This qualitative analysis provided further insight into the interaction between filler geometry and deformation behavior under compressive loads. Specimens with 24 mm central holes exhibited more controlled and uniform folding patterns compared to those with larger holes, which aligns with the findings of Hafid et al. (2023) on optimal hole geometry for crush initiators [ H. Alshahrani et al., 2022].

## 3 RESULT

The effect of filler height is illustrated in Figures 5–8, showing the axial response of crash boxes with 30, 60, 90, and 120 mm fiberglass filled, respectively. Figure 9 compares these responses on a common axis. In all cases, a linear elastic–plastic segment precedes a distinct peak, followed by progressive folding. Both peak crushing force (PCF) which appears during the pressing process on the fiberglass filled and the plateau shape show a clear dependence on filler length. At 30 mm (Figure 5), the PCF peaked sharply at 237 kN before rapidly dropping, with deformation concentrated near the tube mouth. This localized collapse aligns with Kocabaş et al., who reported that short fillers lead to early, unstable buckling [T. Khan et al., 2023]. The energy absorption (EA) reached 6.39 kJ. Doubling the filler height to 60 mm (Figure 6) increase PCF to 840 kN and produced a flatter plateau, with folding shifting deeper into the tube. EA increased to 9.94 kJ, consistent with findings by Yi et al. on enhanced energy distribution with longer cores [X. Yi et al., 2024].

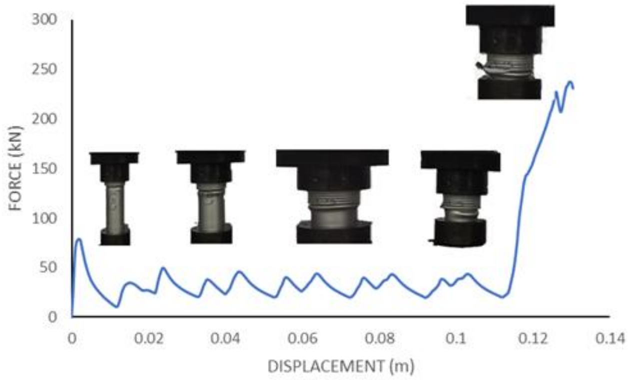


Figure 5. Load–displacement curve for 30 mm fiberglass filler height

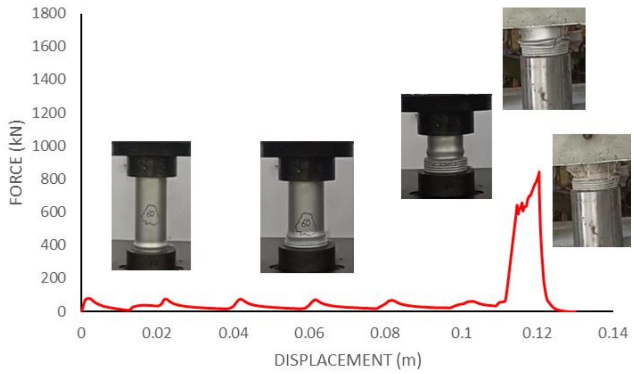


Figure 6. Load–displacement curve for 60 mm fiberglass filler height

At 90 mm (Figure 7), a smoother plateau and symmetric folds emerged, appearing PCF to 1434 kN and increasing EA to 27.95 kJ. The behavior supports Costas et al.'s view of the filler acting as an elastic foundation [G. Fortin et al., 2020]. With the tallest insert (120 mm, Figure 8), PCF further increased to 1573 kN, and SEA peaked at 31.90 kJ/kg. Six uniform lobes formed, indicating improved stability and energy dissipation [Y. Zhao et al., 2023], [F. Wu et al., 2019].

