Business, Management and Economics Engineering
ISSN: 2669-2481 / eISSN: 2669-249X
2024 Volume 22 Issue 01

ANALYTICAL EXPLORATION AND ADVANCED ANALYSIS OF COMPOSITE MATERIAL MECHANICS

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Abstract:
The study examines the structural performance of nine lightweight composite materials under shock and impact loads using both experimental and computational methods. The top three lightweight materials are identified for further analysis. The study also investigates composite materials' behavior under rapid loading in real-time applications like bullet crash analysis, UAV propellers, and car bumpers.The crash analysis of three composites - CFRP, GFRP, and KFRP - is performed using ANSYS Workbench's explicit technique-based finite element analysis (FEA). Comparisons are made based on structural characteristics, and two grid convergence tests validate computational processes and discretization accuracy. Standard methodologies are applied across all three real-time applications, ensuring acceptable error percentages.
Key words: Bumper, Composites, GFRP, CFRP ,FEA, ANSYS,

1. Introduction:

A wide range of industries are using composites more and more because of their high stiffness-to-weight ratio. By addressing the low resistance factor of composites in a variety of testing scenarios, researchers are currently concentrating on expanding the application of composites in complex scenarios. In particular, the choice of appropriate materials is greatly influenced by the composites' capacity to tolerate impact loads. The best material for impact resistance in the industry is still up for debate, despite advances in methodology. Thus, under impact loading conditions, this study compares various composite materials, such as carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), and Kevlar fiber-reinforced polymer (KFRP). Using experimental testing facilities, the Charpy method is utilized to assess the chosen composites' properties.ANSYS Workbench 16.2 is used to conduct computational structural analyses. For both analyses, the dimensions are 80 mm in length, 10 mm in thickness, and 10 mm in width.
There are engineering approaches for complex real-time problems. The success of solving these problems depends on the application of advanced methods designed to address difficult issues. This is demonstrated by cutting-edge techniques like dynamic meshes, moving reference frames, and other creative methods. Problems like rotor aerodynamics, acoustic analysis, and fluid-structure interaction can all be solved with explicit analysis. Explicit analysis is used in this study to optimize materials in crash or collision scenarios.Irregularities arising from crash impacts sometimes point to non-linear oscillations in the interior structure of the damaged items. Three crash situations typically occur: collisions between two items (such automobiles),

crashes involving a vehicle or object and a roadside barrier, and collisions brought on by other vehicles' sideslip forces. The investigation of accidents between components and roadside barriers is the main subject of this study because of its high frequency and substantial demand. Composite materials are preferred for critical applications including high frictional conditions, abrupt mechanical loads, intense temperatures, and hydrodynamic forces because of their unique properties. The matrix's sticky component serves as a base for adding other additives. To improve the qualities of composites, the right combinations like silicon carbide, Teflon, and carbon nanotubes must be used to solve difficult problems.

The composite can efficiently handle rapid impact loads due to its outstanding load transformation capabilities and matrix flexibility. Important variables affecting the reaction to loading circumstances include the fiber type, orientation, and adhesive strength of the matrix. When several parts are involved, the load is gradually changed throughout the composite structure.Furthermore, the growing focus on composites' lightweight qualities greatly expands the range of crucial applications for which they may be used. Composite components must thus efficiently control structural factors such as normal loading conditions and delamination in order to properly handle the inherent problems posed by impact loads. Therefore, in this comparative research, advanced, structurally significant fibers like carbon, glass, and Kevlar are used. Additionally, two matrices were examined for the structural analysis: epoxy resin and polyester resin. Epoxy resin performed better than polyester resin in addressing ultra-structural problems, especially the danger of delamination failure. As a result, epoxy resin is used as the matrix throughout the whole investigation.

Sustaining both internal and exterior loading situations requires a faultless fiber-matrix connection. Failure usually results from this bond breaking under continuous strain, which might push the material into an erratic and non-linear area called the ultimate withstand zone. Each load has a different implementation and kind of impact. There are some external loads that behave linearly, such as tension and compression. Under some loading circumstances, such as shear, fatigue, and impact stresses, material bonding may break nonlinearly. This work uses a variety of engineering techniques, such as the Charpy impact test, scanning electron microscopy (SEM) analysis, and computer simulations, to examine how composite materials behave under impact loading circumstances.

