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Research article

Effect of Trigger Configuration on Crash Box Energy Absorption in Vehicle Collisions using MSC Dytran

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A B S T R A C T

Vehicle crashworthiness is a critical aspect of automotive safety engineering designed to minimize injury to occupants during collisions. This paper investigates the role of trigger mechanisms in enhancing crashworthiness by managing energy absorption and deformation during impact. Trigger mechanisms, including structural features like grooves, holes, or geometric discontinuities, initiate controlled deformation, optimizing energy dissipation. This study evaluates the effectiveness of crash boxes with various cross sections and six trigger designs: bead initiator, diamond notch, smaller thickness, circular notch, circular holes, and oval holes, to absorb energy of collision using computational software, MSC Dytran. The results show that a crash box with an octagonal section absorbs more energy than those with square, rectangular, or hexagonal sections. Among the introduced trigger designs, the models of bead initiator, circular notches, and circular holes were considerably the most effective in energy absorption.

1. INTRODUCTION

Crashworthiness refers to a vehicle's ability to protect its occupants during a crash by absorbing and managing impact energy. Modern automotive design integrates advanced materials and structural engineering to meet stringent safety standards. Among these innovations, trigger mechanisms play a pivotal role in ensuring predictable and efficient energy absorption. These mechanisms are deliberately introduced into structural components to control deformation patterns and prevent catastrophic failure.

Extensive research has been conducted in this area. Choiron [1] used numerical analysis to study the ability of crash boxes with tapered wall thicknesses. The results showed that increasing the angle of tapered thickness enhances energy absorption under frontal impact loading. Liu [2] examined the effect of different crash box types on energy absorption during collisions. His study recommended using a square-shaped pipe as the main structure. Hussain [3] investigated the effect of triggers attached to crash boxes on energy absorption during collisions. He found that fillet triggers absorb more energy than edge slot triggers or a combination of fillet and

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slot edge triggers. Khusairi [4] explored the effects of origami patterns on crash boxes for energy absorption in vehicles. He found that origami patterns can reduce the impact force at the first impact and have stable characteristics with a predictable collapse mode. Balaji [5] studied the effects of grooves and notches on crash boxes under quasi-static loading. The results showed that applying both grooves and notches can increase energy absorption. Dirgantara [6] investigated the characteristics of crash boxes with holes. His study showed that while the peak crushing force decreased, the mean crushing force remained relatively constant. In more advanced research, Marshdatti [7] examined the crashworthiness of S-shaped structures under axial impact loading. Xiang [8] investigated the influence of trigger angle structures on aluminum alloy/ thermoplastic reinforced polypropylene hybrid tubes. They found that a 45° trigger angle provided the best energy absorption performance by promoting progressive failure and reducing instability under multi-angle loading. Sabri [9] analyzed crash boxes with tapered wall angles and trigger circles under quasi-static loading. Their study concluded that the combination of tapered angles and strategically placed trigger circles significantly improved energy absorption and deformation patterns. Chen [10] optimized multi-cell structures for high-speed trains, showing that specific trigger designs enhanced energy absorption and passenger protection during collisions. Syaifudin [11] developed crashworthiness structures for Indonesian high-speed trains, finding that the inclusion of anti-climber and crash buffer modules with triggers effectively absorbed collision energy. Zhang [12] explored the use of hybrid materials with trigger mechanisms in automotive safety components. Their findings indicated that triggers enhanced the energy absorption capacity and stability of the materials under collision loads. Lee [13] investigated the crashworthiness of composite tubes with various trigger configurations. The study concluded that specific trigger designs could optimize energy absorption and minimize peak loads during impacts.

This paper identifies the most effective triggers for absorbing significant energy during collisions. Trigger mechanisms are structural features designed to influence the deformation behavior of vehicle components during an impact. These features are classified into two categories: (i) geometric discontinuities, such as grooves or notches, and (ii) structural additions, such as beads or folds. By initiating controlled deformation, these mechanisms help distribute crash forces more effectively, thereby reducing the risk of injury to occupants.

2. RESEARCH METHODOLOGY

The study utilized computational simulations based on Finite Element Analysis (FEA) models developed using MSC Dytran to simulate crash scenarios. Various trigger designs were analyzed to assess their impact on crash performance, especially on axial impacts.

