JOURNAL of
MATERIALS and MECHATRONICS:A

e-ISSN 2717-8811
JournalMM, 2024, 5(1), 117-129
https://doi.org/10.55546/jmm.1459415

Araştırma Makalesi / Research Article

Low Velocity Impact Behavior of Curved Composite Panels Reinforced with Different Types of Stiffeners Used in Air Vehicle

Tolunay DAĞ[1], Mehmet Ali GÜVENÇ[2*], Mesut UYANER[3]

[1] Iskenderun Technical University, Faculty of Aeronautics and Astronautics, Department of Aerospace Engineering, Hatay, Turkey, ORCID ID: https://orcid.org/0000-0003-1514-5336, tolunay.dag@iste.edu.tr
[2*] Iskenderun Technical University, Faculty of Aeronautics and Astronautics, Department of Aerospace Engineering, Hatay, Turkey, ORCID ID: https://orcid.org/0000-0002-4652-3048, mali.guvenc@iste.edu.tr
[3] Necmettin Erbakan University, Faculty of Aeronautics and Astronautics, Department of Aircraft Engineering, Konya, Turkey, ORCID ID: https://orcid.org/0000-0003-2743-2340, muyaner@erbakan.edu.tr

Geliş/ Received: 27.03.2024; **Revize/Revised:** 07.05.2024 **Kabul / Accepted:** 13.05.2024

ABSTRACT: This study aims to investigate the low-velocity impact behavior of curved composite plates commonly employed in aviation fuselage and wing surfaces using numerical methods. Layered plates fabricated from E-Glass Epoxy were reinforced with various types of stiffeners and subjected to impacts whit a 12 mm diameter impactor at a velocity of 2.5 m/s. The time-dependent variation of force and displacement on the stiffened curved plates resulting from the impact was analyzed. Furthermore, the temporal variation in the amount of energy absorbed by the plate was observed. The results indicate that plates reinforced with I, T, and blade-type stiffeners absorbed 35.78%, 38.11%, and 37.78% of the impact energy, respectively. Among these, plates with T-type reinforcements exhibited the least post-impact deformation. Particularly noteworthy is the permanent deformation of 3.7 mm experienced by the plate reinforced with blade-type stiffeners.

Keywords: Curved plate, Impact behaviour, Low velocity impact, Stiffeners type

1. INTRODUCTION

Many impact types are studied on composite structures. Armors with low weight and high impact resistance are produced in impact events with speeds up to 1000 m/s, which are examined in the ballistic field (Aytav and Işık, 2023). In the field of aviation, in addition to ballistic impact tests,

*Sorumlu yazar / Corresponding author: mali.guvenc@iste.edu.tr
Bu makaleye atıf yapmak için /To cite this article

Dağ, T., Güvenç, M. A., Uyaner M. (2024). Low Velocity Impact Behavior of Curved Composite Panels Reinforced with Different Types of Stiffeners Used in Air Vehicle. Journal of Materials and Mechatronics: A (JournalMM), 5(1), 117-129.

the behavior of low-speed impact in composite materials is at the forefront. For a collision to be classified as a low velocity impact, the speed of the striker must be 10 m/s or less (Khalili and Ardali, 2013; Hossein et al., 2022)

Fibre reinforced composite plates and stiffened plates are rapidly gaining ground in the aerospace industry. Layered composite plate structures are materials with high strength and impact damping properties (Quaresimin et al., 2013; Santiago et al., 2018; Özbek et al., 2022;). Layered composite plates can be hardened with different types of stiffeners to achieve high strength properties. Such structures are generally used in wing and fuselage structures in aerospace structures (Gök et al., 2023). The mechanical behaviour of the sample as a consequence low velocity impact to be applied on stiffened layered composite plates will differ according to the type of stiffeners (Khan et al., 2021). It has been observed that the stiffeners absorb some of the energy generated on the plate as a result of low impact. The energy absorbed by the reinforcing element reduces the amount of deformation on the surface of the plate to lower levels (Wang et al., 2015).

Optimization and forecasting studies are ongoing, especially to reduce the amount of damage. There are studies on the effects of mechanical properties or geometric properties of the structure on damage behavior. In these studies, prediction and optimization can be performed with statistical or artificial intelligence based software (Güvenç et al., 2023).

Metals are used in many fields such as aviation, aerospace, automotive and industry. Alumium is the most preferred production material due to its light weight and easy formability. Despite this, composite plates are rapidly replacing metals in aircraft due to their light weight and high strength properties. Especially in helicopter blades, UAV wings and tails, composite materials can be reinforced to provide higher strength values (Barkanov et al., 2014; Dag et al., 2023; Pan et al., 2019). Stiffened panels are used extensively in aircraft fuselages and wings and tail elements. The most important advantage in the design of these panels is to provide rigidity to the structure (Correas et al., 2021; Güvenç et al., 2023; Sun et al., 2018).

The plate is the element that holds the stiffeners together. Stiffened panels are connected to beam webs to strengthen structures against out-of-plane deformations (Quinn et al., 2009). The orientation of the reinforcing columns called stiffeners varies depending on the desired property according to the area of use of the stiffened panel.

Composite structures, which are especially important components of aircraft, are composites that have a curvature as a result of processing. In addition to normal flat plate composites, the damage behavior of these curved plates is important in an industry such as aerospace, where high loads act on the structures (Adali and Cagdas, 2011; Erdoğan et al., 2019; Saghafi et al., 2014).