1.1. Relevant Research:

Thorough examinations of the literature were essential in completing complex tasks including impact analyses, fatigue life forecasts, and shear stress calculations. ANSYS Workbench was used in this study's bumper collision research, which concentrated on the bumper's function of absorbing impact energy to protect passengers. The goal of the research is to maximize bumper materials by using ANSYS for impact analysis.The conceptual design of the bumper and its preparation for numerical assessment were included in the analytical technique. Important structural variables that were crucial to this study were the overall deformation and the generated equivalent stress. CATIA was used to model the reference component, and ANSYS Workbench 16.2 was used to assess the bumper's effects using steel and glass fiber-based composite materials at constant boundary conditions (velocity = 13.3 m/sec).

The choice of material for the bumper was made. According to Raj Kumar et al. 2019 discussion, a number of elements, including crash analysis time step and length, suitable velocity of moving objects, mechanical characteristics of composite materials, support circumstances, impact strength formulation, and theoretical estimates of crash stress, have a significant impact on the accuracy of production forecasts under high stress situations. 2011 a research by Belingardi and Obradovic on the Formula 1 racing car's front end showed that CFRP performed very well in collisions. This study's primary goal was to evaluate an impact attenuator's crashworthiness response using computational and experimental analysis. The research materials, design specifications, and mechanical characteristics of the materials are noteworthy features of this project. Numerical simulations were used by Smojver and Ivančević (2017) to study the effects of bird attacks on soft bodies. To replicate the harm that a foreign item may inflict on a target's inside organs, high-velocity strikes were used. A coupled Eulerian-Lagrangian formulation was used in the investigation, and experimental data was used to confirm the numerical conclusions.In order to examine cylindrical and conical structures subjected to longitudinal impact stresses, Matzenmiller and Karl (1991) created a numerical simulation. The goal of this work was to offer trustworthy insights for intricate buildings constructed of heterogeneous composite materials. They created boundary conditions for car crash testing by using standard values. The shells had regular spacing between discretizations, yet they became longer axially row by row. The greatest internal force that the shell could bear was determined by its form. Based on wall thickness, Boria and Belingardi (2012) distinguished three distinct failure modes in glass fiber epoxy laminate subjected to progressive deterioration under axial impact loading. According to their findings, materials reinforced with fabric have a tendency to absorb energy more effectively than materials that are unidirectional. The author was provided with a method to produce GFRP material with designated energy absorption capabilities. This study highlights several significant findings, including the importance of orthogonal characteristics, reinforcement forms, and matrix-based inputs. Bussadori et al. (2014) devised and examined two alternative finite element models to precisely predict the energy absorption capacity of CFRP.They looked at things like the inter-laminar material qualities and the coefficient of friction between the model and the affected object. Zhou et al. (2020) defined impact-induced damage to composite laminates as the continuum damage mechanics of intra-laminar damage. The author used a 500 mm by 500 mm square plate with an average thickness of 3.6 mm, in accordance with ASTM specifications. Three primary conclusions emerged from the study: specimen details, boundary conditions, and computational methods.

Kesavan et al. (2021) investigated KFRP (Kevlar Fiber Reinforced Polymer) in detail. Heat-resistant synthetic fibers like Kevlar are used in a wide range of products, including military helmets, reinforced tires, and bulletproof vests. As a result, they are a common composite material in new technical developments. Because of their enhanced qualities, the research recommends more investigation into Kevlar-based composite materials for cutting-edge applications. Employing a novel simulation tool, this study scrutinizes the behavior of Kevlar fiber under both tensile and bending loads utilizing ANSYS. The analysis encompasses various perspectives, with grid convergence tests confirming computational accuracy. Validation based on traditional analytical formulas reduces error margins to acceptable levels. Ultimately, optimization of fiber angle orientation is achieved through assessments of equivalent stress, strain energy, and deformation. Notably, Models 20, 27, and 31 exhibit commendable performance during peak loading conditions (Kesavan et al., 2021).

