



Full Length Article

Finite element analysis regarding folding behaviour of different crashbox versions

Jozsef Kertesz^{a,b}, Tunde Anna Kovács^{c,*}^a Óbuda University Doctoral School on Safety and Security Science, Budapest, Hungary^b University of Debrecen, Faculty of Engineering, Department of Vehicles Engineering, Debrecen, Hungary^c Óbuda University Bánki Donát Faculty of Mechanical and Safety Engineering, Budapest, Hungary

A B S T R A C T

Low-speed collision is one of the most frequent road accident types nowadays. The consequences of this accident could be serious and long terminated. The passive safety system has an important role to reduce and prevent the amount of personal and technical injuries. Applying front and rear bumper beams is a good way to absorb more impact energy at the moment of collision reducing the load of the occupants. The background of the energy absorbing is the prescribed folding deformation of the bumper's support namely the crashbox. The main goal of the present study is to evaluate and compare differently shaped crashboxes as a thin-walled structure using finite element analysing to get information for more effective energy absorption taking into consideration of the weight optimization and space requirements. To be comparable to the folding fluctuation of each specimen the compression test's curves are evaluated with relative standard density. Moreover, the specific energy absorption is also was determined. Based on the values determined by finite element analysis conclusions could be drawn.

1. Introduction

1.1. Overview

When a vehicle has a movement it has kinetic energy, which will be converted into impact energy suddenly at the moment of collision. This energy conversion involves a huge amount of deceleration related to the occupants of the crash (Karapetkov et al., 2019; Dima and Covaciu, 2019; Chi and Gong, 2020; Xu et al., 2022; Dario and Filippo, 2013). The personal injury severity is influenced by the amount of this deceleration. There are many active safety technical novelties in modern vehicles, however, the final effect of a collision is determined by the efficiency of the passive safety systems. There are many passive safety components in modern vehicles to reduce the personal injury of occupant vehicles in case of collision (Saplinova et al., 2020; Qiu and Jiang, 2022; Wang et al., 2020). The synergy of each passive structure gives the final results of the collision, however, these components could be divided into more groups. All of the models of new development vehicles must complete the safety national regulation. Taking into consideration these regulations the vehicles have to fulfil the strict requirements in a wide speed range (Changoski et al., 2022) Referring to this speed range, it must be distinguished for example the low-speed collision occasion. A significant proportion of road collisions is low-speeded collisions, which are usually occurred near intersections and traffic jams. The literature uses the

low-speeded impact definition for the crash where the occupant vehicle's speed does not exceed 16 km/h (Han et al., 2019). Beyond the fact that reduce or prevent personal injury, passive protection structure has to work to reduce the repairing cost and avoid the deformation of the main body-work. One of the most important passive safety systems in the case of a low-speed crash is the front and rear bumper beam. The function of it is to reduce the deceleration at the moment of impact and to prevent the significant deformation of the vehicle structure such as sidemembers (Su et al., 2021; Chinnasamy et al., 2021; Li et al., 2022). The bumpers usually can be separated into three main parts. The bumper beam is mounted to the end of the sidemember through a rear plate, while the crashboxes are fixed with a crossbeam. The prescribed folding of these boxes is responsible for the impact of energy absorption. The absorbing capacity strongly depends on the shape, material and size of the crashbox (Ciampaglia et al., 2021; Wang et al., 2022; Ma et al., 2020; Hou et al., 2023) However, the direction and the line of action also have importance in analysing the efficiency of the absorbers. Designing a crashbox is a hard task since it has to work efficiently in wide speed ranges and situations as able as possible. The buckling of the boxes has a really negative effect on energy absorption, therefore the improved prescribed folding is the main goal during the shape optimization.

* Corresponding author.

E-mail address: kovacs.tunde@bgk.uni-obuda.hu (T.A. Kovács).<https://doi.org/10.1016/j.euomechsol.2024.105375>

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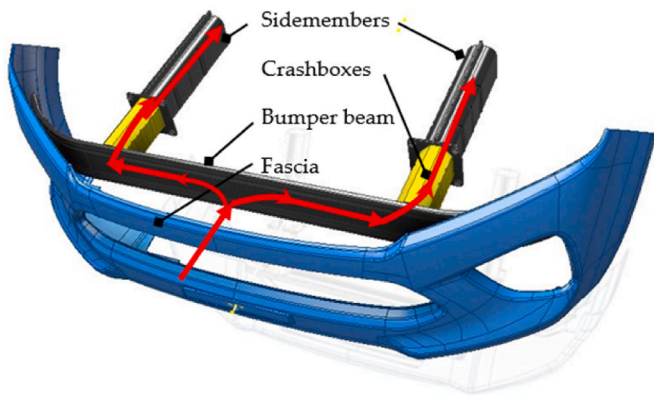


Fig. 1. Bumper system and its components (Authors).

1.2. Structures of bumper

The structure of the frontal passive low-speed protection system is introduced in Fig. 1. The sidemember is one of the most important components of the vehicle's bodywork therefore the prevention of it is a crucial condition designing the safety system. The force conduction is represented in Fig. 1 also. The monoblock bumper is constructed as one part in stamped steel or aluminium. The crashbox as an energy absorber does not exist in this system, as they are installed with the cross-member directly (Zahedan et al., 2021). This concept saves some weight and more importantly, it saves time in production when it is produced basically in one step. The disadvantage however is that the monoblock bumper is more time-consuming to develop because there are many crucial conditions in the design process before a suitable design which fulfils the design specifications is found. Furthermore, the likelihood of damage to the sidemember is significantly higher. The repairing or replacing of sidemembers is so complicated and costly. Therefore it is frequently applied solution to mount a thin-walled crumpling structure namely a crashbox to the end of the sidemember (Primawan et al., 2021). The axial folding of this box could absorb impact energy and prevent the main sidemember of the vehicle [Choi et al. (2022); Tekavde et al. (2016); Dohmen et al. (2011)]. Furthermore, it has importance related to the passengers' prevention meaning with its folding the severity of the personal injury could be improved considerably. The crashboxes installed onto the end of the sidemember are connected to the bumper beam. This component has more functions, Firstly in the case of corner impact it could help to avoid the buckling of the crashbox resulting in energy-absorbing inhibition. Secondly, due to its curved form with its deformation, more energy could be absorbed reducing the effect of the collision related to the main components of the engine and the passenger inside the vehicle. The main features of the bumper are

fixed by regulations, but in addition, there are so many manufacturer requirements related to the low weight, and the small space requirement (Per-Emil) Last but not least the towing port of the vehicle is located on the bumper and installed indirectly to the cross member, which means even more new strict requirements regarding the resistance to tensile stress from the crashbox and the bumper.

1.3. Regulation background

The efficiency of a passive safety system is regulated by strict national and international requirements, and its functionality and performance are evaluated and compared by different real crash tests. To get representative results of this investigation, the crash tests are defined by standards and regulations (Victor Chombo et al., 2021; Davies and Bastien, 2021; Lei et al., 2021). The present study is focusing on the optimization of the bumper crashbox, which has importance in low-speed and higher-range crashes also. Designing and analysing, and testing bumper beams the UN ECE R42 regulations and the UN ECE R94 regulations must be taken into consideration. The formal is related to the low-speed impact procedure, the latter is about the frontal collision and its requirements at higher speed. For compliance with the R42 regulations, the vehicle low-speed prevention system is tested in four directions. Among the purpose of the R42 protective devices, which are simply components found at the front and back ends of vehicles and created in a way that allows contacts and minor shocks to occur without causing any severe damage, ensure exterior protection. The impactor could be a part of a pendulum or fixed to a carriage (moving barrier) (UN ECE R42, UN ECE R94). The procedure includes four test ways which are as follows: frontal, rear, front corner and rear corner impact test which is introduced in Fig. 2.

According to the regulation following these impacts, the vehicle must be safe to drive. That implies, for instance, that the headlights must function and must not leak any liquid or lubricator. The deformation of the main body structures such as sidemember is not allowed, and for the occupant personal injury prevention the crashbox could be folded to reduce the harmful loading of driver and passengers (Lee et al., 2022; Kale and Gulwade, 2021). Beyond these compulsory regulation standards, there are more international institutes where low-speed crash tests are occurred according to the same strict rules and requirements to give feedback to the manufacturers and researchers about its products and compliance (Mortazavi et al., 2021; Abhikash et al., 2022). The German insurance test Allianz CRT (Crash Reparatur Test), which is the most significant test for the European market, and the IIHS (Insurance Institute of Highway Safety) test, which is the most significant insurance test in the United States, are two of the most frequent tests that the bumpers will be developed to manage. German insurance giant Allianz is well-known (Per-Emil). To determine the appropriate cost for an insurance policy for a particular vehicle, they have created crash tests. The

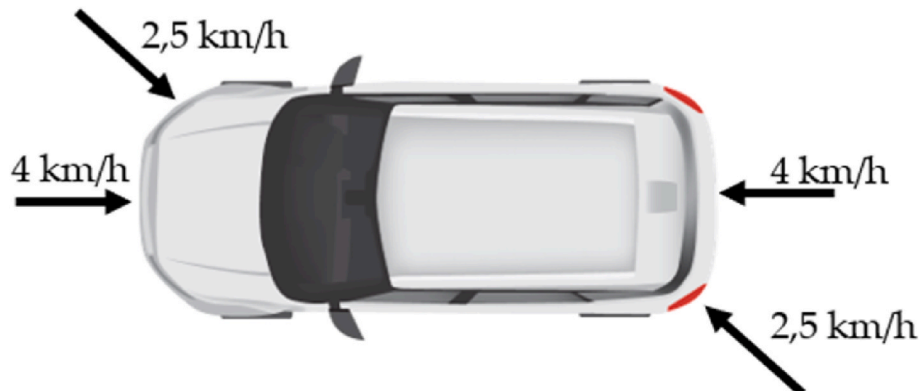


Fig. 2. The direction and intensity of the bumper tests (Authors' s edit based on UN ECE R42 regulation).