2.1 Step 1: Geometry and Material Modeling of the Crash Box

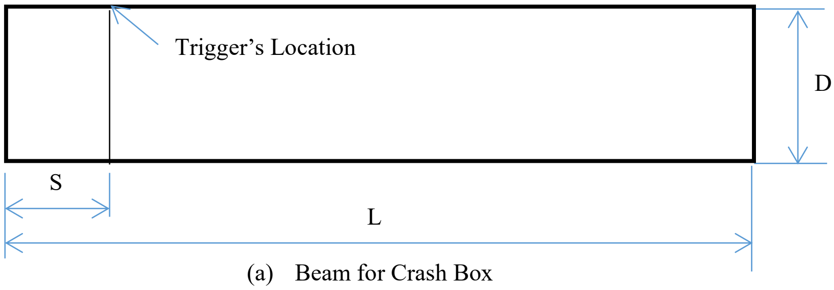
Figure 1 illustrates a rectangular beam with a length of *L*, a width denoted by *D*, and a thickness *t*. A specific area along the length *S*, located at the front of the beam, is designed as the crash box region and is equipped with various trigger variations. There are 6 cross sections of crash box introduced: *square, circle, rectangular, hexagonal and octagonal sections*, with dimensions are provided in Table 1. The material properties for the crash box are also given in Table 2.

2.2 Step 2: Modeling of Triggers for Crash Box

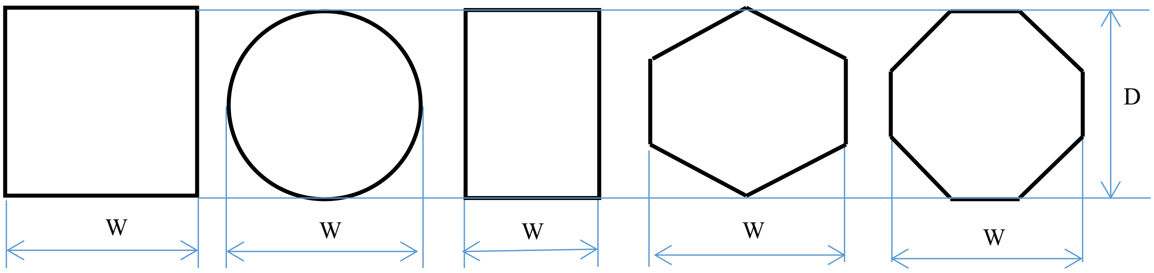
Triggers are intentional structural features, such as geometric discontinuities (e.g., grooves, notches) or structural additions (e.g., beads, folds), incorporated into crash boxes to control and predict the deformation behavior during an impact. By initiating controlled deformation, triggers facilitate the efficient distribution of crash forces throughout the structure, thereby preventing catastrophic failure and protecting vehicle occupants. These mechanisms ensure that the energy from a collision is absorbed progressively and predictably, which minimizes the risk of injuries. The integration of various trigger designs has been extensively studied through computational simulations and experimental analyses, demonstrating their effectiveness in enhancing the safety performance of vehicle structures during frontal, lateral, and oblique impacts. This paper focuses on analyzing six types of triggers: *bead initiator, diamond notch, smaller thickness, circular notch, circular holes, and oval holes*, as shown in Figure 2. However, circular crash box uses only smaller thickness as a trigger in the calculation, due to difficulty in modelling.

2.3 Step 3: Modeling of Load and Boundary Condition

As shown in Figure 3, the applied load is given in the form of velocity along the x-axis, distributed across all nodes on the moving plate. The load is provided as an impact from a moving plate with a velocity of v=4 km/h. The boundary condition at the right support is assumed to be clamped, where all nodal displacements are assumed to be zero. Meanwhile, the moving plate is assumed to move along the x-axis but is constrained in the y- and z-axis.



