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Investigation of mechanical behavior of reinforced u-profile composites under low velocity impact

Merve Uslu[1], Mete Onur Kaman[1], Mustafa Albayrak[2*], Cenk Yanen[1], Serkan Dag[3], Serkan Erdem[1], Kadir Turan[4]

[1]Firat University, Engineering Faculty, Department of Mechanical Engineering, Elazig, Türkiye
[2]Inonu University, Department of Machine and Metal Technologies, Industrial Zone Vocational School, Malatya, Türkiye
[3]Middle East Technical University, Engineering Faculty, Department of Mechanical Engineering, Ankara, Türkiye
[4]Dicle University, Engineering Faculty, Department of Mechanical Engineering, Diyarbakir, Türkiye

Abstract: In this study, the impact resistance of reinforced composite panels with unsupported, and U profile supported by I profile was numerically examined. For this purpose, firstly, unsupported glass fiber/epoxy composite panels were designed, and then I-profile composite supports were added to these panels. The impact strength, and damage behavior of supported, and unsupported specimens under low-velocity impact were compared numerically. In the analysis, the MAT22 material card, also known as the Chang-Chang damage model for composite material, was used in the LS-DYNA program. As a result of the analysis, maximum damage load of the unsupported specimen is determined to be approximately 294 N. It was determined that by adding an I profile to the structure, the maximum damage load increased to 543 N. It was seen that the added I profile supports increased the maximum contact force of the composite structure by approximately 85%. Fiber breakage damages were observed in both supported, and unsupported specimens. However, with the use of I profile support, the damaged area was further reduced. It has been determined that under low-velocity impact, supported specimens exhibit more rigid material behavior than unsupported specimens.

Keywords: u-profile composite; Chang-Chang failure criteria; I profile; impact; MAT22.

1. Introduction

Fiber reinforced polymer (FRP) composites have the characteristics of low density, high strength, high hardness, and corrosion resistance. In recent years, FRP structures have been preferred in many areas, especially aviation, and spacecraft applications, due to these superior properties. When the fuselage, and wing structure designs of civil, and military aircraft are examined, it is seen that composite panels are widely preferred. Reinforced composite panels are used as the basic building blocks that form the main body in aircraft (▶**Figure 1**). Reinforced panels with U-profile provide superior bending strength, and torsional stiffness to the structure, unlike "T-shaped", and "I-shaped" long beams. Therefore, they are one of the most important parts of the structure. Thanks to reinforced composite panels produced from FRP composites, it is possible to obtain structures that have superior material properties, and at the same time prioritize structural safety. With correct damage analysis, it is possible to design safe aircraft wings, and maintain structural integrity. Thanks to the uniquely designed reinforced panels, the lateral forces, and radial forces caused by the bending of the fuselage or wing will be compensated. Hou, et al. investigated the low-velocity impact, and post-impact crushing behavior of reinforced CFRP panels experimentally, and numerically. Experimental tests were initially developed on panels reinforced with T-, and I-shaped beams [1]. Hu, et al. designed a three-dimensional model to predict the mechanical behavior of T-profile reinforced composite structures. They examined the effect of the added profile by subjecting the

