

ENERGY ABSORPTION CAPACITY OF COMPOSITE STRUCTURES IN VEHICULAR CRASH

by

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ABSTRACT

ENERGY ABSORPTION CAPACITY OF COMPOSITE STRUCTURES IN VEHICULAR CRASH

This study investigates the crashworthiness of sinusoidal types of CFRP composite and DP780 steel crash boxes under the same impact conditions to compare their energy absorption capacities and evaluate their behaviours towards dynamic response, particularly focusing on acceleration values. A weight drop impact test was operated using a 305 kg impactor at a velocity of 7.67 m/s targeting crash boxes of the similar dimensions. Both experimental and numerical analyses were performed to provide a comprehensive evaluation. In order to simulate the numerical analyses more closely with the experimental values, the delamination effect in the composite material should also be considered. For this purpose, the delamination effect between the layers in the composite material was also taken into account by using the tiebreak contact type in LS-Dyna. In addition, since the trigger that will provide the initial damage in the composite crash box cannot be given geometrically as in metals due to higher initial peak load and the shock wave formed at the moment the weight first hits the crash box. Therefore, in order to measure the acceleration data correctly, a PVC foam was added on the composite crash box to absorb the shock wave by acting as a representative beam and in the next step, the simulations were completed in LS-DYNA using material cards MAT_024 for DP780 steel and MAT_054 for CFRP composite. The results showed that the CFRP composite crash box reinforced with the foam layer exhibited superior energy absorption capacity compared to DP780 steel. Moreover, the addition of the foam layer further improved the crash performance of the composite by reducing the effects of shock waves during impact, contributing to superior energy absorption and dynamic response. This study highlights the potential of CFRP composite as a lighter and more efficient alternative to metals in crashworthiness applications. In addition, the strong correlation between experimental and numerical results highlights the reliability of LS-DYNA in modelling crash behaviour, particularly in capturing acceleration characteristics, energy absorption mechanisms, and delamination effects of composite structures.

ÖZET

KOMPOZİT YAPILARIN ARAÇ ÇARPIŞMALARINDAKİ ENERJİ ABSORBSİYON KAPASİTESİ

Bu çalışma, enerji sönümleme kapasitelerini karşılaştırmak ve özellikle ivme değerlerine odaklanarak dinamik tepkiye yönelik davranışlarını değerlendirmek için aynı darbe koşulları altında sinüzoidal tipteki CFRP kompozit ve DP780 çelik çarpışma kutularının çarpışma dayanıklılığını araştırmaktadır. Benzer ölçülerdeki çarpışma kutularını hedef alan 7,67 m/s'lik bir hızla çarpan 305 kg'lık bir ram kullanılarak ağırlık düşürme darbe testi gerçekleştirilmiştir. Kapsamlı bir değerlendirme sağlamak için hem deneysel hem de sayısal analizler yürütülmüştür. Sayısal analizleri deneysel değerlerle daha yakından simüle etmek için, kompozit malzemedeki delaminasyon etkisi de dikkate alınmaktadır. Bu amaçla, LS-Dyna'daki tiebreak kontak tipi kullanılarak kompozit malzemedeki katmanlar arasındaki delaminasyon etkisi de dikkate alınmıştır. Ayrıca, kompozit çarpışma kutusunda ilk hasarı sağlayacak tetikleyicinin metallerde olduğu gibi geometrik olarak verilememesi nedeniyle, ağırlığın çarpışma kutusuna ilk çarptığı anda oluşan yüksek tepe yükten dolayı oluşan şok dalgası nedeniyle ivme ölçümleri almak mümkün olmamıştır. Bu nedenle, ivmelenme verilerini doğru bir şekilde ölçmek için, şok dalgasını temsili bir kiriş görevi görerek emmesi için kompozit çarpışma kutusu üzerine bir PVC köpüğü eklendi ve bir sonraki adımda, DP780 çeliği için MAT_024 ve CFRP kompozit malzeme için MAT_054 malzeme kartları kullanılarak LS-DYNA'da simülasyonlar tamamlandı. Sonuçlar, köpük tabakasıyla güçlendirilmiş CFRP kompozit çarpışma kutusunun DP780 çeliğine kıyasla üstün enerji emme kapasitesi sergilediğini gösterdi. Dahası, temsili kirişin eklenmesi, çarpma sırasında şok dalgalarının etkilerini azaltarak kompozitin çarpışma performansını daha da iyileştirerek üstün enerji emilimine ve çarpışma anındaki tepkisine katkıda bulundu. Bu çalışma, CFRP kompozitin çarpışma dayanıklılığı uygulamalarında metallere göre daha hafif ve daha verimli bir alternatif olarak potansiyelini vurgulamaktadır. Ek olarak, deneysel ve sayısal sonuçlar arasındaki güçlü korelasyon, LS-DYNA'nın çarpışma davranışını modellemede, özellikle ivmelenme özelliklerini, enerji emilim mekanizmalarını ve kompozit yapıların delaminasyon etkilerini yakalamada güvenilirliğini vurgulamaktadır.

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LIST OF SYMBOLS

DFAILC	Maximum strain for fiber compression
DFAILM	Maximum strain for matrix tension or compression
DFAILS	Maximum strain for shear
DFAILT	Maximum strain for fiber tension
EA	Young's modulus in longitudinal direction
EB	Young's modulus in transverse direction
g	Acceleration
G	Shear modulus
kg	Kilogram
kJ	Kilojoule
kN	Kilonewton
MPa	Megapascal
SC	Shear strength
TFAIL	Time step size criteria for soft failure
XC	Longitudinal compressive strength
XT	Longitudinal tensile strength
YC	Transverse compressive strength
YT	Transverse tensile strength
α	Shear stress non-linear term
β	Weighing factor for shear term in tensile fiber mode
δ_m	Total mixed mode relative displacement
δ_{shear}	Total shear relative displacement
ν	Poisson's ratio
ρ	Density

LIST OF ACRONYMS/ABBREVIATIONS

AHSS	Advanced High-Strength Steels
B-K	Benzeggagh and Kenane
BIW	Body-in-White
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CM	Compression Molding
CFRP	Carbon-Fiber-Reinforced Polymer
DCB	Double Cantilever Beam
ENF	End-Notched Flexure
FEA	Finite Element Analysis
FEM	Finite Element Method
GDP	Gross Domestic Product
HSS	High-Strength Steels
NFLS	Normal Failure Stress
RIM	Reaction Injection Molding
RTM	Resin Transfer Molding
SEA	Specific Energy Absorption
SFLS	Shear Failure Stress
TEA	Total Energy Absorbed
UD	Unidirectional
VARI	Vacuum Assisted Resin Infusion
VP	Viscoplastic
WHO	World Health Organization

1. INTRODUCTION

Road traffic accidents remain one of the leading causes of global fatalities, with approximately 1.2 million people losing their lives each year due to crashes [1]. As seen in Figure 1.1, this alarming statistic highlights the critical nature of the issue. Despite improvements in vehicle design and architecture and safety features, the number of traffic-related deaths remains a significant issue worldwide. The World Health Organization (WHO) emphasizes that road traffic injuries are the leading cause of death for individuals aged 5–29 years [2]. In addition to human loss, the economic cost of traffic accidents is also quite large, and many countries suffer losses equivalent to approximately 3% of their Gross Domestic Product (GDP) every year due to traffic accidents [3].

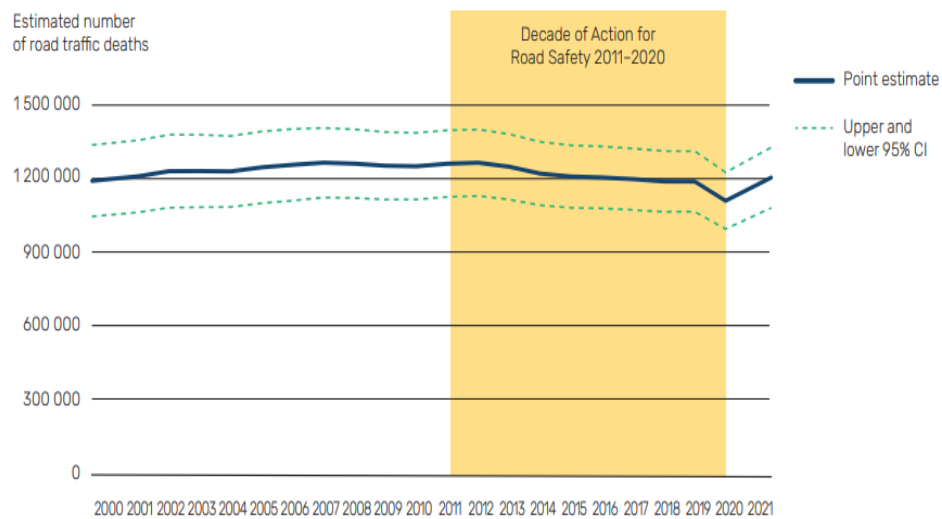


Figure 1.1. Global Road Traffic Fatalities (2000-2021) [1].

The automotive industry has been constantly focused on improving vehicle safety to reduce the risk of fatalities in accidents. Traditional materials such as high-strength steels have been widely used in vehicle structures thanks to their excellent mechanical properties such as strength and ductility. Nevertheless, the energy absorption capacities of these materials are not sufficient to reduce the high fatality rates. In addition, considering the future regulations on fuel consumption and efficiency of vehicles, which will become even stricter, alternatives are needed to increase vehicle efficiency by reducing vehicle weight [40].

Composites have become a viable substitute for traditional materials to meet these two characteristics. These materials not only reduce vehicle weight, but also offer superior energy absorption during crashes, which is crucial in minimizing injuries during crashes [4]. The demand for lighter vehicles, combined with the need to improve crashworthiness, has increased the interest in composite materials. As part of the ongoing effort to improve automotive safety, both numerical and experimental testing have become essential tools to determine the performance of composite materials in crash scenarios. By using different composite materials, making geometric changes in the lay-up orientation, and incorporating infill materials such as foam, the performance of these lightweight structures can be significantly changed.

Physics-based finite element modelling tools like LS-DYNA, Abaqus and Radioss enable the simulation of crash events, allowing researchers to optimize materials and structures for better crash performance. Understanding how these structures deform under various conditions is crucial to optimize their performance and improve safety in automotive applications. In this sense, understanding how composite materials perform compared to traditional materials such as steel, aluminium etc. is very important to improve vehicle safety standards.

1.1. Motivation and Objectives

The motivation for this study stems from the need to improve vehicle safety by exploring alternative materials that can enhance crashworthiness without compromising other essential properties such as impact resistance, strength, durability and energy absorption. While high strength steel has been a keystone material in automotive safety thanks to its strength and durability, the desire to reduce weight in vehicles and increase energy efficiency due to increasing regulations has increased the interest in composite materials. The main aims of this study are listed below:

- To analyse and compare the crash performance of composite materials and high strength steel under same simulated crash conditions.
- To examine the energy absorption capacity of composite materials and steel in low impact scenarios.

- To evaluate the possible advantage of integrating composite materials into the vehicle architecture to improve crash safety.

1.2. Literature Review

1.2.1. Crashworthiness of Automotive Materials

Crashworthiness plays a crucial role in automotive design and safety since it focuses on a vehicle's ability to absorb and dissipate kinetic energy during impacts. Thus, it protects passengers and minimizes injury. The Body-in-White (BIW) structure has a significant role by controlling energy dissipation through deformation, ensuring occupant safety while mitigating harm to others, which are included in the crash. As seen in Figure 1.2, real-world crash data highlights that 50% of accidents are frontal impacts, 33.7% occur on the side, and 15.9% are rear-end collisions, emphasizing the importance of designing structures to address various impact scenarios effectively [5]. To that end, strengthening components like crash boxes and bumper systems becomes highly essential. These elements improve the energy absorption efficiency, reducing the forces transmitted to occupants, and minimizing overall crash damage.

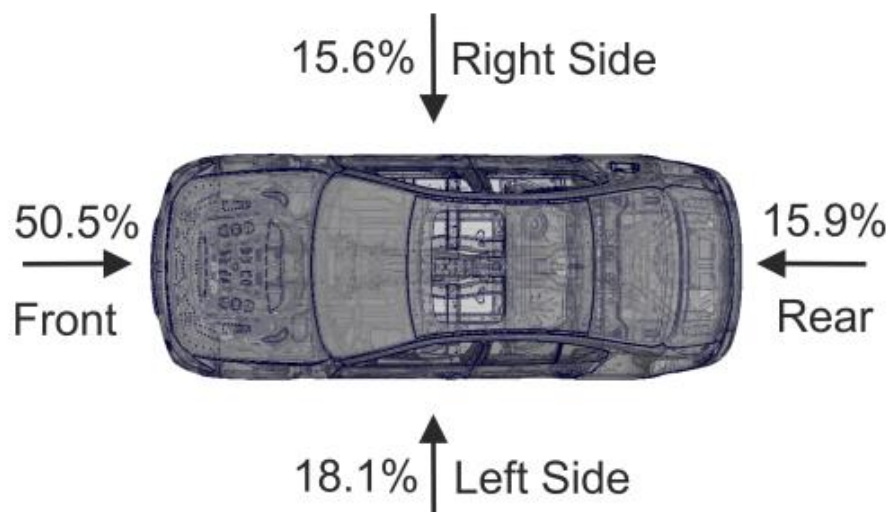


Figure 1.2. Relative distribution of crash positions for vehicles [5].

Steel and composite materials are widely utilized in crashworthiness applications. Steel with its high strength and ductility, deforms plastically under high stress conditions

and effectively dissipates energy. On the contrary, composite properties can be made into lightweight applications by offering high energy absorption per unit weight due to fracture.

As seen in Figure 1.3, the comparison of specific strength (strength-to-density ratio) and specific modulus (elasticity modulus-to-density ratio) between different groups of materials demonstrates the superior performance of composite materials, particularly carbon fiber reinforced polymer (CFRP). The Ashby diagram shows that CFRP not only has a much higher specific strength than metals such as steel and aluminum, but also shows a higher specific modulus, providing both light weight [56]. This combination makes CFRP an ideal material option for applications demanding optimum strength-to-weight and stiffness-to-weight ratios, such as aerospace and automotive engineering [6].

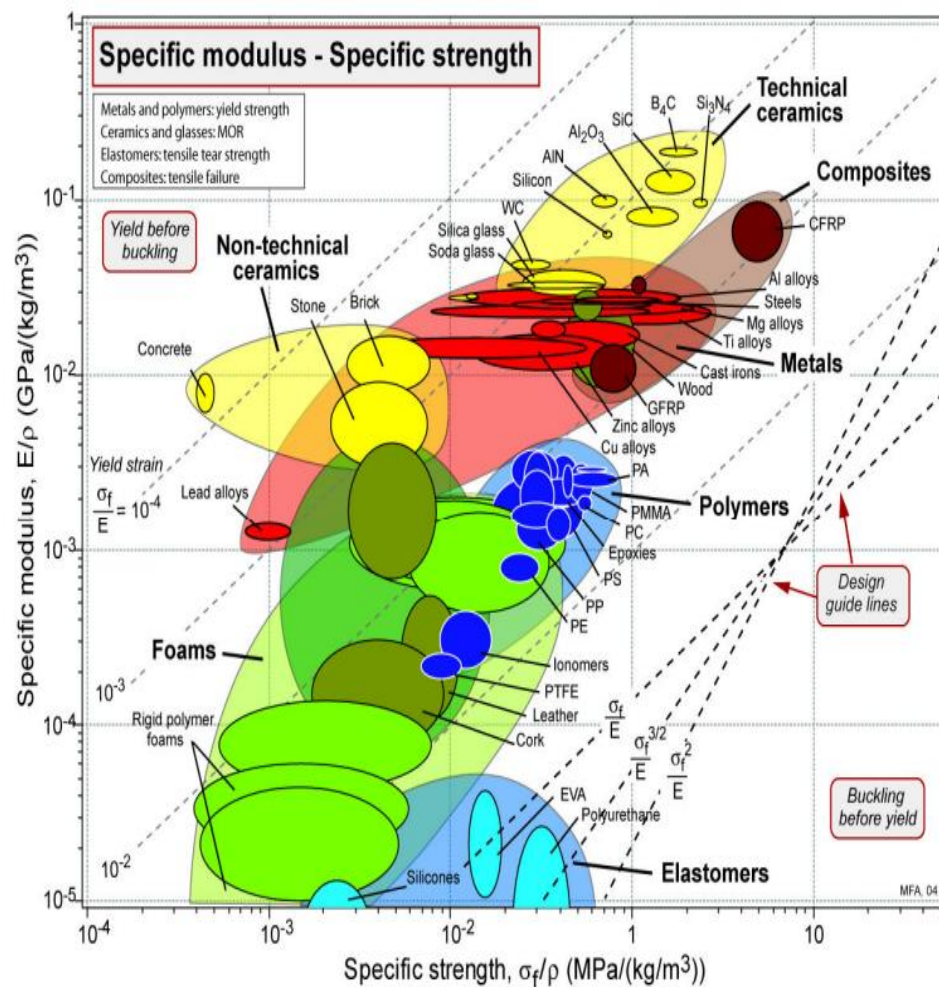


Figure 1.3. Specific modulus versus specific strength Ashby plot for engineering materials [56].

1.2.2. Composite Materials in the Vehicle Structures

Composite is a type of structural material composed of two or more distinct constituents that are combined at a macroscopic level while remaining insoluble in each other. One of these constituents is known as the reinforcing phase, while the other, which serves as the medium in which the reinforcement is embedded, is referred to as the matrix. The reinforcement material can exist in various forms, including fibres, particles, or flakes, whereas the matrix material is typically continuous. Common examples of composites include concrete reinforced with steel and epoxy reinforced with graphite fibres, among others [41].

Composites can be categorized based on the geometry of the reinforcement, such as particulate, flake, and fiber-based types, or according to the matrix material, which can be polymeric, metallic, or ceramic. Figure 1.4 presents a classification of composite materials. [42].

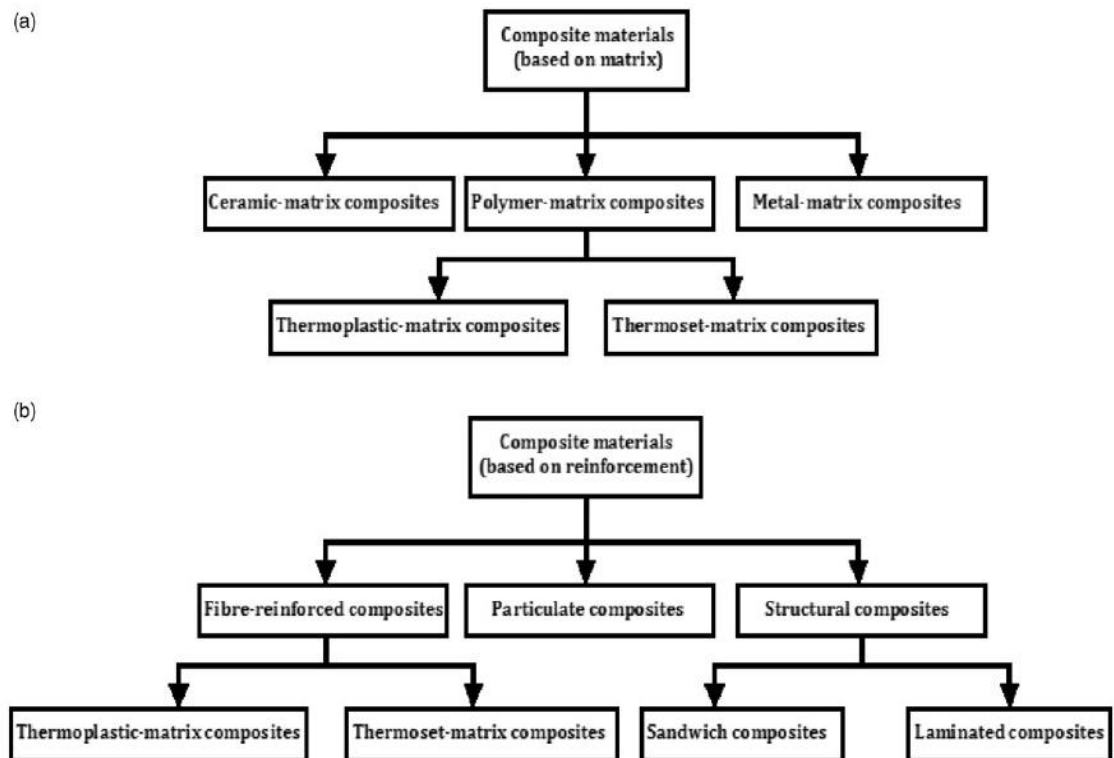


Figure 1.4. Classification of composite materials (a) based on the matrix materials and (b) based on the reinforcement materials [42].

The load carrying capacity of fibres is much higher than particle or flake reinforcement [44]. For that reason, fiber reinforced composite type was chosen in that study. Fiber composites are consisted of matrices reinforced by short (discontinuous) or long fibres (continuous) fibres. The fundamental units of continuous fiber matrix composite laminates can be unidirectional (UD) or woven fiber laminas. These laminas are stacked at different angles to create a multidirectional laminate [41]. As seen in Figure 1.5, an example of laminate made of unidirectional laminas is shown [43].

