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Research Article

Improved Mold Design for Impact Testing of Stiffened Panels: Enhancing Structural Integrity

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ABSTRACT

This study presents the development of a mold design intended to ensure the suitability of stiffened panels for compression after impact (CAI) testing. In the original mold system, specimens exhibited edge separation and adhesive bond failures following impact, making them unsuitable for further testing. To address this issue, a new mold was designed to grip the panel from all sides while preserving its structural integrity. A comparative assessment was conducted using post-impact observations from both the original and improved systems. With the improved mold, a 30 J impact test was performed, after which the specimen retained its structural integrity and remained viable for CAI evaluation.

Keywords: Fiber reinforced composites, impact test, molding design, stiffened panels, structural integrity.

INTRODUCTION

Composite structures have become increasingly prevalent in modern industrial applications, primarily due to their advantages in light weight and high mechanical strength. Commonly employed in the aerospace, automotive, and marine sectors, these structures must preserve their structural integrity, particularly when exposed to impact forces (**Fig. 1**). In real-world scenarios, composite components are frequently subjected to accidental impacts caused by foreign objects, tool drops, or operational loads, which can lead to barely visible impact damages (BVID) that critically affect their performance.

Impact testing serves as a fundamental method for evaluating the damage tolerance and strength of composite systems. It provides essential insights into how composite structures absorb energy and how internal damage mechanisms—such as matrix cracking, fiber breakage, or delamination—are initiated and propagated. As such, a thorough understanding of these failure modes enables engineers to design more robust and safer structural components.

The type and extent of damage induced by impact directly affect the residual load-bearing capability and long-term durability of the composite system. Therefore, compression after impact (CAI) tests are typically conducted following the impact event to assess the structural capacity of the damaged composite. These tests simulate service conditions and offer a quantitative measure of how much strength the structure retains post-impact.

The importance of integrating both impact and CAI tests lies in their combined ability to offer a comprehensive assessment of the structural reliability of composite panels. While impact tests identify damage susceptibility, CAI tests determine whether the structure can still perform its intended function. As composite materials continue to replace traditional metallic components, especially in weight-sensitive applications, understanding their post-impact performance is crucial for safety and certification processes in critical sectors.

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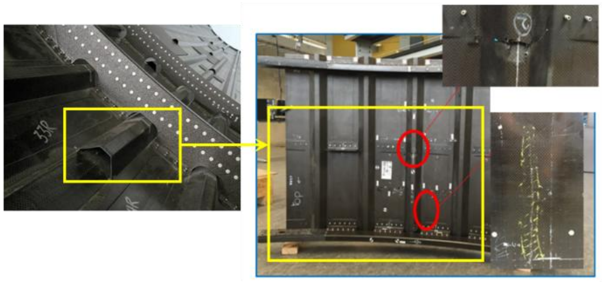

Figure 1. Reinforced panel damages in aircraft structures [1].

Stiffened composite panels are widely used in aerospace, marine, and automotive industries due to their superior stiffness-to-weight ratio and excellent energy absorption characteristics. These structures typically consist of thin composite skins reinforced with integral or bonded stiffeners such as T-, I-, or hat-shaped elements. The inclusion of stiffeners enhances the panel's ability to withstand axial and bending loads, making them ideal for load-bearing applications in aircraft fuselages, ship hulls, and automotive chassis components. Despite their enhanced performance under static loads, stiffened panels are vulnerable to low-velocity impact events during manufacturing, maintenance, or in-service conditions. Barely visible impact damage (BVID), often caused by tool drops or foreign object strikes, may not be detected through visual inspection but can significantly compromise the structural integrity of the panel. Such hidden damage often initiates within the adhesive layer or at the stiffener-to-skin interface, leading to delamination or debonding.As a result, impact testing of stiffened panels requires a well-designed fixture that ensures proper boundary conditions and prevents artificial failure modes. Mold systems must securely grip the panel and distribute the impact force uniformly across the structure. The subsequent compression after impact (CAI) tests are critical in evaluating the residual strength and post-impact load-carrying capability of the damaged structure.Recent advancements in composite technology have introduced hybrid stiffened panels combining woven fabrics, unidirectional fibers, and optimized stiffener geometries to enhance damage tolerance. Moreover, researchers are now exploring digital image correlation (DIC), ultrasonic inspection, and infrared thermography as non-destructive evaluation techniques to detect and quantify internal damage after impact.Understanding the complex failure mechanisms in stiffened panels under impact conditions is essential for improving structural design, ensuring flight safety, and extending the service life of composite structures. Therefore, research continues to focus on developing novel mold designs, advanced materials, and reliable testing protocols for more accurate and repeatable evaluation of impact-damaged stiffened panels.