Many factors can cause damage to composite materials. The most common of these is impact damage. This is also frequently seen in composite materials used in aviation. These damages, especially when landing and taking off on the runways, can cause major damage to the vehicle or cause damage that will cause these critical damages to occur (Gebhardt et al., 2023).

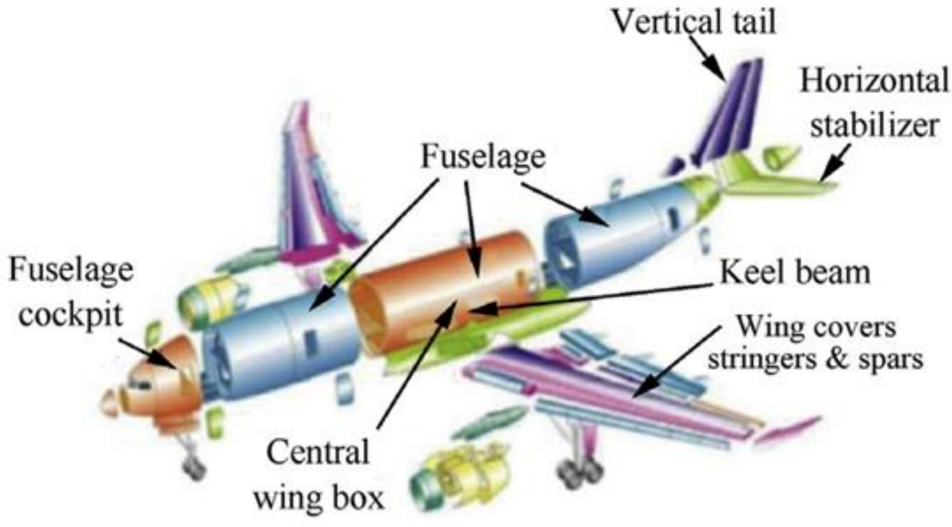


Figure 1. Where composite structures are used extensively on the Airbus 350 (Karataş and Gökkaya, 2018)

W. Sun and al. (Sun et al., 2018) conducted experiments to examine the damage response of the sample in impact tests applied to composite panels and the changes in the damage behavior of the reinforced composite panel with the addition of reinforcement. The three T-strengtheners added were significantly effective against buckling of the panel and the formation of damaged surfaces. The damage threshold of the panel was determined as 34 J, and it was observed that if an impact above this energy was applied, the panel would be damaged. It has been evaluated that there is no need to apply reinforcement elements to the panel for impact energies below this energy level. It was observed that if the impact energy was higher than 34 J, the reinforcement element was disconnected from the panel and delamination occurred between the plates. However, since there was no damage to the panel and only the booster in the middle lost its function, it was seen that the panel could continue to be used with two boosters instead of three boosters.

K. S. Kumar et al. (Kumar et al., 2019) performed low-velocity impact simulations on Glass/Epoxy and Carbon/Epoxy plates consisting of many layers formed with different laying angles. As a result of the test simulated with the finite element method, the impact behavior of the materials was examined. It has been observed that the data of layered plates produced with Glass/Epoxy and Carbon/Epoxy are very close to each other. Gangwar et al. (Gangwar et al., 2024) investigated the change in the mechanical behavior of a curved layered composite plate as a result of loads acting on it depending on the properties of the plate such as thickness and aspect ratio. As a result of numerical analysis by finite element method, the frequency values of the specimen as a result of loading for two different modes were analyzed. When these studies are examined, it is thought that the analysis of the change of mechanical behavior of the curved plate as a result of impact loading depending on the type of sitiffener using the finite element method is incomplete.

In this study, low-velocity impact simulation on a composite plate reinforced with different types of stiffeners, which has a curved form such as wing or fuselage geometries, was carried out by finite element method. The 300x200x4 mm sized curved plate is reinforced with 5 blades, T and I type stiffeners (Jain and Upadhyay, 2010; Tan et al., 2020).

The impactor was modeled as a sphere with a radius of 6 mm and a mass of 15 kg. As a result of the analyses, the effect of stiffener type on impact behaviour was examined. The effect of the stiffener type on the amount of energy accumulated on the curved panel, the maximum contact force value and the amount of deformation was observed.

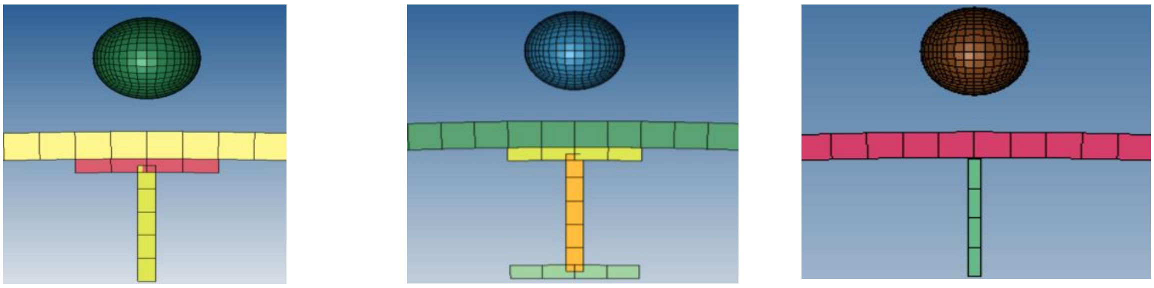
2. MATERIALS AND METHODS

LS-Dyna software was preferred to perform the finite element method in the study. Curved plate and stiffeners modeling were performed using the LS-PrePost interface. The structure with a radius of 6 mm and a mass of 15 kg, which will be used as the impactor, was created with the Sphere Solid command from the LS-PrePost interface. Table 1 shows the dimensions of the striking mass, plate and reinforcing structures. The curved plate is modeled with dimensions of 300x200 mm. The radius of curvature is 469.25 mm and the plate consists of 16 layers. Each ply is 0.25 mm thick and modeled with a laying angle of $[0/45/-45/90]_4$ The stiffeners have a lay-up angle of $[0/90]_4$ and each layer is 0.25 mm thick like the ply. The plate is 4 mm thick and formed with three different types of stiffeners.