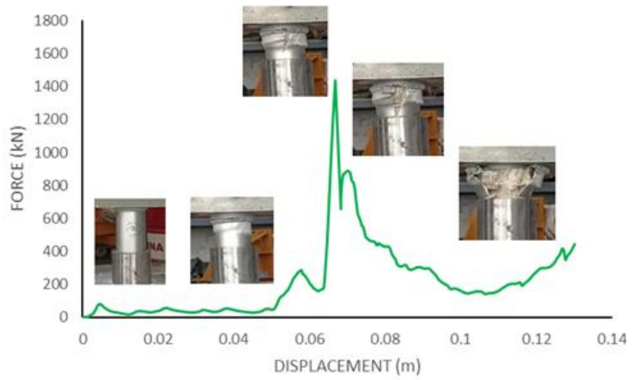


Figure 7. Load–displacement curve for 90 mm fiberglass filler height

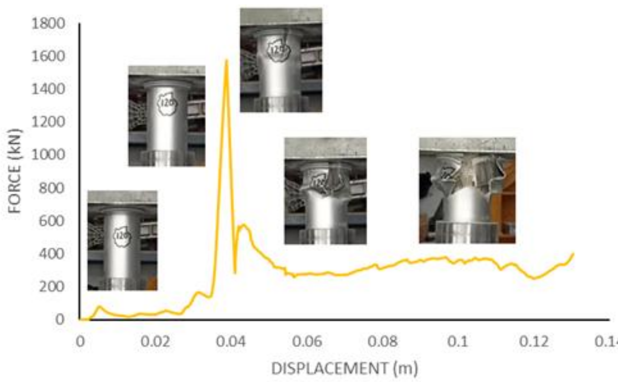


Figure 8. Load–displacement curve for 120 mm fiberglass filler height

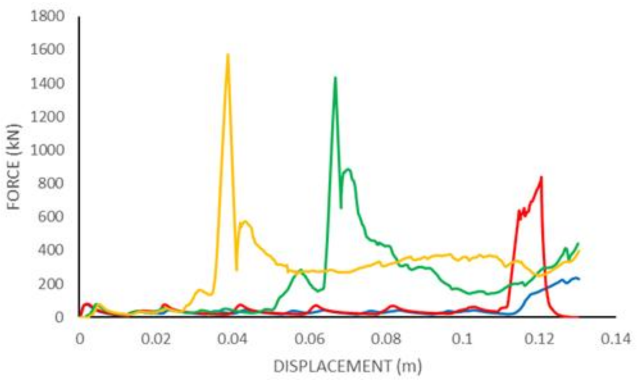


Figure 9. Comparison of load–displacement curves for all filler heights

Increasing the core length progressively uppers the peak-crushing force (PCF) from about 237 kN at 30 mm to roughly 1573 kN at 120 mm while simultaneously flattening the post-peak plateau. The corresponding energy absorption (EA), calculated to 120 mm stroke, rises from 6.39 to 36.92 kJ. Visual inspection showed that short inserts triggered a single, localized buckle near the tube mouth, whereas tall inserts promoted five- to six-lobed progressive folding that engaged the full tube length. These tendencies concur with earlier reports that longer fillers spread axial load, reduce buckling wavelength and lift overall energy uptake [M. Costas et al., 2017], [T. Khan et al., 2023], [X. Yi et al., 2024]. The second experimental series introduced circular holes of 24 mm, 28 mm, and 32 mm through a constant-height 80 mm filler, an un-perforated control supplemented the set. Figures 10–14 display individual load–displacement histories, and Figure 15 overlays the curves to visualize perforation effects. The solid-core baseline in Figure 10 delivered the highest peak force, approximately 1375 kN, consistent with the behavior described above for 90 mm fillers. Although the energy absorbed reached 22.72 kJ, post-peak oscillations were visible, signaling occasional slip between the filler and tube wall.

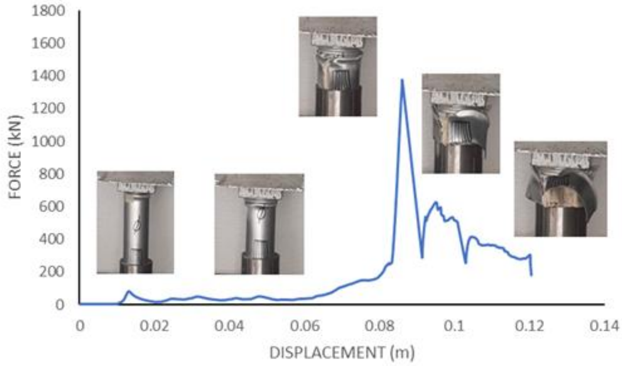


Figure 10. Load–displacement curve for solid filler (0 mm hole)