*Corresponding author:
Email: mustafaalbayrak@inonu.edu.tr

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model to axial pressure tests under various equipment [2]. CAI tests of foam-filled reinforced composite panels subjected to low-velocity impacts were carried out by Liu et al. The effect of damage at different impact locations on strength is discussed [3]. Liu and Xu examined the effects of filler-reinforced composite panels on post-crushing impact damage. They investigated the effect of the added filler material on the damage load, and damage behavior [4]. Meng, et al. performed impact, and post-impact compression tests on reinforced panels. They investigated the damage morphology/mechanisms for three types of impact positions [5]. Peng, et al. experimentally, and numerically examined the effect of impact positions on the post-impact crushing performance of T-shaped reinforced composite panels [6]. Shi, Xiong, Cai, and others conducted a series of impact experiments with a hammer platform falling on reinforced panels. In these experiments, high-velocity deflection fields during short impact duration were recorded and examined using the 3D-DIC (Digital Image Correlation) system [7]. Tan, et al. conducted experiments to investigate the effect of reinforced composite panels with L-shaped reinforcement on the impact behavior and examined the types of damage occurring in the specimens [8]. Wang, Liu, and others investigated the structural deformation mechanism of reinforced plates used in marine structures under impact load. In the test results, they evaluated the deformation state of the reinforced plate [9]. Wu, et al., examined the compressive buckling, and post-buckling behavior of J-type composite reinforced panels before, and after impact load using theoretical, numerical, and experimental methods. They theoretically predicted the load-bearing properties of reinforced panels, including buckling strength, ultimate strength, and damage process [10]. Zhou et al. conducted shear fatigue experiments to investigate the fatigue behavior, and damage mechanism of reinforced composite panels. The shear fatigue behavior of hardened panels subjected to impact was examined. They conducted fatigue experiments at two load levels to investigate the initiation, and propagation of delamination. They discussed the fatigue shear behavior, and damage mechanisms based on experimental results [11]. Zhou, and Gao investigated the effect of adhesive interface properties on the post-buckling response of composite I-profile reinforced panels with lateral beam support under axial pressure [12]. Zou et al. investigated the damage development, and damage mechanism of foam-filled reinforced composite panels at different positions, and different energies under low-velocity impact, and post-impact crushing using experimental, and numerical simulation methods. Delamination damage caused by low-velocity impact was detected by ultrasonic progressive C scanning [13]. Studies in the literature focus on damage analysis, especially in laminates.

There are different studies based on the finite element method by examining the impact resistance, and crushing behavior of the composite structure, reinforced with

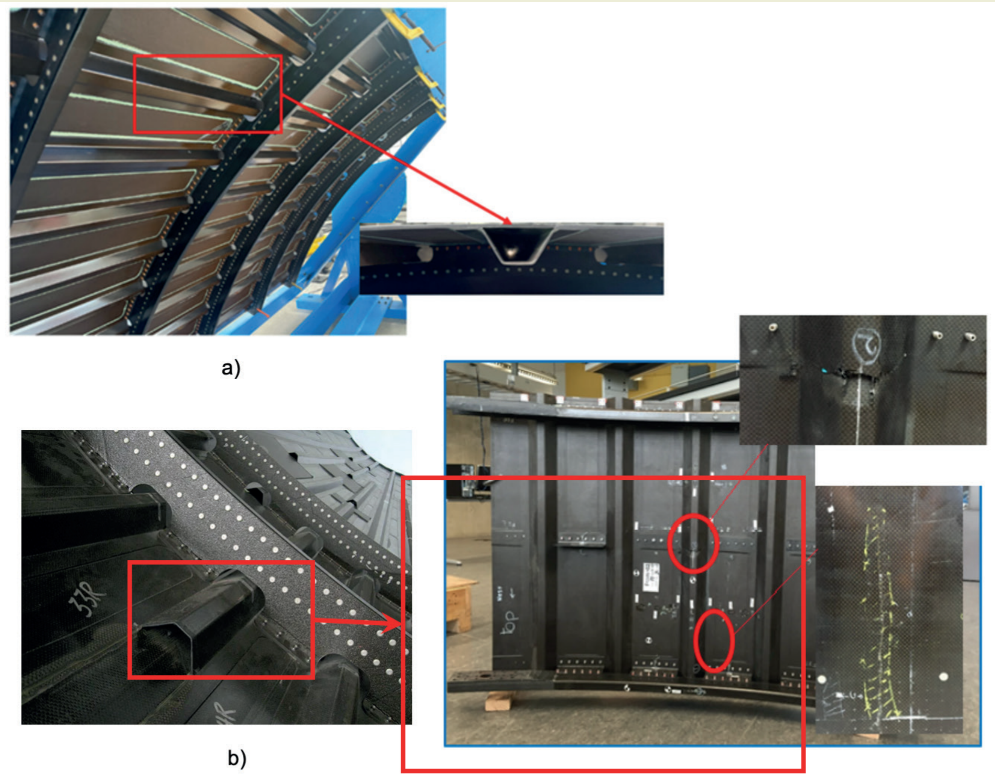

Figure 1. a) reinforced panels [14], and b) damages [15] in aircraft structures

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a U-profile, separately. Within the scope of this study, unlike the literature, the impact resistance of I-profile, and supported, and unsupported U-profile composite panels was examined numerically for the first time. The effect of adding support rods into the U-profile on impact strength was revealed for the first time in this study. The development of numerical solution techniques, and finite element programs has provided the opportunity to numerically examine problems that are difficult to solve experimentally. The problem was solved in the LS-DYNA program, and force displacement graphs of supported, and unsupported specimens were obtained. In addition, damage images after the impact are compared, and presented.

