PAPER DETAILS

TITLE: Response of trigger type to circular CFRP crash box energy absorption performance

AUTHORS: Ertan Kösedag

PAGES: 123-130

ORIGINAL PDF URL: https://dergipark.org.tr/tr/download/article-file/3369020

NÖHÜ Müh. Bilim. Derg. / NOHU J. Eng. Sci., 2024; 13(1), 123-130

Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi
Niğde Ömer Halisdemir University Journal of Engineering Sciences

Araştırma makalesi / Research article

www.dergipark.org.tr/tr/pub/ngumuh / www.dergipark.org.tr/en/pub/ngumuh

Response of trigger type to circular CFRP crash box energy absorption performance

Tetikleyici tipinin dairesel KFTP çarpışma kutusu enerji emilim performansına etkisi

Ertan Kösedağ[1,*]

[1] *Van Yüzüncü Yıl University, Department of Mechanical Engineering, 65080, Van, Türkiye*

Abstract

In this study, carbon fiber reinforced polymer matrix composites were produced to investigate the trigger effect on energy absorption performance. Production was carried out by vacuum infusion method. Three types of trigger geometry were opened on the composite crash boxes produced and also comparison sample without trigger was prepared. The quasi-static compression tests of these four different samples were carried out and the energy absorption performances of the samples were evaluated with the obtained data. In addition, the damages of the samples were examined, and it was revealed how they changed with the trigger. Accordingly, the sample described as S-2, (the triggered sample, which consists of four symmetrical slits downwards from its upper surface) exhibited the best performance in terms of absorbed energy. Additionally, the peak forces were reduced with the triggers opened and the maximum peak force decreases were seen in S-3(with hole type triggers) and S-4 (with horizontal slit type triggers) samples.

Keywords: Carbon fiber reinforced composites, Crash box, Trigger

Öz

Bu çalışmada enerji absorpsiyon performansı üzerine tetikleyici etkisinin incelenmesi için karbon fiber takviyeli polimer matrisli kompozitler üretilmiştir. Üretim vakum infüzyon metodu ile gerçekleştirilmiştir. Üretilen kompozit çarpışma kutularının üzerine üç çeşit tetikleme geometrisi açılmış ve bir de tetikleyici içermeyen karşılaştırma numunesi hazırlanmıştır. Bu dört farklı numunenin yarı-statik basma testleri gerçekleştirilmiş ve elde edilen datalar ile numunelerin enerji emme performansları değerlendirilmiştir. Bunun yanında numunelerin hasarları incelenmiş ve tetikleyici ile nasıl değiştiği ortaya konmuştur. Buna göre S-2 olarak tanımlanan numune (üst yüzeyinden aşağıya doğru dört simetrik yarık ile tetiklenen numune), emilen enerji açısından en iyi performansı sergilemiştir. Ayrıca açılan tetikleyiciler ile tepe kuvveti düşürülmüş ve maksimum tepe kuvveti azalmaları S-3 (delik tipi tetikleyiciye sahip) ve S-4 (yatay yarık tipi tetikleyiciye sahip) numunelerinde görülmüştür.

Anahtar kelimeler: Karbon fiber takviyeli kompozitler, Çarpışma kutusu, Tetikleyici

1 Introduction

Automobile manufacturers compete in the automotive sector to build better cars with essential performance and safety standards. In the event of an accident, a significant quantity of energy is produced due to the velocity and mass of the cars, and this energy needs to be adequately absorbed. Manufacturers strive to produce safer vehicles so that passengers and the vehicle are minimally affected in the event of a collision [1]. The production of forces that may hurt the driver and passengers because of the energy that cannot be effectively absorbed will put their lives in danger. There are parts called crash boxes specially designed for this damping in vehicles [2]. Studies on crash boxes have become more crucial as the relevance of concepts like sustainability, the environment, and fuel efficiency has increased along with the necessity of vehicle lightness and rising competition. Such structures in vehicles are categorized as collision energy absorbent element structures. Every crash endurance study focuses on energy-absorbing structures like bumpers and crash boxes. A vehicle-mounted crash box is a thin-walled structure fixed to the front of the vehicle. In the event of a collision-related crash, the structure functions as an element that absorbs energy in the car. This crash box structure is intended to act as a vehicle's passive safety system, absorbing kinetic energy in frontal collisions, limiting vehicle deceleration to a safe level, and reducing the risk of injury to the occupants [3]. The workspace of the crash-box structure includes a variety of components and methods, but mostly adds to the workspace for crash resistance. Due to these factors, proper decisions should be taken taking on the crash boxes' ability to absorb kinetic energy as well as its manufacturing potential, price, and weight. The layout of the crash box is one of the most frequently discussed subjects. To comprehend the plastic deformation behavior of various thin-walled constructions, including cylindrical, square/polygonal, conical/conical, and hat-section beams, as well as how well they can fit as an energy-absorbing component, these structures are investigated and compared [4–6]. Some studies have investigated the roles of thin-wall structure size and

* Sorumlu yazar / Corresponding author, e-posta / e-mail: ekosedag@yyu.edu.tr (E. Kösedağ)
Geliş / Recieved: 28.08.2023 Kabul / Accepted: 06.11.2023 Yayımlanma / Published: 15.01.2024
doi: 10.28948/ngmuh.1351499

thickness in collision behavior. In the design of the crash box, many designs were assessed under various conditions, including infills, hybrids, and multicellular structures. Studies on the configuration of defects are carried out to assess the energy absorbed by thin-walled structures with trigger defects [7].