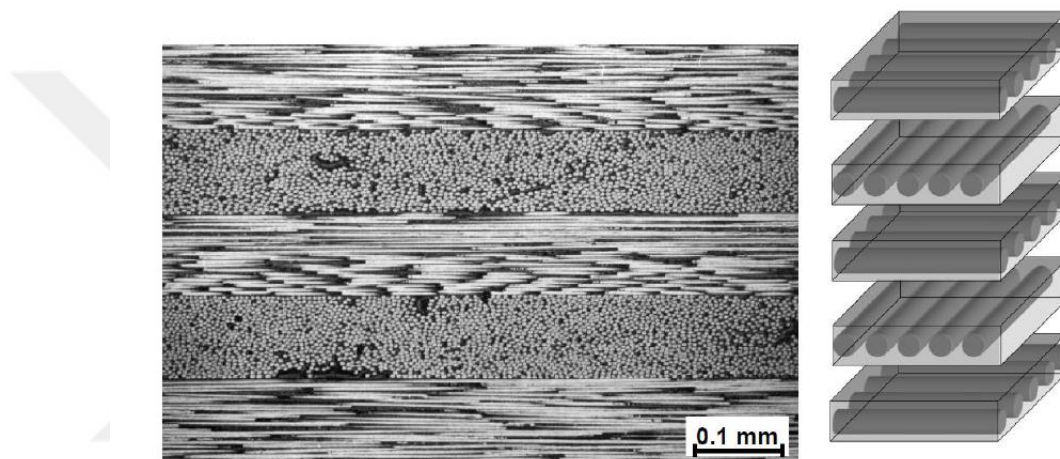


Figure 1.5. UD fiber composite example [$0^\circ/90^\circ/0^\circ/90^\circ/0^\circ$] laminate [43].

In addition, an example of woven fiber lamina is illustrated in Figure 1.6 [45].

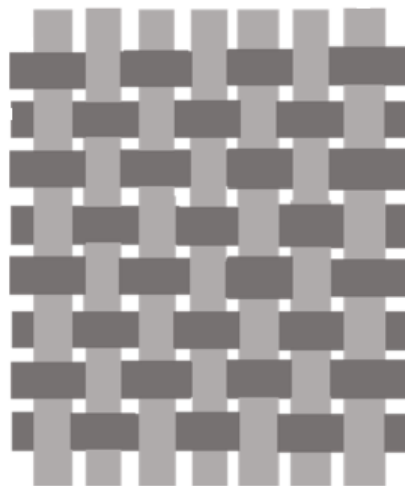


Figure 1.6. The typical woven composite structure [45].

Composite materials with different type and structures explained above are being increasingly utilized in the automotive industry due to their excellent specific strength and energy absorption capabilities. Their lightweight characteristics makes them ideal for improving vehicle safety performance and fuel efficiency while maintaining crashworthiness [29]. Composites exhibit distinct fracture behaviour. During a crash, the matrix and fibres work together to absorb and distribute energy, typically resulting in damage that is less localized compared to metals [7]. Various studies on composite materials over many years have identified many important damage mechanisms in the composite structures, including fiber fracture, matrix cracking, delamination and fibre kinking to identify and classify damage mechanisms due to complexity of crushing process of composite materials. Damage mechanisms in composite materials can be categorized into intralaminar and interlaminar types based on their location. Interlaminar damage, which occurs between layers, is commonly referred to as delamination. Additionally, debonding at the fiber-matrix interface is another form of interface damage. If the damage propagates perpendicular to the fibres, it is classified as translaminar damage.

These mechanisms vary depending on the applied load, geometry and fiber orientation and are shown in Figure 1.7. The most critical damage type in terms of energy absorption during impact in composite materials is damage at the ply level under compressive loads. Especially, the crushing of fibres in the direction of the load plays a major role in terms of effective energy absorption. In this context, the phenomenon in which fibres buckle and suddenly break under compressive load is called as fiber kinking and usually occurs as a result of compressive load applied in the axial direction of the fibres [57].

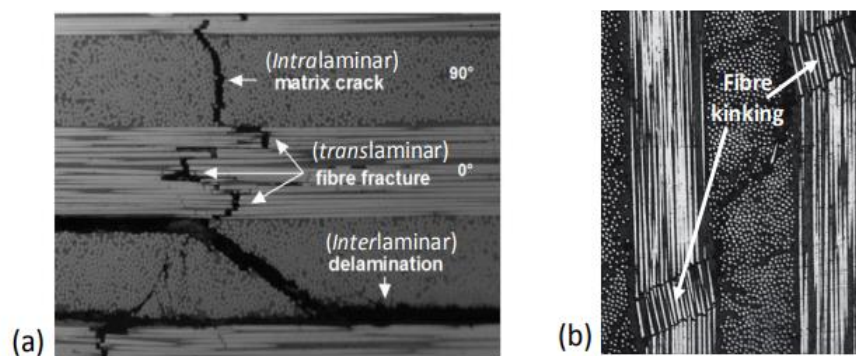


Figure 1.7. Micrograph of ply-level damage mechanisms; (a) tension dominated, (b) compression dominated [67].

The damage mechanisms mentioned above for composite materials cause local damage accumulation within the material, and this accumulation grows into larger-scale damage models over the time, forming failure modes. As seen in Figure 1.8 (a), when the composite material is compressed perpendicular to the fiber direction, matrix failure occurs due to crushing and interaction between fibres and the matrix. Matrix cracks propagate in planes where shear stress is highest. Under tensile loading in the transverse direction, matrix failure happens because of the tensile failure of the matrix material or fiber-matrix interface. As shown in Figure 1.8 (b), cracks develop perpendicular to the tensile load. Figure 1.8 (c) demonstrates fiber failure caused by longitudinal compression, forming kink bands due to shear in the matrix, leading to compressive fiber failure. Under longitudinal tension, fibres breakage is seen at their weakest cross-sections in Figure 1.8 (d) [60].

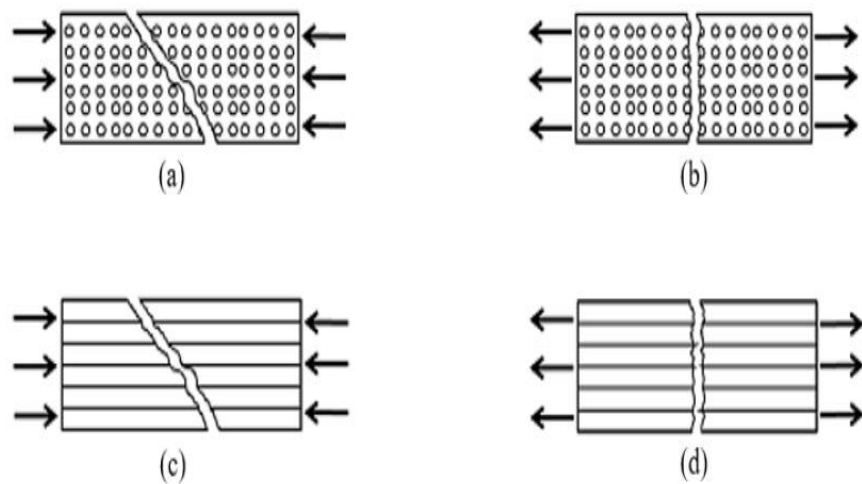


Figure 1.8. Failure modes: (a) compressive matrix failure, (b) tensile matrix failure, (c) compressive fiber failure, (d) tensile fiber failure [61].

Additionally, in composite laminates, delamination represents a significant type of damage. Delamination starts with the progression of a crack, and it changes with the separation of the two layers. The crack progresses through one layer and propagate until it reaches the fibres in the adjacent layer.

These mechanisms play an important role in enhancing energy absorption by promoting progressive failure modes, which provide to the efficiency of the material in managing impact energy [8]. As show in Figure 1.9, composite materials exhibit

significantly higher specific energy absorption capacity compared to metals such as steel and aluminium [28].

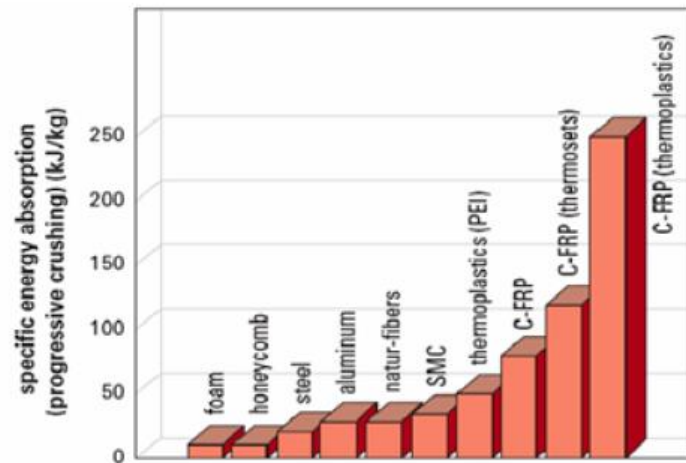


Figure 1.9. Specific energy absorption capacities for various materials [28].

Although composite materials provides higher specific energy absorption values in crash applications (as shown in Figure 1.9), their extensive use in the automotive industry is still limited because of the manufacturing complexity and cost-efficiency concerns. To enhance their viability as alternatives to steel structures, various research efforts are focused on optimizing production technologies and assessing feasibility. The most common manufacturing techniques for automotive composites are Resin Transfer Molding (RTM), Vacuum Assisted Resin Infusion (VARI), Reaction Injection Molding (RIM), and Compression Molding (CM). RTM involves injecting resin into a closed mold containing a dry fiber preform and is considered suitable for medium-scale production thanks to its compatibility with automation. RIM provides fast production with low-viscosity resin systems but typically results in components with limited mechanical properties. CM needs heat and pressure to shape pre-impregnated fiber mats and is known for its short cycle times and applicability in high-volume manufacturing. Another method is VARI, which infuses resin into dry preforms under vacuum in an open mold. VARI is advantageous for its low tooling cost, high fiber volume fraction, and reduced resin waste, making it well-suited for prototyping and small-to-medium production runs. While its relatively long cycle time and dependency on manual labour currently limit its adoption in high-throughput automotive

assembly lines, ongoing advancements in automation and resin systems suggest that VARI-based techniques may become increasingly scalable in the near future [68].

In addition to process-specific constraints, the economic feasibility of composite structures is also critical. As illustrated in Figure 1.10, which illustrates the U.S. body-in-white (BIW) production cost sensitivity to annual production volume -covering (a) total manufacturing cost, (b) part fabrication cost, (c) assembly cost, and (d) the unit cost breakdown per unit at 100,000 units/year composites currently exhibit higher unit costs than traditional steel structures. However, this comparison must be interpreted in context. While composites, particularly carbon fiber, begin with higher raw material expenses, their simplified assembly and reduced component complexity can offset some production challenges. Notably, Figure 1.10 (d) shows that for carbon fiber BIW at 100,000 units/year, over 60% of the unit cost is attributed to raw material, suggesting that innovations in material sourcing, recycling, or fiber production efficiency may significantly reduce this gap. In contrast, steel benefits more from economies of scale in tooling and equipment amortization, which drive down costs at high volumes. Glass fiber composites appear more cost-effective in intermediate production ranges, offering a balance between performance and affordability [68].

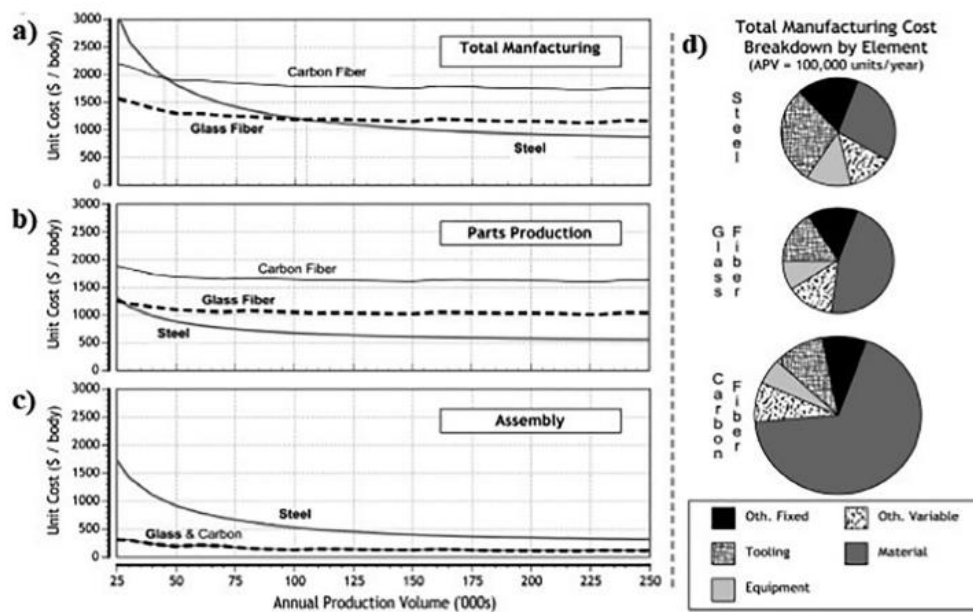


Figure 1.10. Cost sensitivity of BIW production to volume: (a) total manufacturing, (b) part fabrication, (c) assembly, and (d) unit cost breakdown at 100,000 units/year [68].

These findings indicate that although steel remains the most cost-effective solution in high-volume automotive applications, composite materials -particularly when supported by lightweight design strategies and process innovations- possess growing potential for application in performance-critical and weight-sensitive components. As composite manufacturing technologies are grown, the economic competitiveness of these materials is likely to improve, making them increasingly viable for broader automotive use.

1.2.3. High-Strength Steels in the Vehicle Structures

High-Strength Steels (HSS), including Advanced High-Strength Steels (AHSS), such as DP-700, DP-780, HSLA-700, etc. are frequently used in automotive structures due to their excellent strength-to-weight ratio and predictable deformation behaviour. Unlike conventional steels such as mild steels, AHSS types of steel offer superior crash energy management through multi-phase microstructures that combine strength and ductility [9].

Mild or low carbon steels have low carbon content of 0.05 % to 0.25 % and a tensile strength around 400 MPa. In contrast, HSS and AHSS exhibit higher tensile strengths, reaching up to 800 MPa [47]. The key distinction between HSS and AHSS is in their microstructure. HSS generally has a single-phase microstructure, it provides more homogeneous properties. On the contrary, AHSSs are multiphase steel with a complex microstructure containing phases such as ferrite, martensite, bainite, and austenite [46]. Thus, the complex microstructure provides the very high strength and formability possibilities of AHSS.

HSS and AHSS provide controlled energy absorption and deformation, protecting passengers from excessive forces in side-impact beams and crumple zones. Figure 1.11 presents the stress-strain curves of mild steel and DP steels at various strength levels are compared. DP steels provide superior ultimate tensile strength, higher initial work hardening rate and lower yield strength-to-tensile strength ratio compared to mild steel [30].

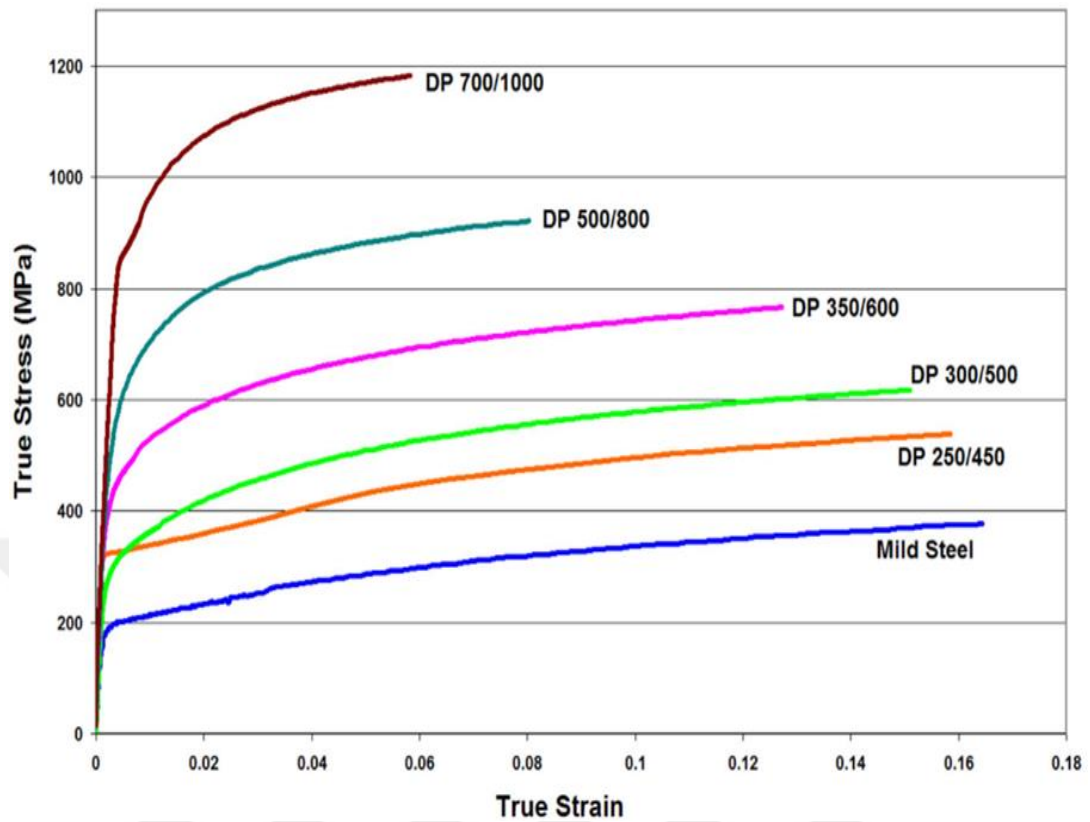


Figure 1.11. Comparison of true stress-strain curves of mild steel and DP steels [30].

In Figure 1.12, the steel distribution can be shown in the typical vehicle interior and exterior architecture according to steel types [48].

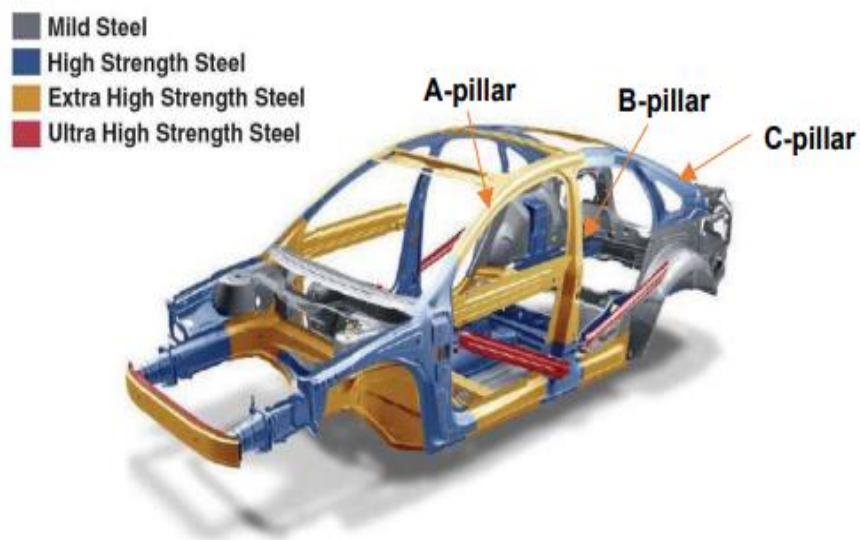


Figure 1.12. Steel distribution in a vehicle [48].

1.2.4. Experimental and Numerical Methods in Crashworthiness Studies

Crashworthiness studies rely on a combination of the numerical simulations and experimental testing to indicate material and their structural performance. The crushing behaviour of various composite structures has been investigated across a range of crushing velocities to assess their energy absorption efficiency. Earlier experimental studies, such as those conducted by Hull [31], examined the axial compression behaviour of composite tubes, shedding light on their progressive crushing mechanisms. In another study by Hull [62], there are two main failure modes of composite materials during impact: splaying mode and fragmentation mode as can be seen in the schematic representation in Figure 1.13. Splaying mode is characterized by delamination and matrix cracks, which cause the layers to bend without significant fiber breakage. Another mode is fragmentation mode, which is the combination of fiber fracture and matrix cracks. In this mode, high-intensity fractures occur and the composite material breaks.

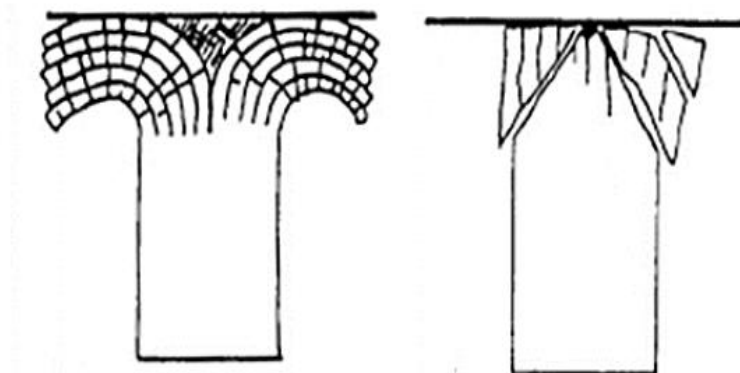


Figure 1.13. A schematic representation of the two failure modes identified by Hull (a) splaying mode, (b) fragmentation mode [62].