Table 1. Geometrical properties of the curved plate, stiffeners and impactor mass

	Curved Plate [mm]	Stiffeners [mm]
Width	200	200
Length	300	16
Heigth	-	16
Thickness	4	2.0
	Impactor	
Radius	6	

Figure 2 shows the modeling of the stiffener types used in the study and their integration with the curve panel.



(a) (b) (c)

Figure 2. LS-Dyna modeling of a)T-type, b) I-type and c) Blade-type reinforcers

In order to make the modeled sample suitable for numerical analysis and recognisable for the finite element method, a mesh is applied. The curved panel was modeled with different mesh sizes and analyses were performed at a speed of 2.5 m/s. In these analyses, the mesh element sizes applied on the panel were determined as 10, 5, 4.5, 4 and 3 mm and low velocity impact analyses were performed on the curved panel by applying these element sizes. The force-time curves obtained in these analyses were evaluated and the most suitable mesh size was selected to be applied to the panel and reinforcements. The maximum contact force value, which is the peak of the force-time curve, was evaluated for each mesh size and the deviation amount was determined as 0.5%. Figure 3 shows the force-time curves obtained as a result of the approach for mesh convergence. As a result of these analyses, it was decided that 4 mm mesh size was the most appropriate mesh size in terms of geometry and accuracy of the results.

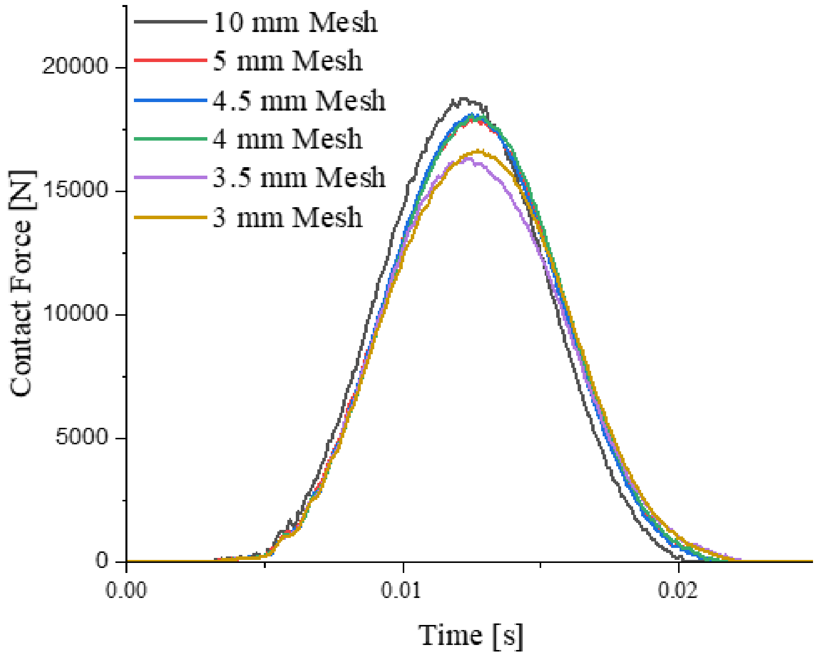


Figure 3. Contact force-time output according to different mesh size

Figure 4 shows a sample T-type stiffened curved panel and impactor mass formed with a mesh size of 4 mm. The curved composite panel is modeled with a total of 13 000 mesh elements.