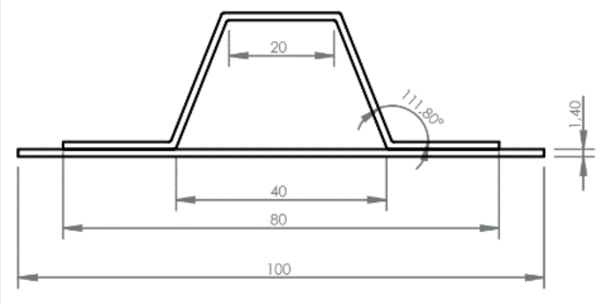

Figure 2. Front view of unsupported composite model.

2. Materials and Methods

1.4 mm thick glass fiber composite models were designed to perform impact tests on U-profile supported, and unsupported glass fiber composite panels. The model shown in ▶**Figure 2**; It is the assembled image of U-profile, and composite plate, that is, glued with adhesive. ▶**Figure 3** shows the addition of support bars to the reinforced panel. Glass fiber materials are both cheaper than carbon fiber, and more advantageous in their production, and use, considering human health. Within the scope of the study, 2x2 glass fiber fabric with 300g/m2 twill weave type was used as a reinforcement element. The matrix material comprised MGSH160 resin, and MGSL160 hardener. Both materials are commercial products obtained from Dost Kimya A.Ş., Istanbul, Türkiye.

Table 1. Glass fiber reinforced composite material properties.

Thickness	0.23mm
Weaving type	Twill
Weight	300gr/m^2
Witdh	100 cm

2.1. Low velocity drop weight impact test method

Upper, and lower molds are needed to fix U profile composites. ▶**Figure 4** shows these molds, and their fixed shape. The striker has a weight of 5.5 kg, and diameter of 20 mm. As a result of the analysis, reaction force, and damage images were obtained according to time.

2.2. Numerical Model

Low-velocity impact analyzes were carried out in the LS-DYNA finite element program. 8-node solid element type was used in modeling composite plates. To obtain realistic boundary conditions, upper, and lower dies were modeled instead of fixing the boundary nodes. As shown in ▶**Figure 5**, the upper, and lower molds, and the striker model are defined as rigid. The dies are fixed in the x, y, and z directions relative to the global axis tool. The batter is only allowed to move in the z direction. In the analysis, the MAT22 material card was selected for the composite material in the LS-DYNA program. Damage conditions for the Chang-Chang damage model are given in equations 1-7. Here, when any corresponding damage criterion exceeds the value 1, the relevant element is damaged for that mode. For longitudinal tension

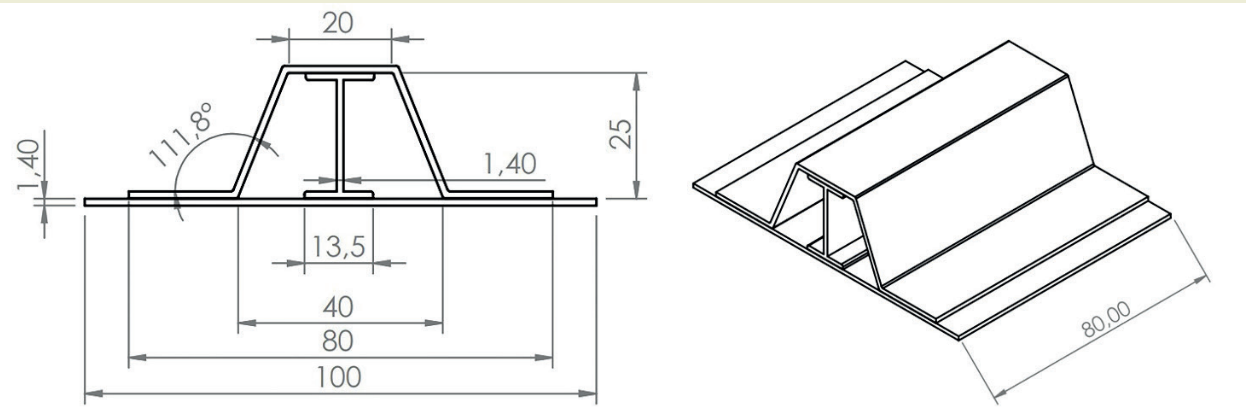

Figure 3. Supported specimen example a) Front view of the model b) Three-dimensional view of the model.