(a) Beam for Crash Box



(b) Cross section (left to right): square, circle, rectangle, hexagon, octagon

Figure 1. Detail geometry of crash box and its cross section

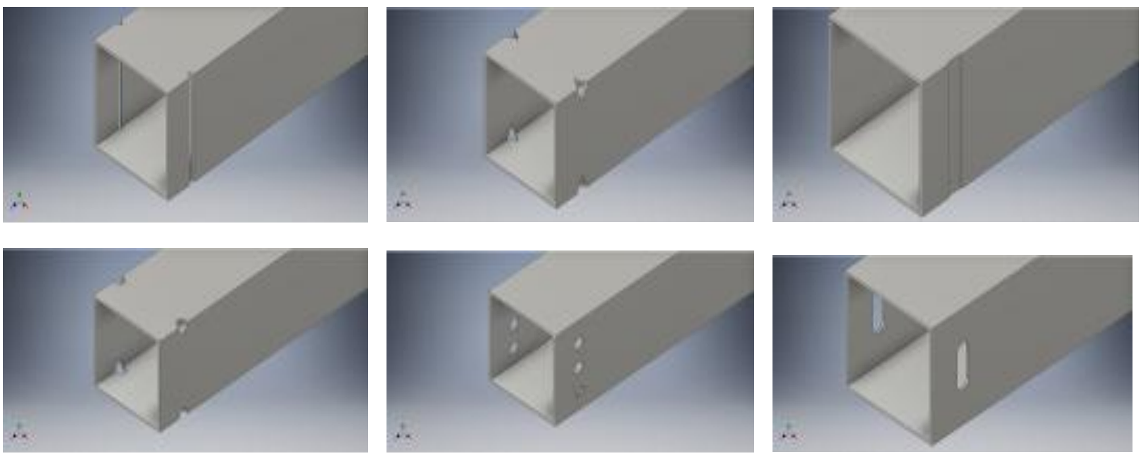


Figure 2. Models of trigger for crash box

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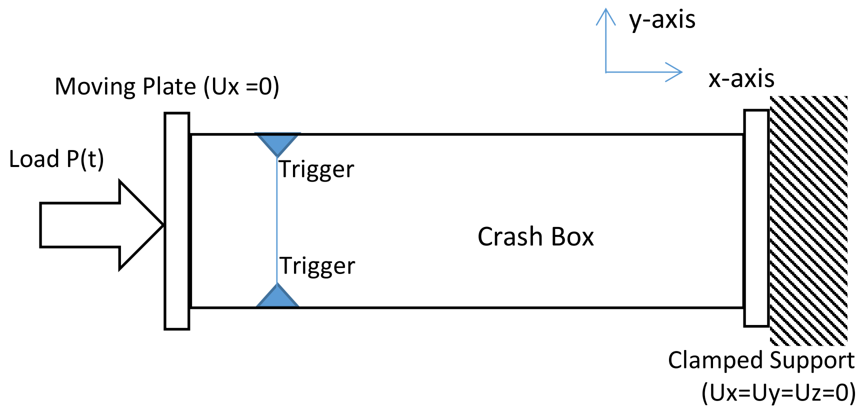