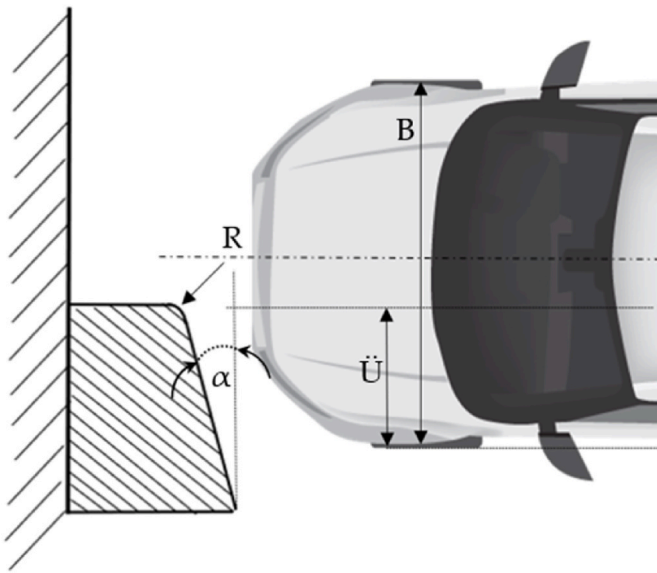


Fig. 3. The conditions of the Allianz bumper test (Authors' edit based on [Sîrbu et al.](#) information).

insurance sector generally accepts this exam, which essentially determines insurance premiums across Europe. The manufacturer wants the cost of insurance to be in line with the cost of the car, therefore this test is crucial for the manufacturer because they have a target market for the car and consequently a target pricing. As a result, the Allianz test is crucial for the bumper system. The CRT test involves smashing the car into a predetermined state and then fixing it to determine how much it will cost to repair it. This test forms the basis of the insurance premium. The front barrier test, illustrated in Fig. 3, is the most crucial test for this investigation. The test is carried out in such a way that the test vehicle is driven into a 40% offset ($\ddot{U}$) barrier with an angle of 10° ($=0.4 \times B$), where the B is wide of the body. The car travels at a speed of $v = 15 \pm 1$ km/h. The barrier has a 150 mm radius. The basic requirement for the Allianz test is that the bumper system should absorb all the energy from the crash and leave the sidemembers intact for which effective crashbox crumpling is essential, this is why the present article is about the crashbox shape evaluation ([Per-Emil](#); [Sîrbu et al.](#); [Rüter et al.](#), 2007)

The IIHS is present in the United States (Insurance Institute for Highway Safety). Reduced losses from fatalities, injuries, and property damage are their aim ([Ham and Cheon](#), 2023; [Paradiso and McDowell](#), 2023; [Olberding et al.](#), 2023) An auto insurer-funded non-profit research and communication group is called IIHS. They perform much the same

duties as Allianz. Fig. 4 describes the US tests that have an impact on the bumper system. The car travels at a speed of 7.96 ± 0.24 km/h, and the total cost of repairs is then calculated. Another new test that IIHS has created is a little bit different. There is a deformable bumper barrier on a predetermined height in this bumper-to-bumper test. This method is supposed to more accurately replicate a low-speed collision between two cars ([Per-Emil](#); [Kim et al.](#), 2009; [Sonawane and Shelar](#), 2018).

2. Functional requirements

There are primarily two parameters to take into consideration for the space, which limits the shape of the crashbox. The crashbox placement is shown by the split line between the sidemember and bumper. One of the most crucial input values to begin the process is this. The borders of the bumpers are determined by the distance between the fascia and side-member split lines. The bumper system must be built to fit into the pre-set exterior design of the car, which is frequently predetermined or at least has a rough drawing. Position lighting and split lines between the fascia/bumper and the front spoiler, for instance, can be taken into consideration ([Wagersten et al.](#), 2013). The length and partial cross-section of the crashbox is determined by the basic factors described above. There are additional components that must be taken into account, such as the cooler and other components surrounding the bumper system. This aspect is important not only because of space requirements but from the point of view of the above-mentioned R42 and Allianz CRT regulations, related to the intact cooling system after collision. The weight of the product is a key point of emphasis ([Sun et al.](#), 2021; [Du et al.](#), 2023; [Nachippan et al.](#), 2021). Every gram counts in the car industry because of the weight needed. The less material that is used during building, the less gasoline or electricity is used. Cost is a constant concern, and lowering costs is always necessary. Cheap manufacture is one technique to reduce costs, as is using less and cheaper material. Therefore safety system optimization is a hard task because the low mass and low cost of materials frequently do not meet with great energy absorbing capacity.

3. Physics of the energy absorbing

The collision lasts from the moment the vehicles touch until they separate. In this case, the state of motion of the vehicles changes substantially in a very short time, while elastic and permanent deformation permanent damage. During the collision, several natural processes, mostly known to us, take place. These processes can be described or approximated by the fundamental laws of physics, Newton's axioms of conservation of momentum and angular momentum, and conservation of energy ([Todorut et al.](#), 2021; [Rivera-Hernández et al.](#), 2022; [Khata](#),

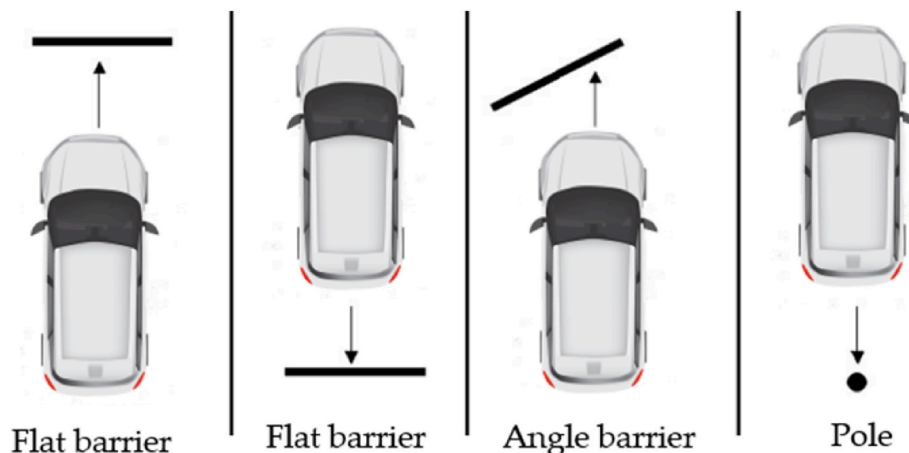


Fig. 4. IIHS bumper tests (Authors' s edit based on [IIHS Bumper Test Protocol](#), 2009)

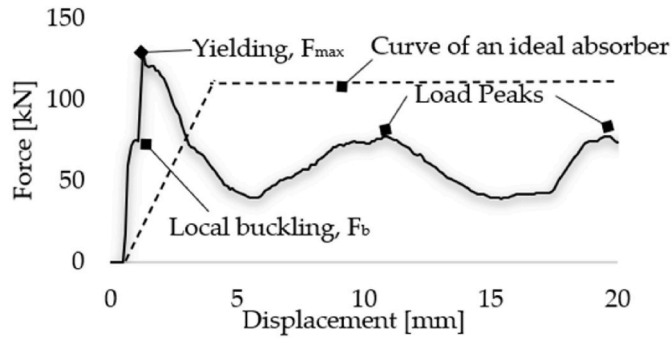


Fig. 5. Typical force-displacement diagram of thin-walled crashbox vs. ideal absorber (Authors).

2021). The description of a real accident process, however, is extremely complex, as vehicles deform, spin, crash, etc. However, in investigations such as the low-speed impact the rollover and the spin can be neglected. In fact, the basic concepts of collision theory refer to ball models with mass and velocity. The balls collide with each other centrally (centrally), so their rotation does not need to be to account for their rotation. The collision can be inelastic or elastic depending on the post-contact motions. The bodies involved in an inelastic collision do not separate after contact but continue to move together at a common velocity (Luo et al., 2023). Near collisions can also occur in real accidents (e.g. head-on collisions), but they are not completely inelastic. The velocity after the collision has importance from the point of view of structure and accident analysing, which could be expressed with the next formula (Melegh, 2004; Rövid and Melegh, 2004):

$$v_a = \frac{m_1 \cdot v_1 + m_2 \cdot v_2}{m_1 + m_2} \quad (1)$$

Where the m_1 and m_2 are the weight the v_1 and v_2 are the velocities of the occupants' vehicles. In an elastic collision, the bodies separate after the collision and continue to move at different speeds, to describe the collision, the process must be broken down into two parts. For some time after contact, they continue to move towards each other while deforming elastically. The deformation work is described by energy from the bodies' kinetic energy. This is the stage of compression. They then separate from each other and the deformed bodies regain their original shape. At this point, the compression deformation work consumed during the collision is completely converted back into kinetic energy in a perfectly elastic collision. This is the ejection phase. In truly elastic collisions, the colliding bodies undergo a permanent deformation. The kinetic energy consumed is no longer is not recovered. This can be taken into account by a collision factor (Melegh, 2004; Rövid and Melegh, 2004):

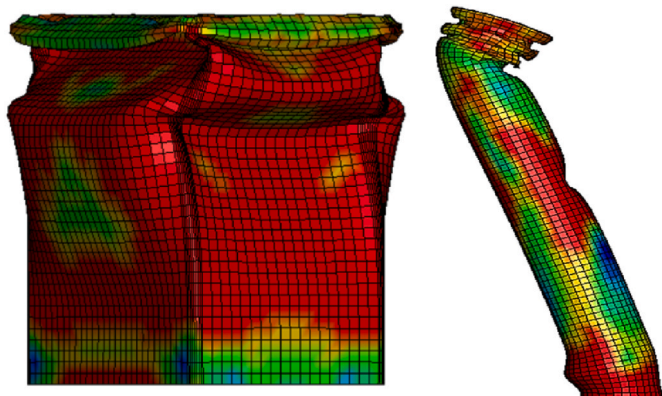


Fig. 6. Different between axial folding and total buckling (Authors).

$$k = \frac{v_2 - v_1}{v_1 - v_2} \quad (2)$$

Where the components of the formula designated with an upper comma are the velocity after the crash, without a comma it velocity before the moment of impact. Knowing these values the deformation energy could be calculated with this nexus (Melegh, 2004; Rövid and Melegh, 2004):

$$\sum E_D = \frac{1}{2} (1 - k^2) \cdot \frac{m_1 \cdot m_2}{m_1 + m_2} \cdot (v_1 - v_2)^2 \quad (3)$$

The ACRT and R42 collision situation could be a consideration as an impact with a rigid wall. In this case, the deformation energy could be determined:

$$E_D = \frac{1}{2} (1 - k^2) \cdot m_1 \cdot v_1^2 \quad (4)$$

A load curve diagram of a crumpling crashbox is frequently used to illustrate the way in which energy is absorbed during a collapse (shown in Fig. 5). The initial peak load, also known as F_{max} , is the load that reacts to the load at which the system collapses and this is the first peak of the load curve. The next collapse mode led to successive peaks.

