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Effect of Adding a Trigger Hole and Cross-Section Foam on the Crash Box in Energy Absorption

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Abstract

While the optimization of crash box geometries for passive safety has been extensively explored, there remains a critical need to evaluate the synergy between complex cross-sectional geometries and specific perforation patterns under both experimental and numerical frameworks. Most existing studies focus on single-geometry performance or idealized simulations. This study addresses this gap by conducting a comprehensive comparative analysis of square, hexagonal, and circular aluminum AA 6061-T4 crash boxes featuring strategic hole modifications, with manufacturing processes including cutting, marking, bending, and TIG welding. Results show that the two-hole hexagonal crash box has the highest energy absorption: 33.05 kJ experimentally and 29.49 kJ in simulation, indicating significantly improved crashworthiness.

Keywords: Crash box; frusta model; Trigger Circle; Cross Section

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1.0 Introduction

The main function of the crash box is to absorb kinetic energy during a collision. Apart from that, the crash box is also designed as a passive protector for the vehicle, safeguarding the main structure from fatal damage (Ma & Xie, 2020). In recent years, the number of passenger vehicle accidents worldwide has increased. This has raised concerns and led to increased development of crash boxes as a passive passenger protection measure. Crash boxes are designed to reduce the damage and pressure caused by other components within the vehicle (Evans et al., 2023). In this research, the innovation consisted of combining a frusta-shaped crash box model with a cross-section plate filling and a circular trigger anchor on the crash box body. The method used to determine the crash box's ability to absorb energy during a collision is to analyse the finite element model in Abaqus software and to conduct compression testing using a universal testing machine.

The crash box with the trigger circle innovation is expected to increase its ability to absorb energy and distribute the load evenly. This is also the key to uncovering deformation phenomena that occur during a collision.

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Looking at previous research on single-cell and multi-cell crash box designs, it can be seen that the multi-cell design better absorbs energy during impact and has a lower maximum force (Noorfizir, 2019). The advantage of the multi-cell design is that the crash box can produce gradual deformation and spread the impact load throughout the cells, thereby increasing its ability to absorb energy (Doko et al., 2020). Looking at the shape.

2.0 Literature Review

2.1 Introduction

Several basic theories will be presented that are directly related to efforts to increase energy absorption in the event of an accident. This part presents the characteristics of collisions in vehicles, the types of accidents in passenger-type cars, and the structural requirements for selecting good materials (Fig. 1). The transportation system is one of the essential needs in life in this modern age. On the other hand, the increasing need will also increase vehicle production, which, in turn, will indirectly contribute to increased accidents. Reviewing these, vehicle safety standards need improvement; one is the crash box.

Usta et al. (2021) highlighted that existing crash box designs often face limitations, such as insufficient energy absorption or inadequate control over deformation. These challenges pose risks to both the vehicle and its occupants in real-world crash scenarios. The research aims to explore more efficient crash box designs, focusing on improving their performance to better absorb impact energy, reduce stress concentrations, and enhance overall vehicle safety during collisions (Usta et al., 2021).

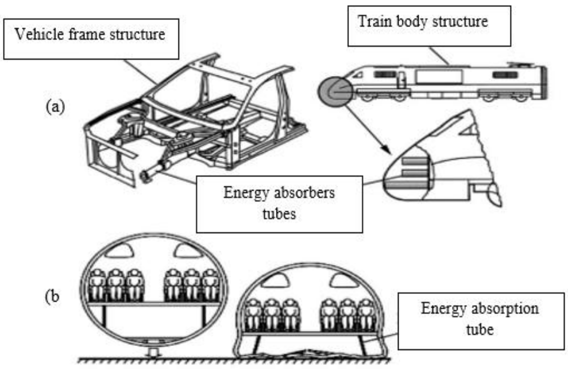


Fig.1. The passive security systems applied in various modes of transportation, consisting of two main sections: (a) trains and cars, and (b) airplanes.