The majority of investigations on the crash box have, according to the study of the literature, concentrated on how well the crash box construction absorbs energy [3, 5, 8]. Existing studies are reviewed and some of them are given below. When the results of previous studies are examined, it is seen that geometric shapes give different results in energy dissipation. The amount of energy dissipated varies depending on the strength of the material of the crash box, the thickness of the walls, the basic shape of the box and some design parameters such as whether infill material is used or not. Although the amount of energy dissipation depends on the strength of the material used, strain is required to dissipate energy. In other words, it is not desirable to bear the impact by using a very strong and rigid structure under impact. In such a case, the deceleration will remain at very high values, high forces will affect the passenger and cause the sensitive parts inside to be deformed by not being able to withstand the load [9]. To reduce the weight, cost, and increase energy absorption of crash boxes, numerous experiments have been conducted. These studies can be divided into classes such as changing the geometry, using infill, and changing the material used, creating triggers to manipulate the damage mechanisms of the crash box.

Zhonggang Wang et al. [10] carried out studies by keeping the weight constant on a classical empty column and columns divided into cells. In this study, it is aimed to examine the folding mechanics. Like the previous study of Nasir et al. [11], the results obtained in the experiments and simulations were compared and the simulations were confirmed, and then the studies were continued with emphasis on simulation. Columns with different cell numbers (n) were used in the studies. To determine the contribution of the column connection types to the energy absorption, the connection types are divided into three as corner, t and diagonal. As the number of cells increased in the columns, the thickness was decreased to keep the weight constant. It was determined that thick-walled low-cell structures were twisted and folded at longer lengths. The oscillation amplitudes in the forces decreased significantly due to the thinning of the walls as the number of cells increased. In this study, it was also determined that the cross-link type was the most effective connection type in energy absorption. Corner and junction points influence energy dissipation in multi-cell studies [12–14]. Heung-Soo Kim [15] draws on studies that report that as more material is added to the corner portion, more crash energy is absorbed. The issue of global instability, however, could materialize since the folding wavelength is substantially longer for columns with thicker corners. Considering this negativity, different profiles are envisaged to both increase the crash energy absorption and provide a more stable and gradual collapse under certain constraints. In this context, the idea of adding an additional folding element to the corner of a cross-section was proposed, and profiles with different cross-sectional areas, produced with aluminum extrusion and one more square column added to the corners, were put to the test. According to the results obtained in a study in which the effect of the number of sides of the polygon on the energy dissipation is discussed [11]; Although the energy absorption often increases with the increase of the number of edges, it may decrease in some number of sides and when approaching some number of sides, and considering that the cylinder is an infinite polygon, it can be said that there is an optimum point on the energy absorption depending on the number of sides. Three categories of materials can be utilized to make crash boxes: metal/alloy, composites, and hybrids of composite-metal/alloy. Studies mostly focused on steel and aluminum as the primary materials in the metal/alloy category. On the other hand, aluminum is a strong yet lightweight material, which has piqued the curiosity of researchers who want to assess how well it can withstand impacts. In the meantime, research on composite materials is constantly in demand because there is such a demand for a metal substitute [16–18]. To enhance energy absorption capacity, crash box designs that are distinctive or original have been made possible by the use of composite materials. Huusayin [19] assessed the energy absorption capabilities of axially crushed glass fiber reinforced plastic (GFRP) crash boxes with various geometries. According to a comparison of the collision outputs, the order of the geometries with respect to energy absorbed was square, cylindrical, hexagonal, and decagonal. The decagon shape had the highest peak force value, and the square shape had the lowest. Nia et al. [20] compared a big collection of aluminum alloy tubes with various cross-sectional forms. The authors found that cylindrical pipes absorbed the most energy per unit mass under the same loading (quasi-static loading). The gradual increase in the cross-sectional area of the samples affected the maximum and average forces as well as the energy absorption capacity [21].

In addition to the geometric shape of the crash box, which is the main factor contributing to the crash-proof performance; loading state can also affect collision behavior. Understanding collision behavior under different loads helps us determine where in a car the crash absorption structure should be placed. Axial loading, oblique loading, lateral loading, and bending loading are basically the four loading states connected to car impact. Crash boxes, can be tested for both axial and oblique impact loads in the quasi-static or dynamic condition. [3, 4, 22]. To comprehend how the breaking rate and energy affect the structure under examination, different test settings might be used. The best structure with the best crash performance should be examined under various load situations.

Another method for creating a crash box structure that is highly crashworthy is to employ triggers. Trigger, often referred to as "crush initiator," "stress concentrator," or "imperfection" in many different researches, is made with the goal of stabilizing the collapse process and lowering the peak force upon impact. Prior research has introduced many trigger kinds, including cutting, grooves/corrugation, holes, and uneven ends [19, 23, 24]. All research that used trigger in the crash box design came to the same conclusion: trigger has a significant impact on the crushing reaction and the energy absorption performance [25].