4. Interpretation of the graphs

Higher peak and sub-peak forces are obtained with stiffer cross sections, and the crushing distance is also reduced. Therefore, the first peak load is a crucial design parameter. The initial peak force (F_{max}) in the case of sidemember must be less than the peak force for the crashbox in order to prevent the sidemember from collapsing first. An ideal absorber structure also has a first linear elastic region with the F_{max} at the end of this section as the dashed curve is represented in Fig. 5. This upper limit has significant importance in the point of above mentioned sidemember deformation prevention. After the elastic region, an ideal structure gives a constant linear range, where it gives nearly constant stress along the strain (Habib et al., 2018). It is the most useful termination of the absorber compression since a high amount of impact energy could be absorbed.

Refer to Fig. 5 significant peak fluctuation could be seen along the strain when a thin-walled crashbox is folding, which is an inverse behaviour compared with an ideal absorber, therefore, the curve peak fluctuation must be avoided or as minimalised as possible. The standard deviation and the relative standard deviation of the curve is one of the good ways to describe the undesired force fluctuation. This evaluation principle is detailed in a later chapter. To get information about the efficiency of the absorber structure, the stress-strain curve given by the compression must be analysed, since the energy is equal to the area under the curve, the integration of it is necessary. In the present study, the simulations were conducted in LS-Dyna PrePost FEA to investigate and compare three different section-type thin-walled crashbox structures to reveal how could influence their load characteristics of them with different notches or shape optimization.

5. Crumpling process

The car's primary structure is made of different metals. The collapsing of them absorbs the energy. The objective in a crash is to minimize the deceleration loaded by the driver and passengers. The structure should simultaneously absorb as much energy as it can while doing so in a controlled way (Kurpisz et al., 2023; Baranowski and Damaziak, 2021; Patil, 2022). A crashbox can fundamentally collapse in two different ways during a collision. The first collapse mode is buckling, which could be normal behaviour but undesirable crumpling way. Axial folding is the second method (Per-Emil). The crashbox ought to be built to handle this as much as possible. An axial folding is simpler and more controllable to regulate and absorbs more energy than a bending or buckling collapse. It is crucial to have a controlled collapse mode. To

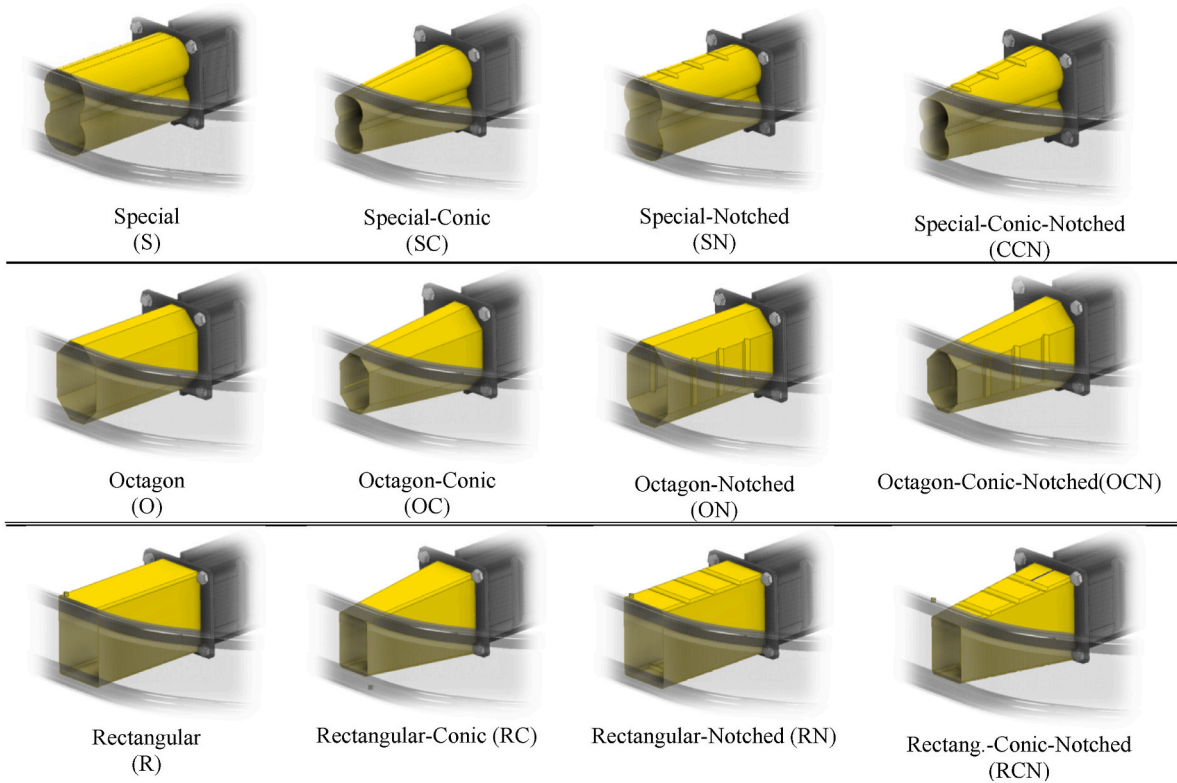


Fig. 7. The investigated crashbox versions and their designations (Authors).

avoid or minimize the possibility of buckling of crashbox the bumper beam has importance - as it was mentioned above - a curved shape of it could help convert the action line of the side corner impact and conduct the force directly into the crashbox. The buckling is the typical way for the beam to collapse, which is not the most energy-efficient way of a passive safety improvement, meanwhile, this collapse way happens frequently (Wang et al., 2022; Choi et al., 2022; Choirotin et al., 2021). The right side of Fig. 6 describes this buckling mode. The likelihood of buckling can be avoided with the modification of the diameter and length ratio. Fig. 6 on the left depicts the axial folding manner of collapse. In comparison to the global bending mode, axial folding absorbs more energy. The combination of the two earlier stated modes is known as axial folding with buckling. In many cases, the collapse can begin as an axial collapse before changing to a bending. Applying notches on the surfaces of the crashbox or conic shape the buckling or bending issue could be avoided or the probability of it could be reduced considerably (Nasution et al., 2023; Harhash et al., 2021; Asri et al., 2021). This type of behaviour is typical of structural collapse. A present

study focuses on the folding behaviour therefore with constraining the buckling effect is inhibited by using proper constraints during the FEA simulation.

The first peak load is one of the most crucial metrics in energy absorption. The sidemember will collapse before the crashbox begins to collapse if the initial peak load (force needed to start the deformation) is lower in the sidemember than in the crashbox. There are essentially two ways to alter the crashbox so that it is the first entry to collapse. The first step is to adjust the metal's thickness of crashbox so that the force needed to cause collapse is less than the force in the sidemember (Kim et al., 2022). This can frequently collide with the requirements the customer has for the crashbox in terms of energy absorption. One more method is the shape optimization of crashbox or the application of notches.

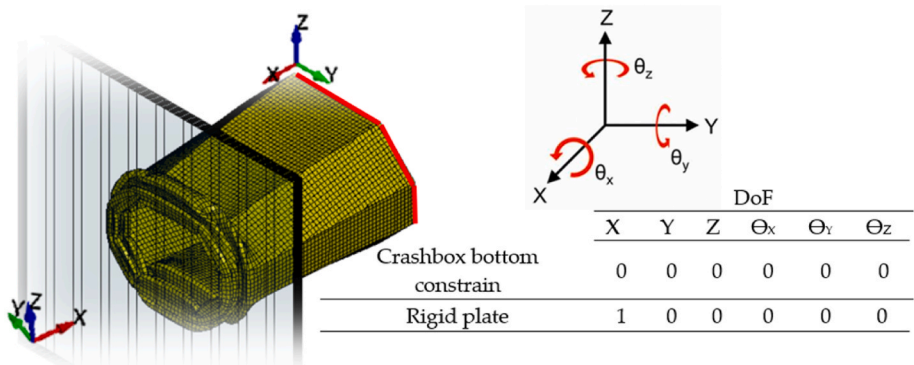


Fig. 8. Set up of DoF (authors).

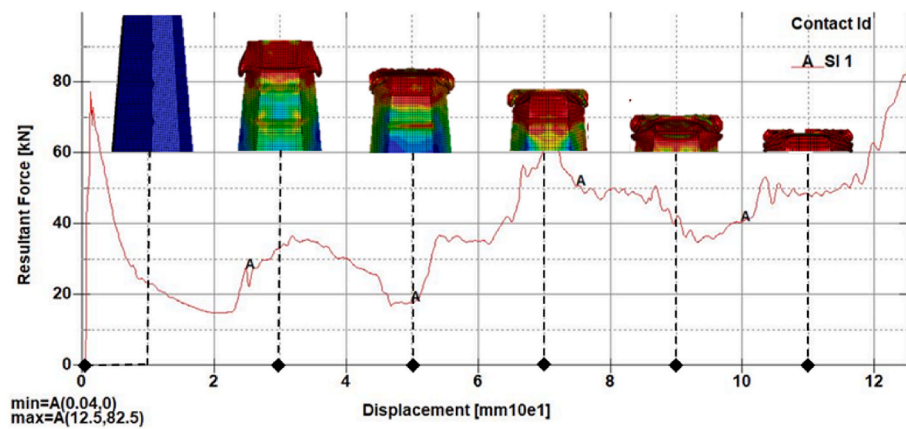


Fig. 9. The process of the simulation (Authors).