Passive security refers to measures designed to reduce the risk of injury or damage during accidents or incidents, without requiring active action from the driver or passengers. Hou et al. (2021) conducted a study using a quasi-static disclosure test method to examine the collapse process of AA6061-Aluminium alloy sandwich columns. The good correlation between experimental tests and numerical analysis confirms the accuracy of the finite element model for the sandwich column. Following this, numerical tests were performed on the sandwich column and related components under static impact loading. The findings indicate that the interaction between the sandwich column and its components significantly enhances its energy absorption. Additionally, the geometric characteristics of the sandwich column further influence its crashworthiness. As a result, this research offers a new approach to designing thin-walled structures with high energy absorption capabilities.

2.2 Crash Characteristics

Crashworthiness is an engineering term referring to a vehicle's ability to protect its occupants during a collision. This concept is not limited to automobiles; it also applies to other modes of transportation, such as ships, planes, and trains. The first detailed, scientific study of crashworthiness took place between 1879 and 1890, focusing on railway axles. Essentially, crashworthiness involves enhancing a structure's ability to perform in crashes by allowing it to absorb impact, thereby protecting occupants from harm (Rasouli et al., 2011). To enhance structural design for crashworthiness, it is crucial to understand the various factors that influence the crash process (Frank et al., 2021). Crashworthiness problems can be characterized. The development of modern vehicle safety structures must address several critical parameters to ensure occupant protection. Current design trends prioritize displacement and energy efficiency, focusing on shortening the frontal structure's length while maximizing impact energy absorption to prevent compartment penetration.

Furthermore, managing the crash pulse is essential to minimize deceleration-induced injuries, particularly to the brain, as measured by the Head Injury Criterion (HIC) thresholds. Structural resilience must also be maintained across various crash positions, including full-frontal, offset, side, and rear impacts, to minimize fatalities in diverse accident scenarios. Finally, automobile compatibility remains a vital consideration, ensuring that the safety structure effectively reduces injuries during collisions between vehicles of varying sizes and weights.

2.3 Material

AA 6061-T4 is a versatile material that can be used in a wide range of applications due to its availability in various forms, including sheets, plates, bars, tubes, and extrusions (Kathiresan, 2020). The considerations for choosing this material are its resistance to corrosion, low weight, and ease of fabrication. These are the advantages of aluminium, which is why it is often used in the automotive and aerospace industries, as shown in Table 1 below (Abdullahi & Gao, 2020).

Table 1: Mechanical characteristics AA 6061-T4

Parameter	**Value**
Density	2.7 kg/mm^3
Poisson's ratio	0.33
Ultimate Stress	171 MPa
Yield Stress	82 MPa
Flow Stress	126.5 MPa
Young's Modulus (E)	68.2 GPa

From this data, it can be seen that the material has quite good ductility, making it easy to carve into complex shapes without breaking. In terms of fabrication, Al is also very easy to work with, allowing for straightforward cutting, drilling, and shaping with standard machining methods. The joining process can also be carried out using various welding methods, including TIG, MIG, and gas welding (Jahuddin, 2023).

The initial treatment process is important to prevent cracks from forming during material formation. As stated above, this material is widely used in the maritime world due to its ability to resist corrosion under various conditions, including saltwater (Shaikh, 2019). Another aluminium alloy commonly used for automotive applications, such as bicycle frames, spare parts, electrical connections, and various structural elements of buildings and bridges, is AA 7075. This material is also used to produce sports equipment, cell phone casings, and computer components (M. Sabri and Otniel Wahana Christian Simanjuntak 2023).

3.0 Methodology

3.1 Finite Element Method (FEM)

This crash box modelling analysis uses Abaqus, a finite-element-based software package (Fig. 2). The impactor and solid portions are treated as rigid bodies. In contrast, the crash box is treated as a malleable body. The model is three-dimensional, with the impact travelling along the Z-axis at a predetermined rate. This movement results in a change in plastic deformation, which is subsequently considered energy absorption (F.E. Modelling) (Lestari et al., 2024).