Figure 3. Modeling of Load and Boundary Condition

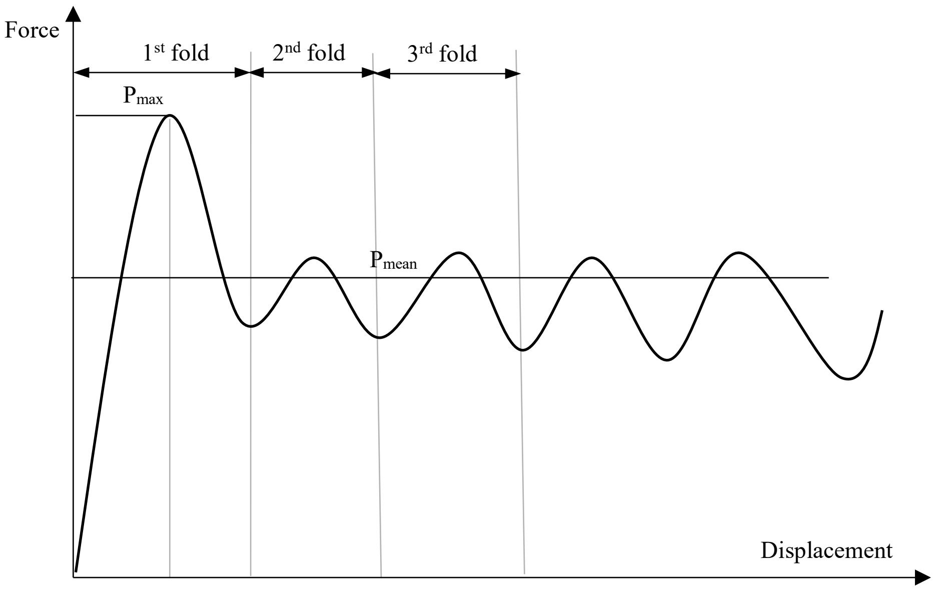

Figure 4. Load vs Displacement Graph

Table 1. Geometries of Beam for Crash Box

No.	Parameter		Unit	Square	Circle	Rectangle	Hexagon	Octagon
1	Length of Beam	L	mm	350	350	350	350	350
2	Distance to Trigger's Location	S	mm	22	22	22	22	22
3	Height of Cross section	D	mm	75	75	75	75	75
4	Width of Cross section	W	mm	75	75	50	75	75
5	Thickness	t	mm	2	2	2	2	2
6	Type dari *Trigger*	-	types	6	1	6	6	6

Tabel 2. Material Properties

Material	Aluminium Alloy 1050	
Density	ρ	2710 kg/m^3
Modulus Elastisitas	E	71 GPa
Yield Strength	σ_y	103 MPa
Rasio Poisson	υ	0.33

2.4 Step 4: Calculation of Crashworthiness Parameters

Figure 4 shows the graph of load vs displacement, which is the output from the computational calculations. There are several parameters of crashworthiness that can be obtained from the graph. First, *the absorbed energy (E_a)*, which is derived from the area under the curve. Second, *the maximum load (P_{max})* that occurs during the first buckle fold. Third, *the average load (P_{mean})*, which is taken from the average impact load. Fourth, *the Crushing Force Efficiency (CFE)*, obtained by comparing the average load to the maximum load. Fifth*, the Specific Energy Absorption (SEA)*, which is calculated by dividing the absorbed energy by the mass of the structure.

3. RESULTS AND DISCUSSION

This paper presents calculations using the finite element method, utilizing MSC-Dytran as the solver and MSC-Patran for pre/post-processing. The input is provided as a load with a velocity of 4 km/h. The impact distance is measured until the deformation of the crash box reaches approximately 80 mm for various crash box cross sections and triggers. From Figure 5, the energy absorbed *(E_a)* and the maximum load *(P_{max})* that the crash box can withstand are calculated, with the results summarized in Table 3 below.

In terms of maximum load, it is generally observed that the square section crash box can withstand a P_{max} of up to 54 kN, compared to other cross sectional shapes that can only withstand loads below 45 kN. This is due to the larger volume and mass of the square section, which is approximately 0.53 kg compared to other sections that are generally below 0.5 kg. However, in terms of energy absorption *(E_a)*, the octagonal sections perform better because the *Crushing Force Efficiency (CFE)* of the octagonal crash box is the highest among the different sections. This means that the maximum load for the second and third buckling cycles, and beyond, is not significantly lower than the P_{max}. This results in a larger area under the curve. The energy absorbed by the octagonal section is approximately 2200 to 2500 J for all triggers, compared to the square section (averaging between 1500 to 2000 J), hexagonal section (around 2200 to 2300 J), circular section (around 2000 J, only for smaller area triggers), or rectangular sections (averaging around 1400 to 1500 J). The absorbed energy values are directly proportional to the *Specific Energy Absorption (SEA)* obtained. Moreover, in terms of trigger mechanisms, three triggers: *circular notches, circular holes, and bead initiators* demonstrate effective capabilities in absorbing impact energy better than other types of triggers. The square crash box can absorb an impact energy of 1700 J with bead initiator and circular hole triggers, but this increases to 2100 J with a circular notch trigger. On the other hand, the octagonal crash box can absorb an impact energy of 2400 J with a bead initiator trigger, but this decreases to around 2100 J with circular hole and circular notch triggers.