6. Simulation's parameters

6.1. Objects of the analysis

It was a comparison investigation since more different cross-section types and notches have occurred simultaneously. The results of the simulations are compared from different aspects. The most important points of view were the first force peak, the absorbed energy during the folding of the crashbox, and the mean value force up to 80% of strain. In addition to this, the fluctuation of the reaction force was analysed at the whole strain range. The present study investigated three different base cross-sections related to the crashbox external shape. All versions were handled as a thin-walled structure with a 2 mm wall thickness and were based on the above-mentioned cross-section types. In the present study, the distinction is made between normal, conic, notched and its combinations. These specimens and their designations are represented in Fig. 7. The specimen is made by Autodesk Inventor CAD software.

To get information about the cross-section and notches effect for the folding behaviour of the crashbox we took finite element analyses. The simulation occurred as a compression test with a rigid body with constant loading at 10 mm/s speed meanwhile the reaction forces and the displacement of nodes of the models were recorded. All of the specimens has the same 150 mm height, so the 125 mm crumpled distance results in more than 80% of strain. The analysing and recording timestep was 0.01 s. In order to focus on the folding behaviour of each specimen the constraint was applied to inhibit the lateral displacement and rotation. The constraints are presented in Fig. 8. The DoF (Degrees of Freedom) of the crashbox's bottom is 0. The displacement of the rigid plate is allowed in the direction of the X-axis, but the other DoF of it is constrained to get relevant information about the axial folding process and inhibit the displacement or rotation around each axis.

The basic step in finite element simulation was the partitioning of a given geometry into finite small elements, called meshing. To create a finite element model, the appropriate element type and meshing density must be chosen, taking into account the desired accuracy and the required run time. Most finite element programs perform the meshing automatically, but manual setup is also possible. A mesh of triangular finite elements is geometrically flexible. This means that it can follow abrupt changes in geometry well, e.g. tapered or rounded corners of plates. This property makes triangular meshes particularly suitable for complex surfaces (Cui et al., 2021; Bracamonte et al., 2023). A rectangular mesh is less flexible but can give better results than a mesh of triangular elements for thin surfaces (Bull, 1988). For example, it is suitable for thin steel plates. Therefore to get respective information at the end of the simulation the automatic deviation mesh generator was occurred to apply the most proper mesh type. The elements of the finite element model and the nodes connecting them can be generated by meshing the geometric model (Solid modelling) or directly (Direct

Table 1

The main characteristics of the applied material (Gleich Aluminium).

Alloy		EN AW 6082 [AlSi1MgMn]
Type of alloy		heat treatable
Temper		T6/T651
Mechanical properties		Typical values
Yield strength $R_{p0.2}$	[MPa]	240–260
Ultimate tensile strength R_m	[MPa]	295–310
Elongation A_{50}	[%]	7–10
Hardness HBW	[2.5/62.5]	89–94
Physical Properties		Typical values
Density	[g/cm ³]	2.70
Module of elasticity	[GPa]	70
coefficient of thermal expansion	[K ⁻¹ 10 ⁻⁶]	23.4
Poisson ratio	[-]	0.3
Thermal conductivity	[W/m K]	170–220

generation). In order to improve the work the models were inserted into the LS Dyna from Autodesk Inventor CAD software. When creating a finite element mesh directly (Direct generation), the location of each node and the properties of the elements must be specified separately. Although the direct method gives more freedom to control the number, distribution, shape and other properties of the elements, it is inefficient for larger numbers of elements and increases the possibility of error. Fig. 9 introduces the moments of compression finite analysing related to one of our specimens.

Care must be taken that weight optimization is also a requirement in our research therefore the applied material is an alloyed aluminium namely EN AW 6082, whose most important physical and mechanical characteristics are summarized in Table 1. The data are used in LS-Dyna to parametric the simulations.

6.2. Evaluation criteria

The force and displacement data are recorded to illustrate the compression curve of each construction. The comparison is based on the FoC (Force of Crumpling), the MFF (Mean Folding Force) and the amount of absorbed energy abbreviated with AE. The FoC introduces the first maximum strength means the end of the elastic zone. The average force during the folding is represented by the MFF. To get each structures's energy-absorbing capacity the force-displacement curve must be integrated. An ideal energy absorber has a long plateau range, where the folding force could be considered constant in the function of strain. To compare the compression curve of each structure with the plateau range of an ideal absorber characteristic the STDEV (Standard Deviation) and the RSD (Relative Standard Deviation) have been determined and given in percent units. The standard deviation is used as a measurement of the variance in a collection of numbers in relation to their average (mean)

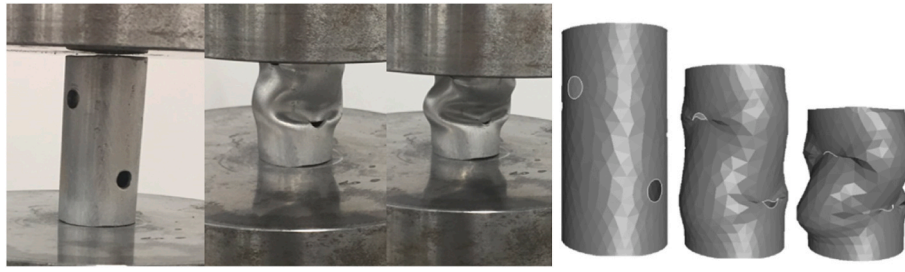


Fig. 10. Real and FEA specimens for process validation.

(Wan et al., 2014). The (5) is the description of the STDEV, where the value of point i in the data set is x_i , and the value of the data set is x . The number of observations in the entire data collection is n .

$$STDEV = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}} \quad (5)$$

Relative standard deviation is also known as the relative percentage standard deviation form, the deviation measurement which tells us how different numbers are dispersed around the mean in a particular set of data. This format shows the percentage distribution of data (Wan et al., 2014). The (6) is the formula of the RSD, where the denominator is the mean value of the database.

$$RSD = \frac{STDEV}{\frac{\sum_{i=1}^n x_i}{n}} \quad (6)$$

The RSD of the crashbox's curve is higher, which means that the folding force is very wide-ranging from the mean of that ideal one. Furthermore, the deviations are presented in the $\varepsilon = 0\text{--}50\%$ and $\varepsilon = 50\text{--}80\%$ range to get more detailed information about the behaviour of each construction. All of the specimen have 150 mm length, and 90 mm $\times$ 60 mm main cross-section dimensions with 2 mm wall thickness. The optimum mass and volume consideration is an important point of view in the present study therefore at the end of the study the SEA_m (Specific Energy Absorbing related to mass) and SEA_v (Special Energy Absorbing related to volume) are also determined and compared. Specific Energy Absorbing (SEA) facilitates the comparison of the energy absorption capacities of two distinct crashbox designs where weight optimization is a key project component (Hussain et al., 2021; Bayu et al., 2022). It should go without saying that increasing the volume or wall thickness of a crash construction will increase its ability to absorb energy. However, this is constrained by mass optimization, and simultaneous attention must be paid to the space needed. As a result, SEA is a great way to estimate how much energy a crashbox's unit mass or volume can absorb.

$$EA = \int_0^{\delta} F(x) dx \quad (7)$$

$$SEA_{\text{mass}} = \frac{EA}{m} \quad (8)$$

$$SEA_{\text{volume}} = \frac{EA}{V} \quad (9)$$

Where m is the mass, V is the specimens' volume, and EA is the quantity of absorbed energy, expressed in kilojoules (kJ). Essentially, it is a nexus determined by the volume or mass to absorbed energy ratio (Hamidreza et al., 2020; Djamaluddin et al., 2017). This can definitely serve as a guide for the creation of a mass optimization passive safety system. In this study, the maximum allowable peak force is maximised at 100 kN force. Since above this value, the cross-member may suffer permanent deformation, which is not allowed in a low-velocity impact, therefore the force applied during the folding of each construction must not exceed 100 kN. To get information about the efficiency of each specimen

the CFE (Crashing Force Efficiency) is used as evaluation criteria as well (Okorugbo et al., 2019). For the determination of this parameter the ration of the first peak force (F_{max}) and the mean crashing force (F_{avg}) must be accounted.

$$CFE = \frac{F_{\text{avg}}}{F_{\text{max}}} [\%] \quad (10)$$

The SE (Stroke Efficiency) could be another useful evaluation parameter of crashbox investigations. The SE expresses the ratio between the crushed length of crashbox after loading and the initial length (Rogala et al., 2022) However during our investigation in all of case of specimen same (125 mm) loading displacement was applied. Therefore to get relevant informations about the efficiency of crushing displacement of crashboxes, this value is determined as the absorbed energy in function of displacement.

$$CDE = \frac{EA}{l} \left[\frac{J}{mm} \right] \quad (11)$$

Where the EA is the absorbed energy given in Joule, the l is the 125 mm occurred loading displacement.

7. Model validation and mesh convergence analysis

7.1. Experimental investigation

The FEA models were parametrized in LS Dyna PrePost using versions of V.4.7.17. For the numerical study "Plastic-Kinematics" material model was used. Tensile stress-strain curves with computed modulus, strength, elongation, and Poisson's ratio are included in this material model (MAT_003) along with a density test. The LS-DYNA material cards require the collection and formatting of this data. This model is used to apply both the initial elastic data as well as the secondary plastic (post-yield) portion of the stress-strain curve. To validate the appropriateness of the parameters of the simulation experimental investigation was performed before the numerical work. Considering the complexity of the investigated specimens, for the validation of parametrization simplified thin-walled structures were applied. For the experimental compressive test AlMgSi material was used with 2 mm wall thickness and 30 mm diameter. To represent the function of crush initiators 8 mm holes were made on some of specimens. Fig. 10 shows the specimens of numerical and experimental investigation before and during the test.