$$\left(\frac{\sigma_1}{X_t}\right)^2 + \bar{\tau} > 1, \quad \sigma_1 > 0 \tag{1}$$

Transverse tension

$$\left(\frac{\sigma_2}{Y_t}\right)^2 + \bar{\tau} > 1, \quad \sigma_1 > 0 \tag{2}$$

Transverse compression

$$\left(\frac{\sigma_2}{2S_{12}}\right)^2 + \left[\left(\frac{Y_c}{2S_{12}}\right)^2 - 1\right]\frac{\sigma_2}{Y_c} + \bar{\tau} > 1 \tag{3}$$

where σ_1, σ_2 are the tension in the fiber direction, and matrix direction, respectively. Likewise, X_t, and Y_t are the longitudinal, and transverse tensile strength, respectively. $\bar{\tau}$ is fiber matrix shearing term, S_{12} is in-plane shear strength, and Y_c is transverse compressive strength.

$$\bar{\tau} = \frac{\frac{\tau_{12}^2}{2G_{12}} + \frac{3}{4}\alpha\tau_{12}^4}{\frac{S_{12}^2}{2G_{12}} + \frac{3}{4}\alpha\tau_{12}^4} \tag{4}$$

The in-plane stress–strain relationships are as follows.

$$\varepsilon_2 = \frac{1}{E_1}(\sigma_1 - \vartheta_{12}\sigma_2) \tag{5}$$

$$\varepsilon_2 = \frac{1}{E_2}(\sigma_2 - \vartheta_{12}\sigma_1) \tag{6}$$

$$\varepsilon_{12} = \frac{\tau_{12}}{2G_{12}}(\sigma_1 - \vartheta_{12}\sigma_2) \tag{7}$$

where E_1 is strain in fiber direction, ϑ_{12} is Poisson's ratio, E_2 is strain in the transverse direction, and $2\varepsilon_{12}$ is shear strain. If index 2 is replaced by 3 in any above criteria, failure theories are applied for the planes 1–3 [16].