Figures 6 and 7 illustrate the deformation that occurs in crash boxes for two cross sections: square and octagonal, and three triggers: bead initiator, circular hole, and circular notch. The selection of these cross sections and triggers is based on their ability to absorb more energy when subjected to impact loads, as demonstrated in Table 3.

In terms of controlled deformation, the displacement from 0 to 0.02 m shows a peak curve pattern, indicating the formation of the first fold in the crash box. The displacement from 0.02 to 0.03 m shows a downward curve pattern, representing the completion of the first fold. The displacement from 0.03 to 0.05 m shows another peak curve, indicating that the first fold is fully formed and the second fold is beginning to form. The displacement from 0.05 to 0.07 m shows a valley curve pattern, indicating the formation of the second fold, with the direction of the fold inward toward the crash box. The displacement from 0.07 to 0.08 m shows an upward curve pattern, indicating the third fold is forming in the crash box.

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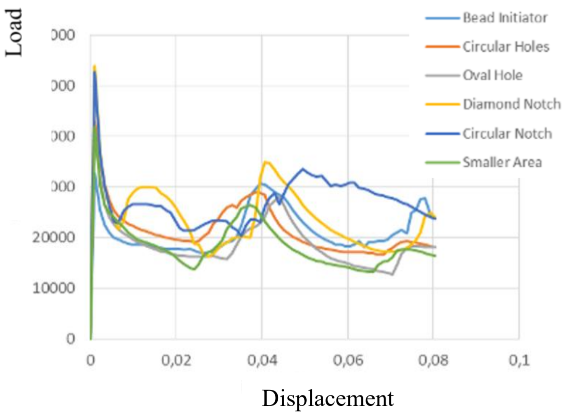
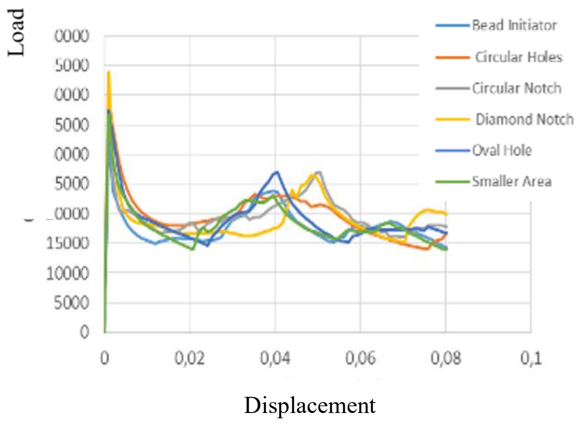
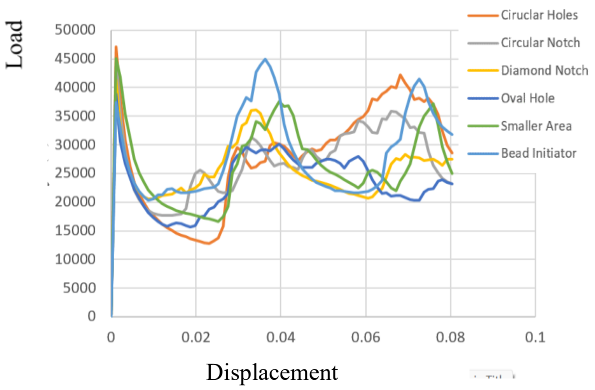