Bisagni [63] identified four different failure modes during the crushing of CFRP tubes. These modes are tearing, socking, splaying, and micro-fragmentation (see from Figure 1.14). Of these modes, micro-fragmentation is similar to the fragmentation mode defined in Hull's study [62]. The other three failure modes, tearing, socking, and splaying, are formed by different combinations of fragmentation and splaying modes in Hull's classification. These differences occur because of the different loading conditions and material behaviours during the crushing process of CFRP structures.

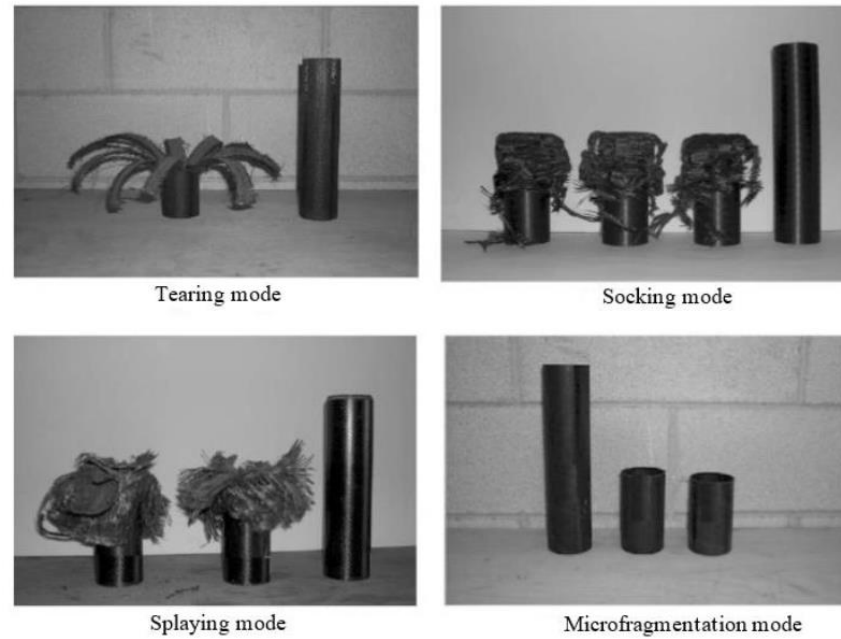


Figure 1.14. Crushing failure modes as described by Bisagni [63].

Chen et al. [64] performed both quasi-static and dynamic experiments on CFRP shaped tubes. At the conclusion of the experiments, the specimens displayed crushing morphology consistent with previous studies, primarily characterized by two major damage mechanisms: fragmentation and splaying. The failure modes are identified by Chen as shown in Figure 1.15. In contrast to other studies, Chen et al. indicated the friction between moving wall and the specimen dissipated about one-fourth of the total energy. The remaining amount of energy was absorbed by the reinforcement of the CFRP tube.

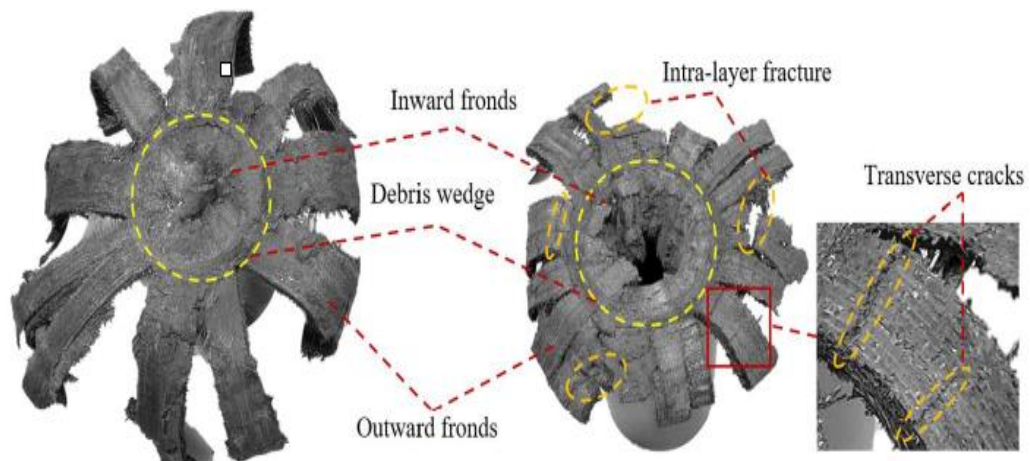


Figure 1.15. Failure modes identified by Chen et al. [64].

Different energy absorption capacities can be achieved through the various damage modes described above. However, there is no general disagreement on which parameters determine these damage modes and which damage mode is dominant. The primary failure mode during the crushing process of the composite structures is influenced by many factors such as material system selection, fiber components, strain rate and trigger scheme.

Although these studies are essential in understanding the complexity of composite materials, such tests have some limitations in terms of cost, time, support, and repeatability. Furthermore, it is impractical to physically test all possible combinations to study in detail the effects of different material configurations, fiber components, and trigger failure on energy absorption. Therefore, Finite Element Analysis (FEA) plays an important role in predicting the behaviour of materials and components during the crash and it provides a cost-effective and systematic approach to investigate the influence of key parameters such as material selection, fiber orientation, strain rate and triggering mechanisms. LS DYNA stands out as a widely used of these FEA methods for simulating crash events. Experimental methods, such as drop-weight, impact and crash tests, are used to validate numerical models and collect data on real-world performance [10]. Thus, to gain a deeper understanding of this complex process, detailed FEA was carried out using LS-DYNA software.

In Hull's study [31], composite tubes were modelled as both single-layer and multi-layer. Energy absorption values were investigated both experimentally and numerically. In these simulations, the composite tube walls were represented as multi-layer thin shell elements, enabling a precise simulation of delamination effects. This hybrid approach, integrating experimental data with numerical analysis, provides a well-rounded perspective on the progressive failure patterns and energy absorption capabilities of composite crash structures. The simulation results showed a closer alignment with the experimental data compared to single-layer cases, highlighting the accuracy and reliability of the multi-layer modelling approach. The experimental and numerical comparison shows that using a multilayer model significantly improves the accuracy of crash analyses in predicting energy absorption versus displacement graph. The delamination effect, which occurs between the layers of composite materials during the crash, plays a very critical role in accurately capturing the progressive crushing behaviour of the crash box. This represents that a crash box modelled as a single layer cannot fully represent the actual energy absorption

mechanisms as experiment. Instead of a single-layer structure, a multi-layer model which takes into account interlayer delamination, is essential to achieve more realistic and precise simulations in crashworthiness studies. The evaluation of experimental and numerical results shows the importance of delamination effects as critical parameters in determining the energy absorption capabilities of the composite structures during crash test [31]. Similarly, delamination was also investigated in the study performed by Reedy et al. in 1997 [32]. In this study, the mechanisms of initiation and propagation of delamination were investigated and was shown that energy-based models (related the energy release rate) more accurately predicted delamination growth. Numerical analyses (FEM and cohesive zone models) and experimental data were compared, and it was found that the cohesive zone model could successfully model both the initiation and propagation of delamination.

Meanwhile, the lay-up configuration also directly influences the load distribution and the failure mode of the material. As shown in study [33] utilizing T650-35/F584 plain weave graphite/epoxy fabric material was evaluated with different lay-up orientations, including $[45]_{10}$, $[45]_7$, $[45_2/0/45_2]_5$ and $[45_2/0_2/45]_5$. The results show that these configurations mainly failed in a lamina bending mode. This behaviour is consistent with similar findings in flat plate specimens using identical lay-up orientations. Interestingly, stiffeners with a simpler $[45]_5$ lay-up showed a different response, as they crushed without forming a central crack. After all, this configuration proved a much lower specific sustained crush stress compared to the other lay-up orientations. These results indicate that lay-up orientation is a key factor influencing the crushing response and energy absorption capability of the composite structures. While certain lay-ups ensure controlled, progressive failure modes like lamina bending, simplified configurations, such as $[45]_5$ can compromise energy absorption efficiency. Therefore, the selection and optimization of lay-up orientation are very critical to achieve a superior crashworthiness performance in composite structures under the impact loading conditions.

Mamalis et al. [34] utilized the explicit LS-DYNA solver to simulate the crash behaviour of square CFRP composite tubes and validated the prediction through experimental results. Numerical analysis has been performed using the MAT_055 material card in LS-DYNA to demonstrate the accuracy of the model. As seen in Figure 1.16, the results obtained with the Finite Element (FE) model demonstrates a high degree of

agreement with the experimental data. Especially in terms of load carrying capacity and energy absorption values, the differences between the two methods are minimal, which illustrates the reliability of the analysis performed with the MAT_055 card in LS-DYNA.

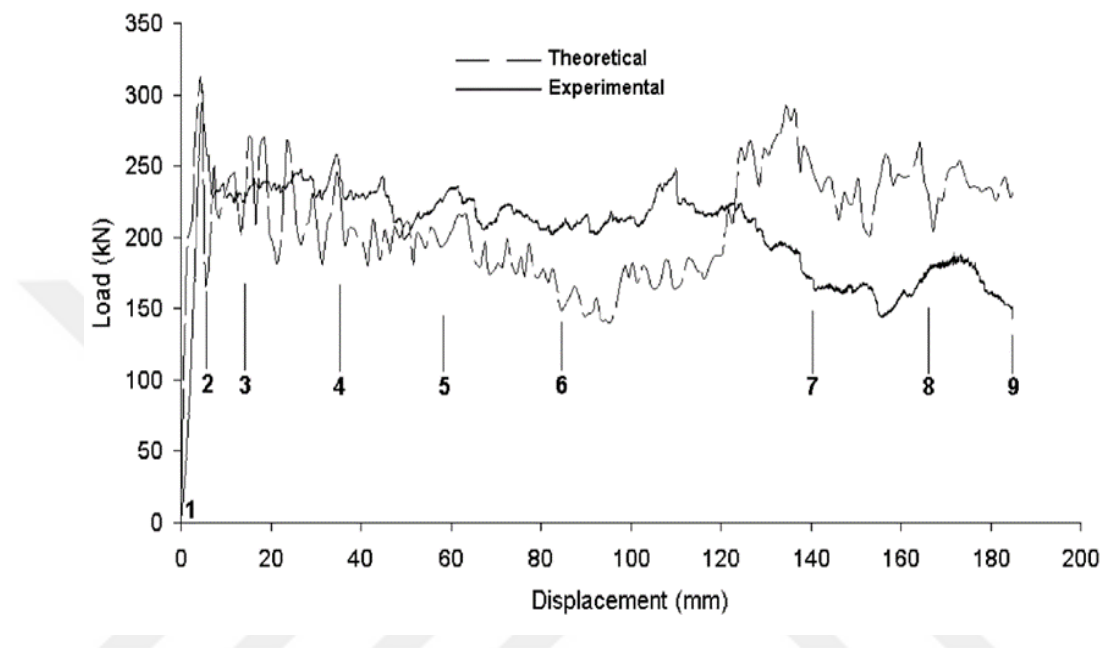


Figure 1.16. Load versus displacement responses experimental vs numerical analysis [34].

In a similar study, Hörmann and Wacker [35] utilized LS-DYNA to simulate the crash behaviour of thermoplastic crash boxes, aiming to establish a correlation between experimental and numerical results. They utilized the MAT_054 and MAT_058 material models. Through optimized inputs, the correlation between load-displacement response and deformation patterns improved significantly for both materials during post-test simulations. Clearly, the MAT_054 model exhibited superior agreement with experimental load-displacement data compared to other material card.

Feraboli [12] utilized the LS-DYNA MAT_054 material card to simulate the axial crushing behaviour of composite materials using sinusoidal specimens. This study is particularly significant for understanding the energy absorption and crashworthiness of composite materials, especially in aerospace applications, where such materials are required to absorb substantial impact forces without failure. The MAT_054 model, with its capability to capture various failure modes such as matrix cracking and fiber failure, is an essential tool

for evaluating composite performance under axial compressive loads. In Feraboli's work, the parameters used in the MAT_054 model are thoroughly explained, and optimization techniques are applied to refine these parameters, making them more relevant for real-world material behaviour. This optimization process includes adjustments to LS-DYNA's input parameters, which are independent of the material properties, thereby improving the accuracy of simulations. A similar study by Alkhatib [36] also focuses on the optimization of failure modelling parameters in LS-DYNA, specifically looking at parameters like SLIMC1, SLIMC2, SLIMT1, SLIMT2 and SLIMS. The material-aligned SLIM values define the residual strength level after the failure threshold in each material direction [65]. These parameters play a key role in fine-tuning the material failure response, and their optimization provides to create more accurate models for simulating the crash behaviour of composite structures. By optimizing these parameters, both studies aim to achieve more reliable and precise simulations of the composite materials, ultimately contributing to the design of structures that can efficiently dissipate energy during crash without compromising their integrity. Such advancements in material modelling are important for the development of safer and more effective composite structures in the industries like aerospace, automotive, and civil engineering [37].

In recent years, the increasing use of composite materials across various industries has emphasized the need for more accurate modelling of these materials, particularly in crash simulations [38]. Damage mechanisms are critical to the performance of composite materials, must be integrated into LS-DYNA crash tests using the MAT_054 material card. This approach helps to improve the reliability and accuracy of the simulations by capturing the complex behaviours of the composites under impact conditions. In spite of advancements, there is still a need for ongoing research to optimize these models, ensuring that they reflect real-world scenarios more accurately. The incorporation of delamination and lay-up orientation into LS-DYNA simulations is essential for enhancing the predicting of energy absorption and failure mechanisms in composite materials during crash tests. As industries increasingly rely on composites for their lightweight and high-strength properties, the ability to simulate their behaviour under extreme conditions remains a critical area for improvement.

1.3. Research Scope and Contributions

This study focuses on the crashworthiness of composite materials and steel, specifically examining their performance in vehicular crash scenarios. The study includes:

- Numerical analysis: using LS-DYNA to model crash events involving both composite materials and steel, assessing their performance in terms of energy absorption, and impact resistance.
- Experimental validation: operating physical tests to validate the simulation results, particularly examining the acceleration-time profiles and the energy dissipation mechanisms during impact.
- Comparative study: comparing the crash performance of composites and steel in terms of safety, and energy absorption capabilities.

The contributions of this research include:

- Providing a comprehensive analysis of the crash behaviour of composite materials compared to high strength steel.
- Offering insights into the potential application of the composite materials in the automotive industry, focusing on their role in reducing fatalities and improving crash safety.
- Helping to the broader field of automotive materials by highlighting the benefits of lightweight composite solutions in improving vehicle safety.

1.4. Overview of the Research Approach

This study adopts a systematic methodology to evaluate the crashworthiness of automotive materials, focusing on the performance comparison between composite materials and high-strength steels. It ensures that the values obtained in the analysis are compatible with the values in the experiment, and by trying to increase the correlation between them, more accurate analysis results can be obtained and, in the future the analysis result can be proceeded without the need for experimental measurements.

Initially, material properties are characterized to define input parameters for the numerical models. This includes density, elastic modulus, Poisson's ratio, and material-specific failure criteria for composites and steels [4]. MAT_054 material card was used for the composite crash box, the MAT_024 material card was used for the steel crash box and material cards were selected that would best reflect the properties of these materials. In addition, the appropriate contact type was used to see the delamination effect so that the composite crash box could be modelled more accurately at the time of crash. Finite Element Method (FEM) is employed to simulate crash scenarios, such as frontal impacts, using LS-DYNA, a widely recognized tool in crashworthiness research [11].

Experimental tests are performed on physical specimens to validate the numerical results. The combination of these methods enables the identification of energy absorption characteristics, and failure mechanisms under the same impact conditions. The approach ensures insights into the performance of Carbon-Fiber-Reinforced Polymers (CFRPs) and DP780 steel under similar conditions, allowing for a detailed comparison of their suitability for automotive applications.

2. METHODOLOGY

2.1. Numerical Analysis using LS-DYNA

LS-DYNA is the advanced software for dynamic analysis, offering robust capabilities for simulating low, medium and high-speed impacts. For this study, numerical models are developed to simulate crash scenarios involving composite and steel materials. The models are built using shell and solid elements, depending on the material type and geometry. For CFRP composite crash box, material properties are described using MAT_054_ENHANCED_COMPOSITE_DAMAGE material card. For DP780 steel crash box, MAT_024_PIECEWISE_LINEAR_PLASTICITY material card has been used. These models include strain-rate dependency, damage initiation criteria, and energy absorption capabilities [11]. Boundary and initial conditions (an impactor weighting is 305 kg and it was initially at rest, the impactor reached a velocity of 7.67 m/s upon release to impact with the crash boxes, the lower part of the crash boxes is constrained by both rotation and displacement in all axes) are applied to replicate experimental crash test setups, such as a ram impacting a crash box. The explicit solver in LS-DYNA provides the accurate capture of transient dynamics and failure mechanisms. Validation is achieved by analysing the correlation between numerical and experimental results, including force-displacement relationships and energy absorption metrics.

2.1.1. FE Models of Crash Boxes and Their Material Properties

The numeric analysis and experimental tests involving DP 780 steel and carbon fiber/epoxy plain weave prepregs crash boxes focus on their material properties and performance under the impact.

2.1.1.1. Composite Crash Box Material Model and MAT_054 Parameters. CFRP composite crash box is produced from KordSA OM10 carbon fiber/epoxy plain weave prepregs, which consist of carbon 3K carbon fiber tows and epoxy matrix [39]. Crash box structure has been manufactured in an autoclave with a depth of 1500 mm and inner diameter of 1200 mm. The autoclave is a closed system, which is used for the curing or sterilization of materials under

certain temperature and pressure conditions. Especially, the curing process in the autoclave fully cures prepreg materials, thus it can provide the desired strength and durability of the final crash box. The crash box is manufactured in the autoclave by stacking 10 layers of prepregs, each with a thickness of 0.25 mm on aluminium mandrels of a sinusoidal cross-section and a total height of crash box is 120 mm. Material properties utilized in the numerical analysis is given in Table 2.1 [14]. The shape of the composite crash box from different views is shown in Figure 2.1.

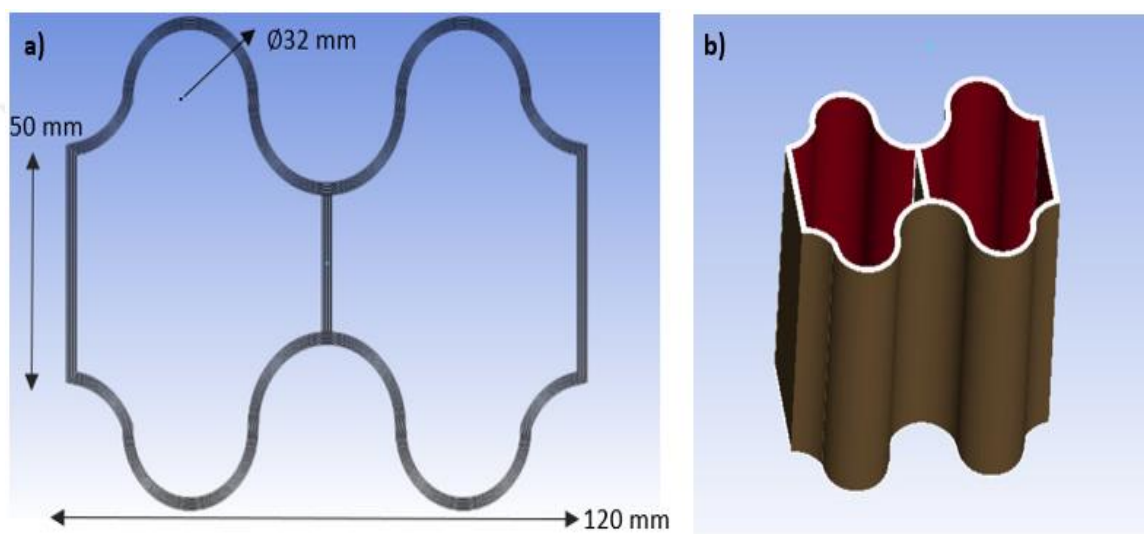


Figure 2.1. Shape of the composite crash box (a) top view of crash box, (b) isometric view of the crash box.

The MAT_054 material model in LS-DYNA is a progressive failure model tailored for simulating the behaviour of the unidirectional (UD) tape or woven fabric composite laminates made of carbon fiber tows and epoxy matrix using shell elements. This model incorporates advanced failure criteria and damage mechanics to capture the response of composite laminates under various loading scenarios. Table 2.1 which is taken from the LS-DYNA documentation typically lists all parameters used in the MAT_054 material model, describing their definitions and methods for determination [12]. These parameters include material properties such as elastic moduli, strengths, and failure strains, as well as numerical controls like softening parameters (SOFT) and failure criteria thresholds (e.g., SLIMC, SLIMT, SLIMS) [13]. The numerical values of properties of the MAT_054 card are used in the simulation-based analysis are shown in also Table 2.1.

Table 2.1. MAT_054 input parameter definitions [12], [14].