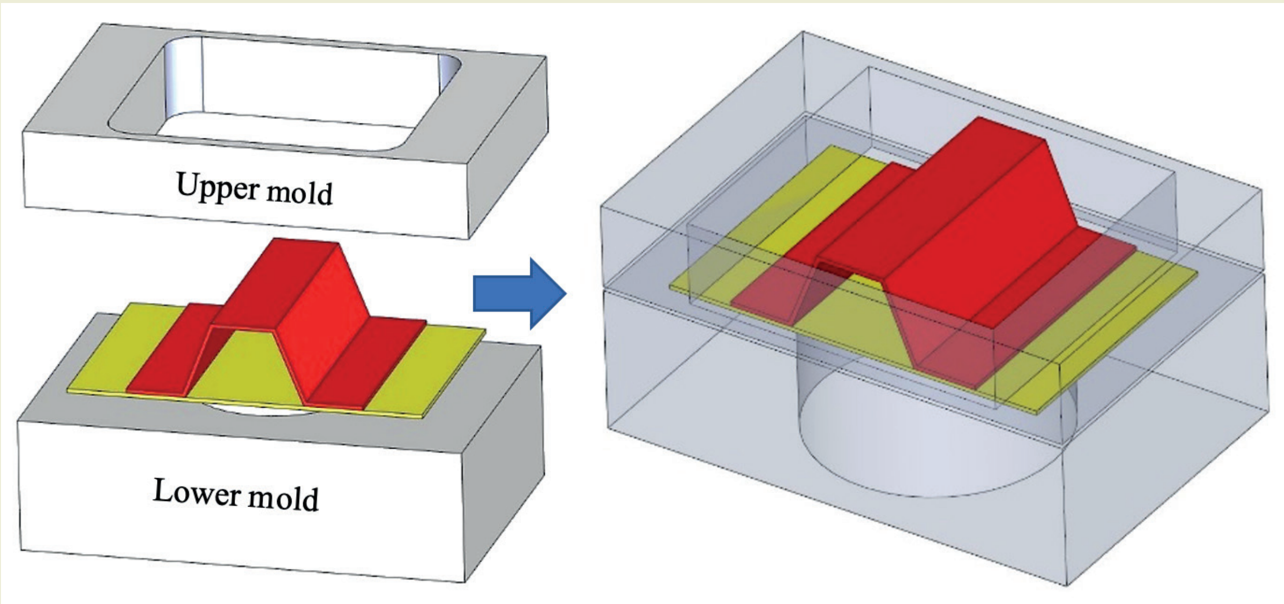

Figure 4. Molds designed to fix the composite panel on the impact test analysis.

Table 2. Mechanical properties of glass fiber reinforced composite [16]

Symbol	Properties	Value	Unit
ρ	Density	1500	kg/m3
E_x, E_v	Elasticity modulus x, and y direction	43.7	GPa
E_z	Elasticity modulus z direction	14.57	GPa
v	Poisson	0.21	-
G_{xv}	Modulus of rigidity in xy plane	14.18	GPa
G_{vz}	Modulus of rigidity in yz plane	14.65	GPa
G_{zx}	Modulus of rigidity in zx plane	14.65	GPa