The impacts of fluid-structure interaction (FSI) loading conditions were investigated by Ramesh et al. in 2022. Reliability of numerical simulation results depends on realistic boundary conditions, which include exact load circumstances, strong supports, and mechanical attributes. For complicated numerical simulations to produce good results, antecedent processes like identifying material attributes and analyzing real-time load situations are crucial. Furthermore, sophisticated numerical simulations can handle complex problems. This work presents the results of an FSI study on the impacts on various composites made of glass, carbon, and Kevlar fibers. The ANSYS Design Modeler is used for developing conceptual designs, while the ANSYS Composite Preprocessor (ACP) tool is used to create various composite configurations. The best material for impact applications is then determined by comparative impact testing (Ramesh et al., 2022).

The mechanical behaviors of several materials under complicated impact loading situations were studied by Vijayanandh et al. in 2022. Fluid-structural interactions are a common source of contemporary difficulties, with aerodynamic and other stresses providing concerns in real-world situations including frontal collisions on trains, automobile accidents, aircraft crashes, and wind turbine operations. Therefore, studies on fluid-structure interactions involving a variety of lightweight materials are crucial because they may lead to the development of materials that can reliably bear aerodynamic stresses in various industrial settings. This work applies numerical analysis to problems in continuum mechanics, where complicated geometries, fluid dynamics, and fluid-structure interactions make computational solutions difficult.

Bhagavathiyappan et al. (2020) investigated the properties of several materials' mechanical behavior under extremely complex impact loading scenarios. By employing sophisticated numerical simulation methods, engineers are frequently able to overcome difficult problems and find workable solutions. These difficulties include, among other things, navigating the complex nature of construction and operating in hazardous conditions. This work mostly addresses equally challenging problems by examining how different composites behave when coupled to a system.The conceptual design of composite test specimens is created using ANSYS Design Modeler 16.2, which serves as the modelling framework and adheres to ASTM standard dimensions. After fiber and matrix assignments are completed in ANSYS ACP-Pre 16.2, it is possible to create a laminate that is made entirely of composite material. Using ANSYS Structural 16.2, ten distinct composite models are created, and the underlying structures of each model are examined when impact loads are applied. After carefully examining each other's findings, the researchers came to the conclusion that the strain-energy-based optimization was the best option (Bhagavathiyappan et al., 2020).

Composite materials undergo experimental and numerical assessment through low-velocity impact testing. A cylindrical head provides a nearly uniform two-dimensional loading condition for a model unidirectional CFRP laminate beam in drop-weight impact testing. Real-time observation of damage initiation and progression, including matrix cracks and delamination, is facilitated by an ultra-high-speed camera. Dynamic strain fields within the laminate are quantified using digital image correlation analysis, while failure patterns are characterized using a digital microscope. Apart from significant diagonal matrix fractures, simulations reveal multiple micro-matrix cracks along the upper interface. Ultimately, the experimental strain field, failure mechanisms, and sequence align with the modeled outcomes.

This paper presents comprehensive experimental data for a hypothetical composite layup to evaluate methodologies for modeling composite and interface damage (Tanay Topac et al., 2017).

Every aircraft component should be designed with a focus on reducing weight, improving durability, and extending lifespan while minimizing life cycle costs. Unmanned combat aerial vehicles (UCAVs) powered by jet engines currently have several difficulties when operating in the air. Crash-resistant landing gears are necessary for high-speed, high-payload UCAVs to get past these barriers. Jet-powered UCAVs have a higher touchdown velocity, which increases the likelihood of crashes. Assessments of loadings and loading conditions were made concurrently. Similar von Mises and maximum main stresses were found in ANSYS finite element analyses of different materials. The safety factor was then computed using these results. Impact scenarios were examined using explicit dynamics in LS-DYNA for the crashworthiness assessment. The impact-induced stress formulations and deformations were accurate, realistic, and non-linear. After that, validation protocols were put into place (Swati et al., 2022).