Some studies in this area are drilling [11, 26, 27], irregular finishers [11] and partial cuts. Thin-walled square tubes with rectangular and slotted windows were added by Zhou et al. [27] to improve the impact resistance of tubular structures. The authors presented quasi-static axial fracture tests, numerical simulation analyzes, four single-window tubes, twelve three-window tubes, and two conventional tubes. The findings demonstrated that although the other collapse modes of conventional tubes belong to the irregular mode, those of conventional tubes belong to the symmetrical mode. Additionally, the installation of windows can significantly lower the first peak load and increase the effectiveness of the crush force compared to standard tube. Despite the significant mass reduction for windowed tubes, the specific absorbed energy did not always increase. Circular, square and hexagonal geometries were commonly studied in crash box studies. The studies carried out with the trigger were carried out by emphasizing the stress concentration. In this context, circular geometry was chosen to avoid corners.

The aim of this study is to produce crash boxes consisting of lightweight and durable carbon fiber reinforced polymer (CFRP) matrix composites by vacuum infusion method and observe the effect of trigger type. Three different irregularities (vertical slit, hole, and lateral slit) were created to induce a trigger effect on the crash boxes produced in this direction. In addition, a regular composite circular CFRP crash box with no slits or holes was produced and tested for comparison. The data obtained from quasi-static tests of four different crash boxes were evaluated.

2 Material and methods

In this study, cylindrical crash boxes were produced from carbon fiber reinforced epoxy matrix composite by vacuum infusion method. The steps of producing carbon fiber reinforced polymer matrix composite in cylindrical geometry by vacuum infusion method are listed below. In addition, a visual taken during production is given in Figure 1. 1) The surfaces of the molds consisting of rollers are cleaned. 2) Mold surfaces are waxed to prevent sticking. 3) Plain carbon fiber fabric is fixed to the mold with spray adhesive to hold one end. 4) The fiber fabric is wrapped in the amount determined according to the thickness planning. 5) Separator fabric is wrapped on glass fiber fabric. 6) Grit meshes are wrapped on the separator fabric for homogeneous progression of the epoxy. 7) Hoses that will provide vacuum and epoxy flow are placed at both ends of the mold pipe. 8) It is taped with heat resistant nylon and vacuum sealing tape. 9) With the hose extended from one end of the mold pipe, the vacuum system is activated and all the air inside is sucked. 10) With the help of the negative pressure created by the vacuum, the end of the other hose is dipped into the epoxy hardener mixture and the whole system is wetted with the resin set. 11) The hose ends are clamped, and the system is taken to the curing oven. 12) The composite system, cured at 100 ℃ for 1 hour, is then separated from the mold pipe and its burrs are removed.

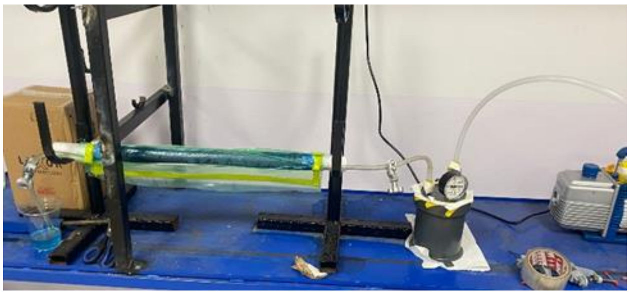

Figure 1. Production of a carbon fiber reinforced polymer matrix crash box

The composite crash boxes obtained by means of these stages were cut to 1/3-5 aspect ratio specified in the literature and taken to the test phase [3]. An image of the produced carbon fiber reinforced polymer matrix composites is given in Figure 2. The inner diameter of the composite crash box was 35 mm, the outer diameter was 40 mm, so the wall thickness was 2.5 mm. Its length was 90 mm. Three types of triggers were opened to carbon fiber composites produced in this geometry, and also a non-triggered sample was reserved for comparison. Composite materials are very sensitive to secondary processes. And in our tests, it has been seen that damage cannot be done only with the disk rotating at high speed. For this reason, the engraving set operating at high speed was used for unloading operations.

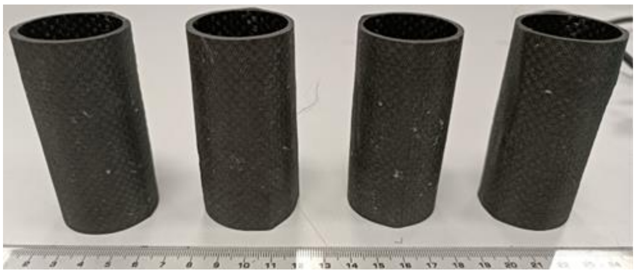

Figure 2. Composite samples that were produced and prepared for adding triggers

Triggers opened on the sample are seen in Figure 3. If these are disclosed: The S-1 sample was the non-triggered sample. The S-2 sample contained four ridges opened 10 mm vertically from the tip. The width of the slit was 3 mm. The S-2 sample consisted of four symmetrical holes drilled 10 mm down from the tip. The diameter of the hole was 3 mm. In the last sample, S-4, there were four symmetrical horizontal slits opened 10 mm below the tip. The width of the slits was 3 mm. The carbon fiber fabric used had a plain structure and an area density of 400 gr/m2. The plain fabric was wrapped in 10 layers. Hexon MGS lr-160 epoxy and lh 160 hardener were used. Quasi-static compression test was performed to determine the energy absorption of the crash box obtained from the produced composite material. The tests were carried out at 2 mm/min and continued for 35 mm. These test conditions were taken from the literature [3].