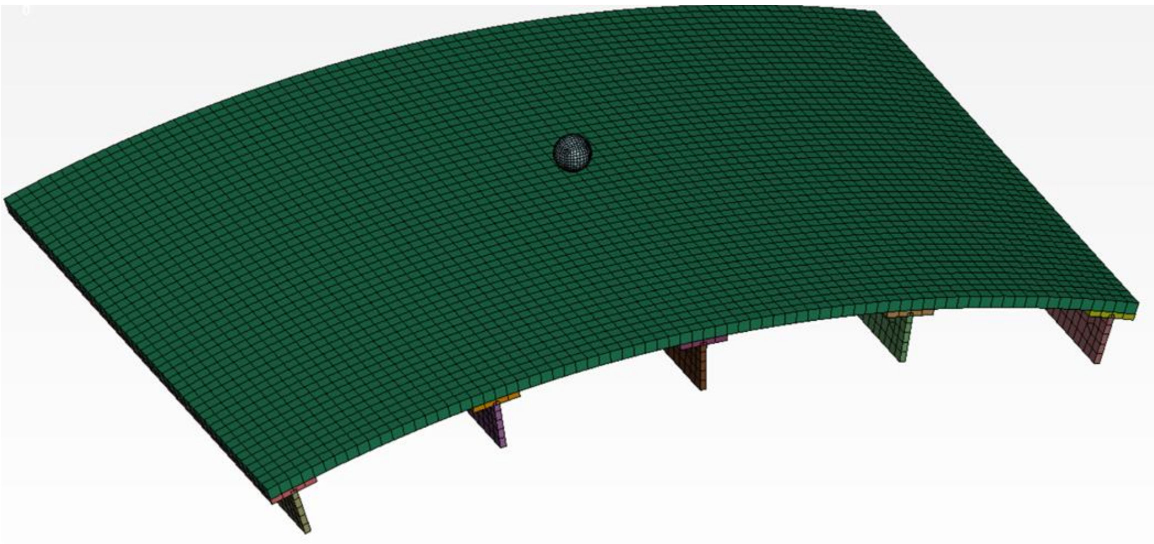


Figure 4. Mesh image of curved panel with T-type stiffener and impactor generated in LS-PrePost interface

The mechanical properties of the impactor are defined by the *Mat Rigid* material card in the LS-Dyna software (Dağ et al., 2022). The striking part of a low velocity impact device with a measured mass of 15 kg was modeled. The geometrical shape of the striking tip of the test device is partially modeled. Since only the impactor tip was modeled, the entire mass was modeled on this sphere. This was achieved by increasing the density of the sphere. Table 2 shows the mechanical properties of the 15-kilogram spherical striker.

Table 2. Impactor mass mechanical properties

	Symbol	Value
Density	ρ	1.685e+07 kg/m^3
Elasticity Modulus	E	207 GPa
Poisson Ratio	ν	0.30

Mat Enhanced Composite Damage card was used to define the material for the curved plate and stiffeners. This composite card provides different damage criteria options. This material card, which covers Chang-Chang and Tsai-Wu damage criteria, can provide various simulation results outputs (Akbulut and Sonmez, 2011; Nyambeni and Mabuza, 2018). The material card with *Mat-055: Enhanced Composite Damage* damage criterion is the material card where Tsai-Wu damage criteria are applied in the matrices of composite structures and Chang-Chang damage criteria are applied in fiber reinforcements. *Mat-055: Enhanced Composite Damage* card inputs are modeled with E-Glass Epoxy mechanical properties as given in Table 3.

Table 3. E-Glass Epoxy Mechanical Properties

	Symbol	Value
Density	ρ	1840 kg/m^3
Elasticity Modulus [Longitudinal]	E_1	42 GPa
Elasticity Modulus [Transverse]	E_2	9.5 GPa
Poisson Ratio	ν	0.34
Shear Modulus	G_{12}	3.5 GPa
Compressive Strength [Longitudinal]	X_C	300 MPa
Tensile Strength [Longitudinal]	X_T	690 MPa
Compressive Strength [Transverse]	Y_C	147 MPa
Tensile Strength [Transverse]	Y_T	66 MPa
Shear Strength	S_C	56 MPa
Maximum Strain for Matrix	DFAILM [Y_C/E_2]	0.001547
Maximum Shear Strain	DFAILS [S_C/G_{12}]	0.016000
Maximum Compressive Strain	DFAILC [$-X_C/E_1$]	-0.007143
Maximum Tensile Strain	DFAILT [X_T/E_1]	0.0164286

After the material assignments of the impactor, plate and stiffeners were completed, the contact cards were defined. The contact card between the impactor and the plate is the *Contact Automatic Nodes to Surface* contact card. The contact card between the plate and the stiffeners was associated with the *Contact Automatic Surface to Surface* contact card (Uyaner et al., 2023).

3. RESULTS AND DISCUSSION

In this section, the results of numerical analyses of the low velocity impact response of the inclined panel supported with 3 different geometries as flat, I and T type as stiffener type are given. Force-time, energy-time and force-displacement graphs were obtained as a result of numerical simulations (Tan et al., 2018; Y. Zhang et al., 2022).

Low velocity impact simulation with a speed of 2.5 m/s on a 200x300x4 mm curved plate with stiffeners was carried out with LS-Dyna software. As a result of the finite element analysis, the variations of contact force, energy and displacement values of the plate after impact against time were obtained. Maximum contact force, energy dissipation rates and permanent deformation amounts are also obtained as a result of the analyses.

Figure 5 shows the time dependent variation of the contact force obtained as a result of the low velocity impact applied on the curved plates supported with different reinforcements.

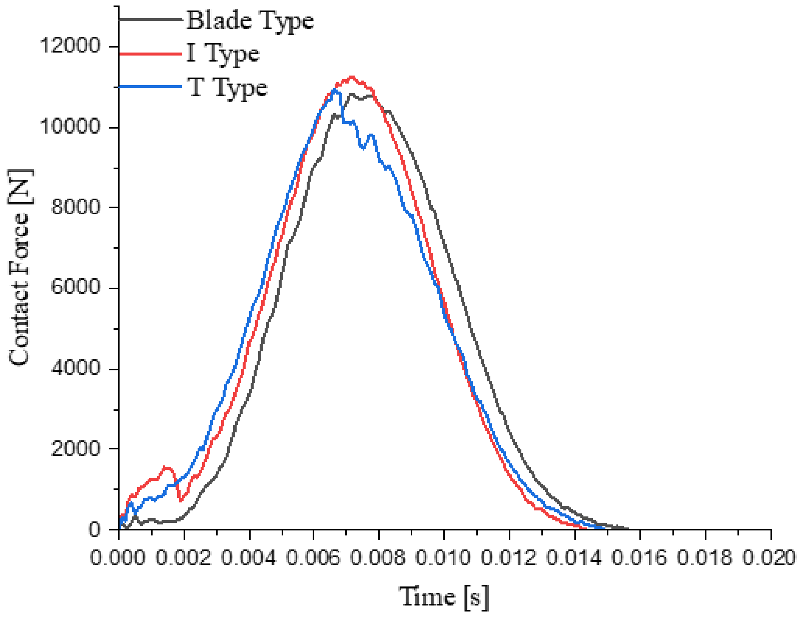


Figure 5. Variation of the contact force on the plate after impact according to the type of stiffener