Detailed explanations are given in Sections 1.2 and 1.3. Furthermore, comprehensive analyses of the impact load-bearing capacities of several lightweight materials are carried out and compared with numerical outcomes. Reliable computational techniques are then extended to evaluate more lightweight materials, resulting in the determination of appropriate materials. Moreover, comprehensive analyses of the crash resistance of several lightweight materials are performed and compared with computational results. The approved high-level computing methods are then used to evaluate more lightweight materials, leading to the discovery of appropriate materials. Finally, a final summary wraps up the investigation.

1.2. Description of the conventional analysis problem:

The main difficulty in structural engineering is choosing a material that will be suitable for enduring unusual loading circumstances without sacrificing its lifespan. As a result, the material needs to be able to successfully combat two important factors: being able to withstand severe loading conditions and guaranteeing durability against typical environmental influences throughout its lifespan. Composite materials are the best option for meeting these essential characteristics. As a result, the main objective of this study is to compare popular composite materials, such as GFRP and CFRP, using structural analysis. The results of structural assessments are usually dependent on the nature and properties of the external load. Furthermore, the geometry and mechanical characteristics of the support have a fundamental impact on the structural reactions seen in the test specimen. The main focus of this research is non-linear loading situations, specifically impact loads as a particular type of external loading. In terms of structure, impact loads can exert a dual effect on the test specimen due to their abrupt nature. Consequently, these sudden impact loads are applied to the composite test specimen as peripheral forces, given their unconventional characteristics. Owing to their critical nature, test specimens subjected to impact loads exhibit varied reactions from different perspectives, influenced by factors such as fiber retention capability and stiffness-to-weight ratio. Because impact loads are sudden, they might have two different effects on the test specimen in terms of structure. Because of their unusual nature, these abrupt impact loads are consequently delivered to the composite test specimen as peripheral forces. Because they are crucial, test specimens that are subjected to impact loads display a range of responses from various angles, which can be impacted by stiffness-to-weight ratio and fiber retention capacity. The flowchart in Figure 1 provides a full breakdown of all the steps involved in this comparative study.

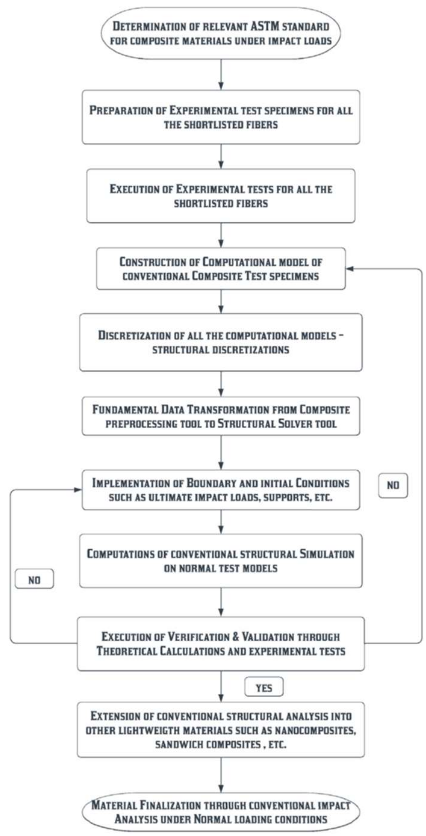


Fig.1. Working flowchart of conventional impact analysis.

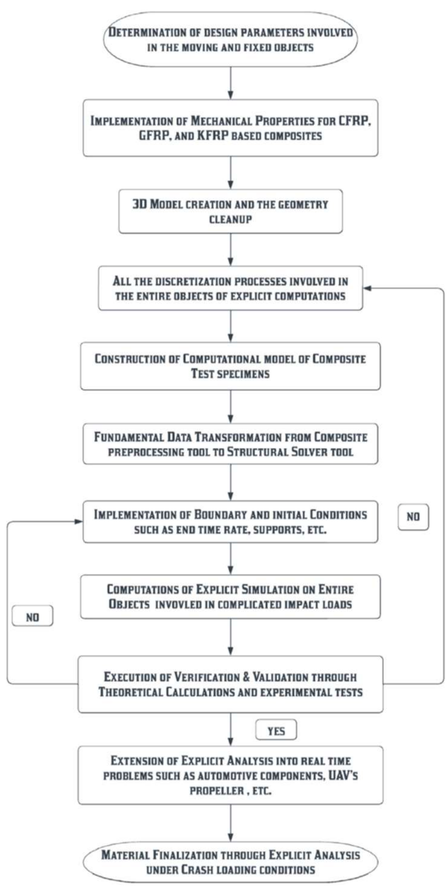
1.3. The issue and the steps taken in the advanced crash analysis process:

Explicit dynamics-based time integration is used in time-critical dynamic simulations. In situations when there are applied loads, high-velocity collisions, and free falls, dynamics must be taken into account explicitly. Since explicit dynamics modeling enables the inclusion of "non-linear dynamics" in the simulation, it is recommended for capturing very transient physical processes.Time integration in transient structural simulations using ANSYS's explicit dynamic analysis is done using the central difference method. The use of explicit dynamic analysis is advantageous in situations when the dynamics are very non-linear and move quickly. When using explicit techniques, the time step needs to be less than a certain number that is established by the element order or the mesh's minimum element size. Alternatively, using the implicit technique makes the time step value less important. For dynamic finite element analysis (FEA) problems with low-order non-linearity and large time steps, implicit dynamics is a good fit. The comprehensive, step-by-step methods used in this comparison study are described in detail in the flowchart in Figure 2.

Fig.2. Diagram for advanced explicit analysis in operation.

2. Approaches Employed and their Outcomes-Traditional Impact Analysis:

The standard impact test's test specimen composition has been greatly impacted by



ASTM D256. Figure 3 depicts the experimental setup for this traditional impact test. The test specimen's parameters are as follows: Its dimensions are 10 mm in width, 10 mm in thickness, and 80 mm in length. It is found that the cross-sectional area is 170.25 mm^ (11.35 × 15). Thirty layers (woven kind) are used in the construction (Bhagavathiyappan et al., 2020).

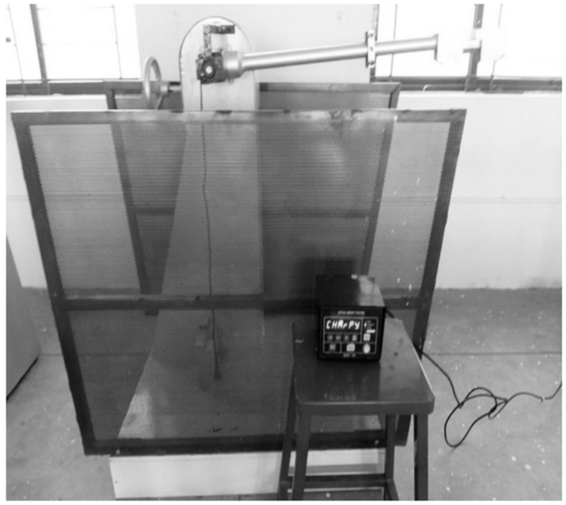


Fig.3. Experimental setup of the impact test.

2.1. Experimental testing and corresponding outcomes:

The standard test specimens for GFRP and CFRP are depicted in Figures 4A and 4B, respectively. These test specimens are fabricated according to the specifications outlined in ASTM D256 (Bhagavathiyappan et al., 2020). The test specimens are securely positioned at the designated location for the required impact collision between the test specimen and the steel hammer. Following the standardized test procedures, impact tests are conducted on both GFRP and CFRP test specimens. Subsequently, the resulting test specimens are meticulously examined, and the experimental findings are recorded. Typical representations of the fractured test specimens are illustrated in Figures 5A and 5B.

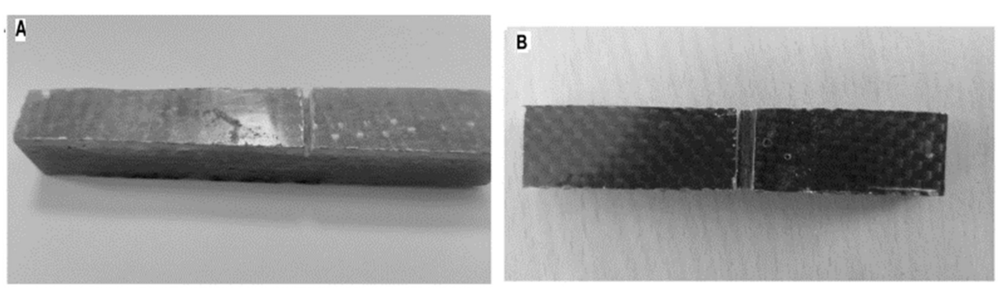


Fig. 4.(A) A representative top view of the test specimen made of GFRP. (B) An exemplary top view of the test specimen based on CFRP.