LITERATURE REVIEW

Numerous studies have investigated the impact resistance of stiffened composite panels under various parameters such as laminate stacking sequence, stiffener geometry, impact energy levels, and support conditions [2]–[4]. These studies aim to understand the failure mechanisms occurring in composite structures under impact, including delamination, fiber breakage, and matrix cracking. While much of the existing research focuses on the mechanical behavior of composites under impact, less attention has been paid to the design of the fixtures and molds used during such testing. One significant research gap in the literature concerns the adequacy and configuration of the fixtures and molds that secure specimens during impact testing [5]–[9]. These elements are crucial for ensuring consistent boundary conditions and eliminating potential test artifacts. Improper mold or fixture design can lead to artificial damage mechanisms, such as edge debonding or misalignment-induced shear forces, which may compromise the accuracy and repeatability of the results. Several studies have highlighted that post-impact adhesive failures frequently occur at the panel edges due to insufficient clamping or fixture support [10]–[15]. These failures distort the actual load path and adversely affect the accuracy of subsequent compression after impact (CAI) tests by causing premature global buckling or undesired local damage. Thus, preserving structural integrity after impact is essential to ensure valid CAI results. Although extensive literature exists on the manufacturing processes of composite panels, there is still a lack of studies specifically addressing how mold geometry, surface characteristics, and mechanical interfaces influence the impact response of stiffened panels [16]–[20]. Parameters such as mold rigidity, surface

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contact quality, and fastening uniformity play a significant role in how the impact energy is distributed and absorbed. Failure to optimize these parameters can result in non-representative damage distributions. Furthermore, the need to maintain the structural integrity of specimens throughout multi-phase tests—from impact to CAI—has been increasingly emphasized in recent research [21]–[25]. Multi-functional fixture systems that ensure both rigidity and adaptability are required to prevent any unintended damage between successive test stages. Only with such systems can reliable, repeatable, and representative data be obtained in laboratory settings. In summary, while much attention has been devoted to the behavior of composite panels under impact loading, the role of fixture and mold design in ensuring accurate and valid testing outcomes remains an area requiring further research. Future studies should aim to develop more advanced, modular, and adaptive mold systems that accommodate various panel geometries and testing protocols.

MATERIAL AND METHOD

Design and Manufacturing of the Mold

This section explains the mold manufacturing process and machining tools used for impact testing of stiffened panels. Initially, a mold was designed to accommodate U-profile stiffened composite panels for impact testing (**Fig. 2**). These panels are produced by bonding a U-profile to a flat plate using an adhesive. According to the test results, damage occurred mainly in the bonding area due to shear stresses transmitted after the impact on the U-profile. This condition prevented the accurate measurement of the actual mechanical performance of the stiffened panels. The deficiencies identified in the initial mold tests are as follows: i) the striker failed to fully secure the specimen,

ii) adhesive debonding occurred, iii) the panel could not remain intact after impact and was unsuitable for further testing (**Fig. 3**).