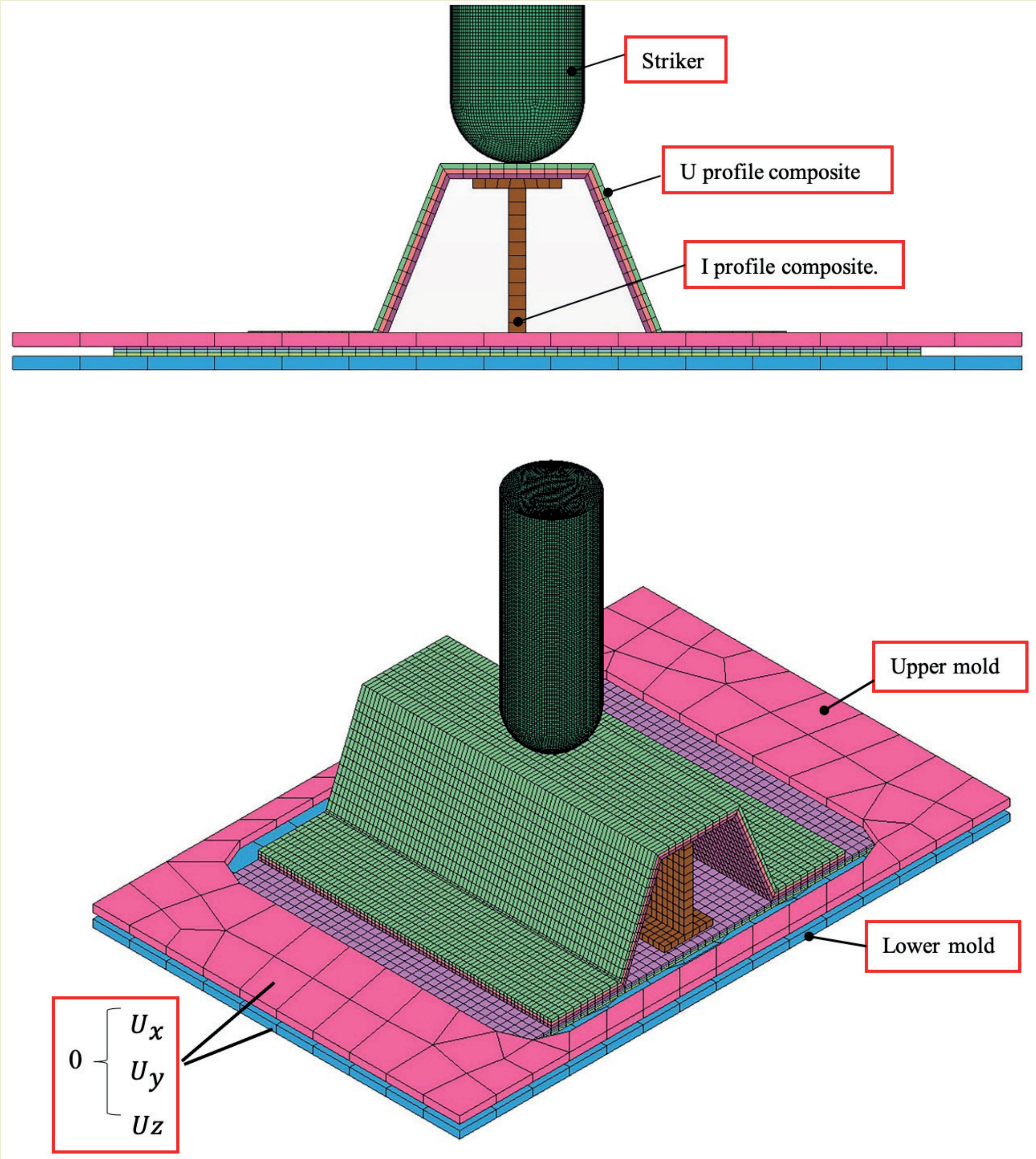

Figure 5. Finite element model of I profile supported composite.

3. Results and Discussions

The mechanical behavior of I-profile supported, and unsupported composites under impact load was examined. The effect of the I profile support added to the composite structure on the damage load, and damage behavior of the structure was evaluated. ▶**Figure 6** shows the reaction force-time graph for supported, and unsupported specimens. According to the graph, it was seen that the reaction force increased in the elastic region with the contact of the striker with the U-profile composite, and after reaching the maximum point, the structure was damaged. When the slope of the force increase in the elastic region was compared, it was determined that the supported specimens exhibited more rigid material behavior. In the supported specimens, the impact was rebounded by the impact of the I profile upon impact with the specimen, and its contact with the specimen was less than that of the unsupported specimen. In the first stage of contact, slight oscillations were observed due to the elastic vibration caused by the initial contact between the striking tip, and the composite plate. The initial sudden force decrease is due to the decrease of bending stiffness, and reaching the delamination damage threshold because of the brittle impact damage behavior of the glass fiber composite. Continuing small force decreases thereafter indicate crack growth [17]. In ▶Figure 7, the maximum damage loads of the specimens are compared.

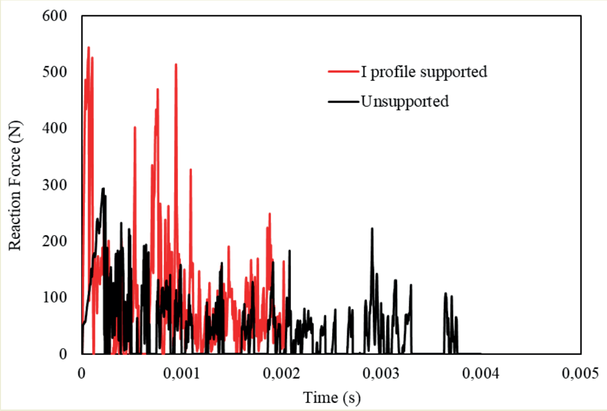

Figure 6. Reaction force-time graph of supported, and unsupported U-profile composites.

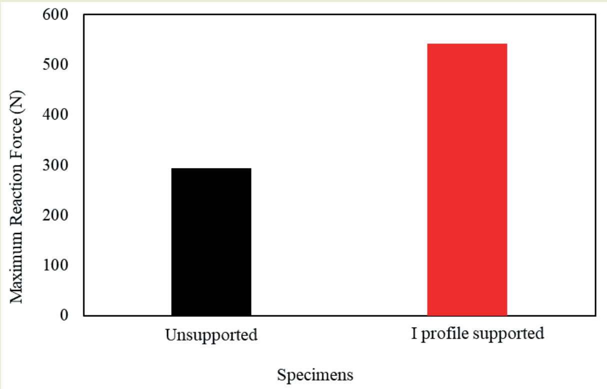

Figure 7. Reaction force- time graph of supported, and unsupported U-profile composites.