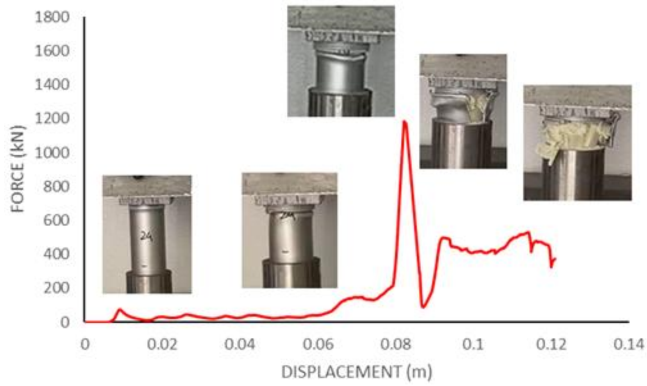


Figure 11. Load–displacement curve for 24 mm hole diameter

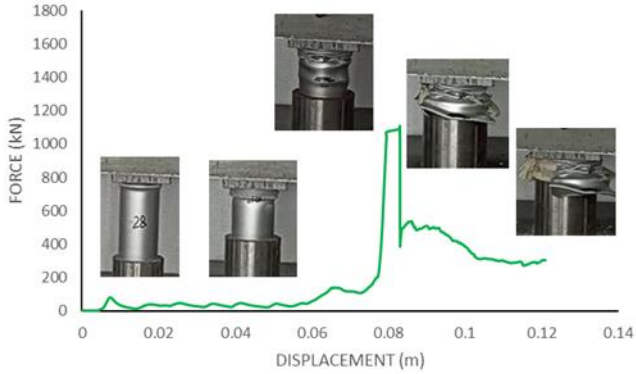


Figure 12. Load–displacement curve for 28 mm hole diameter

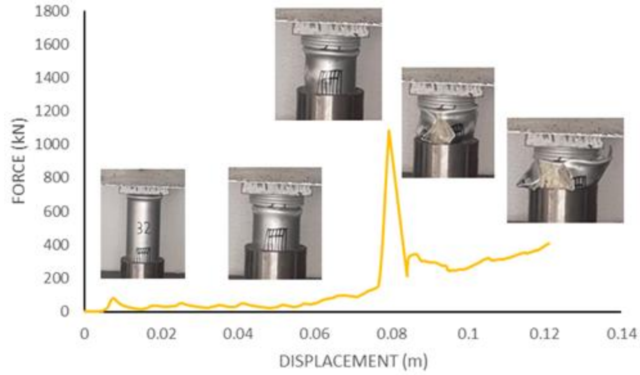


Figure 13. Load–displacement curve for 32 mm hole diameter

Introducing a 24 mm hole (Figure 11) reduced the peak force to 1184 kN and produced a smoother plateau. The hole acted as a stress concentrator, initiating folding around its edge, in line with Rogala & Gajewski's findings on localized buckling [M. Rogala et al., 2023]. EA increased slightly to 23.63 kJ, indicating improved energy distribution despite a minor strength reduction. The response was consistent and progressive, confirming Jahani et al.'s findings that optimally sized perforations enhance folding regularity and post-peak stability [M. Jahani et al., 2019]. At 28 mm (Figure 12), the performance was observed. Peak force dropped to 1108 kN—20% below the control—while the plateau remained stable, yielding lower EA of 23.47 kJ. Five uniform folds formed outward from the hole, demonstrating effective collapse control. In contrast, the 32 mm hole (Figure 13) further reduced peak force to 1080 kN but compromised energy absorption (EA: 19.49 kJ) due to early shear failure and unstable lateral deformation, consistent with observations by Istiyanto et al. and Jeffery [J. Istiyanto et al., 2014], [J. B. Jeffery 2020].

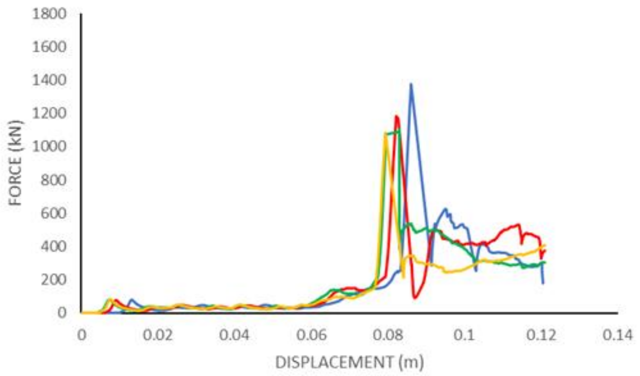


Figure 14. Comparative load–displacement curves for all hole diameters

Figure 14 compares all cases, showing a shift from peak-force control to energy-absorption optimization, with the 24 mm hole offering the most efficient balance. This parabolic trend supports Fan et al.'s trade-off curve between EA and structural integrity [D. Fan et al., 2021]. Table 2 presents the quantitative crash performance metrics, while Table 3 provides a qualitative summary of folding patterns, buckling initiation, and deformation stability across the tested hole diameters.