Figure 3. Sample types and the geometry of the triggers opened on them

The force-displacement curves obtained from these tests were drawn and the maximum force values were determined. In addition, the energy values absorbed were calculated by integrating the contact force displacement curves, that is, by calculating the area under them. Since the samples were about the same weight, the specific energy absorption used in such studies, which provides a mass-independent comparison, was not calculated, and the absorbed energies were compared to evaluate the trigger type effect. In addition, damage patterns were determined, and damage mechanisms were discussed depending on the trigger type. Three replicates were made for each sample and the results were added. The weights of composite tubes were almost equal to each other. As a result of the measurement, the weight of the carbon fiber reinforced composite crash box samples was determined as 36±2 grams.

3 Results and discussion

In this section, the samples were handled one by one, the maximum contact force, the energy they absorbed, and the damage images of the samples were discussed and then their comparisons with each other were made. The first sample was the S-1 sample. There was no trigger mechanism in this sample. The contact force-displacement curve containing the data of the S-1 sample is given in Figure 4. The maximum contact force of this sample was 9.48 kN, while the average contact force was 5.06 kN. The area found by integrating the contact force displacement curve, that is, the energy it absorbed, was 169 joules. When Figure 4 is examined, a sudden decrease after a severe peak force and then partially increasing and decreasing peaks are seen.

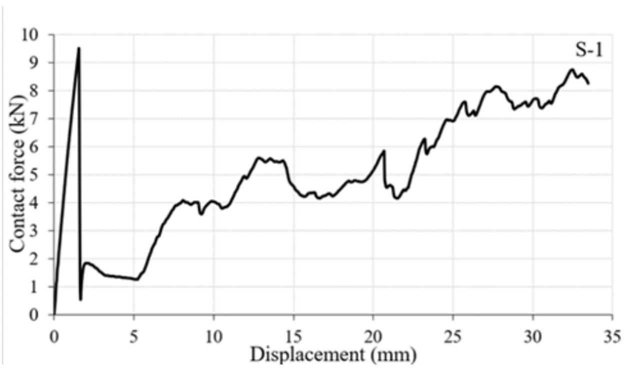

Figure 4. Contact force-displacement curve obtained from the quasi-static compression test of the S-1 sample

Peak force is usually the force that occurs when the sample is first damaged, and if this force is too high compared to the average force, it is a negative situation in terms of crash box efficiency. The small fluctuations seen after the peak force occurred because of the breaking of the horizontal fibers in the composite. The reason for the increase in the force is that some of the delaminated fibers bend inward and create resistance again.

In Figure 5, the images of the S-1 sample during the quasi-static test is given in four steps, respectively. In the first step, the sample was just placed and did not suffered any damage. The second step includes the image when the sample took the first damage, and the peak force occured. The first fracture was located almost in the middle of the sample and surrounded the sample. In the third and fourth steps, it is seen that the fiber broke in the sample and the overlapping parts forced each other to cut.

Figure 5. Damage of S-1 specimen during quasi-static compression

Another sample was the S-2 sample. In this sample, four vertically symmetrical slits were opened from top to bottom with a length of 10 mm. The contact force - displacement curve of the S-2 sample is presented in Figure 6. According to this data, the peak force, which is the maximum contact force of the S-2 sample, was 8.43 kN. In addition, the average force was determined as 6.18 kN. Compared to the S-1 sample, it is seen that there was a decrease in the maximum contact force and an increase in the average force. The energy absorbed by the S-2 sample was 210 joules. It can be calculated that it absorbed 24.2% more energy compared to the S-1 sample.

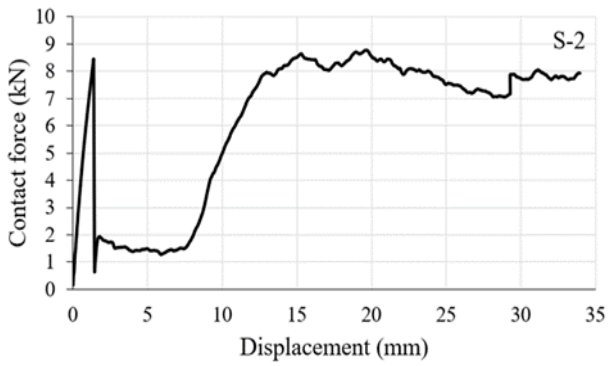

Figure 6. Contact force-displacement curve obtained from the quasi-static compression test of the S-2 sample

In addition, the requirements of decreasing the maximum contact force and increasing the average force, which are the parameters of increasing the performance of the crash boxes, were also realized. The maximum contact force decreased by 11% and the average force increased by 22% compared to S-1.