In general, energy absorption (EA) of car components is the energy absorbed during the impact process and may be analytically determined as.

$$EA\,(d) = \int_0^d f(x)dx \tag{1}$$

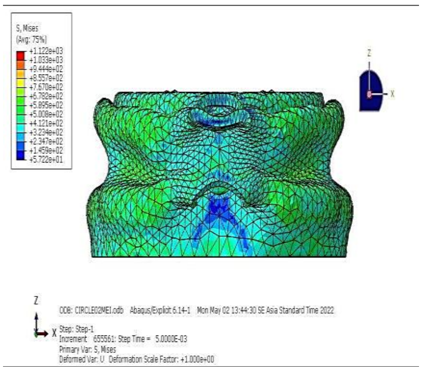


Fig.2. Simulated Deformation Modes Using Abaqus Software

where SEA is the energy absorption per unit mass, and F is the impact load by the displacement function

$$SEA(d) = \frac{EA(d)}{m} = \frac{\int_0^d f(x)dx}{m} \tag{2}$$

M denotes the mass of the part. As a result, the SEA function shows the energy absorption efficiency value of the object under study. The higher the KLHS value, the better the efficiency. The average impact force ($Fmcf$) is the second indicator; EA is calculated by dividing it by the related deformation displacement (φ).

$$MCF = \frac{EA(d)}{d} = \frac{\int_0^d f(x)\,dx}{d} \tag{3}$$

CFE is calculated as Fmcf divided by F$peak$, which is the highest force during the global collision process, and the CFE is provided as,

$$CEF = \frac{MCF}{PCF} \tag{5}$$

The structural model of the crash box is purely surface-based because it is believed to be a thin plate with solid walls. An assembly is needed to model the crash box structure, as it is assembled separately. After modelling the crash box construction in SolidWorks software, the model file is saved in CAE format and then loaded into the analysis software (Abaqus) for numerical simulation purposes (Oh, Hong, and Choi 2023).

Table 2: Result of FEM (EA, Error, CFE, and SEA)

Specimen Model	Hole Config.	Exp. Energy (Eabs) (kJ)	Sim. Energy (Eabs) (kJ)	Error (%)	CFE (%)	SEA (kJ/kg)
Hexagonal	**2 Holes**	**33.05**	**29.49**	**10.7**	**82.5**	**45.2**
Hexagonal	1 Hole	30.12	27.55	8.5	78.2	41.5
Hexagonal	0 Hole	27.45	25.10	8.6	72.1	37.8
Square	2 Holes	28.90	26.30	9.0	75.4	39.6
Square	1 Hole	26.50	24.15	8.8	71.0	36.3
Square	0 Hole	24.10	22.05	8.5	65.5	33.1
Circular	2 Holes	25.40	23.20	8.6	68.2	34.8
Circular	1 Hole	23.20	21.40	7.7	64.1	31.9
Circular	0 Hole	21.05	19.50	7.3	58.7	28.9

The next step, carried out after testing the simulation of the crash box model in Abaqus, was to create and analyse a comparison of force and displacement and to assess the resulting energy absorption. The simulation lasted 0.005 seconds and utilised identical parameters for all models (Sobowale et al., 2023). The ABAQUS simulation results from this work are presented below for three different crash box forms and hole types.

3.2 Experimental Work

The design of the Frusta crash box was the first step in this research. The selection of trigger holes was strategically determined to initiate consistent plastic hinge formation, ensuring a controlled progressive buckling mode rather than global instability (Euler buckling). The dimensions were optimized to reduce the Peak Crushing Force (PCF) while maintaining structural integrity during the initial impact stage. Then, the design was applied to the manufacturing and testing processes using a 1000 kN Universal Testing Machine, as shown in Fig. 3.

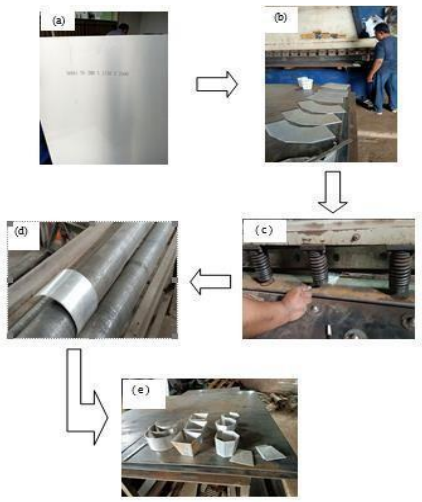


Fig. 3 Manufacture and Experimental Work (a) plate AA 6061-T4, (b) cutting process, (c) pin process, (d) rolling process, (e) finishing process.