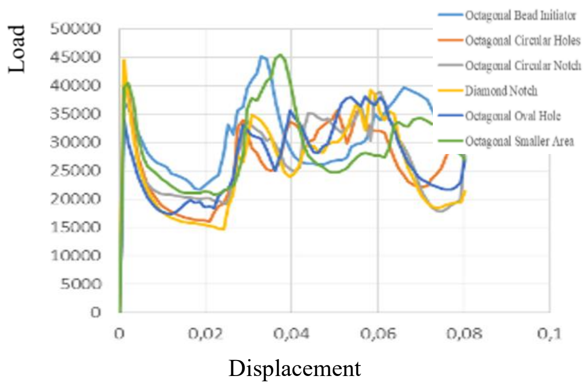
(a) Crash box with square cross section



(b) Crash box with rectangular cross section

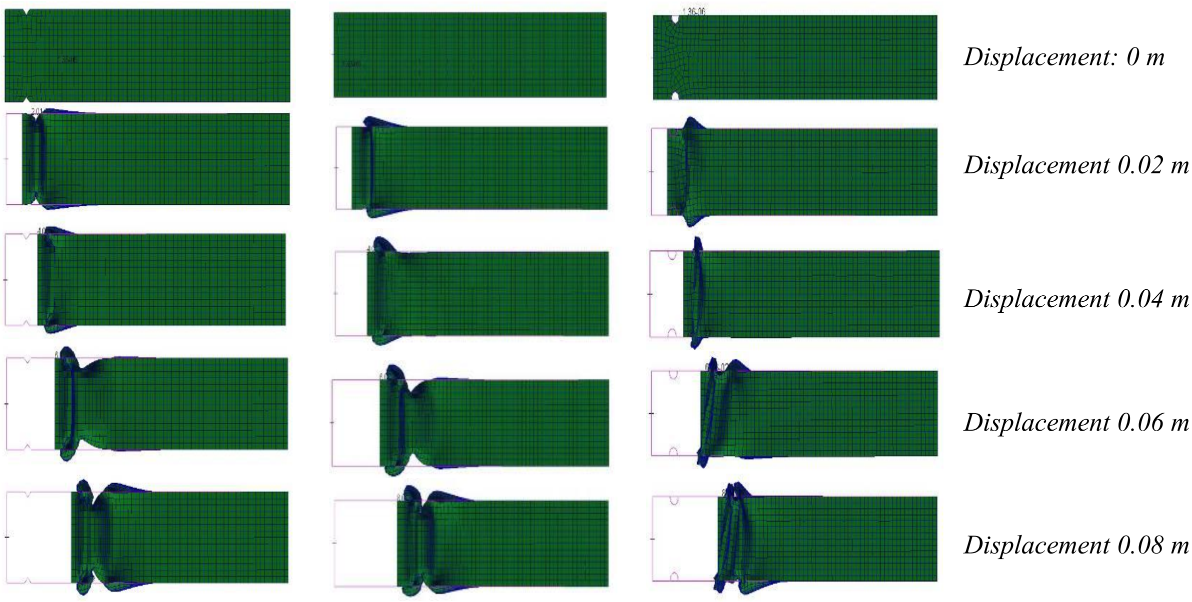


(c) Crash box with square cross section



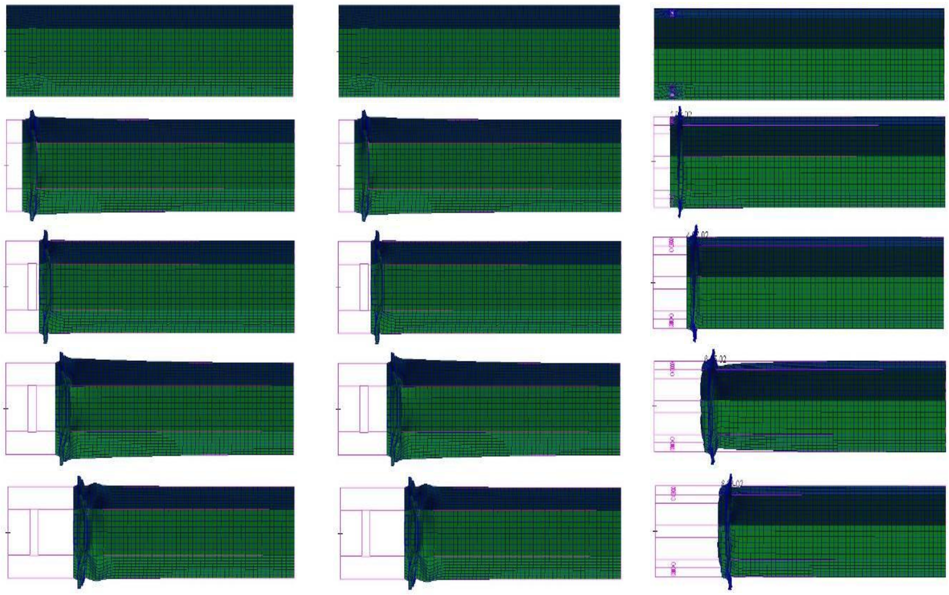
(d) Crash box with rectangular cross section