The damage steps of the S-2 sample during the quasi-static test are given in Figure 7. The first step is the original state of the sample, which was not yet been damaged. In the second step, the first fracture occurred, where the peak force was formed. The first fracture occurred at the lower border of the trigger and encircled the sample across the diameter. In the third and fourth steps, it is seen that the fibers were progressing by breaking after the sample was perforated regularly inward and outward. In particular, the final image of the sample is a type of fracture that is frequently encountered in the literature [28, 29] and is desired. Breaking in this way allows the sample to absorb the maximum amount of energy because of the absorption of the energy exposed by the occurrence of both delamination and fiber breaks.

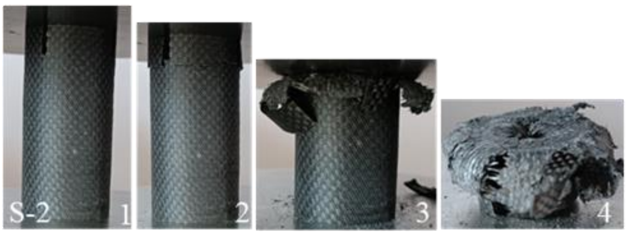

Figure 7. Damage of S-2 specimen during quasi-static compression

The third type of sample was the S-3 sample. The trigger type opened in the S-3 sample was a trigger in which holes with a diameter of 3 mm were drilled. Four symmetrical holes were drilled 10 mm below the upper limit of the sample in this sample. The contact force - displacement curve from the S-3 sample is presented in Figure 8. Accordingly, the maximum contact force that the S-3 sample responded to occurred after the first peak force. While the first peak force was 6.03 kN, the maximum contact force was 8.36 kN. Besides, the average force was determined as 5.70 kN. The amount of energy it absorbed was 198 joules. When compared with the first two samples, the S-3 sample showed a better performance than the S-1 sample without the trigger in terms of both maximum contact force and average force. However, it performed worse than the S-2 sample. As a matter of fact, while the S-3 sample absorbed 14.6% more energy than S-1, it absorbed 6% less energy than S-2. In composite systems, hole application is one of the most common mounting types during montage. According to the results we obtained, there was an improvement in performance compared to the reference sample, but a worse performance was observed compared to the S-2 type. For this reason, it will be more beneficial in terms of stress concentration to perform secondary operations like in S-2 during assembly.

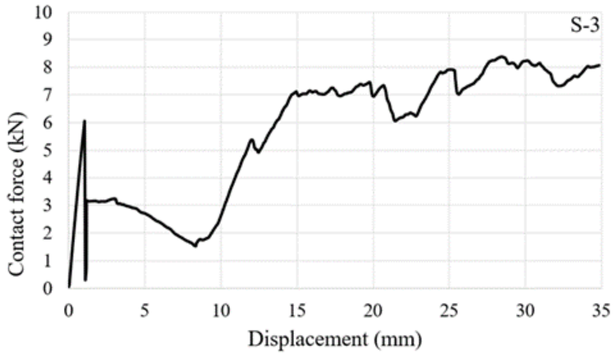

Figure 8. Contact force-displacement curve obtained from the quasi-static compression test of the S-3 sample

Damage images of the S-3 sample during the test phase are shown in Figure 9. Here, too, the first fracture started near the trigger, and then the shear force effectively advanced first on the upper side of the sample, and then the piles on the lower side were met. Thus, the contact force of this sample exceeded the first peak force after 15 mm. From this point on, the fibers progressed by being damaged by breakage and delamination like the previous samples.

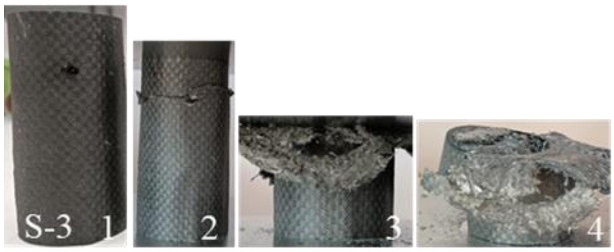

Figure 9. Damage of S-3 specimen during quasi-static compression

The final sample type was the S-4 sample. In this sample, the trigger was the horizontal cuts located 10 mm below the tip of the sample. The cuts were symmetrically positioned and there were four. The contact force - displacement curve consisting of the data of the S-4 sample is presented in Figure 10.

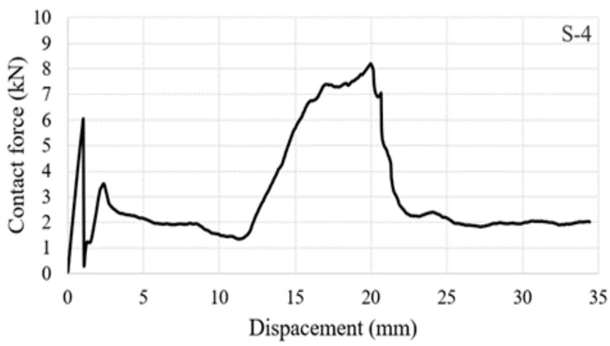

Figure 20. Contact force-displacement curve obtained from the quasi-static compression test of the S-4 sample

Accordingly, the first peak force of the S-4 sample was 6.03 kN, while the maximum contact force was 8.06 kN. The average contact force was 3.06 kN. The amount of energy absorbed by the S-4 sample was 107 joules. When these results were evaluated, it was determined that the absorbed energy decreased compared to the other three samples. The S-4 sample absorbed 96% less energy compared to the best performing S-2 sample. Based on this result, it can be concluded that the S-4 type trigger is in a geometry that negatively affects the crash box performance. In terms of energy absorption performance, ranking was S-2, S-3, S-1, S-4, from best to worst.