*Table 2. Comparison of Crash Test Characteristics for Fiberglass-Filled Tubes with Varying Hole Diameters*

| Hole Dia. (mm) | PCF (kN) | EA (kJ) | SEA (kJ/kg) |
|---|---|---|---|
| 0 (solid) | 1135 | 22.72 | 28.62 |
| 24 | 1184 | 23.63 | 41.91 |
| 28 | 1108 | 23.47 | 48.84 |
| 32 | 1080 | 19.49 | 50.68 |

*Table 3. Qualitative Analysis of Energy Absorption Performance for Varying Hole Diameters in Fiberglass-Filled Tubes*

| Hole Dia. (mm) | Folding Pattern | Buckling Initiation Zone | Deformation Stability |
|---|---|---|---|
| 0 (solid) | Irregular, early folding | Uncontrolled | Low stability |
| 24 | Regular, progressive folds | Controlled initiation | High folding stability |
| 28 | Semiregular folding | Central region | Moderate stability |
| 32 | Early collapse, unstable | Weak initiation | Low stability, lateral deformation |

The data align with previous findings that intermediate perforations trigger stable, energy-efficient collapse, whereas undersized holes delay buckling and oversized holes erode load-bearing area [J. Istiyanto et al., 2014], [M. Jahani et al., 2019]. The sequential process of the axial compression test for deformation stability and the optimal energy absorption (EA) potential observed in the 24 mm hole configuration is illustrated in Figure 15.

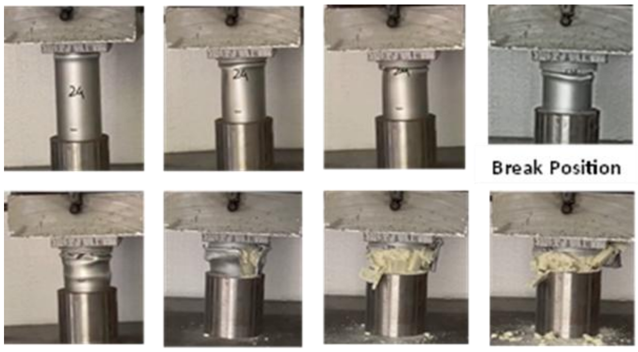


Figure 15. Sequence of deformation during axial compression for the fiberglass-filled tube with a 24 mm central hole

Taken together, the results show that (i) taller fillers mitigate initial force spikes while expanding energy-absorption capacity, and (ii) a mid-range hole diameter (24 mm) provides an effective geometric trigger that further suppresses PCF and regularizes folding without sacrificing EA. The results of the PCF and CFE values from the tests that have been carried out are presented in Table 4.

*Table 4. PCF and CFE test values*

| Hole Dia. (mm) | EA (kJ) | SEA (kJ/kg) | PCF (kN) | CFE (%) |
|---|---|---|---|---|
| 0 | 22.72 | 28.62 | 1.375 | 20.52 |
| 24 | 23.63 | 41.91 | 1.184 | 25.72 |
| 28 | 23.47 | 48.84 | 1.108 | 29.53 |
| 32 | 19.49 | 50.68 | 1.080 | 25.71 |

The results shown in Table 4, for the highest EA on the hole diameter of 24 mm, the highest SEA on the hole diameter of 32 mm and the highest CFE on the hole diameter of 28 mm. The results also show that the basic crashworthiness parameters: EA, SEA, PCF, and CFE were tested using quasi-static due to easier to control and do not require expensive equipment, making them more accessible for initial testing phases. Quasi-static testing is defined by a constant low-speed application, making it cost-effective and easier to control [A. Othman et al., 2014]. There's no additional equipment is used to hold the tube specimen between the fixed and moving plates in the quasi-static test, which allows the analysis of the mechanical behavior and failure modes of the structure with a simpler and more controlled experimental procedure than complex and expensive dynamic tests [M. Emin Erdin et al, 2016]. This method is crucial for understanding energy absorption in crashworthy structures. Other study investigates the impact resistance of crash box structure under multi-load conditions using the Explicit finite element model and validated by quasi-static tests [Ran H. et al., 2025]. However, it cannot completely replace dynamic testing due to the significant effects of strain rate and inertia under actual crash conditions. For real-world applications, quasi-static results must be corrected or retested under impact test conditions as the future study.

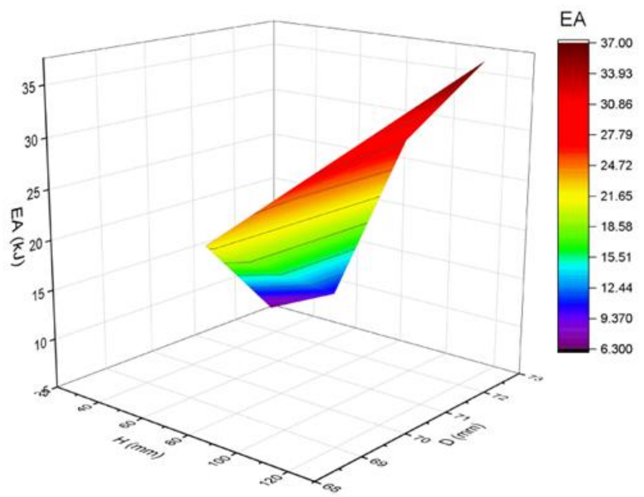


Figure 16. The effects of foam diameter and foam height on the EA

Figure 16 illustrates EA for the crash box, analyzing the effects of foam diameter, foam height and hole foam diameter. The highest EA values occur at specific parameter combinations, marked by the dark red regions. The color scale on the right indicates EA values in kJ, increasing progressively from the lowest (purple) to the highest (dark red).