The maximum contact force value of the plate supported with I-type stiffeners after 2.5 m/s impact is higher than the other two types of stiffeners. Figure 6 shows the curve of the amount of displacement resulting from the contact force.

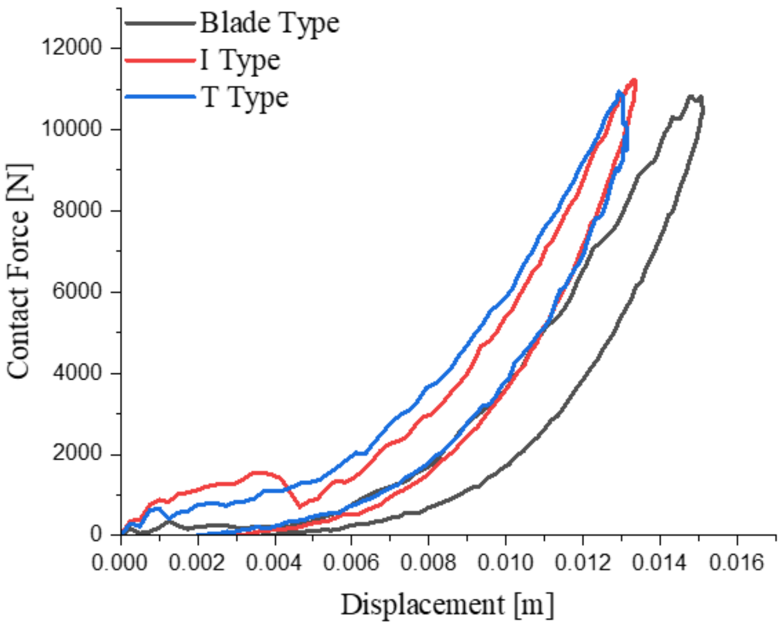


Figure 6. Variation of contact force-displacement of the plate after impact according to the type of stiffener

The curved plate with Blade-type stiffener, which has the maximum displacement value on the plate as a result of the contact force, absorbed 37.78% of the kinetic energy of the striker. Figure 7 shows the time-dependent change in the amount of energy accumulated on the plates after impact (D. Zhang et al., 2013).

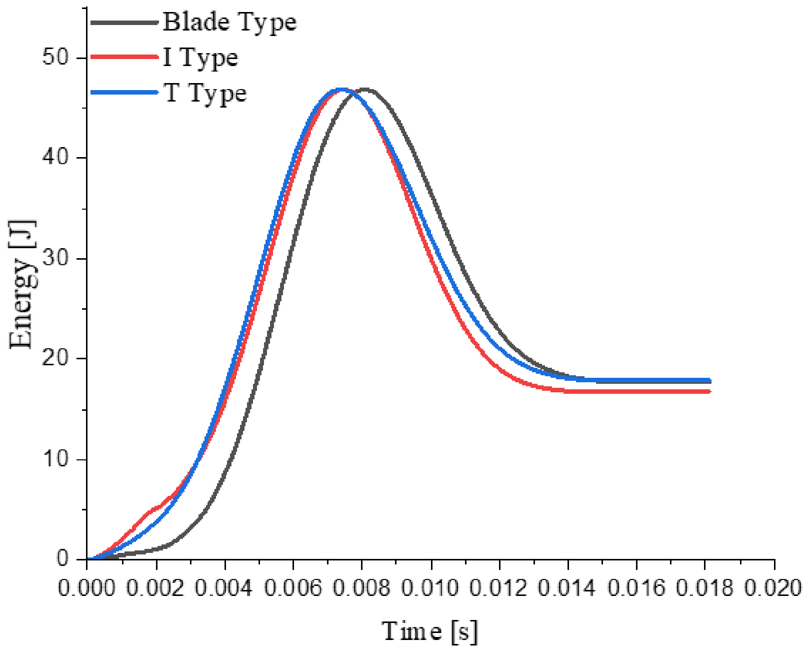


Figure 7. Time-dependent variation of the energy deposited on the plate after impact according to the stiffener type

As seen in Figure 7, the plates with I and T-type stiffeners can reach the maximum energy amount earlier than the plate with Blade-type stiffeners. This is due to the rigidity provided to the plate by the stiffener types.