The crumpling speed was limited with 1 mm/s using 40 mm deformation displacement compared to the 60 mm initial height of specimen. In order to record the force and displacement values for the test, an INSTRON 8801 servo hydraulics material fatigue test machine was employed. It was connected to WaveMatrix data collector and analysis software. The test machine's crosshead velocities were always 1 mm/s, and the system data recording frequency was 1000 s. An implement displacement encoder records the displacement, and a load cell with a 100 kN limit detects the force. At the time of measurement, the measuring instrument had a valid calibration and verification logbook, and the measurement was performed in a laboratory that has received

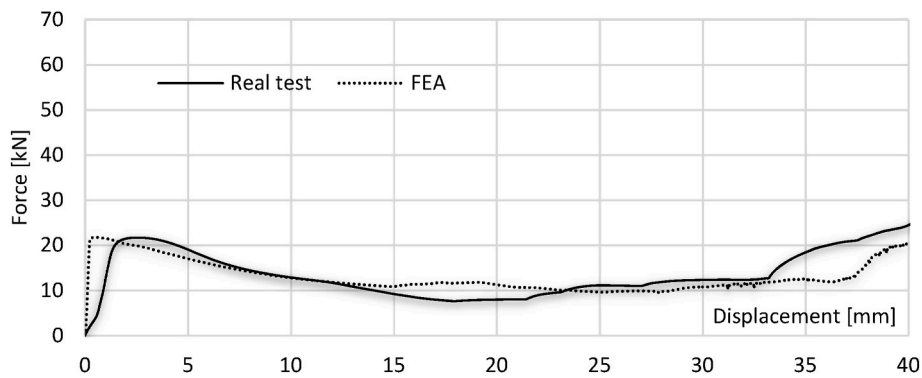


Fig. 11. Results of real and FEA test.

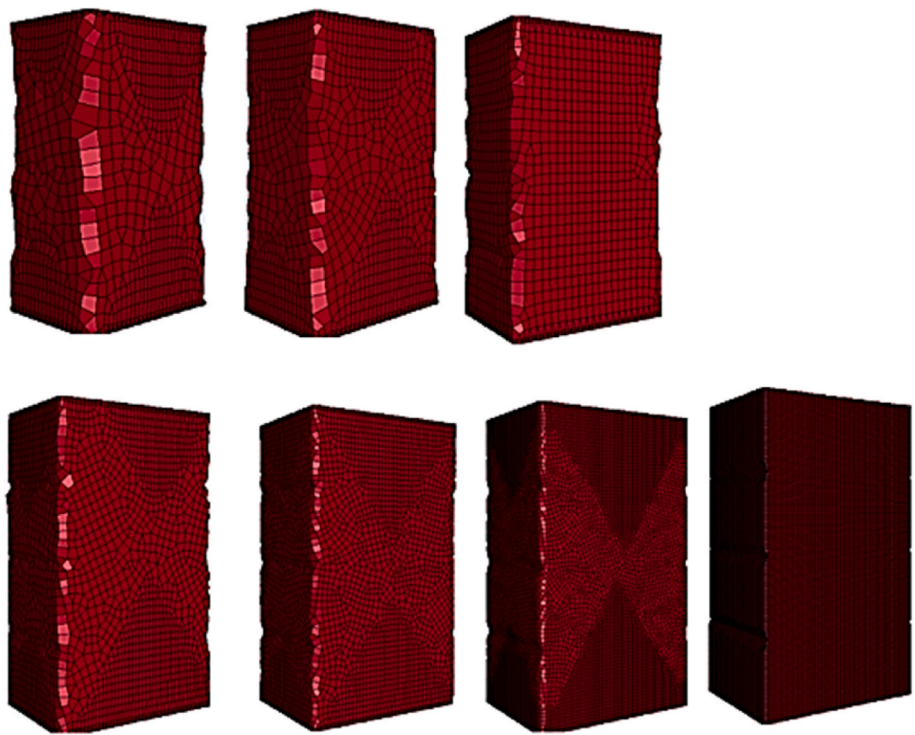


Fig. 12. FEA specimen for mesh convergence analysis.

accreditation. Before the test, the load cell's 80 kN maximum force limit was modified to prevent it from compromising its technical integrity. If this condition is exceeded, the operation is immediately stopped. Fig. 11 shows and the graphs of the real crashing test and the FEA version of it.

The compressive test confirms the appropriateness of the applied "MAT_003 Plastic-Kinematics" material model and parametrization. The major difference can be observed concerning the linear elastic zone, due to the slip of real specimen between the crosshead at the starting

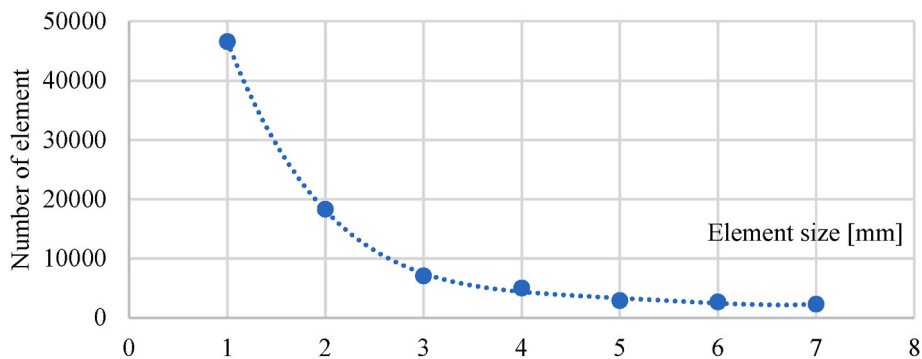


Fig. 13. Effect of element size for number of element.

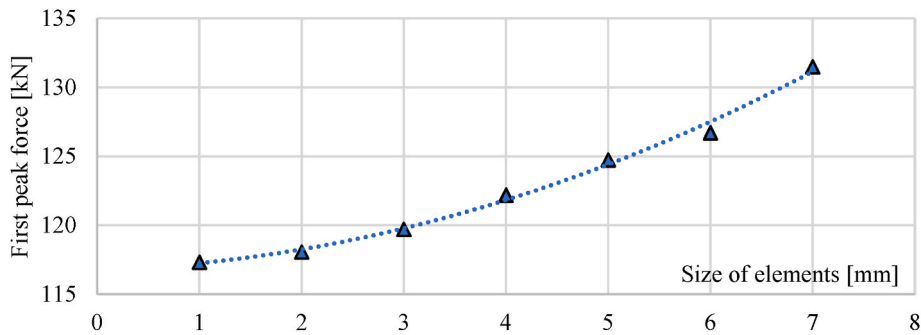


Fig. 14. Result of mesh convergence analysis.

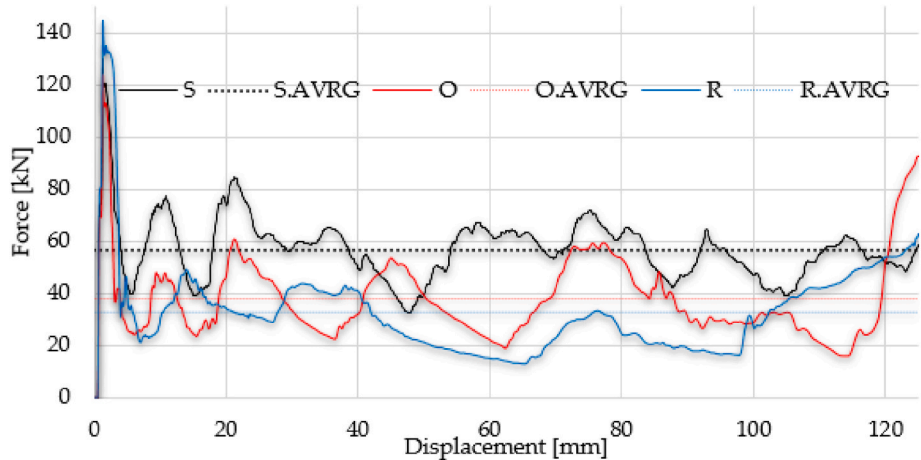


Fig. 15. Curves of the FEA compression test (Authors).

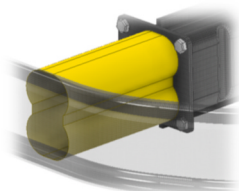
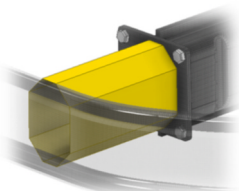
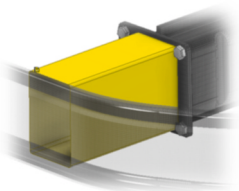
moment of crash. According to the material properties guide of the aluminium tube the yield was 150 MPa whilst, the Young's modulus is 70 GPa.

7.2. Mesh convergence analysis

Mesh convergence analysis in Finite Element Analysis (FEA) must be occurred to ensure that the results of an analysis are not affected by modifying the size of the elements. It involves increasing the number of elements in the model and observing how the results change until they

converge to a repeatable solution. This is important to achieve accurate results while balancing the size and solve time of a FEA model. Naturally the increased element numbers can result in more accurate numerical results, however significant solve time is involved. During the mesh convergence analysis a dedicated deviation must be selected given in percent. If the element size reduction results in less than 1 % accuracy the mesh density can be accepted. This is the limit where the solve time and results accuracy are in balance (Abdullah et al., 2019). A mesh convergence analysis was occurred to eliminate the mesh dependence of the simulated results. The first peak force values were used as the mesh

Table 2
The results of the basic crashbox versions (Authors).