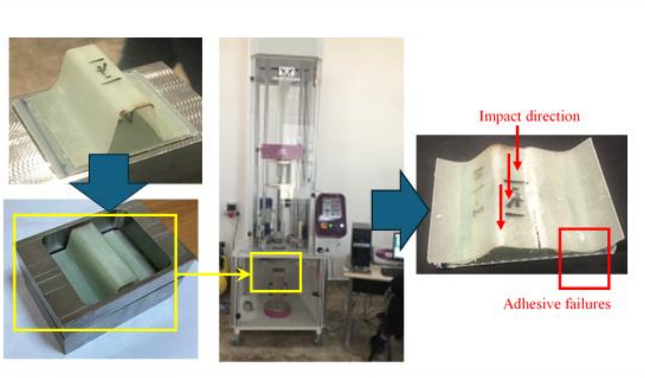
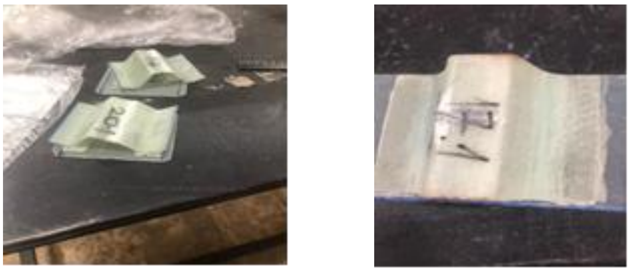


Figure 2. Initial Mold Design and the Damaged Specimen After Impact.



a) b)

Figure 3. Deficiencies in the Previous Mold: a) Adhesive Separation (b) Inability of the Striker to Clamp the Specimen.

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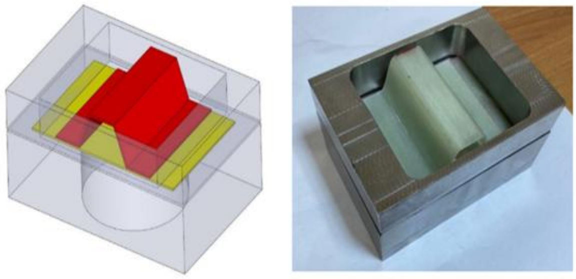


Figure 4. Technical Rrawing of the First Mold and its Appearance After Production.

(Fig.4.) shows the traditional mold system used at the beginning. In this mold, since the fixation of the sample was insufficient, it was observed that the sample was displaced after the impact, edge gaps were formed and separations were observed in the bonding areas. These problems eliminated the suitability of the sample for the CAI (Compression After Impact) test after the test. To overcome these problems, a new mold was designed by

applying structural and mechanical improvements to preserve the panel's integrity after impact. The manufacturing process was carried out in three stages: i) *Design and Modeling* – redesigning the mold based on previous test observations and defining suitable dimensions, ii) *Production* – machining mold parts using milling, turning, and drilling machines, iii) *Assembly* – assembling the parts to make the mold ready for testing.

To prevent adhesive-related damage, counter-support blocks were designed to fit the mold dimensions. This approach restricted movement of the U-profile in the plane direction. A flat steel profile measuring 20 × 250 mm was used and machined using a milling machine (**Fig. 5**). The processed steel profile was cut into two equal pieces and mounted on both sides of the specimen inside the mold.

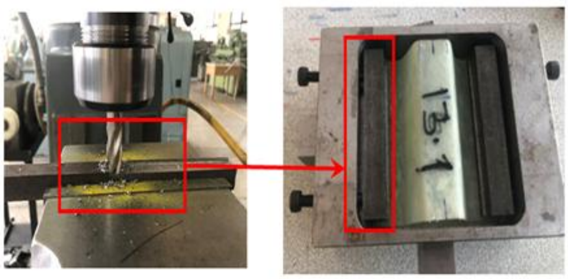
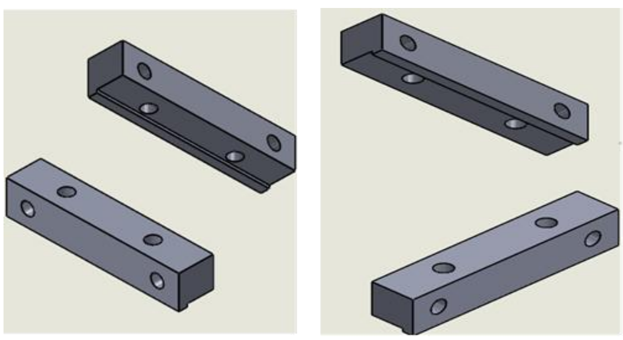