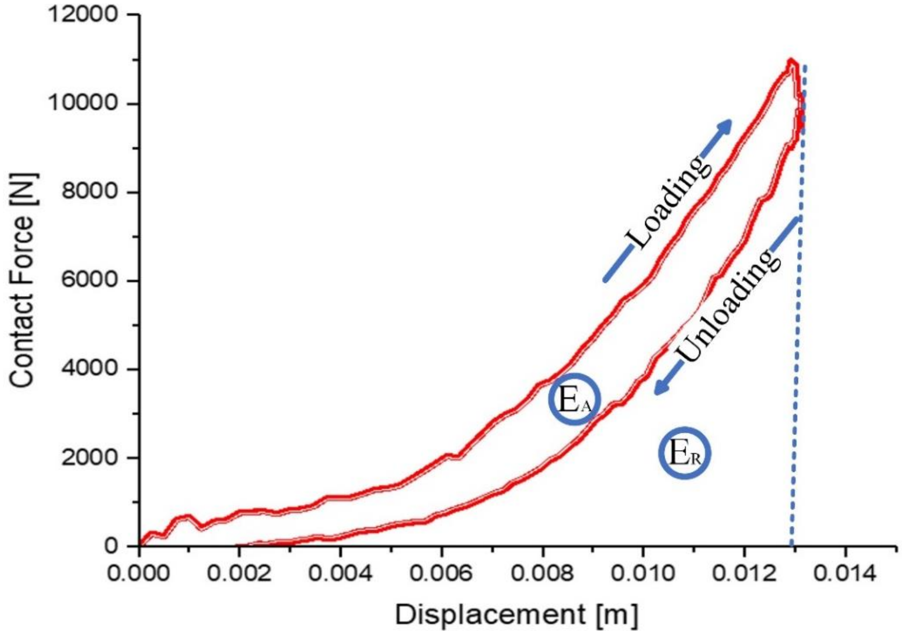


Figure 8. Post-impact displacement-contact force curve of T-type stiffener plate

Figure 8 shows the post-impact displacement-contact force curve of the plate with T-type stiffener. With the sudden loading of the plate after impact and the subsequent rebound effect, the material absorbs some of the kinetic energy of the striker. The area inside the displacement curve in Figure 8 shows the energy absorbed by the plate and the area below the curve shows the energy returned (Tan et al., 2018).

Impact behavior of a curved plate reinforced with T-type stiffeners impacts by a spherical impactor at 2.5 m/s. The impact resulted in delamination of the plate and reinforcement and damage to the vertical flange of the stiffener.

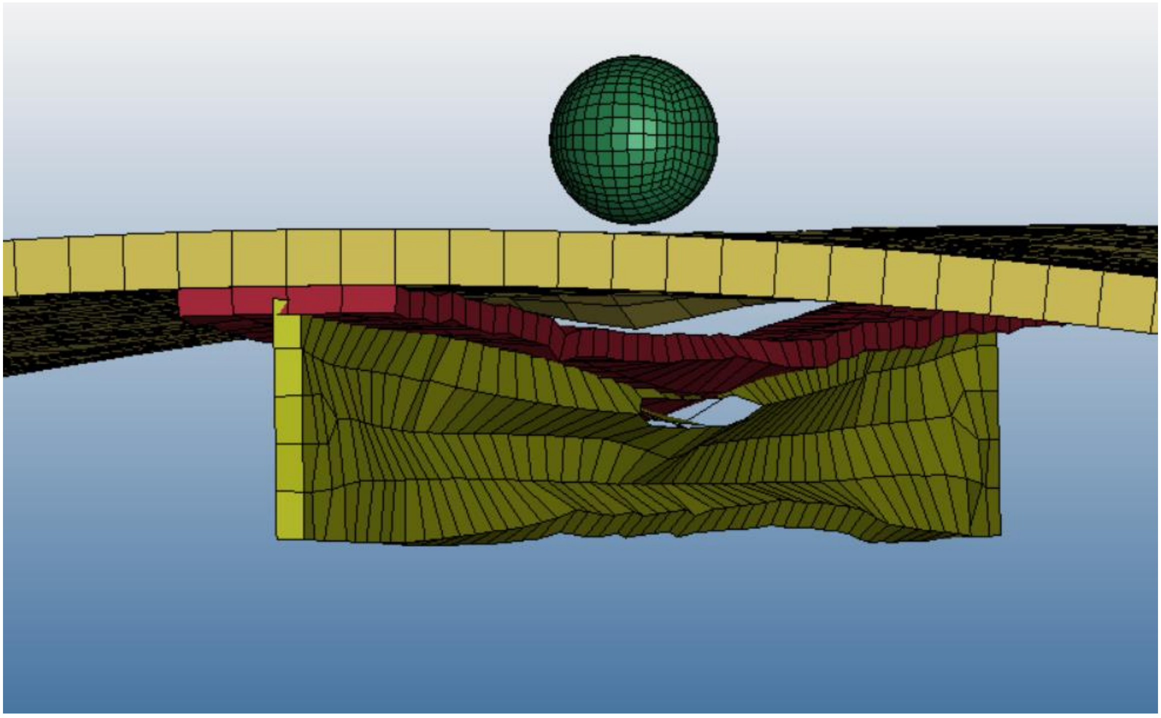


Figure 9. View of curved panel with T-type stiffener after impact

Figure 10 shows the permanent damage of the curved plate without stiffener and the curved plate with T-type stiffener after impact. The permanent deformation of the plate without stiffener is 19.8 mm, while the permanent damage of the plate reinforced with T-type stiffener is 2 mm. Thanks to the horizontal flange of the T-type stiffener, the curved plate takes less damage and prevents critical damage to the plate. The horizontal flange absorbs the loading acting on the plate and minimizes the amount of plate damage.