The fracture steps of the S-4 sample are given in Figure 11. Unlike the other samples, it is seen that the fiber breakage and delamination rate was low in S-4. Apart from this, after the first trigger point was broken, a second circular cut occurred, and these fractures progressed. Such a form of damage reduced the rate of fiber delamination. Therefore, the amount of energy absorbed also decreased.

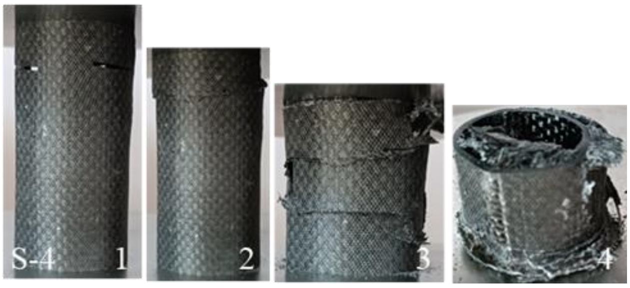

Figure 31. Damage of S-4 specimen during quasi-static compression

The amount of energy absorbed by all samples, the average contact forces and the first peak forces are presented in Table 1. In addition, the graphs obtained for these data are presented in Figure 12, Figure 13. When Figure 12 is examined, it is seen that the highest first peak force was in the S-1 sample. One purpose of triggering is to lower this peak force. Peak force decreased in all three triggered samples. In addition, it is desired to increase the average force in crash boxes. As seen in Figure 12, the average forces increased in the S-2 and S-3 samples.

Table 1. Some data from quasi-static tests for each crash box sample

Crash box samples	First peak force (kN)	Average force (kN)	Absorbed energy (joule)
S-1	9.48	5.06	169
S-2	8.43	6.18	210
S-3	6.03	5.70	198
S-4	6.04	3.06	107

The visual figure, where the amounts of absorbed energy are given together, is seen in Figure13. When Figure 13 is examined, it is seen that the energy absorbed in the triggered S-2 and S-3 samples increased and decreased in S-4. In summary, it can be determined that the triggered sample showing the best performance was S-2.

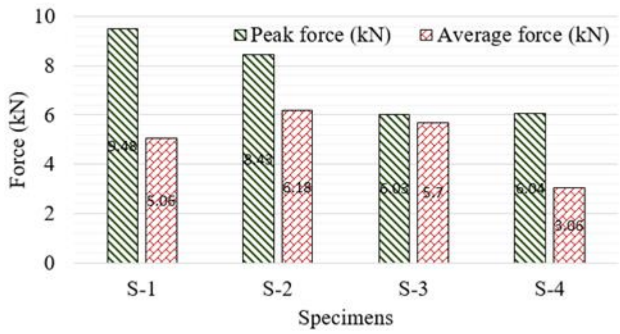

Figure 42. Comparison of first peak forces and average forces of composite crash boxes

According to the results obtained in a numerical study [19], when three types of triggers were opened on glass fiber reinforced polymer matrix composite and evaluated in terms of absorbed energy, it was revealed that the trigger had a positive effect on energy absorption. This result overlap with our results. In addition, one of the trigger types in the study was in the form of vertical slots, which we used in our study (S-2). It has been stated that this type of trigger increases energy absorption, similar to that in our study. Similarly, it is possible to come across many metal [30], polymer-based [31] numerical [32] or experimental [33] studies on the energy absorption performance of the trigger. In all of them, opening the trigger positively affected the energy absorption, similar to the results in our study.

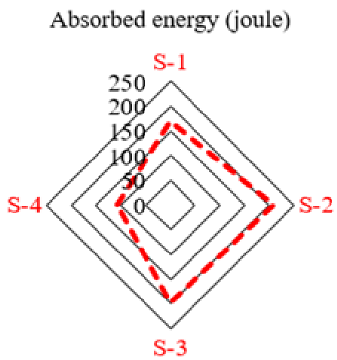

Figure 53. The relationship between composite crash boxes in terms of energy absorbed

4 Conclusion

This study is about increasing the performance of crash boxes. In this context, carbon fiber reinforced polymer matrix composites are good candidates when considering the need for lightness and high strength in vehicles. In this study, carbon fiber reinforced composites in the form of a cylindrical thin-walled structure as a crash box were produced by vacuum infusion method. It is known from the literature that the trigger effect improves performance in crash boxes. For this reason, three types of trigger geometries were created on the samples to reveal how they affect the absorption performance. In addition, one non-triggered reference sample was produced. Quasi-static compression tests were performed to determine the energy absorption and mechanical responses of all these samples, and the obtained data was evaluated to compare the trigger profiles. According to the results, vertical slits type triggers (in S-2) and hole type triggers (in S-3) showed better performance in terms of energy absorption. The horizontal slits type triggers (in S-4) showed the worst performance. In addition, contact force - displacement curve behaviors and sample damage images were compared, and it was determined that they were compatible with each other. Additionally, the peak forces were reduced with the triggers opened and the maximum peak force decrease was seen in S-3 and S-4 samples.