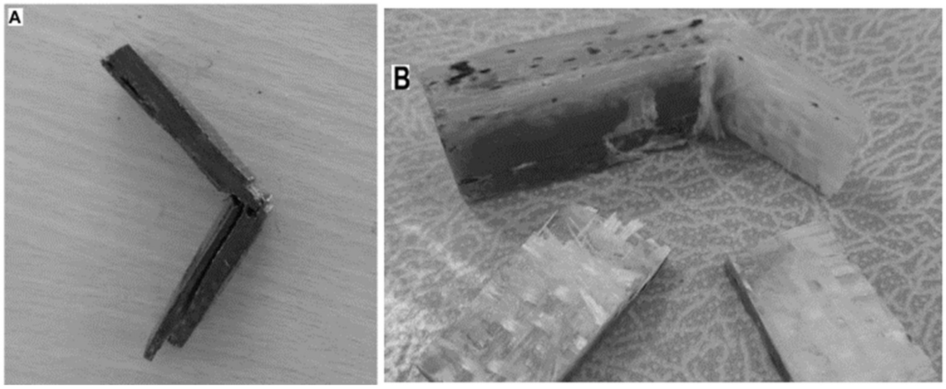


Fig.5.(A) Carefully constructed top view of the final CFRP test specimen. (B) The obtained GFRP test specimen seen from an isometric viewpoint.

3. Advanced Methodology Applied and Its Outcomes—Explicit Crash Analysis:

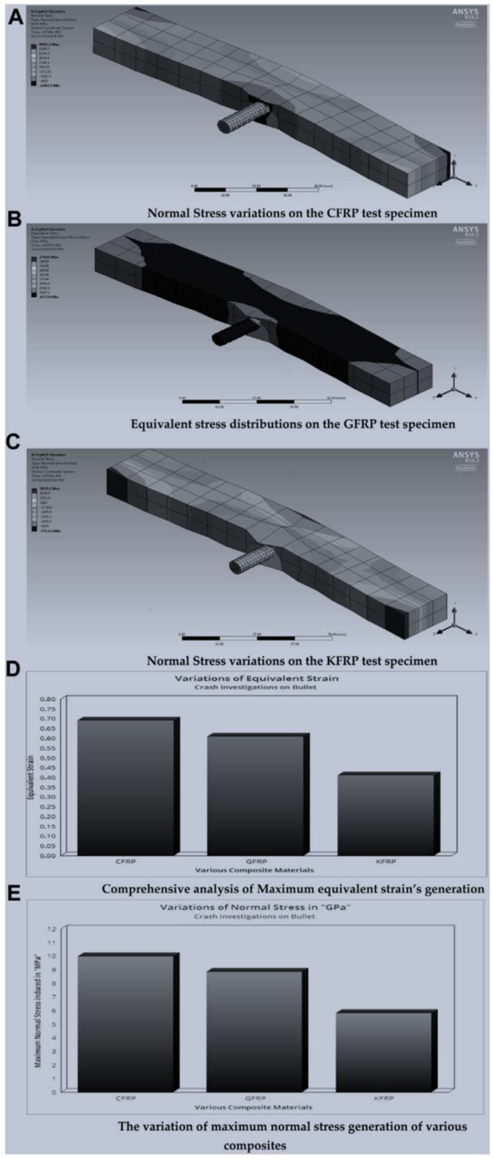
In situations like static equilibrium, slow-moving linear and weak non-linear processes, huge time steps, drop tests, impacts and penetrations, fractures, shock waves, and considerable deformations, the complex and non-linear character of the underlying problems necessitates the use of explicit dynamics. This study's sophisticated comparative crash analyses were solely based on explicit analysis using ANSYS. To further validate the numerical explicit results, normal theoretical computations were performed. The research includes two kinds of explicit-dependent numerical analyses: an explicit analysis focused on the propeller of the UAV and a standard crash analysis based on ASTM standards.In computational terms, issue formulation means describing the problem in detail as well as the steps involved in solving it. Finite Element Analysis (FEA) typically entails the development of a computer model of the test specimen, the discretization procedure applied to the specimen, an explanation of the nature of the issue, boundary condition requirements, numerical solver control settings, and the governing equations utilized in the analysis. The following sections go into further information about each of these points.Fixed supports, which are frequently present on both sides of the barrier, are essential to producing the resistive force inside the structure. Mobile objects are equipped with composites constructed of different materials, such as GFRP, CFRP, and KFRP, in order to maximize material use. Whereas the primary reinforcement in GRP is E-Glass-Fabric-M10E/3783-based fiber, the primary reinforcement in KFRP is Kevlar-49-UD-based fiber. Carbon-woven wet-based fiber (230 GPa) serves as the main reinforcement in CFRP. For all of these composites, epoxy resin is frequently utilized as the adhesive.For every composite, a unique comparison simulation was created, and the results of these simulations helped determine that epoxy resin was the material with the best performance level. Table 1 (Naveen Kumar et al., 2021) provides a thorough analysis of each composite material's fundamental mechanical properties.

