ÇUKUROVA UNIVERSITY

INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

Development of Fiber Reinforced Composite Liner for Ballistic Protection

Yılmaz ERBİL

Mechanical Engineering Department

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This Doctorate Thesis was evaluated by the following Jury Members on 19/11/2024 and was approved by unanimity / majority of votes.

Jury : Asst. Prof. Dr. Durmuş Ali BİRCAN (Advisor) ……..……

: Prof. Dr. Abdulkadir YAŞAR ……..……

: Assoc. Prof. Dr. Mehmet İlteriş SARIGEÇİLİ ……...…….

: Assoc. Prof. Dr. Hüseyin MUTLU ……...…….

: Asst. Prof. Dr. Alper GÜNÖZ ……....

This Thesis was written in the Department of Mechanical Engineering, Institute of Natural and Applied Sciences.

Thesis Number:

Prof. Dr. Sadık DİNÇER
Director
Institute of Natural and Applied Sciences

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Yılmaz ERBİL

Advisor: Asst. Prof. Dr. Durmuş Ali BİRCAN

Department of Mechanical Engineering

ABSTRACT

Ballistic protection systems play a critical role in modern defence applications. Evolving threats and increasing security requirements have increased the demand for lightweight and high-performance materials. Spall liner is a Fiber Reinforced Composite (FRC) material used for lining the interior of armoured vehicles to reduce the effect of shrapnel and fragments which poses a potential risk of death and injury to occupants inside caused by impact on the exterior of the vehicle. The primary objective was to evaluate the ballistic performance of various composite configurations by exploring the effects of different fibers, matrices, and Fiber Volume Fractions (V_f). The sets of samples were prepared and subjected to mechanical and ballistics tests using epoxy, vinylester, and polyester matrices combined with carbon, glass, and aramid fibers. In this study, Resin Transfer Moulding (RTM) method was used as the production method. The spall liner panels were fabricated with different V_f values (40%, 50% and 60%) to evaluate their effect on ballistic resistance. Tensile, in-plane shear, compression, and three-point bending tests were performed to establish a baseline for the mechanical properties of the produced spall liner panels. Subsequently, ballistics tests were conducted to determine the V_{50} values, which represent the velocity at which there is a 50% probability of penetration. The results indicate significant differences in ballistic performance based on the fiber type, matrix type, and V_f. Among the fibers, the aramid fiber composites demonstrated the highest V_{50} values, highlighting their effectiveness in absorbing and dissipating ballistic energy. Comparatively, a higher V_f is generally correlated with enhanced ballistic performance. The 60% V_f composites consistently exhibited the highest V_{50} values across all the configurations. By analyzing the effect of the interaction between fiber type, matrix type and V_f on ballistic performance, this study provides a framework for the design and development of advanced composite spall liners that can enhance the survivability of armoured vehicles and personnel by meeting the evolving requirements of modern defence applications.

Keywords: Armoured Vehicle, Ballistic Protection, Spall Liner, Fiber-Reinforced Composite, V_{50}