	Type of cross-section			
	Special (S)	Octagonal (O)	Rectangular (R)	
				
FoC	130.17	123.46	144.26	[kN]
MFF _ε = 0–50%	57.25	35.89	30.77	[kN]
MFF _ε = 50–80%	55.08	38.24	30.97	[kN]
STDEV _ε = 0–50%	11.77	10.43	9.59	[kN]
STDEV _ε = 50–80%	7.78	16.66	13.27	[kN]
RSD _ε = 0–50%	20.55	29.05	31.16	[%]
RSD _ε = 50–80%	14.12	43.58	42.84	[%]

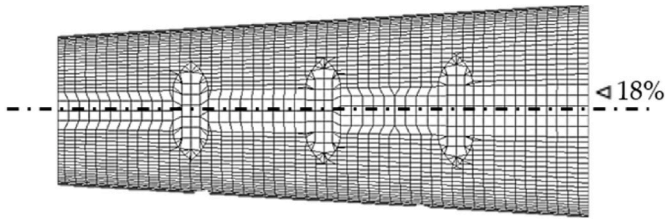


Fig. 16. 18% conic was applied on the crashbox specimen (Authors).

convergence criteria, relative error values were calculated between the maximum force values and convergence was detected if deviations were smaller than 1%. For the mesh convergence analysis the RN (Rectangular-Notched) specimen was used. The analysis contained 7,6,5,4,3, 2 and 1 mm element size investigation, which is presented in Fig. 12. The results of the convergence analysis is presented in Figs. 13 and 14.

8. Effect of the shape of the cross-section

Fig. 15 shows the results of the first comparison test. There was no

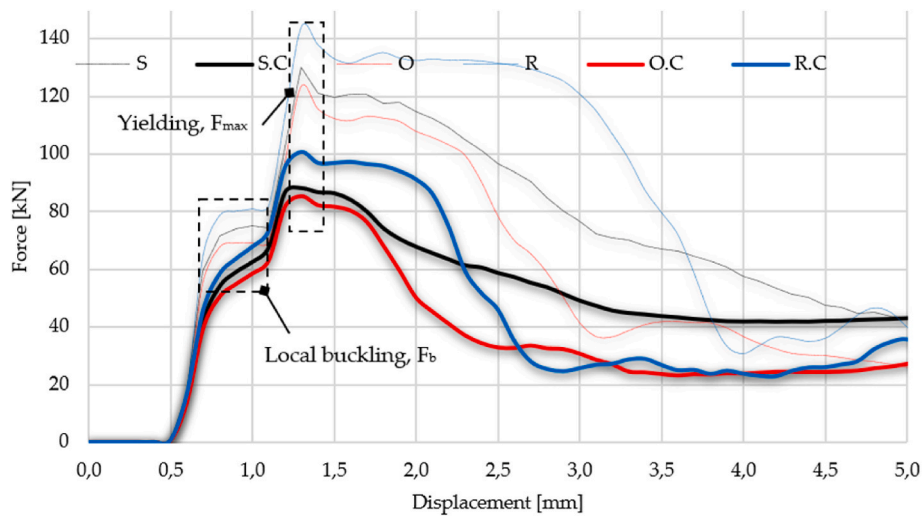


Fig. 17. The effect of the conic shape for the peak force (Authors).

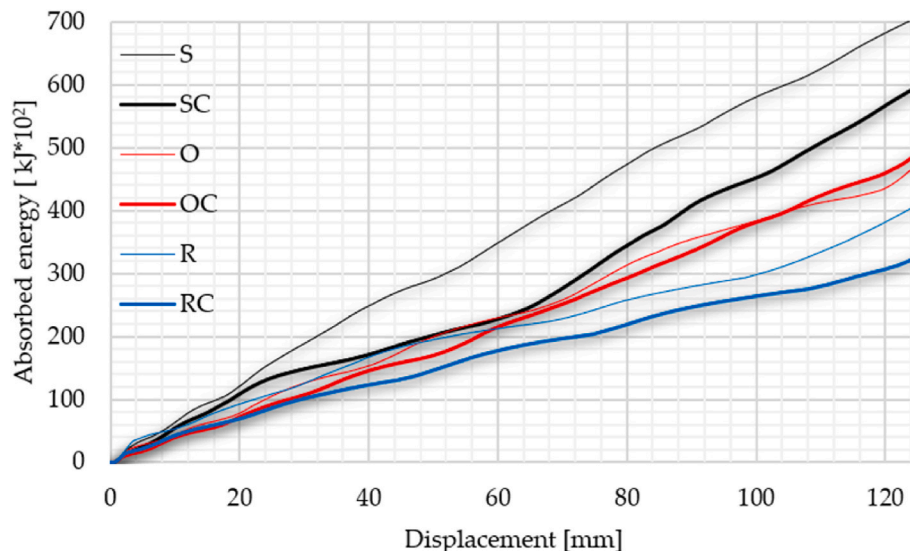


Fig. 18. Comparison curves related to the absorbed energy in the function of displacement (Authors).

significant difference related to the first maximum folding force. The rectangular cross-section specimen had the highest force level with 144 kN exceeding the 100 kN limit. However, none of them could miss the requirements related to the force limit in order to prevent cross-member. After the first force peak, the folding process can be seen well, since the next range has a waving fluctuation but the specimen with a special shape had the highest average folding force. According to the diagram curves comparison, it can be clearly shown that the amount of absorbed energy can be improved using more edges, filleted or more complex inner cross-sections. Considering the high force peak and the low-performance folding force of the rectangular version is not the best way to apply it as a crashbox. Results of the test are collected in Table 2 can help reveal the dissimilarity of each curve.

9. Effect of the conic

In the previous chapter as it can be seen clearly the first peak load has importance related to the prevention of the integrity of sidemember. The function of crashbox is to prevent serious permanent injury to the vehicle's bodywork meanwhile reduce the collision force loading the passengers in the case of low-speed impact. It must be avoided that the



Fig. 19. The notched versions of the crashbox specimens (Authors).

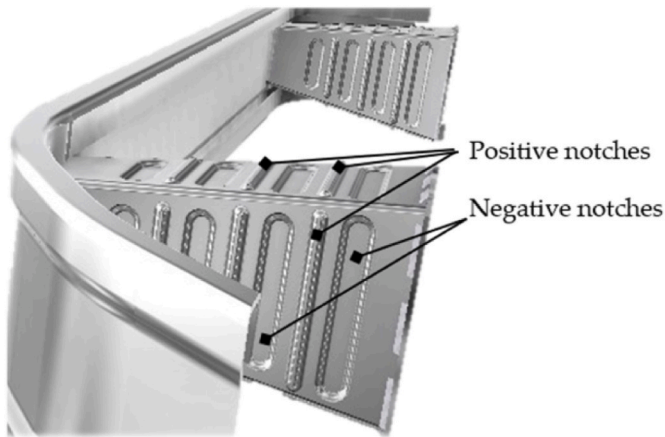


Fig. 20. Interpretation of the positive and negative notches (Authors).

first peak load of the crashbox exceeds the cross-member stiffness. Otherwise, the crossmember will be collapsed and deformed earlier which is an undesirable process. With shape optimization, the first peak load can be reduced significantly. One of these solutions is the conic shape on behalf of the length of crashbox. The conic could be described with the differential of the diameters and the length ratio. Case of all three types of specimens same conic modification was applied namely 18% presented in Fig. 16.

To reveal the positive effect of the applied conic the curve of normal specimens and conic ones are compared and presented in Fig. 17. Where the thick lines are matched with the conic type. Independently from the shape of the cross-section applying a conic shape the first peak load of the crashbox could be optimized significantly. The information detailed in Fig. 12 can be clearly observed also. The shape of the curve could be considered similar since each type and its conic version are nearly parallel. In the case of uniform one, the peak load is reduced by 32 % and

reached 88 kN. Analyzing the octagonal and rectangular ones the tendency was the same since in the case of the former the reduction was 30.89% while the rectangular's peak was improved with 30.61%, in numerical terms 85.36 kN and 100.74 kN, respectively. Referring to the maximum allowed 100 kN force in order to sidemember protection the rectangular type with conic optimization still does not meet the requirement. In the case of the other two, the peak force is remarkably lower than the permitted limit. The buckling (P_b) force can be observed despite the application of a conic shape. The results of the compression test clearly demonstrate the positive effect of the conic shape related to the peak force limit of the crashbox. From another point of view, this optimization influences the energy-absorbing efficiency of each version. Fig. 18 shows the value of the absorbed energy in the kJ unit.

As can be seen the absorbing performance of the crashbox with a special (S) shape has worse after using conic. Numerically the normal version absorbed 7.01 kJ while the conic version of it was only 6 kJ. Referring to the curves of the octagonal (O) and octagonal-conic (O.C) there was no significant deviation, further with 4% the conic could absorb energy. In the case of rectangular ones, the conic version absorbed 3.2 kJ energy which is worse by 15% compared with the conicless type. This comparison also confirms that the rectangular cross-section application as a crashbox is not the best way, since it has the lowest energy-absorbing performance of these three types.

10. Effect of the notches

Notches are geometrical differences along the structure that are designed to help the structure collapse in the desired way and reduce the force fluctuation during the compression. In the present study, the main goal of the notch application is to feed the effect of it for the energy absorbing capacity, for the peak force and the values of the STDEV and RSD. All of the specimens are modified with three same depth notch with the same location along the side of the constructions. These specimens are introduced in Fig. 19.

Basically, the distinction is made between negative and positive notches according to the direction of their design. In this investigation the negative version is applied means the notch points inwards relative to the plane of the part. The difference is represented in Fig. 20.