Table.1.Composite material mechanical characteristics.

Material properties	Material name		
	CFRP	GFRP	KFRP
ρ (kg/m^3)	1,451	1,900	1,380
E_1 (GPa)	59.16	24.5	80
E_2 (GPa)	59.16	23.8	5.5
E_3 (GPa)	7.5	11.6	5.5
G_{12} (GPa)	17.5	4.7	2.2
G_{23} (GPa)	2.7	3.6	1.8
G_{13} (GPa)	2.7	2.6	2.2
υ_{12}	0.04	0.11	0.34
υ_{23}	0.3	0.20	0.40
υ_{13}	0.3	0.15	0.34

The CFRP composite test specimen's normal stress, equivalent stress, and equivalent shear strain variations are computed; Figure 6 A shows the normal stress variation with respect to the CFRP's applied crash load. Figure 6 B shows the structural output of CFRP composites by extending the structural analysis to GFRP and KFRP composites under the same loading circumstances. It mostly shows identical stress fluctuations throughout the bullet and barrier. Lastly, the normal stress structural outcome of Kevlar composites is shown in Figure 6 C.Figures 6 D and 11E offer more thorough depictions of all the structural outputs of the composites, showing that under the identical loading circumstances, the Kevlar composite has a low internal resisting force. Because KFRP can tolerate higher impact loads due to its decreased induction of resistance, KFRP-based composite products are more suited for crash-based applications.

Fig.6.(A) The CFRP test specimen's typical stress fluctuations. (B) The GFRP test specimen's equivalent stress distributions. (C) The KFRP test specimen under normal stress changes. (D)



A thorough examination of the creation of the greatest equivalent strain. (E) Variation in different composites' maximum normal stress generation.

Results and Discussions:

Owing to the strong validation, two more crucial real-time applications for explicit-based Finite Element Analysis (FEA) are being investigated: crash investigations involving UAV propellers and automobile bumpers. Due to the difficult settings in which they both operate, there is a much higher chance of failure. Therefore, it becomes essential to analyze the accident investigations in these missions in order to fully understand the intricate operating circumstances of all involved components. By means of this expansion, this study definitely guarantees that a comprehensive comprehension of peak loading situations and their structural repercussions will be obtained, hence augmenting the lifespan of the components employed in the previously described applications.

Comparing several composite materials under impact loading circumstances, including CFRP, GFRP, and KFRP, is the focus of the research. Because of their unique qualities, these composite materials are preferred for applications involving high friction, intense temperatures, and hydrodynamic forces. Explicit-based Finite Element Analysis (FEA) is being explored for collision investigations involving automotive bumpers and UAV propellers in real-time. In the study, sophisticated approaches such as explicit crash analysis are utilized to tackle intricate and non-linear issues.

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