When the graph is examined, the maximum damage load of the unsupported specimen is determined to be approximately 294 N. It was determined that by adding an I profile to the structure, the maximum damage load increased to 543 N. Accordingly, it was determined that the increase in the maximum reaction force was approximately 85%. Hou et al. stated in their study that I, and T-reinforced composites increased the impact strength, and post-impact compressive strength. ▶Figures 8, and 9 show the images of unsupported, and supported specimens after the impact test. As can be seen, fiber breakage was observed under impact loads on the surface where the U profile, and the striker encountered the unsupported specimens. The MAT22 material model shows fiber breaks by destroying the elements in this region. When the damage image of the supported structure given in ▶Figure 9 is examined, it is again possible to see fiber breaks. However, as can be seen, fewer damage areas were observed compared to the unsupported specimens.

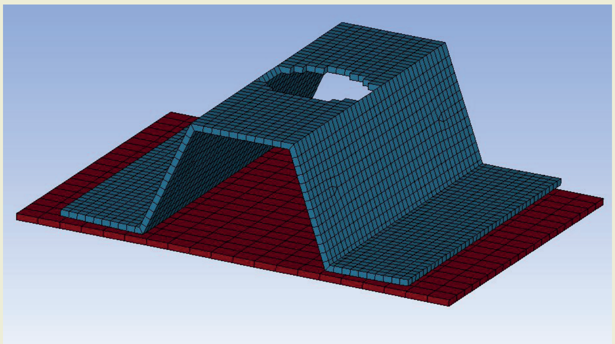

Figure 8. After-impact image of the unsupported U-profile composite.

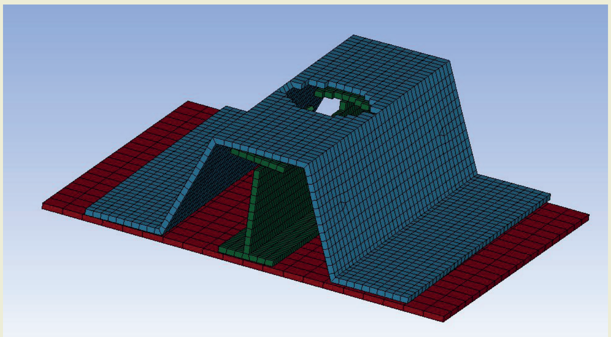

Figure 9. After-impact image of the I profile supported U-profile composite.

4. Conclusions

In the study, supported, and unsupported glass fiber composites with U profiles were designed. Afterwards, impact tests were carried out on the specimens with an impact energy of 27.55J. The results are compared, and summarized as follows.

- It has been determined that the maximum damage load of the structure increases by approximately 85% by adding I profile support to unsupported U profile composites.
- It has been determined that supported specimens exhibit more rigid material behavior than unsupported specimens under impact load.
- After the impact analysis, it was observed that the damage area was reduced on the upper surface of the U profile, which was contacted by the striker, thanks to the I profile support.

- Adding an I profile to reinforced panels with a U-profile is recommended to designers, both in terms of structural integrity, and the damage load it can carry.

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Research ethics

Not applicable.

Author contributions

Methodology: [Mete Onur Kaman], Formal Analysis: [Mustafa Albayrak], Investigation: [Merve Uslu], Resources: [Cenk Yanen], Data Curation: [Serkan Erdem], Writing - Original Draft Preparation: [Merve Uslu], Writing - Review & Editing: [Serkan Dağ], Visualization: [Kadir Turan]

Competing interests

The author(s) state(s) no conflict of interest.

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Data availability

The raw data can be obtained on request from the corresponding author.

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Orcid

Merve Uslu https://orcid.org/0000-0001-7819-8377
Mete Onur Kaman https://orcid.org/0000-0003-0178-6079
Mustafa Albayrak https://orcid.org/0000-0002-2913-6652
Cenk Yanen https://orcid.org/0000-0002-5092-8734
Serkan Dag https://orcid.org/0000-0003-4608-3924
Serkan Erdem https://orcid.org/0000-0002-2504-0135
Kadir Turan https://orcid.org/0000-0002-4065-9649

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