Fig 3 shows the crash box manufacturing process. The process begins by cutting AA 6061-T4 aluminium and creating a trigger hole in the crash box shaft. Next, bending is performed to achieve the desired shape as per the design. The final step is welding to join the components; TIG welding is used for the crash box. The unique feature of the crash box model in this research design is its frustum shape, with a cross-section featuring various trigger holes. In this study, nine crash box specimens were created, each with a different number of trigger holes. The first model is a circular frustum, the second is a hexagonal frustum, and the third is a square frustum (Bhuyan et al., 2024).

The material used in the manufacturing process of the frusta crash box in this study is Aluminum AA 6061-T4. The use of aluminium in crash box fabrication is due to its beneficial properties in energy absorption and structural strength. Aluminium is a lightweight material that benefits crash boxes by reducing the vehicle's overall weight, improving fuel efficiency and lowering emissions. Aluminium is corrosion-resistant, making it a durable material for crash boxes that may be exposed to moisture or other corrosive substances. Aluminium materials can be formed into complex geometries and structures using techniques such as welding, which allows crash box manufacturers to increase energy absorption (Jonsson & Kajberg, 2023).

The frusta crash box formed during fabrication is then tested through compressive testing. The following is the use of a Shimadzu 1000 kN *Universal Testing Machine* (UTM) analysis machine with a capacity and speed of 5 mm / s according to the *American Society for Testing and Materials* (ASTM) E9-19 Standard Test Methods of Compression Testing (Kosedag, 2023).

Compressive analysis aims to illustrate what happens in the real world when an impact occurs. Compressive analysis is frequently used to examine the mechanical properties of crash box materials. This test measures the modulus of elasticity, compressive strength, and material deformation. Using these characteristics, the energy absorption value can be calculated. This test employs nine specimens with three circular, three hexagonal, and three square models, along with variations in the number of triggers (Thiyagarajan & Kumar, 2022).

Table 2: Results of Experimental (Displ, PCF, and EA)

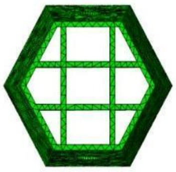
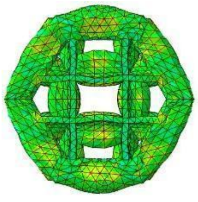
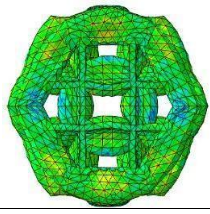
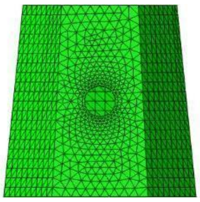
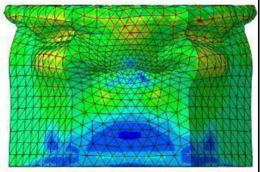
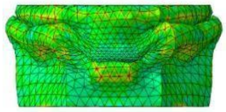
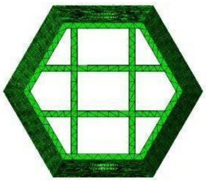
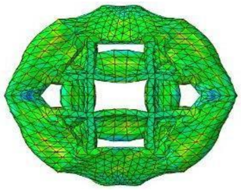
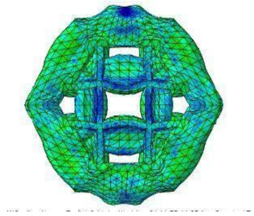
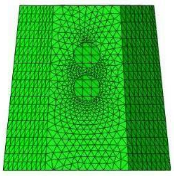
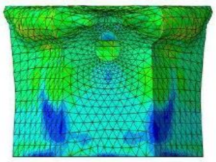
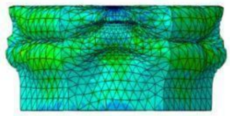
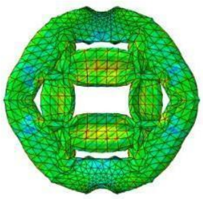
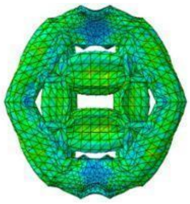
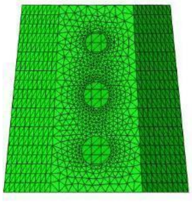
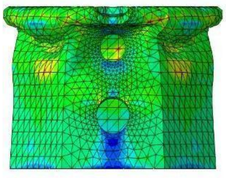
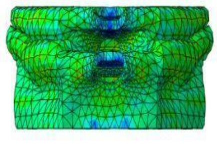
Specimen Geometry	No. of Trigger Holes	Max. Displacement (mm)	Peak Crushing Force (kN)	Energy Absorption (Eabs) (kJ)	Observed Deformation Mode
Hexagonal	**2**	**120.5**	**274.3**	**33.05**	**Progressive Buckling**
Hexagonal	1	118.2	295.1	30.12	Progressive Buckling
Hexagonal	0	115.4	340.8	27.45	Mixed Mode
Square	2	110.3	262.5	28.90	Progressive Buckling
Square	1	108.7	288.4	26.50	Progressive Buckling
Square	0	105.2	325.6	24.10	Global Buckling
Circular	2	112.4	225.8	25.40	Progressive Buckling
Circular	1	110.1	245.2	23.20	Mixed Mode
Circular	0	107.5	280.9	21.05	Global Buckling