Variable	Definition	Suggested Value	Value	Unit
RO	Mass per unit volume	ρ from material properties	1.56e-6	kg/mm ³
EA	Elastic modulus in longitudinal direction	E_1 from material properties	65.1	GPa
EB	Elastic modulus in transverse direction	E_2 from material properties	64.4	GPa
PRBA	Minor Poisson's ratio, $\nu_{ba}=\nu_{21}$	Calculated using ν_{12} , E_1 and E_2	0.037	-
PRCA	Minor Poisson's ratio, $\nu_{ca}=\nu_{31}$	Not used	-	-
PRCB	Minor Poisson's ratio, $\nu_{cb}=\nu_{32}$	Not used	-	-
GAB	Shear modulus, G_{ab}	G_{12} , from material properties	4.5	GPa
GBC=GCA	Shear modulus, G_{bc} , G_{ca}	Assumed equal to G_{ab}	4.5	GPa
EFS	Effective failure strain	EFS = 0	0.55	-
TFAIL	Time step size criteria for soft failure	Must be very small but nonzero	1e-8	s
ALPH	Shear stress non-linear term	$1e-3 \leq \text{ALPH} \leq 1$	0.1	-
BETA	Weighing factor for shear term in tensile fiber mode	Any value: $0 < \text{BETA} < 1$	0.6	-
XC	Longitudinal compressive strength	F_1^{cu} , from material properties	0.704	GPa
XT	Longitudinal tensile strength	F_1^{tu} , from material properties	0.776	GPa
YC	Transverse compressive strength	F_2^{cu} , from material properties	0.698	GPa
YT	Transverse tensile strength	F_2^{tu} , from material properties	0.760	GPa
SC	Shear strength	F_{12}^{tu} , from material properties	0.095	GPa
SLIMT1	Factor to determine the minimum stress limit after stress maximum (fiber tension)	Small but nonzero, $0 < \text{SLIMT1} \leq 1$	0.1	-
SLIMC1	Factor to determine the minimum stress limit after stress maximum (fiber compression)	$0 < \text{SLIMC1} \leq 1$	0.5	-
SLIMT2	Factor to determine the minimum stress limit after stress maximum (matrix tension)	Small but nonzero, $0 < \text{SLIMT2} \leq 1$	0.1	-
SLIMC2	Factor to determine the minimum stress limit after stress maximum (matrix compression)	$0 < \text{SLIMC2} \leq 1$	0.5	-
SLIMS	Factor to determine the minimum stress limit after stress maximum (shear)	$0 < \text{SLIMS} \leq 1$, recommended value is 1.0	1	-
CRIT	Failure criterion used (MAT_054 Chang-Chang, MAT_055 Tsai-Wu)	Assign value of 54 or 55	54	-

To ensure the analysis is performed accurately, it is essential to understand the failure mechanism described by the LS-DYNA MAT_054 card. The MAT_054 material model incorporates the stress-strain equations from MAT_022 for the elastic region. Accordingly, this section presents relevant details from the LS-DYNA theory manual related to MAT_022, alongside the full description of the MAT_054 material model.

For MAT_022, also known as the Chang-Chang composite failure model [11], in-plane stress-strain relationships are defined the functions of the applied stresses and they can be expressed as

$$\varepsilon_1 = \frac{1}{E_1}(\sigma_1 - \nu_{12}\sigma_2), \quad (2.1)$$

$$\varepsilon_2 = \frac{1}{E_2}(\sigma_2 - \nu_{21}\sigma_1), \quad (2.2)$$

$$2\varepsilon_{12} = \frac{1}{G_{12}}\tau_{12} + \alpha \tau_{12}^3. \quad (2.3)$$

As shown in Equation (2.3), α is the nonlinear shear stress parameter. The MAT_054 and MAT_055 material models are advanced damage models for composites with similar formulations. MAT_054 applies the Chang- Chang matrix failure criterion, similar to MAT_022, while MAT_055 employs the Tsai-Wu matrix failure criterion. These models allow for defining arbitrary orthotropic materials, such as unidirectional fibres or woven fabric layers in composite shell structures. Users can specify various failure criteria based on the approaches proposed by Chang- Chang or Tsai and Wu. Additionally, these models incorporate specific provisions for addressing failure under compressive loading. However, their applicability is restricted to thin-shell element types. The Chang-Chang failure criteria are mathematically described as follows.

For the tensile fiber mode:

$$\sigma_{aa} > 0 \text{ then } e_f^2 = \left(\frac{\sigma_{aa}}{x_t}\right)^2 + \beta \left(\frac{\sigma_{ab}}{s_c}\right) - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \quad (2.4)$$

$$\text{On failure: } E_1 = E_2 = G_{12} = \nu_{12} = \nu_{21} = 0,$$

for the compressive fiber mode:

$$\sigma_{aa} < 0 \text{ then } e_c^2 = \left(\frac{\sigma_{aa}}{x_t}\right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \quad (2.5)$$

$$\text{On failure: } E_1 = \nu_{12} = \nu_{21} = 0,$$

for the tensile matrix mode:

$$\sigma_{bb} > 0 \text{ then } e_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \quad (2.6)$$

On failure: $E_2 = \nu_{21} = G_{12} = 0$,

and for the compressive matrix mode:

$$\sigma_{bb} < 0 \text{ then } e_d^2 = \left(\frac{\sigma_{bb}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right] \left(\frac{\sigma_{ab}}{Y_c}\right) + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \quad (2.7)$$

On failure: $E_2 = \nu_{21} = \nu_{12} = G_{12} = 0$

$X_c = 2Y_c$ for 50 % fiber volume.

As shown in Equation (2.4) and Equation (2.6), σ_{aa} is the normal stress in fiber direction and σ_{bb} is the normal stress in matrix direction (perpendicular to fibres). When $\beta=1$ the tensile fiber mode corresponds to the original Hashin criterion. On the other hand, setting $\beta=0$ results in the Maximum Stress Criterion, which better aligns with experimental data. Failure can be occurred due to one of the following mechanisms:

1. If DFAILT (the maximum strain for fiber tension) is zero, failure happens, and the Chang-Chang failure criterion is met under tensile fiber loading conditions.
2. If DFAILT is greater than zero, failure can be occurred in these conditions:
 - The fiber strain exceeds DFAILT or falls below DFAILC (the maximum strain for fiber compression).
 - If absolute value of matrix strain is higher than DFAILM (maximum strain for matrix straining in tension or compression).
 - If absolute value of shear strain exceeds DFAILS.
3. If EFS exceeds zero, failure occurs when the effective strain exceeds the EFS threshold.
4. If TFAIL is greater than zero, failure is also affected by the element's time step, as per the definition of TFAIL.

When all layers (through-thickness integration points) of the composite element fail, the element is automatically excluded from the simulation. This exclusion also impacts nearby elements, as those sharing nodes with the removed element are treated as crash front

elements. The crash front elements' strength can be adjusted by utilizing the SOFT parameter in combination with TFAIL>0, allowing for a gradual deterioration of material properties.

To monitor the failure behaviour of each layer (integration point) and the entire element, additional integration point variables are available. Integration points offer detailed insights into the mechanical properties and failure mechanisms throughout the simulation. For shell elements, the number of integration points stored in the LS-DYNA database is controlled by the NEIPS parameter defined in the DATABASE_BINARY command. For material models like MAT_054 and MAT_055, integration points are organized to provide layer-specific data. This includes detailed information on stress, strain, and damage evolution across shell integration points (i). These parameters improve post-processing capabilities and help to interpret the material's behaviour during crash scenarios.

Integration point history variables are important to ensure that simulations accurately replicate the behaviour of composite materials and their interactions with adjacent elements under crash conditions. This is outlined in Table 2.2.

Table 2.2. Composite material failure modes and history variables.

History Variable	Failure Mode	Value	LS Prepost Output Variable
ef(i)	tensile fiber mode		1
ec(i)	compressive fiber mode		2
em(i)	tensile matrix mode	1-elastic	3
ed(i)	compressive matrix mode	0- failed	4
efail	max[ef(ip)]		5

In the Table 2.3, three history variables show the fraction of elastic (no-failed) integration points in the tensile fiber, compressive fiber and tensile matrix failure modes. They are indicated as effective plastic strain in the Ls-Dyna software.

Table 2.3. Integration points of effective plastic strains for non-failed elements [11].

Description	Integration Point
$\frac{1}{nip} \sum_{i=1}^{nip} ef(i)$	1
$\frac{1}{nip} \sum_{i=1}^{nip} ec(i)$	2
$\frac{1}{nip} \sum_{i=1}^{nip} em(i)$	3

After the composite crash box material properties were defined, a configuration was required to dampen the shock waves and reducing initial peak loads. In order to replicate crash box-bumper beam assembly, 50 mm x 125.5 mm PVC foam was placed on top of the composite and the outer perimeter was wrapped with 4 layers of composite shell, each layer thickness of 0.25 mm. Additionally, an intermediate plate made of composite material was placed between the foam and the crash box. Then, the configuration (foam + plate) is called as a representative beam.

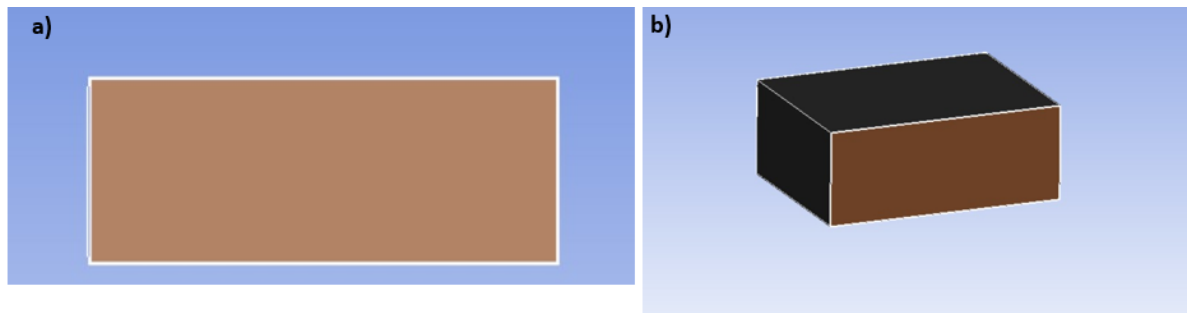


Figure 2.2. PVC Foam (a) top view, (b) isometric view.

The reason why PVC foam was chosen as the damping material is that PVC foams have many advantageous material properties such as energy absorption and low density [49, 50]. For this 4-layer composite structure, the MAT_054 card and its features were used, as in the crash box, while the MAT_163_MODIFIED_CRUSHABLE_FOAM card was used for the PVC foam. The material properties selected for Divinycell H-100 PVC foam in the

analysis were obtained from quasi static and dynamic experiments and is illustrated in Table 2.4 [51,52] and Figure 2.3 [53-55] with different strain rates.

Table 2.4. Material properties of PVC foam [51,52].

Variable	Definition	Value
RO	Mass per unit volume	100 kg/m ³
E	Young's modulus	87 MPa
TSC	Tensile stress cut-off	3.5 MPa
DAMP	Damping coefficient	0.1

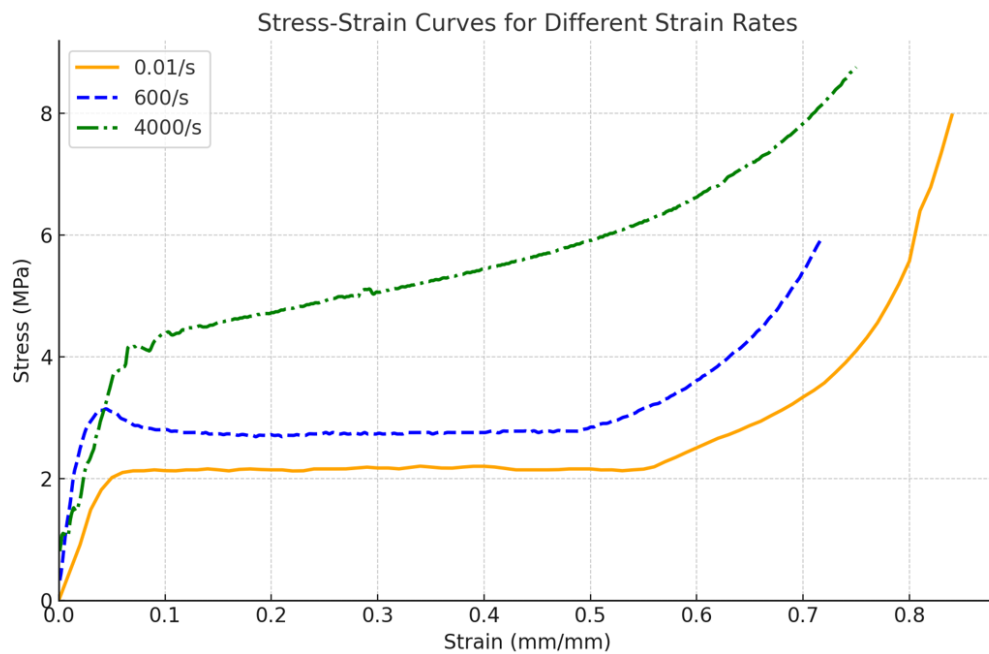


Figure 2.3. Stress-strain characteristics of Divinycell H-100 PVC foam under uniaxial compression at different strain rates.

2.1.1.2. Steel Crash Box Material Model and MAT 024 Parameters. Metal crash box is manufactured from DP780 steel. Metal crash box structure has been occurred by combining two symmetrical sheet metals and contains a trigger in the middle to assure accordion-like folding. Total thickness is 1.6 mm, and total height is 120 mm, the shape of the steel crash box from different views is shown in Figure 2.4.

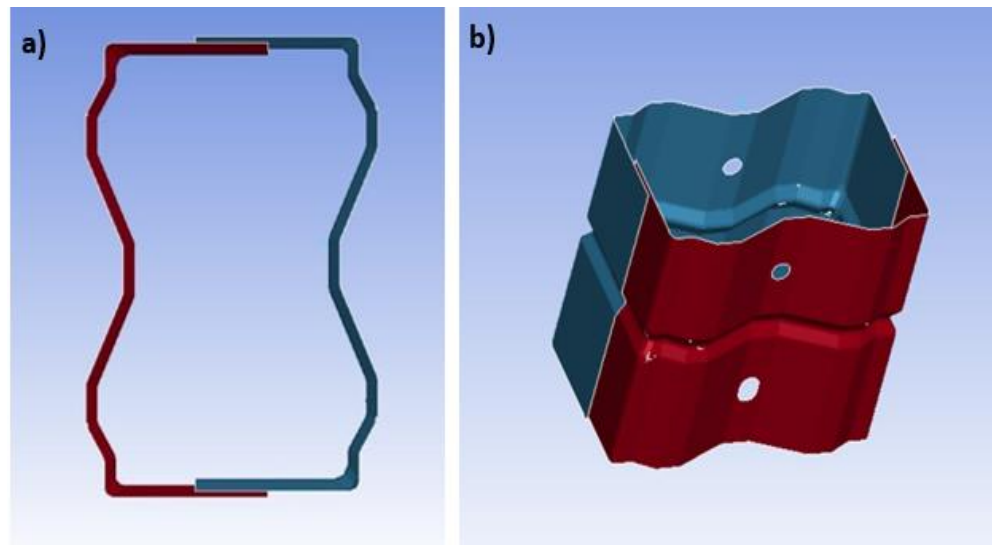


Figure 2.4. Shape of the metal crash box (a) top view of crash box, (b) isometric view of the crash box.

MAT_024 (Piecewise Linear Plasticity) is widely used in LS-DYNA for modelling materials that exhibit elastic-plastic behaviour. It is particularly suitable for simulating metals under various loading conditions [11]. Additionally, the stress-strain curve presented in Figure 2.5 [15] was employed under different strain rates.

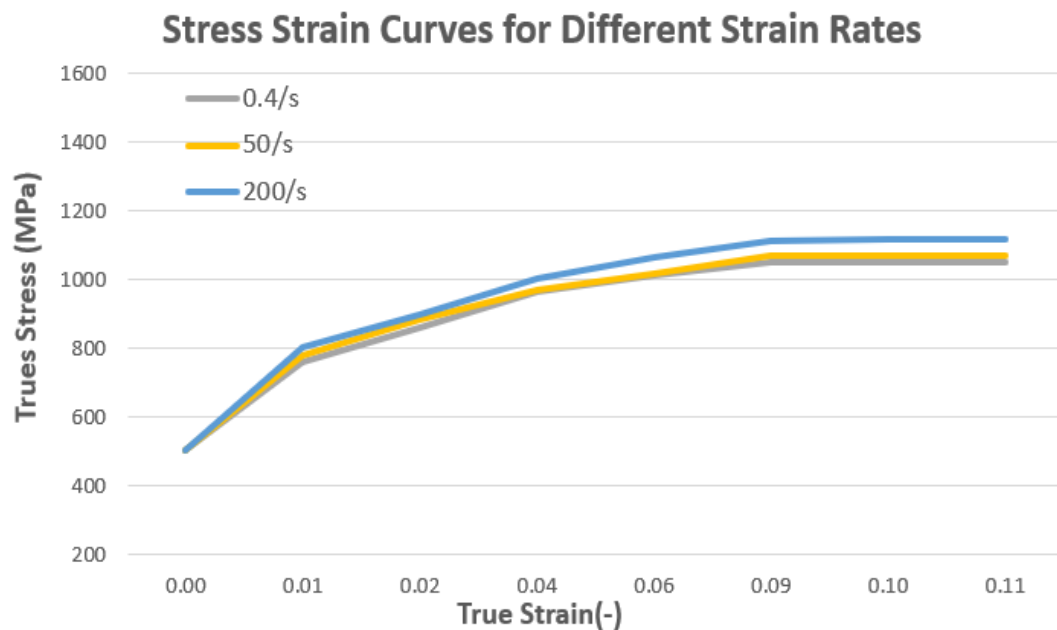


Figure 2.5. Determined true stress–strain curve of the DP780 steel under different strain rates.

Tabular stress strain relation is demonstrated in Table 2.5 to use in LS Dyna MAT_024 card. To investigate the mechanical behaviour of the plastic deformation, the stress strain graph starts from yield strength (beginning of the plastic deformation) to fracture. Since the stress strain values (EPS1, ES1) to (EPS8, ES8) for only one strain rate value can be specified on the material card, the stress strain values of 200/s strain rate were chosen considering the velocity of the impactor and the length of the crash box.

Table 2.5. Tabular stress–strain values of the DP780 steel [15].

Strain	Stress (MPa) for 200/s strain rate
0.000	504.5
0.010	804
0.024	900
0.042	1002
0.060	1067
0.086	1114
0.099	1116
0.110	1117

Table 2.6 in the LS-DYNA documentation typically lists all parameters used in the MAT_024 material model, describing their definitions and methods for determination. These parameters include material properties such as elastic moduli, strengths etc. The stress-strain behaviour can be represented using a bilinear stress-strain curve, which is defined by the tangent modulus ETAN. Alternatively, the relationship between effective stress and effective plastic strain can be specified using points (EPS1, ES1) to (EPS8, ES8), since there are eight data points in the tabular format of stress-strain curve as shown in Table 2.6. Additionally, strain rate effects can be considered through this method.

Table 2.6. MAT_024 input parameter definitions.

Variable	Definition	Suggested Value
MID	Material identification number	Any arbitrary integer
RO	Mass per unit volume	ρ from material properties
E	Young's modulus	E from material properties
PR	Poisson's ratio	ν from material properties
SIGY	Yield stress	SIGY from material properties
ETAN	Tangent modulus	ETAN from material properties
TDEL	Minimum time step size for automatic element deletion	Very small or 0
C	Strain rate parameter, C	C from material properties
p	Strain rate parameter, p	p from material properties
VP	Formulation for rate effects	-1,0,1
EPS1-EPS8	Effective plastic strain values	EPS1-EPS8 from material properties
ES1-ES8	Corresponding yield stress values to EPS1 - EPS8	ES1-ES8 from material properties

The Cowper and Symonds model that adjusts the yield stress by scaling it with a specific factor [17] given by

$$1 + \left(\frac{\dot{\epsilon}}{C}\right)^{1/p}, \quad (2.8)$$

where $\dot{\epsilon}$ is the strain rate. If VP=-1, the deviatoric strain rates can be used instead.

If the viscoplastic option is active (VP=1) and SIGY>0 then the dynamic yield stress is computed from the sum of the static stress, $\sigma_y^s(\epsilon_{eff}^p)$, which is typically given by a load curve ID and the initial yield stress, SIGY, scaled by the Cowper-Symonds rate term [11] is presented as

$$\sigma_y(\epsilon_{eff}^p, \dot{\epsilon}_{eff}^p) = \sigma_y^s(\epsilon_{eff}^p) + \text{SIGY} \times \left(\frac{\dot{\epsilon}_{eff}^p}{C}\right)^{1/p}. \quad (2.9)$$

Here the plastic strain rate is used. The properties of the MAT_024 card used in the analysis are shown in Table 2.7.

Table 2.7. Material properties of DP780 steel crash box.