Figure 5. Machining and Placement of Support Blocks into the Mold.



a) b)

Figure 6. Technical Drawing of Mold Support Bars. a) Left Support Bar, b) Right Support Bar.

Support bars are one of the most critical structural elements of the modified mold system. These bars, shown in (**Fig.6.**), are placed to prevent lateral movement of the sample during impact, to control the distribution of energy

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and to maintain structural integrity. The left and right support bars placed symmetrically inside the mold ensure that the U-profile panel is fixed inside the mold. This fixation prevents off-axis shifting and torsion that may occur especially due to impact.

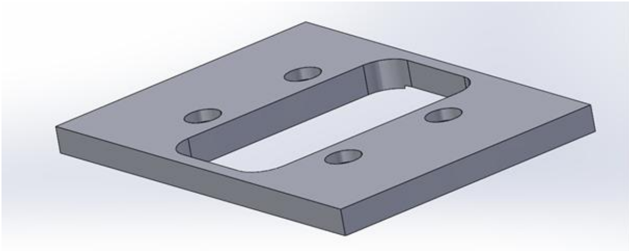

Figure 7. Technical Drawing of the Mold with a Screw-Fixed Cover

The mold design shown in (**Fig. 7)** is an advanced version featuring a screw-fastened cover intended

to mechanically secure the specimen from all sides. This screw-based system enhances the

transmission of impact energy directly onto the panel while maintaining its position throughout the test. Among the advantages of the screw system are adjustable clamping force, adaptability to different panel dimensions, and creation of a repeatable test setup. Furthermore, the system allows for broader distribution of reaction forces following impact, thereby reducing localized structural damage. However, during testing, it was observed that this mold could not be properly mounted on the test device due to its overall height, which caused alignment issues. For this reason, a more compact mold compatible with the device was selected instead.

Another identified issue was that the fixing arm (clamp) of the impact test device, shown in (**Fig. 8)**, touched the specimen instead of the mold, which damaged the sample. To prevent this, a new mold cover with adjustable height and screw locking was designed to support the support blocks and prevent contact with the specimen.

This new mold cover was made of sheet steel to avoid adding extra weight. The sheet was cut to size and drilled on a drilling machine. However, during tests, it was found that the mold could not be properly mounted on the testing device due to excessive height, which caused errors and prevented testing. Therefore, a second redesign was carried out. Two symmetric metal profiles with dimensions 30 × 100 mm and thickness of 35 mm were manufactured to match the negative geometry of the U-profile panel.

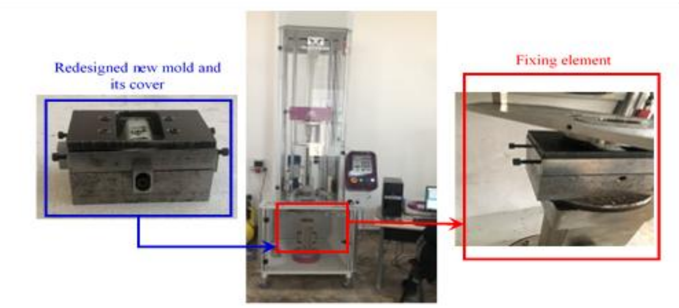

Figure 8. Redesigned Mold and its Screw-Fixed Cover.