To get informative data about the effect of the notches they are compared with the normal version of them. This comparison is introduced in Fig. 21 where the thick lines are on behalf of the notched versions. Applying the notches the force peak of the compression can be improved, the effect of it is lower than the conic shape, but on average 10–15 % better value can be achieved with them compared with the normal ones. It is interesting to see that in the first 10 mm displacement,

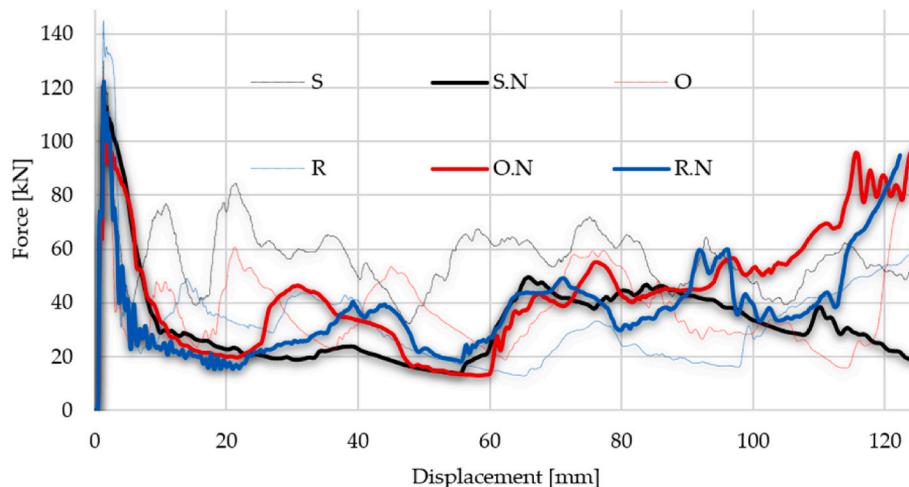
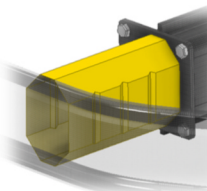
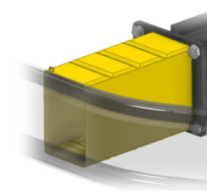


Fig. 21. Graphs of the FEA compression test of notched versions (Authors).

Table 3
The results of the compression test of notched versions (Authors).

	Type of cross-section			
	Special-notched (SN)	Octagonal-notched (ON)	Rectangular Notched (RN)	
				
FoC	120.34	107.57	122.31	[kN]
STDEV _e = 0–80%	16.47	21.53	16.79	[kN]
RSD _e = 0–80%	50.49	48.25	44.85	[%]
AE	4.07	5.51	4.61	[kJ]

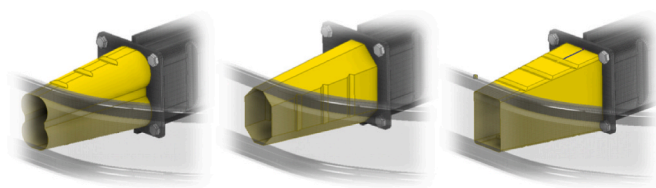


Fig. 22. Simultaneous application of notches and conic on the crash-boxes (Authors).

the special (S) and the octagonal (O) has the same compression curves, which involves the similarity of the notched versions curve. The steepness of the curves can be clearly influenced by the application of notches in the case of special and octagonal, so we can use it to influence the amount of energy absorbed. Meanwhile, the rectangular version with notches has no particularly different characteristics. Compare with the conic solution these notched boxes exceed the allowed force peak. However independently from the cross-section type, the notched versions have significantly lower energy-absorbing performance behalf on the notches applying. Above the 100 mm displacement (80% strain) there is a notable increasement related to each curve which can be explained by the formation of a densification zone. As it can be seen at the end of the compression more version approach the allowed 100 kN limit. The main results of the compression test about the notched version are collected in Table 3. According to the table with these quality and quantity notches the consistency of the folding could not be improved based on the STDEV and RSD values as evidenced by the STDEV and RSD

values.

11. Simultaneous application of notches and conic

In the next the previous two versions are combined to analyze the effects of them for the absorbed energy and the peak force. Our hypothesis was that applying conic and notching the peak force - at the beginning of the compression - could be improved more effectively than using one of them. Naturally due to the conic shape only smaller notches could be applied owing to the lack of enough space. In this chapter, the tested constructions are introduced in Fig. 22. The results of the compression tests can be seen in Fig. 23.

The use of notches and a conic simultaneously fulfilled the hypothesized effect of significantly reduced peak force compared to the original design numerically we could reach an average 35% improvement. Comparing the rectangular (R) with the conic-notched (RCN) version the improvement was 36.8% on behalf of the peak force. Analyzing the octagonal (O) and the octagonal-conic-notched(OCN) versions the latter one had a lower peak force with 37.33% numerically 77.37 kN. With the application of notches and conic in the case of special (S), the SCN specimen had remarkably better values, since the peak force is 88.26 kN, which is a 32.1 % improvement. The average STDEV and RSD were 12.35 kN and 34.51%. The ideal compression energy absorber has a nearly horizontal curve after the yield force. With the notches, our goal was to cushion the curve's fluctuation to get a more consistent horizontal graph. However, the finite element analysis confirmed that the simultaneous use of both conical and notched elements is not sufficient to achieve the plateau phase typical of metal foams. More specifically,

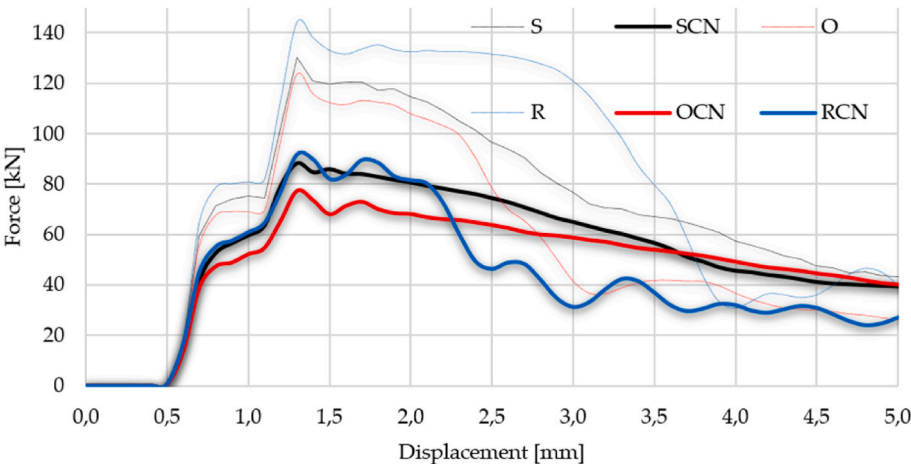


Fig. 23. The effect of the simultaneous application of notches and conic for the yielding force(F_{max}) (Authors).

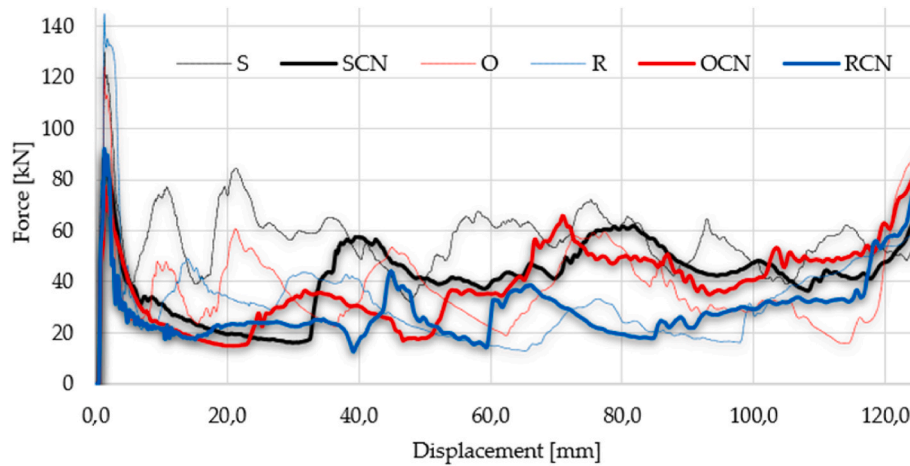


Fig. 24. The effect of the simultaneous application of notches and conic on the graph's characteristics (Authors).

Table 4

The results of the compression test with SEA values (Authors).

	S	SC	SN	SCN	Unit
Mass	219	174.1	220.2	186.9	g
Volume	81.2	64.5	81.6	69.2	cm ³
Absorbed Energy	7.05	6	4.07	5.22	kJ
SAE _{mass}	0.032	0.034	0.018	0.028	kJ/g
SAE _{volume}	0.086	0.093	0.050	0.075	kJ/cm ³
	O	OC	ON	OCN	
Mass	205	174	206	175	cm ³
Volume	75.9	64.4	76.3	64.8	g
Absorbed Energy	4.72	4.88	5.5	4.86	kJ
SAE _{mass}	0.023	0.028	0.027	0.028	kJ/g
SAE _{volume}	0.062	0.076	0.072	0.075	kJ/cm ³
	R	RC	RN	RCN	
Mass	238	202	240	203	g
Volume	88.1	74.8	88.9	75.2	cm ³
Absorbed Energy	4.07	3.24	4.61	3.56	kJ
SAE _{mass}	0.017	0.016	0.019	0.018	kJ/g
SAE _{volume}	0.046	0.043	0.052	0.047	kJ/cm ³

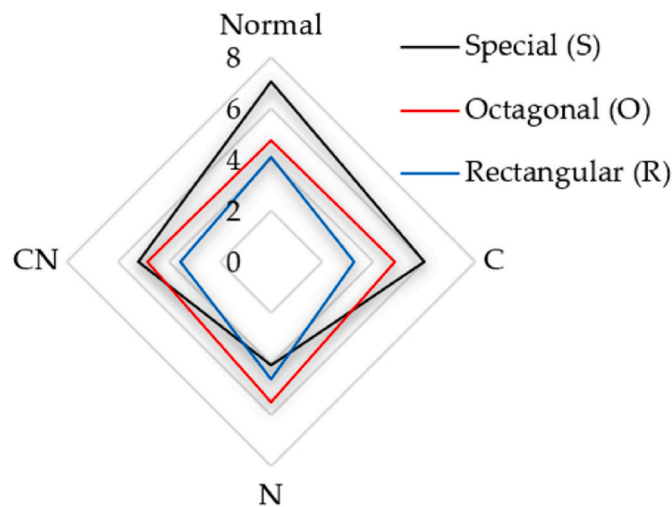


Fig. 25. The effect of the conic, notches on the amount of absorbed energy in a unit of kJ (Authors).

the number and design of the notches used here are not adequate for this purpose. To obtain characteristics similar to the ideal plateau section, further investigations are necessary. Fig. 24 shows the compression results from up to 80% strain.