Variable	Value	Unit
RO	7.8e-6	kg/mm ³
E	210	GPa
PR	0.3	-
SIGY	0.460	GPa
ETAN	-	-
TDEL	-	-
C	-	-
p	-	-
VP	-	-
EPS1-EPS8	[0, 0.01, 0.024, 0.06, 0.086, 0.0986, 0.11]	-
ES1-ES8	[0.505,0.804 ,0.900,1.002,1.067,1.114,1.116,1.117]	GPa

2.1.2. Modelling of Delamination for Composite Crash Box

In LS-DYNA software, delamination, or the separation between layers of the composites, can be simulated through material models, cohesive zone modelling, or tie-break contact methods. Material models can naturally account for delamination failure, while cohesive zone modelling uses cohesive elements inserted between layers to capture interfacial behaviour explicitly. Alternatively, tie-break contact types, such as automatic surface-to-surface or one-way surface-to-surface tie-break, can tie coincident nodes of composite layers until a specified failure criterion is reached, after which the bond is released. In studies involving the MAT_054 material model, tie-break contacts have been effectively used to simulate delamination between the layers. Among them, the automatic surface-to-surface tie-break contact is frequently chosen, often utilizing options 7, 9, or 11 for both shell and solid elements, depending on the simulation requirements. This method is especially effective for modelling the interaction and cohesion of composite plies under various loading conditions. In LS-DYNA, tie-break contact models using specific options (e.g., 7, 9, or 11) employ a bilinear constitutive law to describe the relationship between stress and displacement at the interface. This law is applicable under tensile loading, as in a double cantilever beam (DCB) test, and shear loading, as in an end-notched flexure (ENF) test. Tensile loading corresponds to Mode I delamination, characterized by normal opening displacements, whereas shear loading can represent Mode II or Mode III delamination, based

on the relative in-plane or out-of-plane shear displacements concerning the crack orientation. These modes are used to capture the progressive failure of the interface under complex loading conditions.

The traction-separation behaviour of the tie break elements for various modes of fracture are shown in Figure 2.6. The relative displacements δ_1^0 and δ_{23}^0 indicate the onset of damage. Before these displacement thresholds are reached, the material responds elastically and maintains cohesion without permanent damage. However, when these displacement limits are exceeded (indicating that the maximum normal or shear forces are exceeded), damage initiates and then propagates. This failure progression continues until the relative displacements δ_1^f and δ_{23}^f are reached. At these final displacement values, bond failure between the layers occurs, causing irreversible damage.

The area under the tensile loading curve represents the Mode I fracture energy. Similarly, for shear loading, this corresponds to the fracture energies of Modes II and III. In Mode II, the layers slide relative to each other along the 2-direction (in-plane shear), whereas in Mode III, the sliding occurs along a 3-direction (out-of-plane shear). It should be emphasized that Mode I fracture toughness is generally lower than Modes II and III. Since Mode II components are naturally present in Mode III tests, it is difficult to accurately determine Mode III fracture toughness. Finally, for delamination analyses, Mode III fracture toughness is generally assumed to be equivalent to Mode II [18].

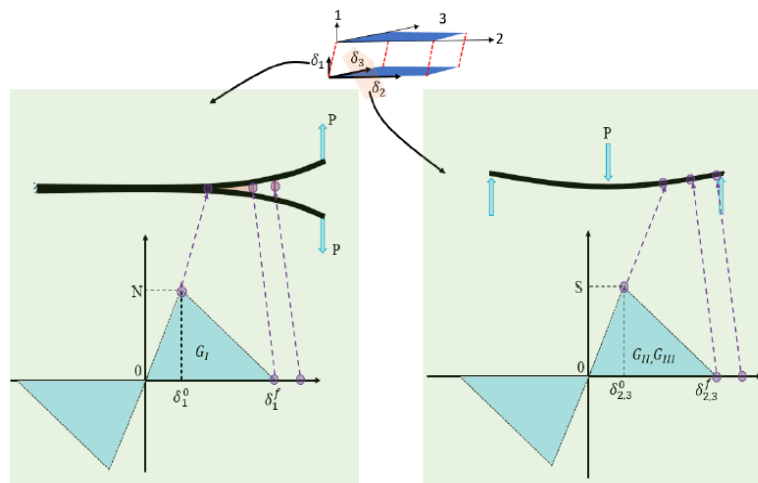


Figure 2.6. The bilinear constitutive law in Mode I and Mode II and III [18].

Under combined loading conditions, which involve both tensile and shear forces, mixed mode interaction is observed. The mixed-mode behaviour is described using the bilinear constitutive law, as presented in Figure 2.7. In this scenario, damage propagation may begin when the damage initiation threshold is reached, as outlined in the previous section. The relative displacement due to shear loading is determined by combining the relative displacements in 2 and 3 directions, as shown in Figure 2.6. The overall shear relative displacement value can be calculated as

$$\delta_{shear} = \sqrt{(\delta_2)^2 + (\delta_3)^2}. \quad (2.10)$$

Then, the total mixed mode relative displacement [22] can be defined as

$$\delta_m = \sqrt{(\delta_1)^2 + (\delta_{shear})^2}. \quad (2.11)$$

Then, the contribution of the different modes is found as

$$\beta = \frac{\delta_{shear}}{\delta_1}. \quad (2.12)$$

Additionally, mixed mode traction can be computed as

$$\left(\frac{t_1}{N}\right)^2 + \left(\frac{t_{shear}}{S}\right)^2 = 1. \quad (2.13)$$

Here, Equation (2.13) is used to determine when damage initiates under mixed-mode loading. Damage initiation and damage propagation criteria in mixed mode loading are illustrated in Figure 2.7 below. For damage initiation, a quadratic delamination criterion is used, which allows the interaction of different loading modes is accurately captured [19]. The damage initiation and propagation criterion in mixed mode are shown in Table 2.8.

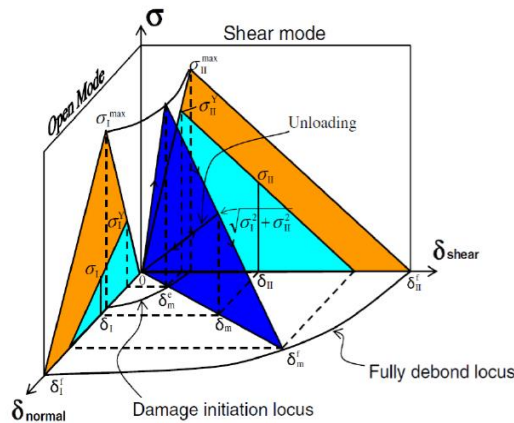


Figure 2.7. The bilinear constitutive law in mixed-mode loading [66].

As shown in Table 2.8, mixed-mode damage initiation and progression criteria are addressed by three basic methods. The damage initiation criterion is evaluated is the maximum surface stresses in the normal and tangential directions, the parameters N (peak traction in the normal direction) and S (peak traction in the tangential direction) and predicts that damage is initiated when the squared sum of the normalized stress components ($\frac{t_1}{N}$ and $\frac{t_{shear}}{S}$) is equal to 1. This approach determines the failure initiation criteria of the material under Mode I (opening), Mode II (shearing) and Mode III (tearing) loading conditions. Secondly, the power law criterion evaluates determines the damage propagation condition in Mode I, Mode II and Mode III loading cases using the relations between the fracture toughness's (G_{IC}, G_{SC}). Using the power law relationship between the fracture energy components, the ultimate mixed mode displacement value δ_m^f is calculated and it is determined whether the deformation will progress. This criterion helps predict how delamination will proceed by combining the energy release rates in both modes with a specific exponential function. Finally, the Benzeggagh and Kenane (B-K) criterion determines crack propagation using a weighted combination of Mode I and Mode II and Mode III fracture energies. It includes an exponential parameter (η) to determine the weight of the Mode II component and thus can more precisely represent the fracture behaviour in different modes. The B-K criterion is specifically designed to accurately capture the change in fracture toughness as a function of the mode mixing ratio ($\frac{G_{shear}}{G_{IC}+G_{shear}}$) [20]. The B-K criterion fitting parameter, η , is determined through a curve fitting process applied to experimentally obtained fracture toughness values. These values are measured using mixed mode bending tests at various mode mixity ratios. For pure Mode I ($\frac{G_{shear}}{G_{IC}+G_{shear}}=0$), double cantilever beam tests are conducted, while for pure Mode II ($\frac{G_{shear}}{G_{IC}+G_{shear}}=1$) end-notched flexure tests are used. Based on the mode mixity ratio being studied, the behaviour under mixed-mode conditions (shown as the blue-shaded area in Figure 2.7) can represent behaviour more similar to either Mode I or Mode II.

In this study to simulate delamination failure, the automatic one-way surface to surface tiebreak contact type is selected using option 9. The necessary parameters for this tiebreak contact type NFLS, SFLS, PARAM are directly taken from [21], the CT2CN and CN values are taken from [23] the ERATEN, ERATES are evaluated from [24] and [14] and all values

are summarized in Table 2.9 to generate delamination failure between layers. The N (peak traction in the normal direction) value in Table 2.9 is equivalent to NFLS in option 9 of the tiebreak contact in LS-Dyna. The S (peak traction in the tangential direction) value is represented as SFLS in LS-Dyna. Additionally, η is represented as PARAM in LS-Dyna. G_{IC} and G_{SC} are equivalent to ERATEN and ERATES in LS-Dyna, respectively. This type of contact has been implemented between each individual layer to ensure accurate simulation of their interaction. The parameters used to define this contact, along with their corresponding values, are detailed in Table 2.9 provided below. These parameters are essential for capturing the mechanical behaviour and load transfer between layers under various conditions.

Table 2.8. Mixed-mode damage initiation and propagation criteria [18].

Damage initiation	$\left(\frac{t_1}{N}\right)^2 + \left(\frac{t_{shear}}{S}\right)^2 = 1$ $\delta_m^0 = \begin{cases} \{\delta_S^0 \delta_N^0 \sqrt{\frac{1 + \beta^2}{(\delta_S^0)^2 + (\beta \delta_N^0)^2}} \} \leftarrow \delta_1 > 0 \\ 1 \leftarrow \delta_1 \leq 0 \end{cases}$
Power law criterion	$\left(\frac{G_I}{G_{IC}}\right)^a + \left(\frac{G_{shear}}{G_{SC}}\right)^a = 1$ $\delta_m^f = \begin{cases} \left\{ \frac{2(1+\beta^2)}{k\delta_m^0} \left(\left(\frac{1}{G_{IC}}\right)^a + \left(\frac{\beta^2}{G_{SC}}\right)^a \right)^{-1/a} \right\} \leftarrow \delta_1 > 0 \\ \delta_s^f \leftarrow \delta_1 \leq 0 \end{cases}$
Benzeggagh and Kenane's criterion	$G_{IC} + (G_{SC} - G_{IC}) \left(\frac{G_{shear}}{G_{IC} + G_{shear}} \right)^\eta = G_I + G_{shear}$ $\delta_m^f = \begin{cases} \left\{ \frac{2}{k\delta_m^0} (G_{IC} + (G_{SC} - G_{IC}) \left(\frac{\beta^2}{1 + \beta^2} \right)^\eta) \right\} \leftarrow \delta_1 > 0 \\ \delta_s^f \leftarrow \delta_1 \leq 0 \end{cases}$

Table 2.9. Tiebreak contact properties between composite layers.

Variable	Definition	Suggested Value
OPT	Option	9, Crack Model with power law and B-K damage models.
NFLS	Normal failure stress	0.040 GPa
SFLS	Shear failure stress	0.078 GPa
PARAM	Exponent in the damage model	2.25
ERATEN	Normal energy release rate	5.04e-4 J/m ²
ERATES	Shear energy release rate	1.566e-3 J/m ²
CT2CN	Tangential stiffness /Normal stiffness	0.400
CN	Normal stiffness (stress/length)	50 GPa

2.1.3. Impact Scenario Setup

For the crash boxes, the impact velocity is assigned to be as 7.67 m/s using the INITIAL_VELOCITY GENERATION command, using 3/4 of the value in the study [25], considering the absence of a beam in the structure. In addition, the impactor weight used in the analysis was 305 kg. These parameters were carefully chosen to simulate realistic loading conditions and to ensure that the results provide an accurate representation of the part's response under such impacts. In composite crash boxes, unlike metals, it is not possible to introduce a geometric trigger to initiate the initial damage due to the material behaviours differences, so it is not possible to measure the acceleration data during the initial impact because the higher initial peak load and shock wave generated at the moment of impact of the impactor cannot be effectively recorded. Measurement of the acceleration data becomes feasible only after this shock wave has dissipated. A representative beam (PVC Foam, which is wrapped with external composite layer and composite plate) was added to the composite crash box system developed during the drop weight test to dampen the shock wave. This allowed a meaningful comparison between the composite crash box and a metallic crash box. The representative beam used for shock absorption was constructed from 100 kg/m³ PVC foam, a four-layer composite CFRP material shell and composite plate. This setup provided a practical method to capture reliable data and analyse the behaviour of the composite structure under impact. Analyses were performed by fixing both metallic and

composite impact boxes to the ground and dropping an impactor onto them. The translational and rotational motion of the nodes on the fixed side was restricted. This setup is provided consistent test conditions to assess the structural behaviour and capacity for energy absorption of each material type under impact. By standardizing the boundary conditions, it was possible to directly compare the results and evaluate differences in behaviour such as damage initiation, shock wave attenuation, and overall performance.

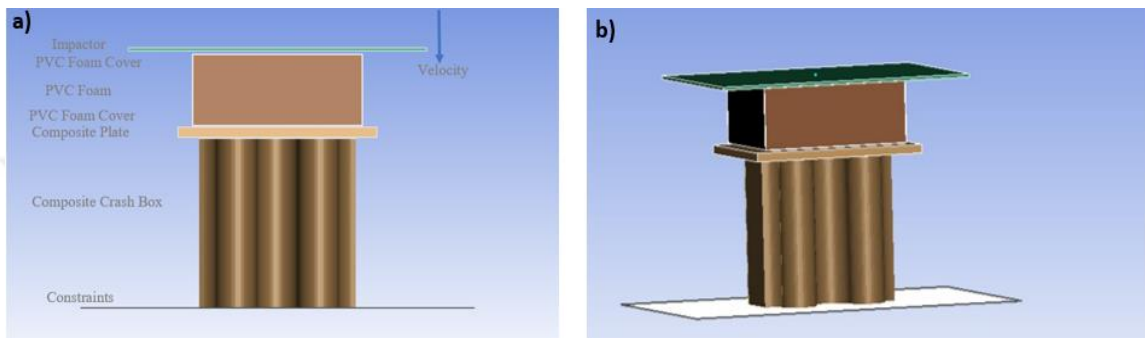


Figure 2.8. Crash box analysis setup for composite part (a) front view, (b) isometric view.

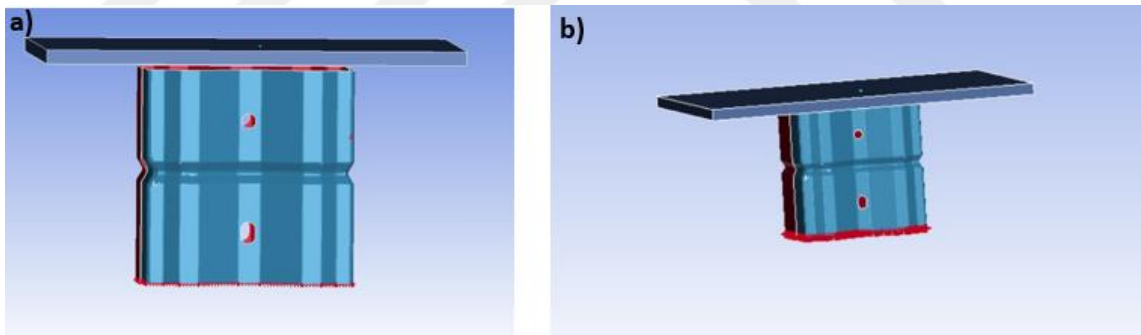


Figure 2.9. Crash box analysis setup for metal part (a) front view, (b) isometric view.

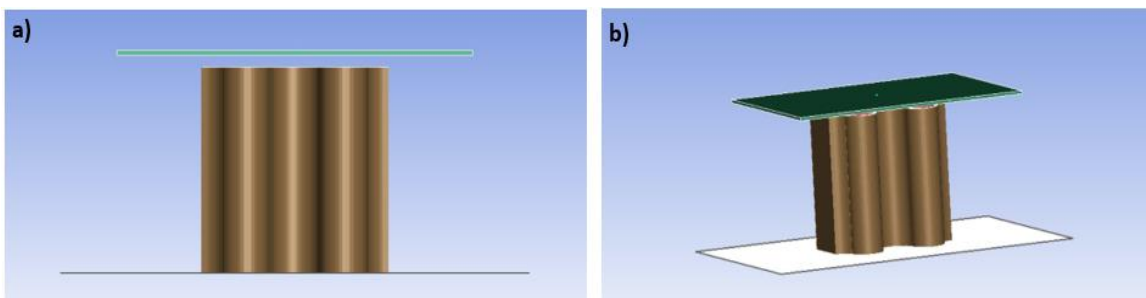


Figure 2.10. Crash box analysis setup for composite part without representative beam (a) front view, (b) isometric view.

Although not tested experimentally during this study, additional numerical simulations are performed without the representative beam to qualitatively observe the response of the crash box alone. The numerical analysis of the impact test setup for composite crash box without representative beam is shown in Figure 2.10.

Furthermore, a realistic 2 mm thick bumper beam (96 mm x 140 mm x 60 mm) made of the same type of sheet steel with the crash box is implemented in the metallic crash box setup to better reflect an actual vehicle configuration during impact. The impact test numerical analysis setup for steel crash box with front bumper is shown in Figure 2.11. For the bumper structure, a high-strength low-alloy steel - DOCOL 1400 - is used to represent the material typically employed in automotive applications requiring high energy absorption capacity.

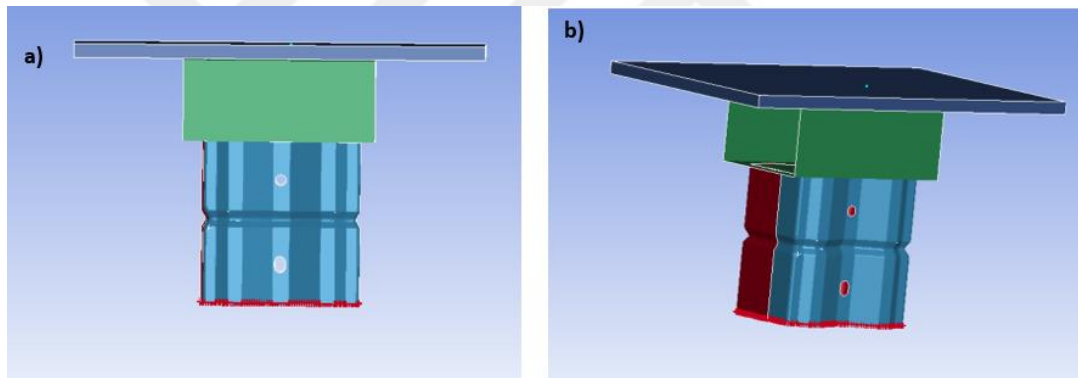


Figure 2.11. Crash box analysis setup for steel part with steel front bumper (a) front view, (b) isometric view.

2.1.4. Data Acquisition

Various physical values such as force, displacement, internal energy, kinetic energy and potential energy can be read using the DATABASE_CROSS_PLANE_SET option applied to the nodes at the bottom of the components. This option allowed us to define the cross-sectional planes where data could be collected and provided detailed insights into the structural response during impact analysis. By analysing these parameters, a comprehensive view of the behaviour of the parts under dynamic loading conditions was obtained, including energy distribution and deformation mechanisms.

2.2. Experimental Setup

As summarized in Section 2.1.2, the numerical analysis setup was based on the methodology detailed in [25]. However, certain modifications were required due to the absence of a bumper in the physical test configuration. In particular, adjustments were made to the mass and velocity parameters of the impactor, summarized in Table 2.10. In this study, an impactor with a mass of 305 kg was released from a certain height to reach a velocity of 7.67 m/s (27.6 km/hr). The structures to be compared consisted of impact boxes of the similar dimensions, made of CFRP composite and DP780 steel, to provide a standard comparison of their energy absorption capacities.

As seen in Figure 2.12, the impact test setup is demonstrated as both a CAD drawing and an actual test configuration. The accelerometer is placed on the impactor.

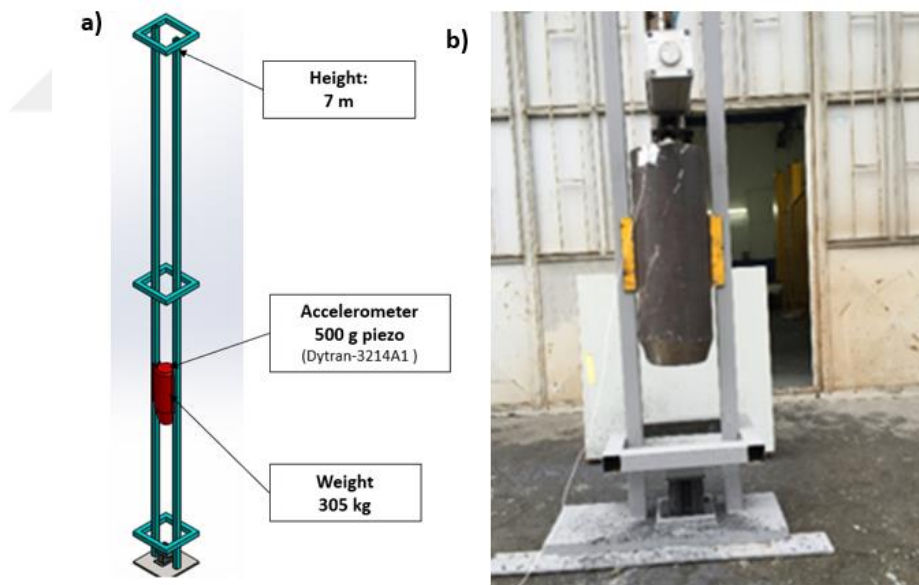


Figure 2.12. Experimental setup for impact test (a) CAD drawing, (b) experiment photo.