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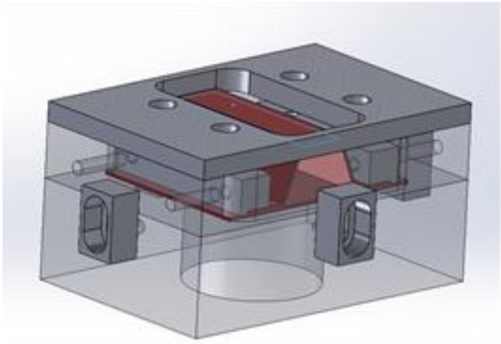

Figure 9. Technical Drawing of the Modified Mold with Screw-Fixed System.

(Fig. 9) illustrates the technical drawing of a mold designed for maximum clamping security, reinforced with a screw-fixed system. Initial tests revealed that this version could not be properly supported on the test device, limiting its practical usability. Due to the height of the screw heads, the clamping arms of the testing machine could not align correctly with the mold, resulting in damage to the specimen. Despite these limitations, the design holds theoretical advantages: improved fixation through screws, controlled energy distribution, and dual-side impact testing capability. For successful application, this mold would require further adaptation to integrate seamlessly with the testing apparatus. These profiles were machined using a milling machine (**Fig. 10**). In this second design, the metal profiles contact the fixture of the impact testing machine, and the screw-fixed cover was removed. Additionally, this redesign enabled **dual-sided impact testing**, allowing the panel to be struck from both the upper and lower surfaces (**Fig. 11**).

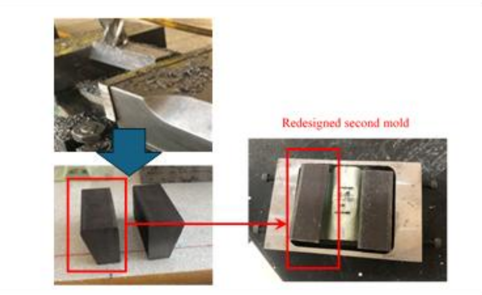

Figure 10. Machining and Assembly of Metal Profiles into the Redesigned Mold.

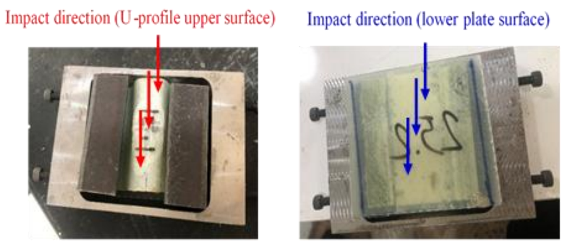

Figure 11. Dual-Sided Impact Testing Setup Inside the Redesigned Mold.

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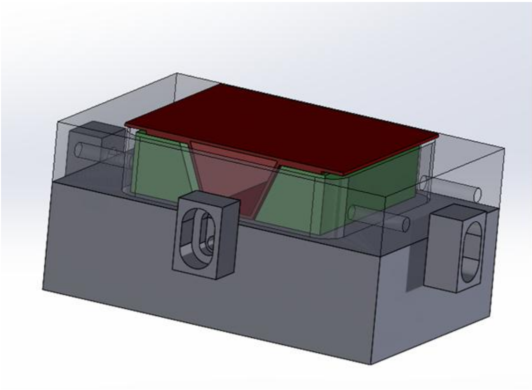

Figure 12. Image of the Inverted Specimen Inside the Modified Mold.

(Fig. 12) shows the final mold configuration, which is fully compatible with the test device and used

in actual impact testing. The previously developed screw-fastened mold could not be used due to assembly and height issues. Instead, this more compact mold with symmetrically positioned metal profiles was selected.

The specimen was placed in an inverted orientation to investigate behavioral differences under reversed impact direction. The internal design of the mold ensured rigid fixation of the panel in both standard and inverted positions, thus enabling repeatable test conditions. The preservation of

structural integrity post-impact confirmed the effectiveness and suitability of this mold system.