Conflict of interest

The author declares that there is no conflict of interest.

Similarity rate (iThenticate): %18

References

[1] W. Zhang and J. Xu, Advanced lightweight materials for Automobiles: A review. Materials and Design, 221, 110994, 2022. https://doi.org/10.1016/j.matdes.2022.110994

[2] A. Yunus Nasution, M. Rejab, Q. Ma, and M. Firmansyah, Design optimization of passenger SUV's crash box and bumper beam by using finite element method. Materials Science and Engineering, 1068, 2021. https://doi.org/10.1088/1757-899X/1068/1/012023

[3] N. A. Z. Abdullah, M. S. M. Sani, M. S. Salwani, and N. A. Husain, A review on crashworthiness studies of crash box structure. Thin-Walled Structures, 153, 106795, 2020. https://doi.org/10.1016/j.tws.2020.106795

[4] F. Tarlochan, F. Samer, A. M. S. Hamouda, S. Ramesh, and K. Khalid, Design of thin wall structures for energy absorption applications: Enhancement of crashworthiness due to axial and oblique impact forces. Thin-Walled Structures, 71, 7–17, 2013. https://doi.org/10.1016/j.tws.2013.04.003

[5] A. Reyes and T. Børvik, Quasi-static behaviour of crash components with steel skins and polymer foam cores. Materials Today Communications, 17, 541–553, 2018. https://doi.org/10.1016/j.mtcomm.2018.09.015

[6] E. Kösedağ and D. İşler, Effect of section geometry and material type on energy absorption capabilities of crash boxes. Karaelmas Fen ve Mühendislik Dergisi, 13(1), 1,2023. https://doi.org/10.7212/karaelmasfen.1150591

[7] Z. Tang, S. Liu, and Z. Zhang, Analysis of energy absorption characteristics of cylindrical multi-cell columns. Thin-Walled Structures, 62, 75–84, 2013. https://doi.org/10.1016/j.tws.2012.05.019

[8] L. Peroni, M. Avalle, and G. Belingardi, Comparison of the energy absorption capability of crash boxes assembled by spot-weld and continuous joining techniques. International Journal of Impact Engineering, 36(3), 498–511, 2009. https://doi.org/10.1016/j.ijimpeng.2008.06.004

[9] A. B. Nellippallil, P. R. Berthelson, L. Peterson, and R. K. Prabhu, Chapter 10 - Robust concept exploration of driver's side vehicular impacts for human-centric crashworthiness. Multiscale Biomechanical Modeling of the Brain, R. Prabhu and M. Horstemeyer, Eds., Academic Press, 45, 153–176, 2022. https://doi.org/10.1016/B978-0-12-818144-7.00002-5

[10] Z. Wang, J. Liu, and S. Yao, On folding mechanics of multi-cell thin-walled square tubes. Composites Part B: Engineering, 132, 17–27, 2018. https://doi.org/10.1016/j.compositesb.2017.07.036

[11] N. Nasir Hussain, S. Prakash Regalla, and Y. V. Daseswara Rao, Low velocity impact characterization of glass fiber reinforced plastics for application of crash box. Materials Today: Proceedings, 4(2) 3252–3262, 2017. https://doi.org/10.1016/j.matpr.2017.02.211

[12] H. Mohammadi et al., Lightweight glass fiber-reinforced polymer composite for automotive bumper applications: a review. Polymers, 15(1), 2023. https://doi.org/10.3390/polym15010193

[13] M. Zarei Mahmoudabadi and M. Sadighi, A study on the static and dynamic loading of the foam filled metal hexagonal honeycomb – Theoretical and experimental. Materials Science and Engineering: A, 530, 333–343, 2011. https://doi.org/10.1016/j.msea.2011.09.093

[14] O. Mohammadiha and H. Ghariblu, Crush behavior optimization of multi-tubes filled by functionally graded foam. Thin-walled structures, 98, 627–639, 2016. https://doi.org/10.1016/j.tws.2015.10.025

[15] H. S. Kim, New extruded multi-cell aluminum profile for maximum crash energy absorption and weight efficiency. Thin-walled structures, 40(4), 311–327, 2002. https://doi.org/10.1016/S0263-8231(01)00069-6

[16] E. Kösedağ and R. Ekici, Free vibration analysis of foam-core sandwich structures. Politeknik Dergisi, 24(1), 69-74, 2021. https://doi.org/10.2339/politeknik.571396

[17] E. Kosedag and R. Ekici, Low-velocity and ballistic impact resistances of particle reinforced metal–matrix composites: An experimental study. Journal of Composite Materials, 56(7), 991–1002, 2022. https://doi.org/10.1177/00219983211068101