Table 2.10. Initial conditions used in literature [25] vs. this study.

Article	Experiment
Mass:323 kg	Mass:305 kg
Velocity: 9.16 m/s	Velocity: 7.67m/s

One of the critical challenges in testing of composite crash boxes is the initiation of failure at the desired location. Unlike metallic crash boxes, where geometric triggers can be integrated into the design to control failure initiation, composite materials lack such simple solutions. For this issue, a representative beam, which is a part of the bumper beam, is included in the test setup for composite part. While it provides to reduce the effects of the shock wave, its main function is to reduce the initial peak load. This beam, composed of 100 kg/m³ PVC foam and reinforced with a four-layer CFRP composite shell, was mounted on top of the composite crash box representing a section of the bumper beam. Its purpose was to reduce the effects of the shock wave and ensure accurate data acquisition of acceleration signals. This beam is not only mimicked the bumper beam required in practical applications but was also compatible with strategies to integrate crash boxes into vehicle chassis or BIW structures. Furthermore, the inclusion of this beam allowed for a more realistic assessment of the behaviour of the composite crash box under impact conditions. By comparing the results of the modified test setup and both crash box materials, critical insights were provided into their relative crashworthiness. The composite crash box exhibited distinct energy absorption characteristics as influenced by the material properties and its interaction with the representative beam. Figure 2.13 (a) presents the configuration of the representative beam used in the experimental setup for composite crash box. Figure 2.13 (b) presents the configuration of the DP780 steel section used in the experimental setup for metal crash box, showing the trigger to initiate successive folding of the metallic structure in an accordion form.

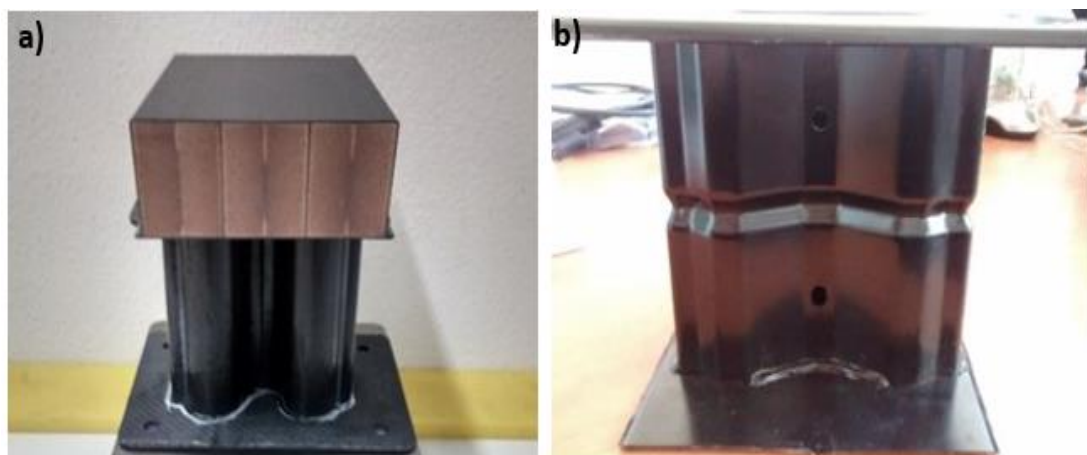


Figure 2.13. Crash boxes (a) composite crash box with the representative beam, (b) steel crash box.

This additional setup ensured that the comparative study accounted for the unique failure and damping mechanisms of composite materials. It also highlighted the importance of developing specific strategies for integrating advanced materials into vehicle crash structures, particularly in scenarios where traditional geometric triggering methods cannot be applied.



3. RESULTS AND DISCUSSION

3.1. Comparison of Experimental and Numeric Analysis of Composite and Steel Crash Boxes

Figure 3.1 demonstrates the crushing modes of the CFRP composite crash box comparing snap shots experimental and numerical analysis in the impact test between $t=0$ and $t=0.02$ seconds.

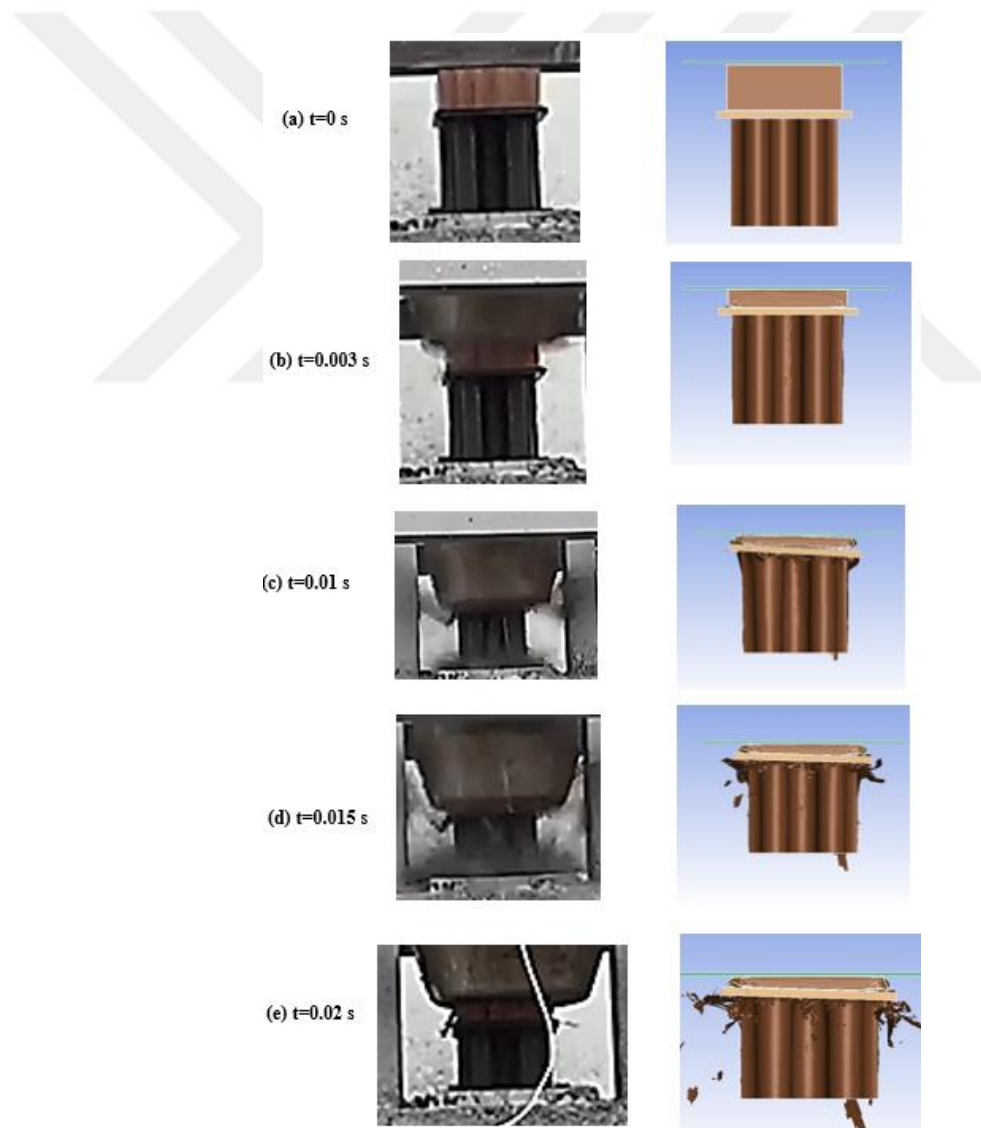


Figure 3.1. Behaviour of CFRP composite crash box during the impact test in experimental drop-weight testing and numeric analysis until $t=0.02$ seconds.

As seen in Figure 3.1, in time interval (a) – (b) the initial deformation occurs as the representative beam undergoes compression, transmitting the impact load to the upper surface of the CFRP composite crash box. At this stage, slight elastic buckling is observed in the upper region, indicating the onset of localized instability. The material remains within the elastic deformation range, and no significant damage initiation is observed. The material has not yet reached the ultimate failure threshold, meaning the observed deformation is still within the elastic range. During the time interval (b) - (c), as the representative beam continues to compress, the load transfer intensifies, causing the stress in the composite crash box to reach the critical threshold. This leads to the initiation of fiber breakage and matrix cracking, particularly at high-stress concentration zones. Additionally, early-stage delamination starts to develop due to interlaminar shear stresses. In the time span (c) - (d), damage propagation accelerates as localized fractures extend through the composite layers. The increasing load from the compressed foam induces severe delamination and fiber-matrix debonding, significantly reducing the structural integrity of the crash box. The deformation also results in out-of-plane bending, further contributing to crack propagation along the axial direction. Finally, in the time interval (d) - (e), the final stage of failure occurs. As the impact load continues to increase, the composite crash box undergoes catastrophic failure due to the excessive accumulation of compressive stress. Due to the progressive accumulation of compressive stress, the primary failure mode is compressive fiber failure, where fiber micro buckling transitions into complete fiber breakage. The excessive stress leads to severe matrix crushing, delamination, and extensive structural fragmentation. As a result, the energy absorption capability of the crash box significantly decreases, and the structural integrity is lost.

Similarly, Figure 3.2 demonstrates the crushing modes of the DP780 steel crash box comparing snap shots experimental and numerical analysis in the impact test between $t=0$ and $t=0.02$ seconds. As seen in Figure 3.2, in the time interval (a) - (b), the initial deformation occurs, and local buckling is observed in the upper region of the DP780 steel crash box as the foam compresses and transfers load to the structure. During the time interval (b) - (c), plastic deformation initiates, and localized folding starts to develop due to material yielding, particularly at stress concentration areas. In the time span (c) - (d), the deformation intensifies, and global buckling becomes more pronounced, leading to progressive folding and collapse of the structure. The plastic hinges formed in earlier stages continue to

propagate downward, significantly altering the crash box geometry. Finally, in the time interval (d) - (e), the final stage of collapse occurs, characterized by extensive plastic deformation and material folding. The crash box reaches its maximum energy absorption capacity through progressive collapse, with multiple folds forming along its length, effectively dissipating the impact energy.

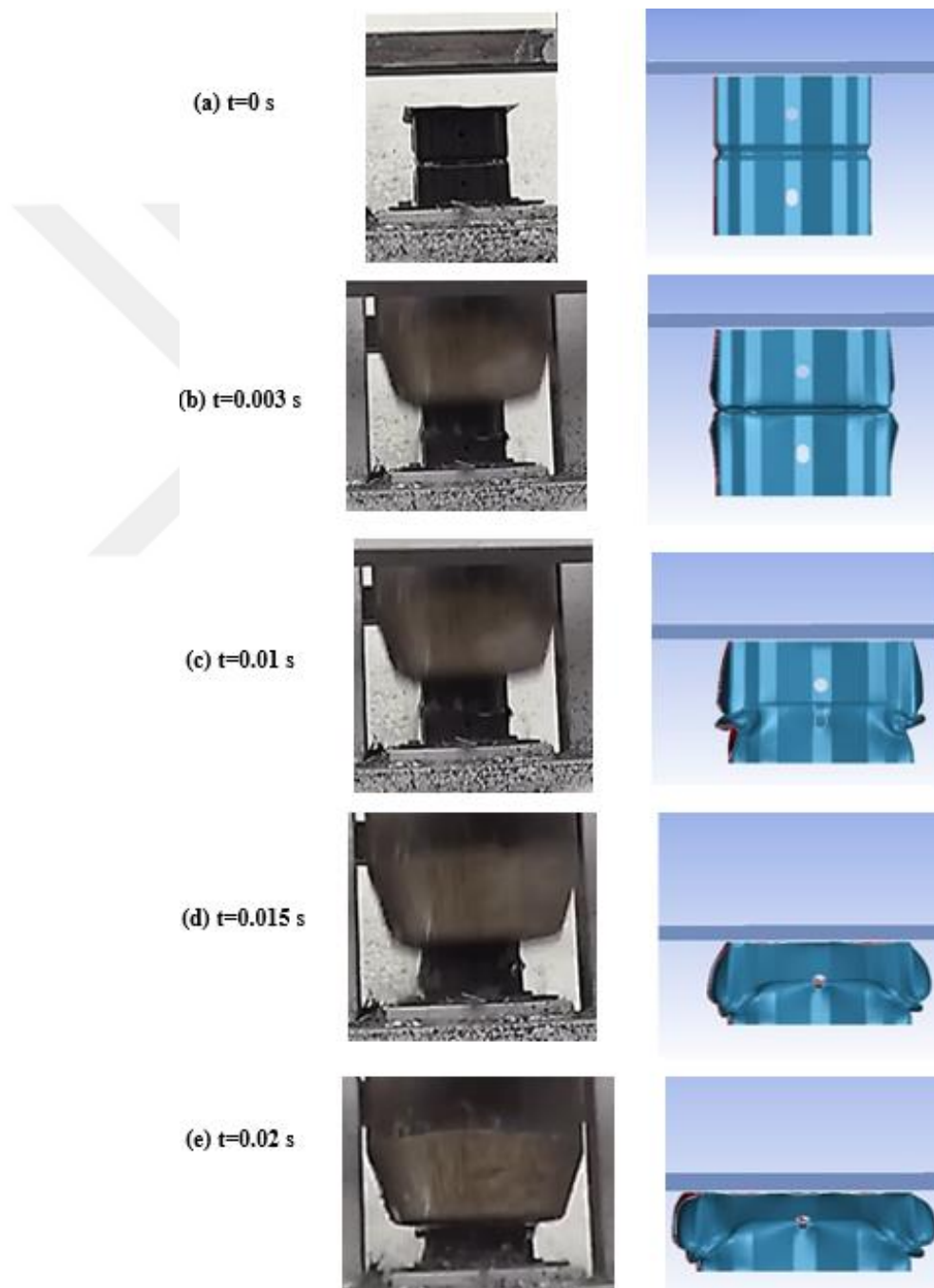


Figure 3.2. Behaviour of DP780 steel crash box during the impact test in experimental drop-weight testing and numeric analysis until $t=0.02$ seconds.

To gain a comprehensive understanding of the crash behaviour under dynamic loading of the crash boxes, this study also demonstrated the impact behaviour of CFRP composite and DP780 steel crash boxes under drop-weight impact conditions. The acceleration vs. time data was analysed, and the maximum and average acceleration values for experimental and simulation results were compared in the Figure 3.3 both numerically and experimentally.

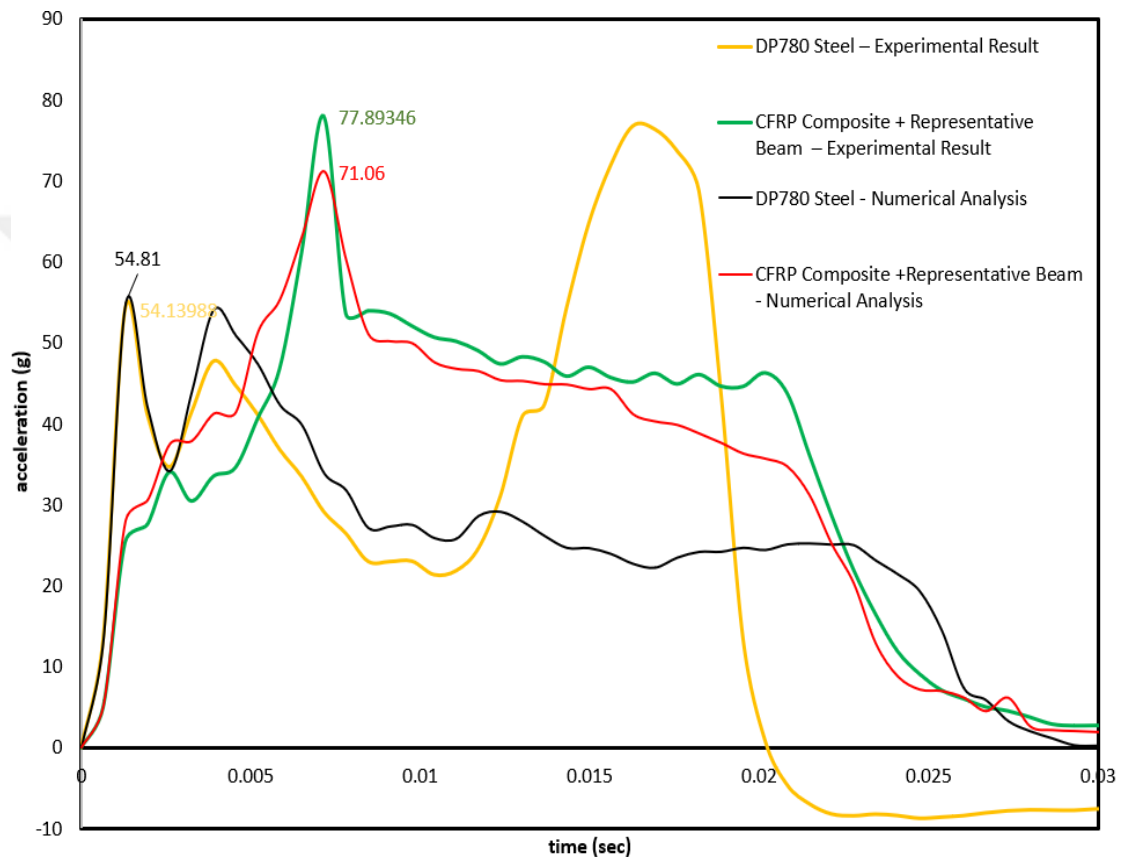


Figure 3.3. Acceleration vs time graph for numerical and experimental results for both crash boxes.

Summaries of the average and maximum acceleration for experimental and numerical results are shown in Table 3.1 for composite crash box and metal crash box. The experimental results showed slightly higher maximum and average acceleration values for the CFRP composite compared to the numerical analysis (CAE). This close correlation (~6.68 g difference at maximum acceleration, 1.10 g on average acceleration) highlights the reliability of the simulation model. To better capture the progressive failure mechanisms, delamination parameters were included in the CAE model. These parameters allowed the simulation to account for delamination, which is critical to understanding the energy

absorption behaviour of the composite material. Results for DP780 steel showed minimal differences between the experimental and simulated values (0.67 g for maximum and 0.90 g for average acceleration). This close match demonstrates the robustness of the simulation in capturing the plastic deformation behaviour of the steel. However, it seems that DP 780 steel makes a sudden pick after $t = 0.012$ in experimental test, that is, after the metal crash box loses its energy absorbing ability. There may be several reasons for this. First, a loose or unbalanced mounting of the accelerometer to the impactor may vibrate during impact, creating a temporary peak. Secondly, the stress waves propagating within the impact applied to the material may overlap at a certain point, creating a temporary increase in the acceleration values. Finally, the accelerometer has its own natural frequency; If the pulse frequency is close to this value, the sensor may resonate and create a short-term momentary deviation in the measurement. Since the impact tests of DP780 steel in previous studies have also been examined, it is obvious that this pick is not compatible with the material characteristics. Moreover, since the metal crash box lost its energy absorbing ability before this pick, this rise is not significant in this study.

Table 3.1. Average and maximum acceleration results for experimental and numeric results.

Material	Max Acceleration(g)	Average Acceleration (g)
DP780 Steel – Experimental Result	54.14	40.95
DP780 Steel - Numerical Analysis	54.81	41.85
CFRP Composite + Representative Beam – Experimental Result	77.89	49.82
CFRP Composite + Representative Beam - Numerical Analysis	71.06	48.72

In the composite material, the inclusion of delamination parameters in the simulation significantly improved its ability to replicate experimental results. Delamination plays a very important role in energy dissipation after the initial impact, contributing to the composite's

ability to continue absorbing energy over time. The progressive failure mechanisms modelled in the CAE simulation aligned closely with the extended oscillations observed in the experimental data. However, the analysis results are very sensitive to the parameters used to model the delamination effect. For parameters that are not material specific, the correct values must be determined with many iterations. Otherwise, the analysis characteristics can change significantly.

The material behaviour can be compared between CFRP composite and DP 780 steel. CFRP composite exhibits a brittle fracture mechanism with high initial energy absorption capacity. Progressive fracture mechanisms (delaminations and in-planes failures) allow for long-term energy dissipation. CFRP composites are suitable for applications requiring high energy absorption and reduced structural weight, such as automotive crash structures, due to their controlled energy dissipation and lightweight properties. In order to demonstrate the weight reduction effect with numerical data, the steel bumper-beam and crash box system produced in the patent configuration shown in [59] was measured as 5.4 kg, and the composite bumper beam and crash box was measured as 3.1 kg. This reveals that a weight saving of 2.3 kg is achieved on a vehicle basis. On the contrary, DP780 steel shows ductile deformation with energy absorption via plastic deformation. After the initial impact, it stabilizes rapidly with minimal post-impact energy dissipation. With its high toughness and rapid stabilization, DP780 steel is ideal for applications requiring resistance to deformation and impact toughness.