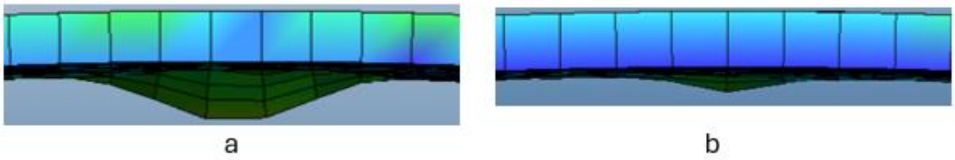


Figure 10. a) Curved plate without stiffeners, b) Curved plate with T-type stiffeners

The form of the center stiffener after the impact is as shown in Figure 11. It prevents damage to the plate by absorbing some of the impact energy.

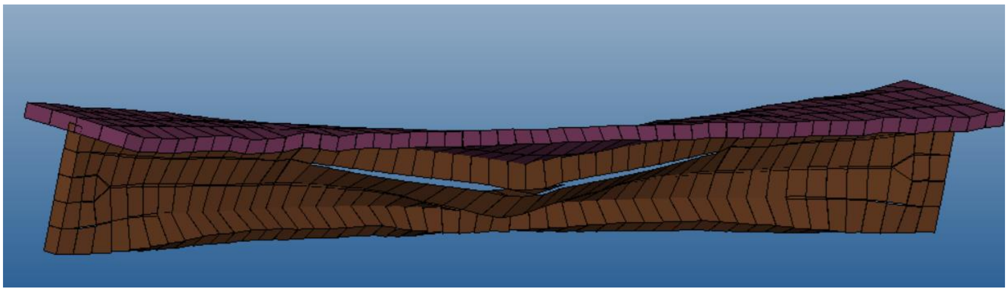


Figure 11. The appearance of the T-type stiffener after the impact

Even if the stiffener, which is seen to have received critical damage, has become unusable, the plate continues to function by maintaining its structural integrity. However, in case of any loading after the impact, the structure with low strength can be severely damaged (Li et al., 2014).

In Table 4, the changes of the maximum contact force, energy absorption amount and deformation amount of the curved plate after impact are given numerically according to the stiffener types.

Table 4. Impact behaviour of plates with different stiffeners

	I Type	T Type	Blade Type
Maximum Contact Force [N]	11241.81	10944.08	10822.96
Energy Damping Rate [%]	35.78	38.11	37.78
Maximum Deformation Amount [m]	0.0134	0.0131	0.0151
Permanent Deformation Amount [m]	0.0026	0.0019	0.0037

4. CONCLUSION

As a result of the 2.5 m/s low velocity impact applied on the curved plate reinforced with different stiffeners, it was observed that the plate with T-type stiffener was less damaged than the others. The maximum contact force of 10.94 kN was determined on the plate with 1.9 mm permanent deformation. It absorbed 38.11% of the kinetic energy of the impactor mass and rebounded the impactor.

- Considering the maximum deformation and permanent deformation amounts, the most damaged structure is the curved plate reinforced with Blade type stiffener. As a result of the impact, the structure was deformed by 3.7 mm and damage occurred.
- As a result of the numerical analysis performed with the finite element method, the T-type stiffener element reduces the amount of damage by a significant amount of 90%. In the future, the effect of changing the geometric properties of stiffener types on impact behavior may be the subject of investigation.
- As a result of the impact applied on the plate with I-type stiffener, it absorbed more than one third of the energy and was subjected to a maximum contact force of 11.24 kN.

5. ACKNOWLEDGEMENTS

This work was conducted scope of Master of Science Thesis of Tolunay Dağ.

6. CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

Tolunay Dag: Conceptualization, Methodology, Software, Visualization, Investigation. Mehmet Ali Guvenc: Investigation, Resources, Data curation, Writing-original draft, Supervision. Mesut Uyaner: Data analysis and interpretation of results, Supervision.

8. REFERENCES

Adali, S., Cagdas, I. U., Failure analysis of curved composite panels based on first-ply and buckling failures. Procedia Engineering, 10, 1591–1596, 2011.

Akbulut, M., Sonmez, F. O., Design optimization of laminated composites using a new variant of simulated annealing. Computers and Structures, 89(17–18), 1712–1724, 2011.

Altin Karataş, M., Gökkaya, H., A review on machinability of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials. In Defence Technology 14(4), 318–326, 2018.

Aytav, E., Işık, A. M., Experimental Investigation of Ballistic Performance of Free Particle Armor Systems. Journal of Materials and Mechatronics: A, 4(2), 518–543, 2023.

Barkanov, E., Ozoliņš, O., Eglitis, E., Almeida, F., Bowering, M. C., Watson, G., Optimal design of composite lateral wing upper covers. Part I: Linear buckling analysis. Aerospace Science and Technology, 38, 1–8, 2014.

Correas, A. C., Crespo, A. C., Ghasemnejad, H., Roshan, G., Analytical Solutions to Predict Impact Behaviour of Stringer Stiffened Composite Aircraft Panels. Applied Composite Materials, 28(4), 1237–1254, 2021.

Dag, T., Yildirim, N., Senturk, G., Durmazoglu, M., Yildirim, S., Uyaner, M., Virtual Investigation on the Response of Glare to Low Velocity Impact. Proceedings of 10th International Conference on Recent Advances in Air and Space Technologies, RAST 2023, 2023.