4.0 Discussions

4.1 Finite Element Method

The circular model crash box experiences maximum deformation, as shown in picture d above. The buckling shown in the picture occurs at 0.001 seconds. Then, at 0.0025 seconds, the square model experiences the least amount of bending, namely one bend, whereas there are two bends in the other two types. At 0.005 seconds, the square model bends only twice, the hexagon model bends three times, and the circular model bends three times, with deformation occurring in between (Table 4).

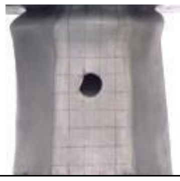
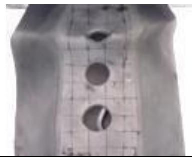
Table 4: Simulation Test Result

	D		**0**	**20 mm**	**60 mm**
Crash Box Models	Top View	Hexagon 1 Hole			
	Front View				
	Top View	Hexagon 2 Hole			
	Front View				
	Top View	Hexagon 3 Hole			
	Front View				

The insertion of holes aims to reduce the first peak load and buckling, thereby allowing the crash box to bend quickly and improving its impact energy absorption. The hole is the initial fold, so the hole area folds first. As a result, the hole serves as the crash box's initial defect. Experimental Work

Compressive analysis is often performed on crash box material samples to evaluate their mechanical characteristics (Table 5). In this test, the parameters measured are the modulus of elasticity, compressive strength, and deformation of the material. Using these characteristics, the energy absorption value can be calculated. This test uses nine specimen samples: three circular form models, three hexagon-shaped models, and three square-shaped models, as well as variable trigger counts. Figure 4 shows the technique for analyzing the results of compressive analysis performed by the Universal testing machine using a camera and a monitor directly attached to the machine unit.