To further observe the effect of the representative beam on the composite crash box response, a comparative numerical simulation is performed without the representative beam. Numerical analysis setup is shown in Figure 2.10. To ensure a consistent comparison, the initial and boundary conditions are kept identical to those used in the representative beam case conditions. As shown in Figure 3.4, removing the representative beam caused a much sudden and higher initial peak load (175.49 g compared to 71.06 g) in the numerical analysis. This sharp rise in acceleration values led to a sudden failure, including extensive delamination and extensive structural fragmentation of the composite layers. The representative beam provides to delay and reduce the peak load by absorbing part of the shock wave, resulting in a more controlled response during impact.

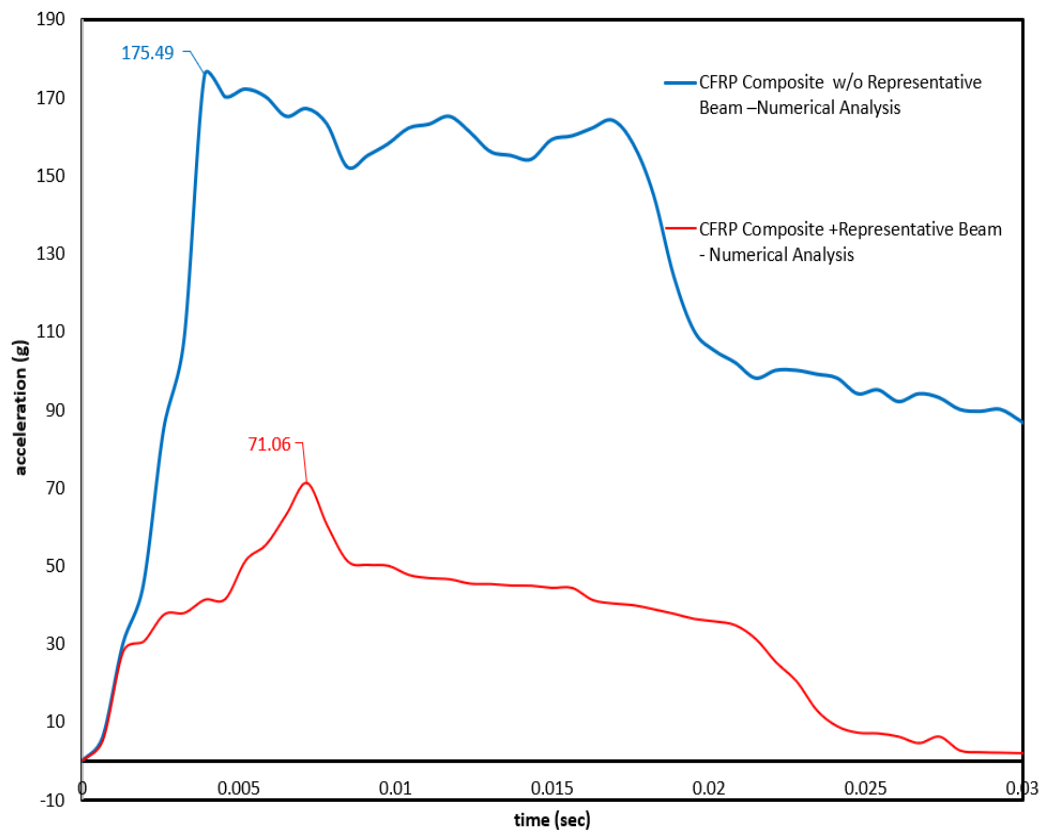


Figure 3.4. Effect of the representative beam on acceleration response in composite crash box numerical analysis.

Similarly, for the steel crash box, a more realistic scenario was simulated by incorporating an actual bumper structure as shown in Figure 2.11. This setup aimed to represent real vehicle conditions and allowed for a more meaningful comparison with the composite crash box configuration using the representative beam. The bumper structure acted as an integrated energy absorber, similar in function to the representative beam, helping to distribute the impact force more gradually and reduce the initial acceleration value. The resulting acceleration-time graph is shown in Figure 3.5, where the effect of the front bumper can be clearly observed in terms of peak load reduction and smoother impact response. The addition of the realistic bumper structure significantly reduced the initial peak acceleration (from 54.81 g to 35.23 g), showing better impact force reduction and a smoother crash response. Additionally, the bumper acted as an integrated energy absorber and its performance confirmed that the representative beam effectively simulated the real-world load distribution and shock wave reduction behaviour of a full bumper system.

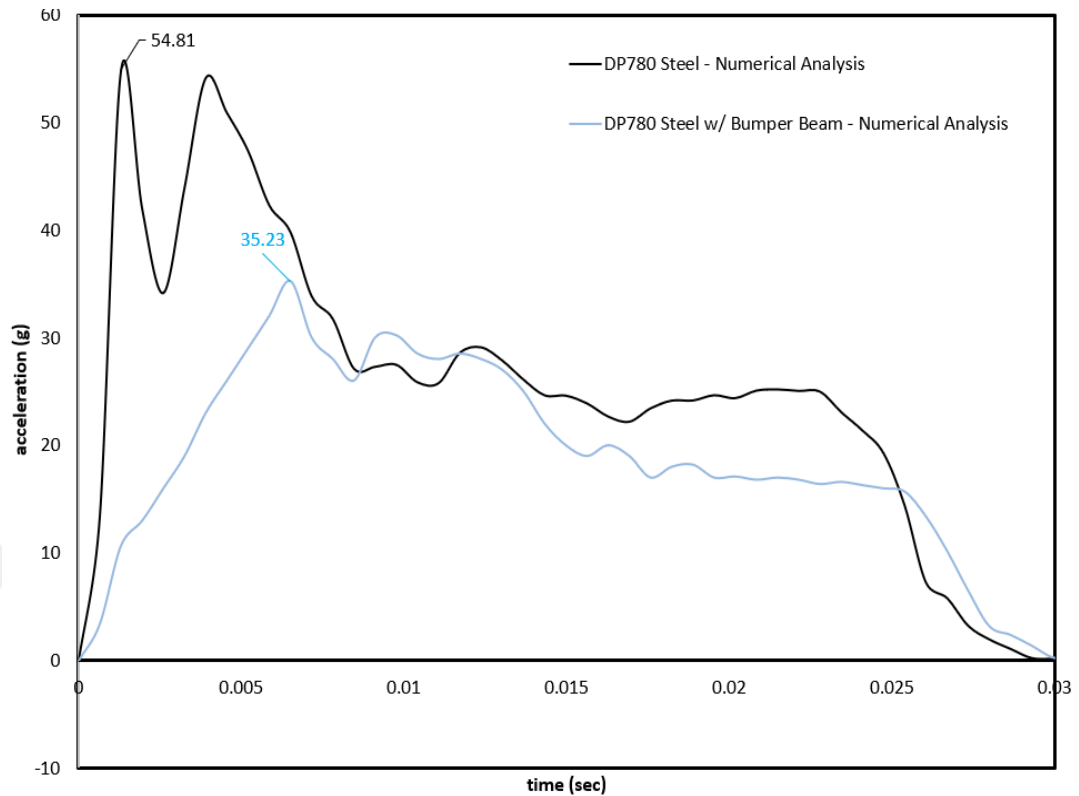


Figure 3.5. Effect of the front bumper on acceleration response in steel crash box numerical analysis.

In addition, when the various failure modes in the composite structure is examined, it is seen that the most dominant failure after the impact is compressive fiber damage (history variable 2) followed by fragmentation. According to the history variables defined as in Table 2.2, the value of 1 represents the material elasticity and the value of 0 represents the damaged (material failure) situation. When Figure 3.6 is examined, it is observed that the fibres under the compressive loading in the impact region break, and the value of 0 is commonly detected in these regions. This result indicates that high compressive stresses cause premature breakage of the fibres and loss of structural stability. As evaluated in terms of tensile fiber damage, the structure remained elastic to a large extent with a value of 1, so no significant damage occurred in the tensile mode. When the behaviour of the matrix under tension and compression is examined, it is determined that the matrix cracks and separates following the damage to the fibres. However, it is seen that these failure modes are less common compared to fiber damage and develop as secondary damage mechanisms.

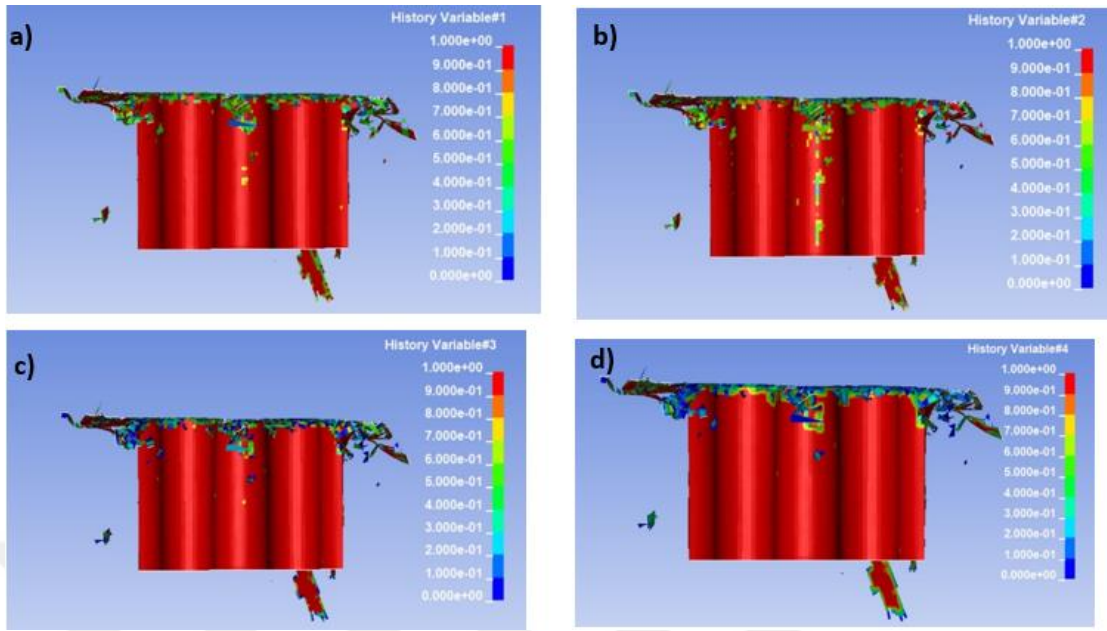


Figure 3.6. Failure mode analysis of composite structure at the final time step (a) tensile fiber mode, (b) compressive fiber mode, (c) tensile matrix mode, (d) compressive matrix mode.

In line with these findings, compressive fiber damage was determined as the main damage mechanism of the composite structure under impact load. This shows that fiber fractures in the compressive direction in composite materials are a dominant failure mode after impact and directly affects the carrying capacity of the structure.

3.2. Energy Absorption Analysis

The total energy absorbed (TEA), represented by the area under the load-displacement curve, is a measure of the energy dissipation during the crushing process. This value mathematically can be expressed as:

$$TEA = \int P \, ds = P_{avg} (d_f - d_i), \quad (3.1)$$

where P_{avg} denotes the average crushing load, d_f represents the terminal crushing distance, and d_i is the starting crushing distance. The resulting value of TEA is measured in kilojoules (kJ), which is the standard SI unit for energy [26]. The area under the load-displacement curve can be divided into two distinct regions, each corresponding to a specific phase of the crushing process. The first region is referred to as the pre-crushing phase. In this phase, the

area corresponds to the triangular portion of the curve, and it can be determined by using the formula for the area of a triangle. Specifically, this area is calculated as one-half the product of the initial peak load P_i and the initial displacement d_i , resulting in a value expressed in kN, which is equivalent to kJ in SI units. The second region represents the post-crushing phase, where energy absorption is determined by utilizing an equation that incorporates parameters derived from previously provided tables or experimental data. To calculate the total energy absorbed throughout the entire process, the energy contributions from both the pre-crushing and post-crushing regions are summed together [27]. The combination of these regions contributes the comprehensive evaluation of the energy dissipation during the crushing event, reflecting the mechanical behaviour and the specimen's material characteristics under applied loads. In addition, specific energy absorption (SEA) plays a crucial role in designing lightweight components. SEA is the energy absorbed per unit mass of the specimen and is expressed in kJ/kg. It can be calculated from below:

$$SEA = TEA/mass. \quad (3.2)$$

First of all, to find the force values, all nodes at the bottom of the crash box are selected by adding Cross_Section_Plane in the LS Dyna database and assigning it for numerical analysis. To find the section force in this section, SECFORC is activated in the database section. However, since it is not possible to measure force in the experimental tests, it can be found theoretically using acceleration data with respect to time. Force is determined using Newton's Second Law of Motion ($F=m*a$). Then, force value is obtained for experimentally and numerically. In addition, since displacement is not measured in the experimental test, the acceleration-time graph is integrated twice to obtain the displacement-time graph. This displacement value is necessary to calculate the energy absorption for both crash boxes. According to Equation (3.1), total energy absorption values can be calculated for both DP780 steel and CFRP composite crash boxes considering the results of both experimental and numeric analysis. Total energy absorption values can be illustrated in Figure 3.7. The total energy absorption value is 7.51 kJ for experimental result and 7.55 kJ for numeric analysis for DP780 steel. For CFRP composite crash boxes, total energy absorption value is 8.76 kJ for experimental result and 8.69 kJ for numeric analysis. It is clear that the total energy absorption capacity of the CFRP composite material is higher than that of the DP780 steel.

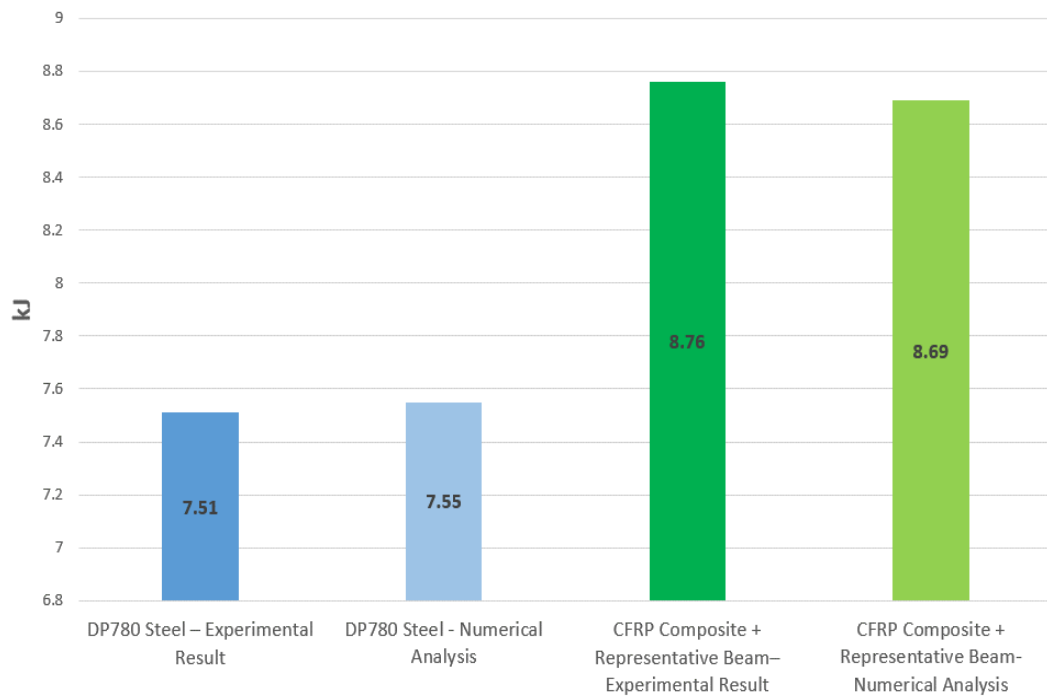


Figure 3.7. Total energy absorption values for both crash boxes.

The weight of both crash boxes was not measured directly, but since the size details of the crash boxes are known, the volume of the crash boxes can be found from the solid models and the weight can be calculated by multiplying the corresponding densities. Since the total energy absorption value is known, SEA can be found for both crash boxes.

Table 3.2. Crash box material, volume, and weight data.

Crash Box Material	Thickness (mm)	Volume (mm ³)	Weight (kg)
CFRP Composite	2.5	145156	0.22
DP780 Steel	2.5	168712	0.90

After the masses are calculated for each crash box, the SEA value can be found separately for crash boxes by dividing the TEA value by the mass using Equation (3.2). As seen in Figure 3.8, SEA value was found to be approximately 4.5 times higher in the composite material compared to DP780 steel. This result shows that composites have better energy absorption capabilities than steels as expected, and it actually overlaps with the values in other studies in the literature [28].

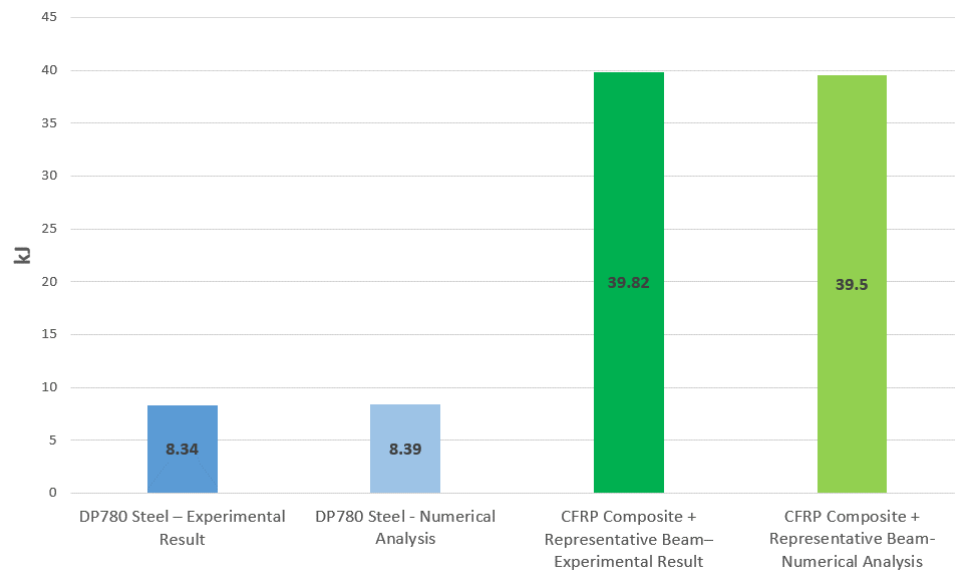


Figure 3.8. Specific energy absorption values for both crash boxes.

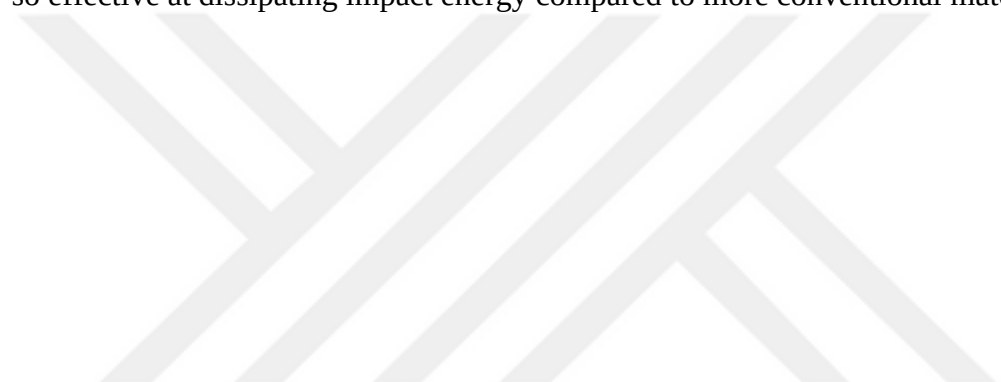
In addition, it has been observed that energy absorption values and crash mechanism can be changed when PVC foam of different densities is used. When every parameter in the numerical analysis it is kept constant and the foam material with density values of 100, 200, and 250 kg/m³, there were minor variations observed in the total energy absorption values, however the difference is marginal as can be seen in Table 3.3.

Tablo 3.3. Effect of PVC foam material properties on the total energy absorption.

Foam	Total Energy Absorption (kJ)
PVC Foam – 100 kg/m ³ (H100)	8.69
PVC Foam – 200 kg/m ³ (H200)	8.74
PVC Foam – 250 kg/m ³ (H250)	8.89

These results demonstrate that PVC foam material properties affected the crash characteristics and energy absorption capabilities of the composite crash box. As the density of foam PVC foam increases, slight improvement is seen in its ability to absorb energy during impact. In addition, as the foam's density property increases, the amount of

compression of the foam also decreases and the amount of load transmitted to the crash box changes. This behaviour can be assigned to the unique stress-strain characteristics of PVC foam, which are quite different from traditional industrial materials like steel or aluminium. In contrast to metals that typically have a well-defined elastic-plastic transition and a sharp yield point, the stress-strain response of PVC foam is shaped by its cellular structure. The foam first goes through a linear elastic phase, then enters a plateau stage where the cells collapse at almost constant stress and finally achieves a densification phase where stress increases rapidly as the material becomes compact. This distinct behaviour not only helps explain why energy absorption varies with foam density but also shows why PVC foams are so effective at dissipating impact energy compared to more conventional materials.