## 4 DISCUSSION

This study confirms that adjusting filler height and central hole diameter significantly affects the crash performance of fiberglass-filled aluminum tubes. Each parameter contributes to different aspects of the crushing process—filler height influences energy absorption capacity and deformation stability, while hole diameter controls the onset of buckling and peak load reduction 1375 kN, 1184 kN, 1108 kN, 1080 kN. Increasing filler height from 30 mm to 120 mm higher the peak crushing force from 237 kN to 1573 kN and improved EA from 6.39 to 36.92 kJ. These results align with Kocabaş et al., who reported that longer fillers distribute axial load more evenly and reduce localized force spikes [T. Khan et al., 2023]. The more progressive folding and higher EA observed at greater heights support findings by Yi et al. and Costas et al., who highlighted the role of internal cores in stabilizing folding and enhancing energy absorption [M. Costas et al., 2017], [X. Yi et al., 2024]. The stable multi-lobe patterns also suggest improved crush reliability, important for structural predictability in real-world applications. Hole diameter played a distinct role. A 24 mm perforation yielded the best balance—reducing peak force to 1184 kN and achieving the highest EA at 23.63 kJ. This supports studies by Jahani et al. and Rogala & Gajewski, which showed that well-sized holes can initiate controlled buckling and enhance deformation regularity [30], [31]. In contrast, oversized holes (32 mm) weakened structural integrity, leading to early collapse and lower EA, consistent with findings by Istiyanto et al. and Jeffery [16], [J. B. Jeffery 2020]. Together, these results show that optimal crashworthiness depends on the synergy between filler height and hole size. The 90–120 mm filler range combined with a 24 mm hole appears most effective for managing both peak loads and energy absorption. These findings align with multi-objective optimization principles in crash box design, as shown by Prasad et al. and Zha et al., who focused on balancing force minimization and energy maximization [G. Prasad et al., 2021], [Y. Zha et al., 2022]. Material selection remains important. While fiberglass offers superior EA and stable deformation, its recyclability is limited. Polymer foams are lighter and more recyclable, but may lack the mechanical consistency of fiberglass [A. Othman et al., 2014], [F. Mischo et al., 2020]. Hybrid designs, combining both materials, offer potential for improved performance and sustainability [A. Baroutaji et al., 2017], [J. Song et al., 2024]. The current tests were conducted under quasi-static conditions. However, high-speed studies indicate that loading rate affects collapse behaviour. Fortin et al. and Junchuan & Thinvongpituk observed different failure mechanisms at dynamic speeds, including fibre fracture and unstable folding [G. Fortin et al., 2020], [V. Junchuan et al., 2020]. Despite this, Lykakos et al. found that the ranking of trigger performance remains consistent under dynamic conditions, suggesting that the 24 mm hole remains valid as an optimized feature [S. S. A. Lykakos et al., 2021]. This study also contributes valuable experimental data for computational modelling and optimization efforts. The interaction between filler geometry and buckling response provides a foundation for future finite element and machine-learning-based crash simulations. Moreover, future work should explore additional design factors such as tube wall thickness, fiber orientation, and thermoplastic matrices, which could enhance both structural performance and end-of-life recyclability.

## 5 CONCLUSION

The study confirms that filler height and hole diameter significantly influence the crash performance of fiberglass filled aluminium crash box. Longer fillers increase peak crushing force and improve energy absorption by promoting stable, progressive folding. A 24 mm central hole provides an effective geometric trigger, lowering peak force without compromising energy capacity. The combination of taller fillers and mid-sized perforations offers optimal crashworthiness, balancing load reduction and energy efficiency. These results align with current multi-objective optimization trends and contribute new experimental insights to the design of hybrid crash tubes. Additionally, fiberglass composites deliver reliable energy absorption, though future integration with recyclable thermoplastics may enhance sustainability. Further research is recommended under dynamic loading conditions and with alternative geometries to validate these findings for real-world applications.

## ACKNOWLEDMENTS

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