Table 5: Experimental Work Result

D		0	20 mm	60 mm	Top View
Crash box Models	Hex Hole				
	Hex Hole				
	Hex Hole				

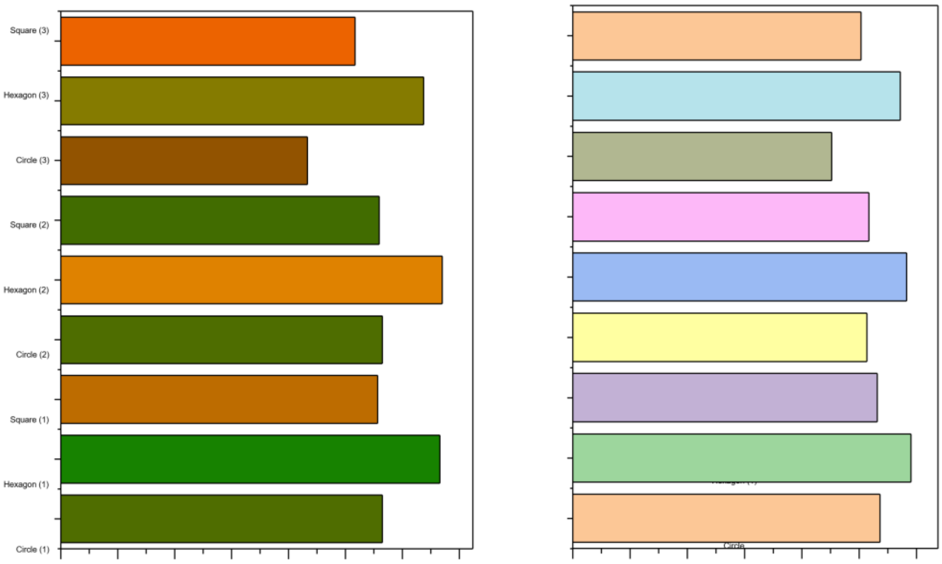


Fig.4. Graph of Energy Absorption for Crash box (a)Simulation Results (b) Experimental Results Figure

The energy absorption value of the Frusta crashbox is calculated based on the first peak in each graphical acquisition of the effect of load along displacement on the three models of Frusta crash box on the trigger hole variation, which is the basis for calculating the absorption energy in Frusta crash box. Fig. 4 shows that the energy absorption values for each model differ significantly, with the hexagon model exhibiting the highest energy absorption across all variations.

Fig. 5 shows the energy absorption for each model and the number of Frusta crash box triggers. Based on Abaqus simulation results, the highest energy absorption is observed in the Hexagon model with 1 trigger hole, at 29.493 kN. Meanwhile, for experimental work, the highest energy absorption value is found in the hexagon model 2 crash box, specifically 33,505 kN. These energy-absorption results demonstrate that creating trigger holes and cross-sections significantly increases energy absorption in the crash box. The crash box model with a significant effect is the frusta hexagon model, because it has six corners that help support the load when force is applied.

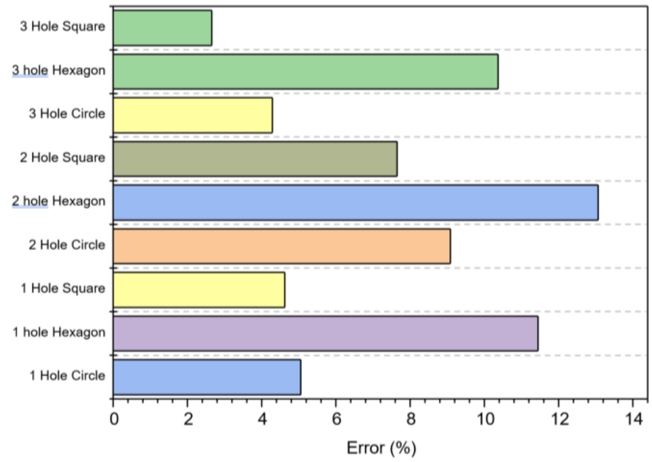


Fig.5. Error % Experimental vs Simulation crash box

In Fig. 5, you can see the percentage error between experimental testing and simulation. The percentage error is still quite small, ranging from 2.55% to 13.06%. The lowest value is in the 3-hole square model, and the largest is in the 2-hole hexagon model. This difference in error percentage is due to several factors, including crash box fabrication results that are still less than perfect, imprecise bending, and inadequate weld strength.

5.0 Conclusions

The Finite Element Method and experimental method are used to evaluate crash box test items with various models, such as circular, hexagonal, and square models, filled column cross-sections, and nine-cell columns with three-hole trigger rings. Testing is conducted using FEM and Abaqus Software, as well as experimental methods, on equipment with a universal test capacity of 1000 kN and a speed of 5 mm/min. The results of both tests show that the hexagon model has the highest energy absorption, namely 33.50 kJ for the experimental results and 29.49 kJ for the simulation.

Based on the values obtained, it can be seen that combining the crash box model with filling the cross-section plate and providing a trigger on the crash box can increase the crash box's energy-absorption capacity. The crash box's energy absorption is proportional to its maximum force. Buckling can be triggered by crash box holes, although there is a two-hole limitation. A three-hole trigger absorbs less energy than a two-hole trigger. The direction of future research is to develop alternative trigger models and to investigate variations in trigger size.

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Paper Contribution to the Related Field of Study

This study contributes to automotive safety engineering by demonstrating that optimised hexagonal crash box geometries significantly enhance energy absorption, validating finite element simulations with experimental testing to improve passive safety design using Aluminum AA 6061-T4 structures.

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