4. CONCLUSION AND FUTURE WORKS

This study aimed to assess the crashworthiness of CFRP composite crash box in comparison to a conventional crash box made of DP780 steel. The purpose is to determine whether the CFRP composite crash box, enhanced with a representative beam, could outperform DP780 steel crash box in terms of energy absorption and structural damping during low velocity impacts. To achieve this, a comprehensive experimental and numerical approach was adopted, involving physical drop-weight tests and simulations using LS-DYNA. By aligning the conditions of the physical tests and numerical analysis, this study established a robust methodology to investigate the dynamic response of these materials and validate the performance of the simulation models. In the experimental setup, an impactor weighting is 305 kg, and it was initially at rest, the impactor reached a velocity of 7.67 m/s upon release to impact with the crash boxes made of DP780 steel and CFRP composite. The target structures were of similar dimensions to standardize the comparison. Numerical simulations were performed to replicate these experimental conditions. For the DP780 steel, the material model MAT_024 is utilized in LS-DYNA, which accurately represents the elasto-plastic behaviour of metallic materials under high strain rates. For the CFRP composite, MAT_054 material card is used, and additional contact parameters were incorporated to capture delamination effects, a critical aspect of composite behaviour during impact. These parameters were carefully defined to ensure the accurate representation of both materials in the simulation environment. Findings derived from experimental tests and numerical simulations demonstrated a strong correlation, confirming the reliability of the simulation setup and the material models used. In terms of total energy absorption, the DP780 steel crash box absorbed 7.51 kJ in the experiment and 7.55 kJ in the simulation. The CFRP composite crash box, combined with the representative beam, demonstrated superior energy absorption capabilities, recording 8.76 kJ in the experiment and 8.69 kJ in the simulation. This considerable increase in energy absorption highlights the potential of CFRP composites as a viable alternative to metals in crashworthiness applications. Additionally, specific energy absorption, the DP780 steel crash box absorbed 8.34 kJ/kg in the experiment and 8.39 kJ/kg in the simulation. The CFRP composite crash box, combined with the representative beam, demonstrated superior energy absorption capabilities, recording 39.82 kJ/kg in the experiment and 39.50 kJ/kg in the simulation. These results demonstrate that

composite crash box exhibit a significantly higher SEA compared to steel crash box, which indicates that they are not only lighter but also more effective in energy absorption. Another critical parameter analysed was acceleration, which functions as an identifier of the material's ability to dissipate impact forces. For the DP780 steel crash box, the experimental tests yielded a maximum acceleration of 54.14 g and an average acceleration of 40.95 g, while the simulations provided comparable results of 54.81 g and 41.85 g, respectively. On the contrary, the CFRP composite crash box with foam has higher accelerations, with a maximum of 77.89 g and an average of 49.82 g in the experiment, and 71.06 g and 48.72 g in the numeric analysis. While the higher accelerations for the composite indicate a stiffer response, the improved energy absorption suggests a more effective dissipation of impact energy. One of the significant challenges in testing composite materials was initiating damage in a controlled manner. Unlike metallic crash boxes, where geometric triggers are integrated to direct the failure, composites lack such straightforward mechanisms due to their heterogeneous structure. To address this, the representative beam segment is incorporated to the structure.

Delamination effects were explicitly modelled in LS-DYNA by defining appropriate contact parameters. This approach allowed for a detailed examination of damage propagation in the composite crash box during impact and provided valuable insights into its failure mechanisms. Additionally, the inclusion of representative beam on the composite crash box design proved to be useful. The foam layer acted as a damping medium, reducing the severity of the shock wave generated during the initial impact. This setup improved the accuracy of acceleration data collection and enhanced the overall crash performance of the composite structure. In contrast, an additional simulation without the representative beam resulted in a significantly higher initial peak acceleration (175.49 g), leading to sudden failure due to extensive delamination and fragmentation. This outcome further confirms the effectiveness of the representative beam in moderating the shock response, similar to the role of the steel front bumper structure in the steel crash box setup. The comparison of experimental and numerical results further confirmed the effectiveness of this design, as the correlation between the two datasets was within acceptable limits, demonstrating the robustness of the applied methodology.

In conclusion, the findings of this study provide compelling evidence of the superior crashworthiness of CFRP composite materials over DP780 steel. The composite crash box exhibited higher energy absorption capabilities, an essential criterion for safety-critical applications. Furthermore, a significant weight reduction can be achieved when composite is replaced as a material of choice for crash box applications. Considering that there are four of these crash boxes in passenger cars, and a weight reduction from 0.90 kg to 0.22 kg can be achieved for each, a total of $4 \times (0.90 - 0.22) = 2.72$ kg of weight can be saved. Although this seems an insignificant figure it should be kept in mind that other passive safety parts such as bumper beams can also be made from composite, adding up to a considerable sum. A study determined that a 100 kg reduction in vehicle weight could lead to a decrease in combined city/highway fuel consumption by approximately 0.4 L/100 km for cars and around 0.5 L/100 km for light trucks. Nevertheless, it is important to note that despite the composite materials technical advantages, its large-scale adoption in the automotive industry remains tied to ongoing developments in production efficiency and material cost reduction. While steel continues to be more economically viable due to mature and highly automated manufacturing methods, research focused on reducing the raw material cost of composites- particularly carbon fiber- may significantly improve their cost competitiveness in the near future.

While the stiffer response of the composite material resulted in higher accelerations, the overall performance, including energy dissipation and delamination behaviour, underscores its potential as a lightweight and efficient alternative to traditional metals. The close consistency between experimental and numerical outcomes validates the reliability of LS-DYNA simulations for such analyses and highlights the importance of combining experimental and numerical approaches to achieve a comprehensive understanding of material behaviour under impact conditions.

The applicability of the composite crash box studied in this thesis to actual vehicles should also be discussed. The main challenge for the widespread penetration of carbon fiber reinforced composites (CFRPs) in the automotive industry is their high cost, particularly in terms of material cost, manufacturing and processing cost and cycle time. Carbon fiber itself is significantly more expensive than traditional automotive materials like steel or aluminium. CFRP parts typically require complex and time-consuming manufacturing processes, such

as autoclave curing or resin transfer molding, which are not easily scalable for mass production. Many composite manufacturing techniques have long cycle times, making them less suitable for the high-speed production lines used in the automotive industry. While the proposed design presents manufacturing challenges with hand lay-up and autoclave curing, it is well-suited for high-volume production using continuous processes like pultrusion, making it a viable option for meeting automotive industry demands. Further studies should be carried out in terms of cost analysis, and manufacturing cycle optimization.



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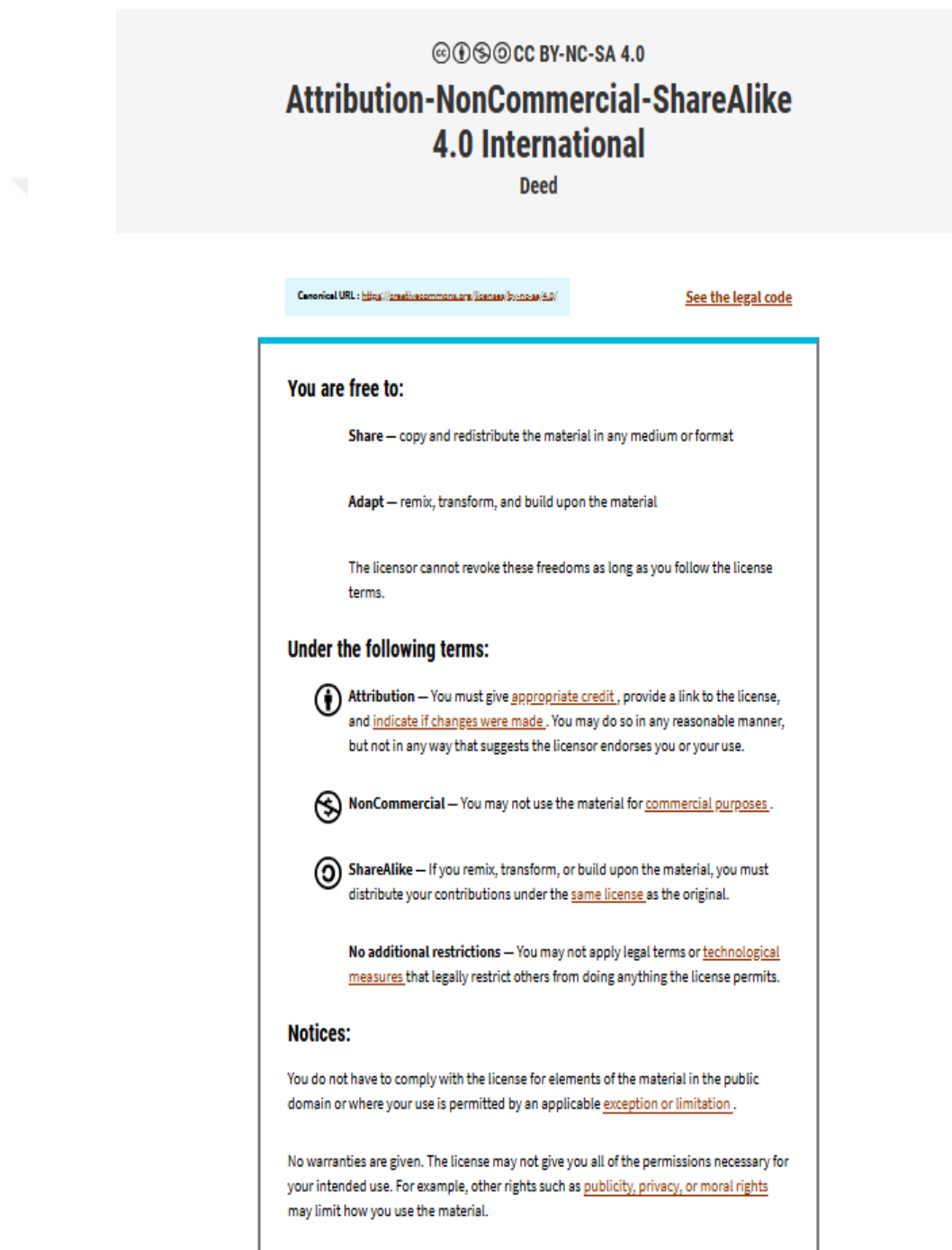


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Material and Process Charts

Material property charts

Introduction

The charts in this booklet summarise *material properties* and *process attributes*. Each chart appears on a single page with a brief commentary about its use. Background and data sources can be found in the book "Materials Selection in Mechanical Design" 3rd edition, by M.F. Ashby (Elsevier-Butterworth Heinemann, Oxford, 2005).

The material charts map the areas of property space occupied by each material class. They can be used in three ways:

- (a) to retrieve approximate values for material properties
- (b) to select materials which have prescribed property profiles
- (c) to design hybrid materials.

The collection of process charts, similarly, can be used as a data source or as a selection tool. Sequential application of several charts allows several design goals to be met simultaneously. More advanced methods are described in the book cited above.

The best way to tackle selection problems is to work directly on the appropriate charts. Permission is given to copy charts for this purpose. Normal copyright restrictions apply to reproduction for other purposes.

It is not possible to give charts which plot all the possible combinations: there are too many. Those presented here are the most commonly useful. Any other can be created easily using the CES software.

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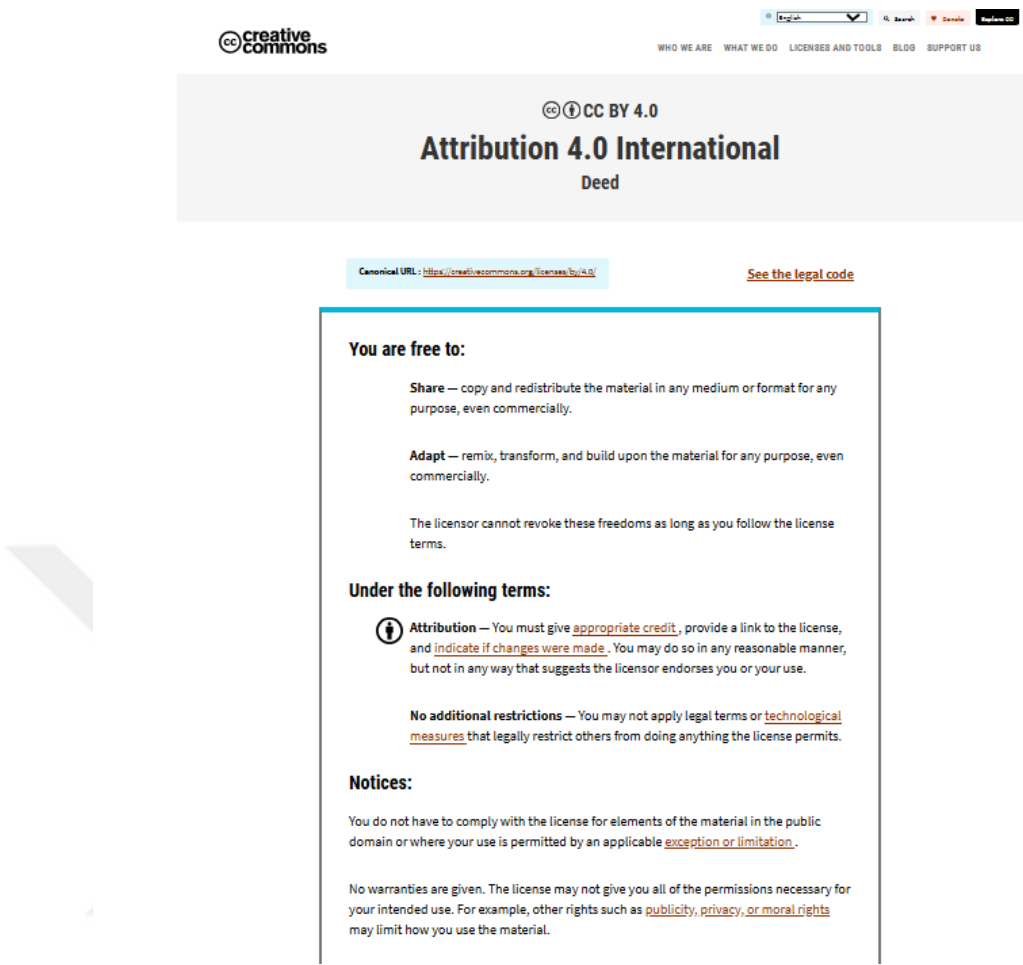


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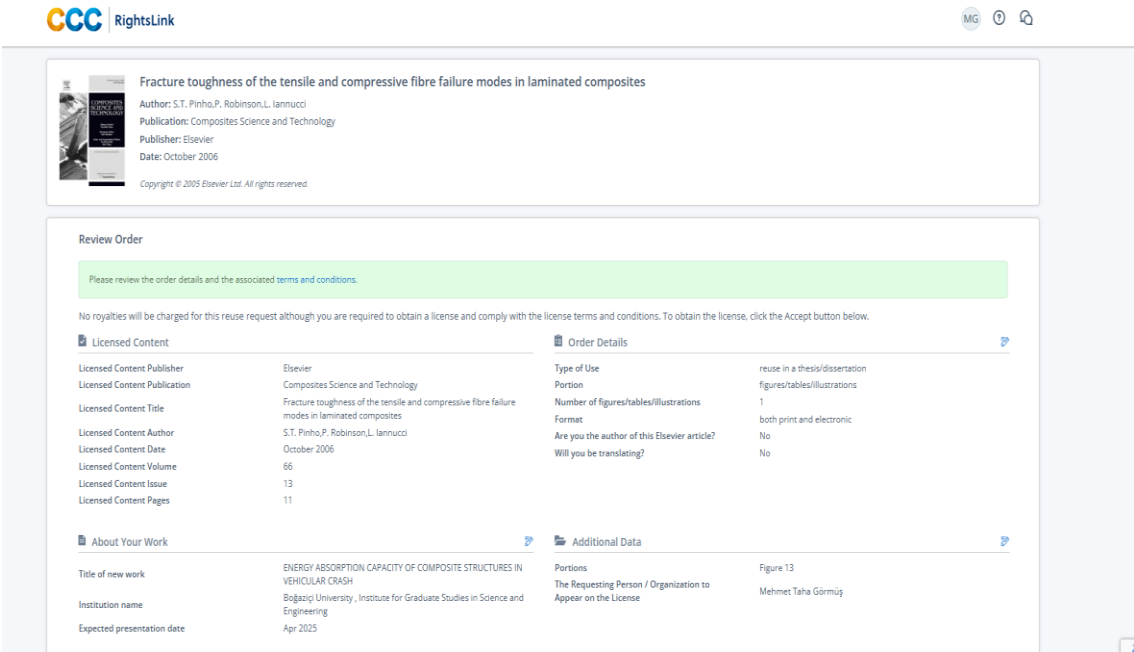


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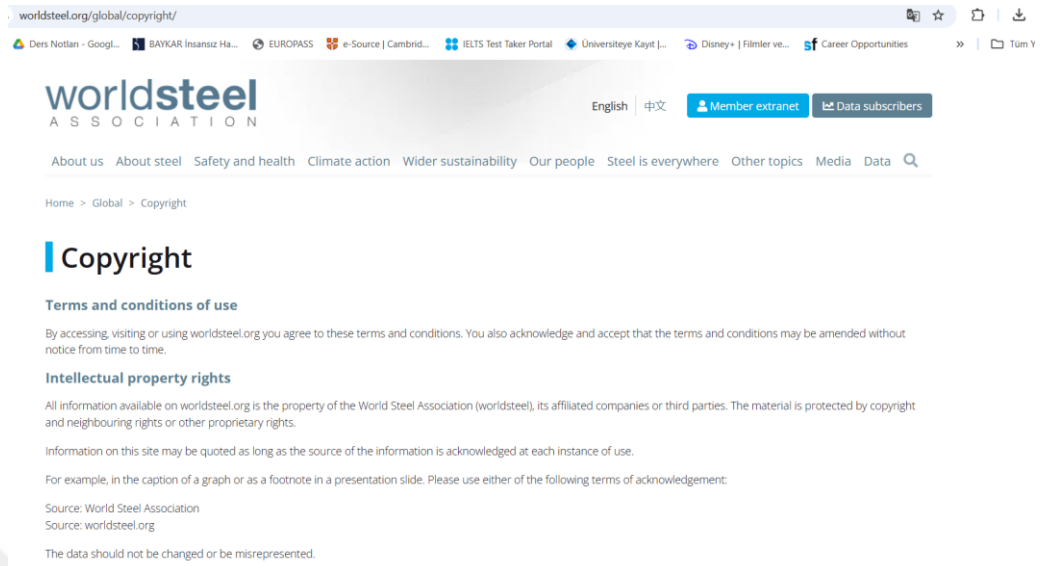


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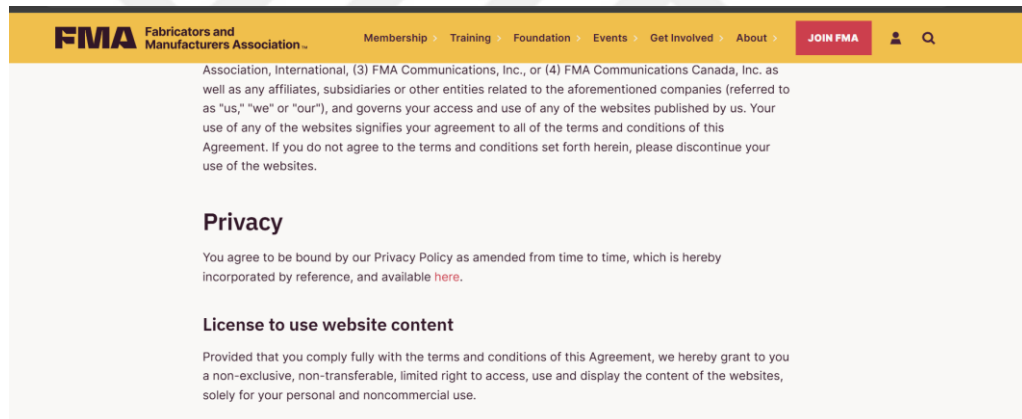


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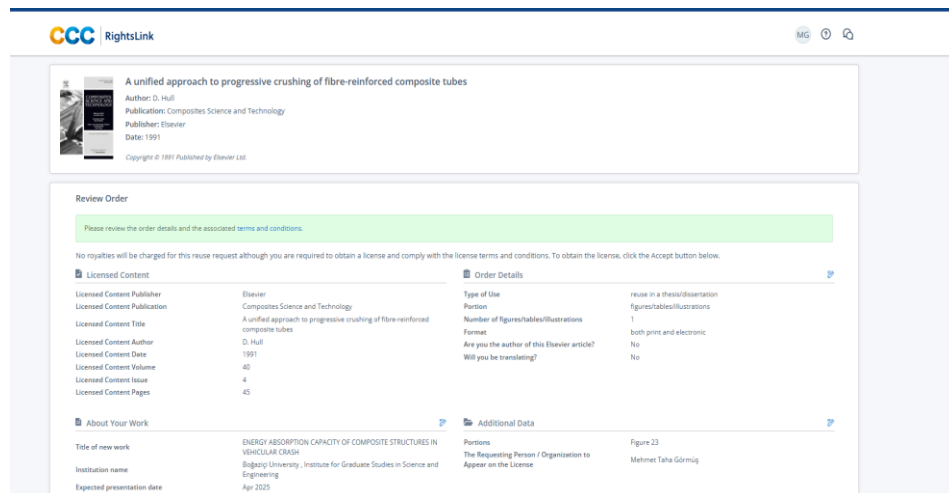


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