12. Specific Energy Absorbing (SEA)

With SEA, the performance of the development may be described objectively, and it may also assist in determining the most efficient design for passive safety systems. The specimens' mass and volume can be checked using LS-Dyna. The values are compiled in Table 4. With the SEA it can be determined how could be influenced the absorbing capacity of a specimen increasing the wall thickness or the dimensions of it. It goes without saying that if you want to absorb more energy, you need to increase the length of the crashbox. This in turn can have a negative impact on folding, as it increases the likelihood of buckling, which is undesirable. From another point of view, the design and the fixing of a single component do not allow the use of a crashbox that is too long (Choi et al., 2022; Yusof et al., 2017).

Based on the values of Table 4 and Fig. 25 can be established that with a more complex cross-section more impact energy could be absorbed during the compression. Fig. 25 compares each type of crashbox in the function of modification. Naturally, the letters mean in order C as conic, N as notched and CN conic-notched modification on behalf of the normal version. According to the comparison it can be stated that the conic and notches have no significant positive effect on the energy absorption in the case of special (S) and rectangular (R) ones. Meanwhile applying conic and notches on the octagonal (O) specimen does not result in reducing related to the energy.

Using Fig. 26 where the SEA of specimens are compared the best one can be selected if the main aspect is the energy absorbing in the function of mass or volume. The left side of Fig. 26 is about the SEA_{mass} given in kJ/g, while the right one is about the SEA_{volume} with kJ/cm³. In both cases, the conic version of the special (S) named crashbox has the best performance out of the twelve versions. Of course, the selection of the best one cannot be focused solely on the energy absorption rate, the peak force rate expressed in the previous chapters and the STDEV and RSD of the yield after the section are also important factors. After all, the peak force should be kept below 100 kN and the deviation values as low as possible.

13. Conclusions

Owing to the notable increase in the number of vehicles on the roads involve more and more likelihood of collision between two. In crowded city road rear-end collision is one of the most frequent accident types

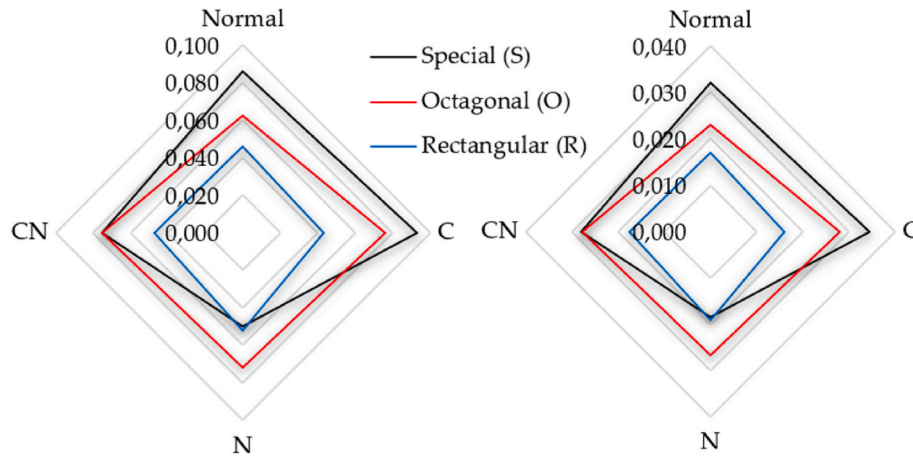


Fig. 26. Comparison graph of SEA_{mass} (left) and SEA_{volume} (right) (Authors).

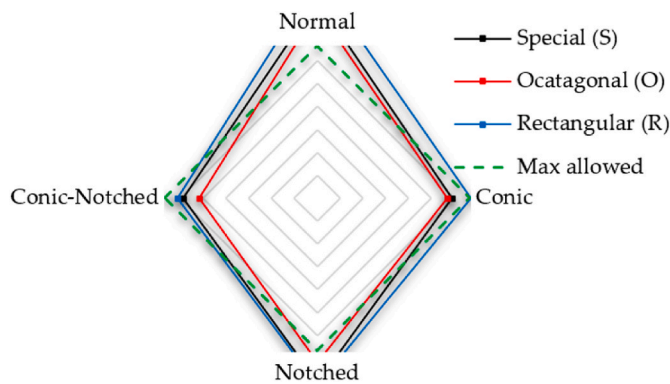


Fig. 27. The effect of the modifications for the F_{max} (Authors).

nowadays. We are speaking about low-speed collisions when the speed difference between the occupants is less than 16 km/h. The typical personal injury related to a rear-end collision is the whiplash damage to the passengers. The passive safety parts are applied to reduce the effect of impact related to the drivers and the passenger of the occupants' vehicle. Among others, the bumper and the crashboxes are the most important components of the vehicles which are responsible for the impact causing serious personal and technical damage prevention in the case of low-speed impact. UN ECE R42 and R94 regulations state the requirements related to the bumper and its accessories like crashbox.

They must prevent damage to the sidemember of the vehicle during a low-speed collision, meanwhile, absorb as most as impact energy. The working principle behind energy absorption is about the prescribed crumpling. The crashboxes as thin-walled structures can absorb impact energy during their folding and this folding process could be influenced by shape, material, and wall thickness modification. Using LS-Dyna FEA software is a good way to get relevant information about the effect of each modification related to the folding behavior of the crashboxes. The three basic cross-sections (special (S); octagonal (O); rectangular) occurred and then these were modified with a conic shape and application of notches on their surface. The ideal absorber has a plateau section at the stress-strain curve after the linear elastic section. Our long-term goal is to develop a crashbox which has a plateau curve during the folding. Therefore in the present study, the comparative criteria were the absorbed energy, the standard deviation, the relative standard deviation and last but not least the first force peak. Based on the results of the FEA it can be clearly stated that the yielding (F_{max}) can be modified with shape optimization. It was an important point of view that the force peak could not reach the allowed 100 kN force limit. Applying a conic shape and notching the peak of each construction could be considerably reduced. Of this requirement, the octagonal-conic-notched (OCN) specimen met the best. Fig. 27 reports the peak force – given in the kJ – unit comparison graph. As can be seen non of the normal version of the crashbox specimen do not meet the 100 kN maximum force limit. The diagram shows that by using a conical shape, the peak force can be significantly reduced and even kept below the maximum allowable value. The use of notches was not sufficient for any of the cross-sectional

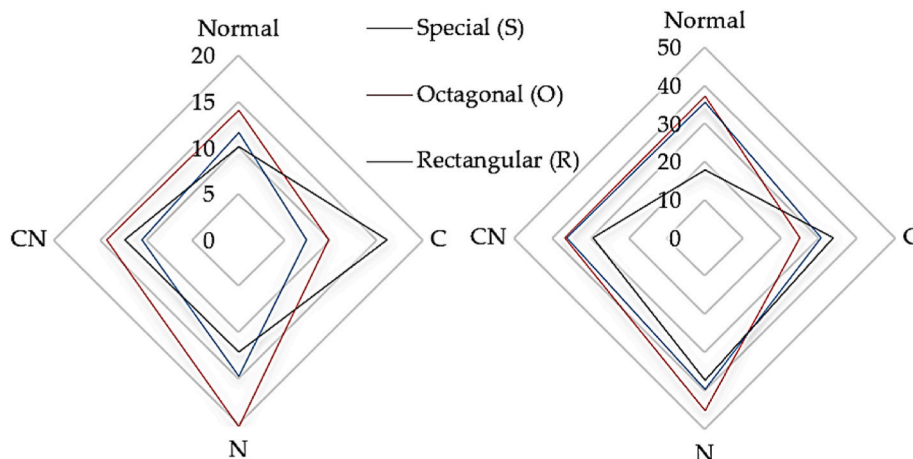


Fig. 28. The STDEV (left) and RSD(right) of the graphs (Authors).

Table 5

The result comparison with crucial evaluation parameters.

	S	O	R	SC	OC	RC	SN	ON	RN	SCN	OCN	RCN
First Peak Force (F_{max}) [kN]	130.2	123.5	144.3	88.1	85.4	100.7	120.3	107.6	122.3	88.3	77.4	90.1
Crasing Force Efficiency (CFE) [%]	44.0	29.1	21.3	46.5	32.9	28.8	31.8	37.2	28.6	46.7	45.8	31.4
Crashing Displacement Efficiency (CDE) [%]	56.4	37.8	32.6	56.1	48.2	25.6	32.6	44.1	36.9	41.8	38.9	28.5

variants, as none of them met the 100 kN limit. However, the simultaneous use of a tapered surface and notches is most appropriate when the reduction of the F_{max} force is the primary consideration.

According to these aspects the special (S) has the best-absorbing performance numerically more than 7 kJ meanwhile the worst is the conic version of the rectangular (RC) one. Analyzing the first force peak application of conic and notches the peak could be significantly improved, which means all of the cross-sections have an average 35% lower yield after the shape improvement. With STDEV and RSD of the curves, the impulse fluctuation can be described. The results of this analysis are introduced in Fig. 28 where the values are calculated in the section after the force peak. As the diagrams present the standard deviation (force fluctuation) can be improved using a conic shape resulting in more consistent folding characteristics. Finally Table 5 is about the main evaluation parameters for each specimen to be more comparable.

CRedit authorship contribution statement

Jozsef Kertesz: Conceptualization, Data curation, Investigation, Software, Validation, Writing – original draft, Writing – review & editing. **Tunde Anna Kovács:** Formal analysis, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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