Figure 5. Force-Displacement Curves of Crash Box under variation of cross section and triggers



(a) Bead initiator, *left* (b) circular hole, *center* (c) circular notch, *right*

Figure 6. Square beam with triggers



(a) Bead initiator, *left* (b) circular hole, *center* (c) circular notch, *right*

Figure 7. Octagonal Beam with triggers

Table 3. Energy Dissipation of Crash Box under variation of section and triggers

Crash Box Model	Triggers	Velocity (km/h)	P_{max} (N)	P_{mean} (N)	CFE	Absorbed Energy (J)	Mass (kg)	SEA (J/kg)
Square	Bead Initiator	4	32740.76	21149.41	0.65	1708.51	0.541	3158.05
	Circular Hole		42996.03	21253.53	0.49	1720.05	0.5362	3207.86
	Circular Notch		52692.64	26713.36	0.51	2161.43	0.5363	4030.27
	Diamond Notch		53819.95	23645.18	0.44	1911.44	0.5372	3558.15
	Oval Hole		41272.41	18675.22	0.45	1510.17	0.5357	2819.07
	Smaller Area		41905.18	18452.48	0.44	1493.02	0.5401	2764.35
Rectangle	Bead Initiator	4	32047.52	17659.53	0.55	1429.6	0.4454	3209.69
	Circular Hole		39342.35	19501.35	0.5	1578.22	0.4416	3573.87
	Circular Notch		42074.07	19509.94	0.46	1578.31	0.8832	1787.03
	Diamond Notch		44039.53	18966.6	0.43	1532.9	0.4431	3459.49
	Oval Hole		37418.61	18893.29	0.5	1528.67	0.441	3466.38
	Smaller Area		36668.71	18190.07	0.5	1473.04	0.4447	3312.43
Hexagonal	Bead Initiator	4	45003.51	28080.16	0.62	2682.6	0.4682	48446.4
	Circular Hole		41653.29	28476.57	0.68	2302.56	0.464	4962.41
	Circular Notch		44602.27	26815.56	0.6	2170.04	0.4636	4680.84
	Diamond Notch		41346.76	25453.08	0.62	2056.78	0.464	4432.72
	Oval Hole		38831.29	23317.06	0.6	1885.23	0.4635	4067.38
	Smaller Area		45014.2	26240.2	0.58	2122.19	0.4673	4541.38
Octagonal	Bead Initiator	4	45049.96	30652.67	0.68	2480.04	0.4486	5528.41
	Circular Hole		41807.32	26617.02	0.64	2146.52	0.445	4823.65
	Circular Notch		40510.48	26782.36	0.66	2163.67	0.4426	4888.54
	Diamond Notch		44515.1	25203.93	0.57	2039.81	0.4446	4587.96
	Oval Hole		38024.02	26710.38	0.7	2159.34	0.4426	4878.76
	Smaller Area		45507.01	29013.03	0.64	2346.84	0.4474	5245.52
Circle	Smaller Area	4	36758.77	26540.44	0.72	2143.08	0.4249	5043.73

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4. CONCLUSION

Trigger mechanisms are a vital component of vehicle crashworthiness, enabling controlled energy absorption and deformation during impacts. This study demonstrates their effectiveness in improving safety outcomes through experimental and computational analyses. There are several points that can be conluded in this paper:

- The square cross section crash box with diamond notch trigger provides the highest maximum force (P_{max}), that is around 53.819 kN compared to other cross sections.
- The octagonal cross section crash box with bead initiator trigger provides the highest energy absorption (E_a), that is around 2480.04 kN compared to other cross sections.
- Among the six triggers, three optimal triggers to absorb energy in the crashworthiness are bead initiator, circular hole and circular notch. For example, the square cross section crash box provides the energy absorptions are 1708.51 J, 1720.05 J, and 2161.43 J for bead initiator, circular hole, and circular notch trigger respectively. Moreover, the octagonal cross section crash box provides the energy absorptions are 2480.04 J, 2146.52 J, and 2163.67 J for bead initiator, circular hole, and circular notch trigger respectively.

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