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

DOKTORA TEZİ

Balistik Koruma Amaçlı Fiber Takviyeli Kompozit Parçacık Astarı Geliştirilmesi

Yılmaz ERBİL

Danışman: Dr. Öğr. Üyesi Durmuş Ali BİRCAN

Makine Mühendisliği Anabilim Dalı

ÖZ

Balistik koruma sistemleri modern savunma uygulamalarında kritik bir rol oynamaktadır. Gelişen tehditler ve artan güvenlik gereksinimleri, hafif ve yüksek performanslı malzemelere olan talebi artırmıştır. Parçacık astarı, aracın dış kısmına çarpma sonucu oluşan ve içerideki yolcular için potansiyel ölüm ve yaralanma riski oluşturan şarapnel ve parçacıkların etkisini azaltmak amacıyla, zırhlı araçların içini kaplamak için kullanılan bir Fiber Takviyeli Kompozit (FRC) malzemedir. Birincil amaç, farklı fiber, matris ve Fiber Hacim Oranları'nın (V_f) etkilerini araştırarak çeşitli kompozit parçacık astarı konfigürasyonların balistik performansını değerlendirmektir. Karbon, cam ve aramid fiberlerle birleştirilmiş epoksi, vinilester ve polyester matrisler kullanılarak numune setleri hazırlanmış ve mekanik ve balistik testlere tabi tutulmuştur. Bu çalışmada üretim metodu olarak Reçine Transfer Kalıplama (RTM) yöntemi kullanılmıştır. Parçacık astarı panelleri, balistik direnç üzerindeki etkilerinin değerlendirilmesi için farklı V_f değerleri (%40, %50 ve %60) ile üretilmişlerdir. Üretilen parçacık astarı panellerinin mekanik özelliklerine ilişkin bir temel oluşturmak için çekme, kayma, basma ve üç nokta eğme testleri gerçekleştirilmiştir. Daha sonra, %50 penetrasyon olasılığının olduğu hızı temsil eden V_{50} değerlerini belirlemek için balistik testler yapılmıştır. Sonuçlar, fiber tipi, matris tipi ve V_f'ye bağlı olarak balistik performansta önemli farklılıklar olduğunu göstermektedir. Fiberler arasında aramid fiber takviyeli kompozitler en yüksek V_{50} değerlerini göstererek balistik enerjiyi absorbe etme ve dağıtma konusundaki etkinliklerini ortaya koymuştur. Karşılaştırmalı olarak, daha yüksek bir V_f genellikle daha yüksek balistik performans ile ilişkilendirilmiştir. %60 V_f kompozitler, tüm konfigürasyonlarda sürekli olarak en yüksek V_{50} değerlerini sergilemiştir. Fiber tipi, matris tipi ve V_f arasındaki etkileşimin balistik performans üzerindeki etkisini analiz eden bu çalışma, modern savunma uygulamalarının gelişen gereksinimlerini karşılayarak zırhlı araçların ve personelin beka kabiliyetini artırabilecek gelişmiş kompozit parçacık astarlarının tasarımı ve geliştirilmesi için bir çerçeve sunmaktadır.

Anahtar Kelimeler: Zırhlı Araç, Balistik Koruma, Parçacık Astarı, Fiber Takviyeli Kompozit, V_{50}.

GENİŞLETİLMİŞ ÖZET

Tarih boyunca, çatışma ve barışı koruma dönemlerinde hiçbir mekanizmanın önemini tekrarlayamayacağı şekilde, her canın korunmasının paha biçilmez olduğu çeşitli örneklerle kanıtlanmıştır. Savunma sektöründe beka kabiliyetini artırmaya yönelik stratejiler hem personeli hem de ekipmanı çeşitli potansiyel tehditlere karşı korumayı amaçlayan çok çeşitli taktiklerden oluşur. Modern savaşta, taktik manevraların operasyonel etkinliği üzerinde herhangi bir zararlı etkiyi önlemek için askerlerin ve yüksek hareket kabiliyetine sahip araçların yeterli ve etkili balistik koruma ile hazırlanması hayati önem taşımaktadır. Dünya çapındaki uluslar, rekabet avantajını korumak için yıllar boyunca araştırma ve geliştirme çabalarına önemli kaynaklar yatırmıştır. Hafif malzemelerin kullanımı, bileşenlerin mukavemetlerinden ödün vermeden daha düşük bir ağırlığa ulaşmalarını sağladıkları için savunma uygulamalarında çok önemlidir.

Balistik tehditlerin birincil sınıflandırması tipik olarak mermi ve parçalara odaklanır; ancak askeri personelin mermilerden ziyade parçacıklardan/şarapnelden kaynaklanan daha büyük bir riskle karşı karşıya olduğunu kabul etmek önemlidir. Bu ikincil mermiler füzeler, el bombaları, havan topları, top mermileri, mayınlar ve el yapımı patlayıcılar (EYP'ler) gibi bir dizi tehditten kaynaklanabilir ve platforma farklı saldırı açılarından çarparak bir şok dalgası oluşturur ve zırh malzemesinde penetrasyondan bağımsız olarak strese neden olur. Parçacık/şarapnel etkisinin önemi genellikle hafife alınmakta ve platformlardaki personel için önemli bir tehlike oluşturmaktadır. Ne yazık ki, birçok koruma sistemi bu etkileri göz ardı ederek yetersiz korumaya yol açmaktadır.

Balistik koruma, modern savunma sistemlerinde kritik bir rol oynamaktadır. Gelişen tehditler ve artan güvenlik ihtiyaçları, hafif ve yüksek performanslı malzemelere olan talebi artırmıştır. Parçacık astarları, zırhlı araçların iç kısımlarını kaplamak için kullanılan bir FRC malzemedir. Kullanım amacı, dış yüzeyde üst seviye bir tehditle karşılaşma sonucu oluşan parçalanma ile ilişkili tehlikeyi en aza indirmektir. Bu astarlar, bir balistik saldırı senaryosunda zırhın arkasından fırlayan şarapnel ve yüksek hızlı mermi parçalarının yanı sıra dış yapıya çarpan patlamaların neden olduğu sert parçacıklar gibi bir dizi tehlikeye karşı koruma sağlar.