Experiments

This section describes the impact testing procedure using the newly developed mold (Fig. 10). The goal was to evaluate the redesigned mold by comparing it with the previous version and to analyze whether the panel retained its structural integrity after impact. The new mold was expected to provide a more robust structure, making the specimen suitable for post-impact compression testing. Prior to testing, the stiffened panel specimens were prepared and surface-treated. In the second step, the mold was mounted on the testing machine. The custom screw-fixed mold cover was also installed. In the third step, the impact energy level was set, and the tests were performed at 30 J. Force–time data was recorded for each specimen after impact.

RESULTS AND DISCUSSION

The impact test results conducted using the initial and redesigned molds were comparatively evaluated. The primary goal was to assess whether the adhesive bond separations observed in the first mold (**Fig. 4**) were resolved in the newly designed mold. Figure 8 shows the force–time graph of impact tests performed using the redesigned second mold. Each test was repeated twice. The consistency between the tests indicates that the redesigned mold meets the necessary manufacturing standards. The force increased linearly until reaching its maximum value, and then decreased parabolically to zero. In the test image presented in (**Fig. 13)**, it is observed that although the striker pierced the panel, no adhesive failure occurred at the bonding surfaces. This clearly demonstrates the effectiveness of the redesigned mold.

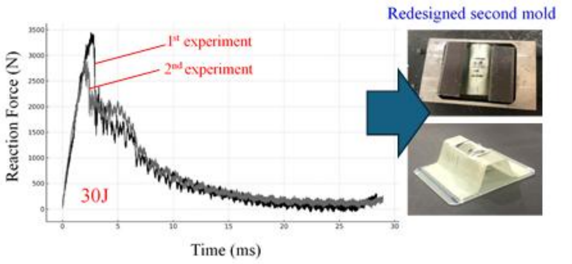

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Figure 13. Force–Time Diagram of Specimens Tested with the Redesigned Mold.

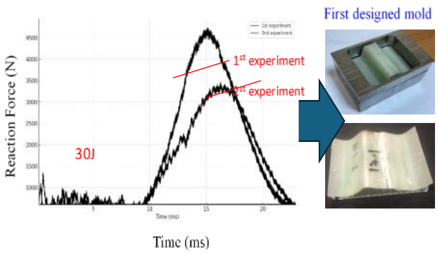

Figure 14. Force–Time Diagram of Specimens Tested with The First Mold.

In (**Fig. 13**), a single controlled peak force around ~3500 N is observed for the 30 J impact test. (**Fig. 14)** shows the force–time diagram of the specimens tested with the first mold. The modified mold distributed the impact energy more effectively, stabilized the peak force, provided more regular damping after the impact, and enabled controlled energy absorption by the structure. These results demonstrate that the mold modification improved both the structural strength and the post-impact stability of the system.

CONCLUSIONS

In this study, deficiencies in the mold designed for impact testing of stiffened panels were evaluated, and an improved mold design was developed. The edge openings and adhesive debonding observed in earlier tests prevented the panel from maintaining structural integrity after impact, making it unsuitable for subsequent compression testing. To address these issues, side support mechanisms were reinforced, fastening elements were improved, and design modifications were implemented to ensure more balanced distribution of impact energy. The following enhancements were included in the new design:

- Reinforced side support mechanisms: Lateral supports were added to prevent edge openings due to impact loading.
- Improved fastening components: Alternative bonding methods were used to prevent adhesive failures. Enhanced energy distribution: Additional components were machined and inserted to improve the mold's energy absorption capability.
- Dual-side impact testing capability: A new mold cover was designed to allow specimens to be flipped, enabling impact from both top and bottom surfaces.

As a result, this study presents a more reliable method for evaluating the impact resistance of stiffened composite panels.

Acknowledgments

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