Dağ, T., Yıldırım, N., Kepir, Y., Uyaner, M., E/Cam Epoksi Laminelerin Üzerine Uygulanan Düşük Hızlı Darbe Davranışının Sayısal Simülasyonu. ASREL, 2022

Erdoğan, A., Gök, M. S., Koç, V., Günen, A., Friction and wear behavior of epoxy composite filled with industrial wastes. Journal of Cleaner Production, 237, 2019.

Gebhardt, J., Schlamp, M., Ehrlich, I., Hiermaier, S., Low-velocity impact behavior of elliptic curved composite structures. International Journal of Impact Engineering, 180, 2023.

Gök, M., Küçük, Y., Pehlivanlı, M., Erdoğan, A., Investigation of Dry Sliding Wear Behavior of CFRP Composite Used in New Generation Aircraft Wings. Journal of Aviation, 7(2), 190–195, 2023.

Guvenc, M. A., Bilgic, H. H., Mistikoglu, S., Identification of chatter vibrations and active vibration control by using the sliding mode controller on dry turning of titanium alloy (Ti6Al4V). Facta Universitatis, Series: Mechanical Engineering, 21(2), 307, 2023.

Guvenc, M. A., Eren, B., Basar, G., Mistikoglu, S., A new hybrid meta-heuristic optimization method for predicting UTS for FSW of Al/Cu dissimilar materials. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 237(20), 4726–4738, 2023.

Hossein Alizadeh, M., Kamali Dolatabadi, M., Shaikhzadeh Najar, S., Eslami-Farsani, R., Energy absorption of the Kevlar®/PP hybrid composite: fabric to composite optimization. Journal of the Textile Institute, 113(6), 1018–1026, 2022.

Jain, H. K., Upadhyay, A., Buckling behavior of blade-, angle-, T-, and hat-stiffened FRP panels subjected to in-plane shear. Journal of Reinforced Plastics and Composites, 29(24), 3614–3623, 2010.

Khalili, S. M. R., Ardali, A., Low-velocity impact response of doubly curved symmetric cross-ply laminated panel with embedded SMA wires. Composite Structures, 105, 216–226, 2013.

Khan, S. H., Khan, A. A., Husain, A., Effect of fibre orientation on damage resistance of composite laminates. International Journal of Crashworthiness, 26(3), 270–282, 2021

Li, D. H., Liu, Y., Zhang, X., Low-velocity impact responses of the stiffened composite laminated plates based on the progressive failure model and the layerwise/solid-elements method. Composite Structures, 110(1), 249–275, 2014.

Nyambeni, N., Mabuza, B. R., Considerations of Failure Analysis in a Multi-Layered Composite Structure under Thermomechanical Loading. Proceedings, 2, 447, 2018.

Özbek, Ö., Çakır, M. V., Doğan, N. F., Halloysit Nanotüp Katkısının Al-GFRP Tek Bindirmeli Yapıştırma Bağlantısında Kayma Dayanımına Etkisi. Journal of Materials and Mechatronics: A, 3(1), 117–128, 2022.

Pan, J., Li, N., Song, Z. J., Xu, M. C., Influence of boundary condition and stiffener type on collapse behaviours of stiffened panels under longitudinal compression. Advances in Mechanical Engineering, 11(10), 2019.

Quaresimin, M., Ricotta, M., Martello, L., Mian, S., Energy absorption in composite laminates under impact loading. Composites Part B: Engineering, 44(1), 133–140, 2013.

Quinn, D., Murphy, A., McEwan, W., Lemaitre, F., Stiffened panel stability behaviour and performance gains with plate prismatic sub-stiffening. Thin-Walled Structures, 47(12), 1457–1468, 2009.

Saghafi, H., Minak, G., Zucchelli, A., Effect of preload on the impact response of curved composite panels. Composites Part B: Engineering, 60, 74–81, 2014.

Santiago, R. C., Cantwell, W. J., Jones, N., Alves, M., The modelling of impact loading on thermoplastic fibre-metal laminates. Composite Structures, 189, 228–238, 2018.

Sun, W., Guan, Z., Ouyang, T., Tan, R., Zhong, X., Effect of stiffener damage caused by low velocity impact on compressive buckling and failure modes of T-stiffened composite panels. Composite Structures, 184, 198–210 2018

Tan, R., Guan, Z., Sun, W., Liu, Z., Xu, J., Experiment investigation on impact damage and influences on compression behaviors of single T-stiffened composite panels. Composite Structures, 203, 486–497, 2018.

Tan, R., Xu, J., Guan, Z., Sun, W., Ouyang, T., Wang, S., Experimental study on effect of impact locations on damage formation and compression behavior of stiffened composite panels with L-shaped stiffener. Thin-Walled Structures, 150, 2020.

Uyaner, M., Kara, M., Kepir, Y., Gunoz, A., Virtual Testing of Laminated Composites Subjected to Low-Velocity Impact. Iranian Journal of Science and Technology- Transactions of Mechanical Engineering, 47 (2), 595–610, 2023.

Wang, X. M., Cao, W., Deng, C. H., Wang, P. Y., Yue, Z. F., Experimental and numerical analysis for the post-buckling behavior of stiffened composite panels with impact damage. Composite Structures, 133, 840–846, 2015.

Zhang, D., Sun, Y., Chen, L., Pan, N., A comparative study on low-velocity impact response of fabric composite laminates. Materials & Design, 50, 750–756, 2013.

Zhang, Y., Zhou, Y., Sun, Y., Bird-strike damage analysis of composite panels with different stiffeners. Aircraft Engineering and Aerospace Technology, 94 (6), 933–947, 2022.