[18] E. Kosedag, Effect of artificial aging on 3-point bending behavior of glass fiber/epoxy composites. Journal of Reinforced Plastics and Composites, 42(21-22), 2022. https://doi.org/10.1177/07316844221146287

[19] N. N. Hussain, S. P. Regalla, and Y. V. D. Rao, Comparative study of trigger configuration for enhancement of crashworthiness of automobile crash box subjected to axial impact loading. Procedia Engineering, 173, 1390–1398, 2017. https://doi.org/10.1016/j.proeng.2016.12.198

[20] A. Alavi Nia and J. Haddad Hamedani, Comparative analysis of energy absorption and deformations of thin walled tubes with various section geometries. Thin-Walled Structures, 48(12), 946–954, 2010. https://doi.org/10.1016/j.tws.2010.07.003

[21] M. A. Khan and M. Phil, Energy absorption capacity-an overview ScienceDirect Topics. https://www.sciencedirect.com/topics/engineering/energy-absorption-capacity (accessed Aug. 28, 2023).

[22] G. M. Nagel and D. P. Thambiratnam, Dynamic simulation and energy absorption of tapered thin-walled tubes under oblique impact loading. International Journal of Impact Engineering, 32(10), 1595–1620, 2006. https://doi.org/10.1016/j.ijimpeng.2005.01.002

[23] N. N. Hussain, S. P. Regalla, Y. V. D. Rao and A. M. Mohammed, An experimental and numerical analysis on influence of triggering for composite automotive crash boxes under compressive impact loads. International Journal of Crashworthiness, 27(4), 1152-1166, 2022. https://doi.org/10.1080/13588265.2021.1914953

[24] S. Palanivelu, W. V. Paepegem, J. Degrieck, D. Kakogiannis, J. V. Ackeren, D. V. Hemelrijck, J. Wastiels and J. Vantomme, Parametric study of crushing parameters and failure patterns of pultruded composite tubes using cohesive elements and seam, Part I: Central delamination and triggering modelling. Polymer Testing, 29(6), 729–741, 2010. https://doi.org/10.1016/j.polymertesting.2010.05.010

[25] M. A. Jiménez, A. Miravete, E. Larrodé, and D. Revuelta, Effect of trigger geometry on energy absorption in composite profiles. Composite Structures, 48(1), 107–111, 2000. https://doi.org/10.1016/S0263-8223(99)00081-1

[26] M. S. Zahran, P. Xue, M. S. Esa, and M. M. Abdelwahab, A novel tailor-made technique for enhancing the crashworthiness by multi-stage tubular square tubes. Thin-Walled Structures, 122, 64–82, 2018. https://doi.org/10.1016/j.tws.2017.09.031

[27] C. Zhou, S. Ming, C. Xia, B. Wang, X. Bi, P. Hao and M. Ren, The energy absorption of rectangular and slotted windowed tubes under axial crushing. International Journal of Mechanical Sciences, 141, 89–100, 2018. https://doi.org/10.1016/j.ijmecsci.2018.03.036

[28] H. Zarei, M. Kröger, and H. Albertsen, An experimental and numerical crashworthiness investigation of thermoplastic composite crash boxes. Composite Structures, 85(3), 245–257, 2008. https://doi.org/10.1016/j.compstruct.2007.10.028

[29] H. Böhm, J. Richter, J. Kim, G. Joo, H. Jang, M. Jeong, A. Hornig and M. Gude, Glass-fiber mat/PA6 composite tubes subjected to dynamic axial crush loading—Experimental evaluation and high fidelity modeling of failure phenomena. Composite Structures, 319, 117115, 2023. https://doi.org/10.1016/j.compstruct.2023.117115

[30] M. Harhash, M. Kuhtz, J. Richter, A. Hornig, M. Gude and H. Palkowski, Trigger geometry influencing the failure modes in steel/polymer/steel sandwich crashboxes: Experimental and numerical evaluation. Composite Structures, 262, 113619, 2021. https://doi.org/10.1016/j.compstruct.2021.113619

[31] S. Palanivelu, W. V. Paepegem, J. Degrieck, D. Kakogiannis, J. V. Ackeren, D. V. Hemelrijck, J. Wastiels and J. Vantomme, Comparative study of the quasi-static energy absorption of small-scale composite tubes with different geometrical shapes for use in sacrificial cladding structures. Polymer Testing, 29 (3), 381–396, 2010. https://doi.org/10.1016/j.polymertesting.2010.01.003

[32] N. Bahramian and A. Khalkhali, Crashworthiness topology optimization of thin-walled square tubes, using modified bidirectional evolutionary structural optimization approach. Thin-Walled Structures, 147, 106524, 2020. https://doi.org/10.1016/j.tws.2019.106524

[33] S. Montazeri, M. Elyasi and A. Moradpour, Investigating the energy absorption, SEA and crushing performance of holed and grooved thin-walled tubes under axial loading with different materials. Thin-Walled Structures, 131, 646–653, 2018. https://doi.org/10.1016/j.tws.2018.07.024

CC BY NC