Farklı özelliklere sahip çok çeşitli parçacık astarlarının varlığına rağmen, bunların kullanımı ve etkinliğine ilişkin derinlemesine teknik araştırmalar literatürde nispeten sınırlıdır. Bu sınırlı erişim, testlerle ilgili karmaşıklıklara ve askeri kuruluşlar ve savunma şirketleri tarafından tutulan bilginin gizli doğasına bağlanabilir. Parçacık astarının yaygın uygulamalarından biri, "Zırh Arkası Enkazının (BAD)" etkisini azaltarak zırhlı araç yolcularının korunmasını iyileştirmek için çelik, alüminyum ve titanyum gibi metalik hedeflerin arkasına yerleştirilmesi şeklindedir. Bir parçacık astarı'nın etkinliği, etkili parçaların sayısını azaltma ve üst-seviye bir tehdide yanıt olarak BAD bulutunun yayıldığı açıyı kontrol etme yeteneği ile ölçülebilir. Araç gövde zırhının iç tarafında bulunan parçacık astarı, nihai koruyucu katman olarak işlev görür. Bu temel unsur ikili bir amacı yerine getirir: ilk amaç, delme kapasitesi balistik eşiğe ulaştığında şarapnel ve/veya parçalanmış zırh

malzemesinin araca girmesini önlemektir. İkinci olarak ise, bir delicinin zırhın kapasitesini aşması durumunda, parçacık konisini önemli ölçüde azaltmayı amaçlar. Parçacık astarlarının etkinliği, mürettebatın hayatta kalma kabiliyetini artırmak ve öncelikle mürettebat bölmesindeki hasarları azaltmak için çok önemlidir. Bu nedenle, askeri araçların genel koruma ve güvenliğini arttırmak için parçacık astarlarının entegrasyonu esastır.

Mekanik testler, gelişmiş kompozitlerin gelişmesinde ve doğrulanmasında çok önemli bir rol oynamaktadır. Bu tür testler, malzemenin özellikleri ve çeşitli yükleme senaryoları altındaki davranışı hakkında değerli bilgiler sağlar ve böylece balistik koruma gibi uygulamaların katı gereksinimlerine uyulmasını garanti eder. Temel mekanik değerlendirmeler arasında çekme, basma, düzlem içi kesme ve eğilme mukavemeti testlerine ilişkin analizler yer almaktadır.

Bu çalışmanın birincil amacı, çarpma, parçalanma ve şok dalgası yayılımı gibi balistik etkilerin ikincil etkilerini azaltmada çok önemli olan yenilikçi bir kompozit parçacık astarı geliştirmektir. Bu, hafif ve uygun maliyetli bir yapıyı korurken, mekanik ve balistik deneylerin kullanılmasıyla gerçekleştirilecektir. Süreç, malzeme seçimi, kompozit tasarım ve üretim tekniğinin kapsamlı bir değerlendirmesini gerektirmektedir. Çalışma aynı zamanda balistik koruma için geliştirilen fiber takviyeli kompozit parçacık astarlarının gömleklerinin performansını da değerlendirmektedir. Çalışmanın temel amacı, farklı fiber tiplerinin, matris tiplerinin ve fiber hacim oranlarının balistik performans üzerindeki etkilerini araştırmaktır. Bu kapsamda epoksi, vinilester ve polyester matrisler ile karbon, cam ve aramid fiberler kullanılarak çeşitli kompozit numuneler hazırlanmış ve mekanik ve balistik testlere tabi tutulmuştur.

Parçacık kalkanı panel tasarımında, mekanik (4 mm) ve balistik (5 mm) testlere yönelik test numuneleri üretmek için gerekli katman sayısı, %40, %50 ve %60 teorik fiber hacim oranları (V_f) ile belirlenmiştir. Gerekli katman sayısı belirlendikten sonra, belirtilen numuneler için gerçek V_f, ilgili formülasyon kullanılarak hesaplanmıştır. Tasarlanan parçacık astarı panellerini planlanan V_f'ye mümkün olduğunca yakın üretmek için, her bir konfigürasyon için gerekli katman sayısı doğru bir şekilde belirlenmiştir. Katman sayıları kesinleştikten sonra, her bir konfigürasyona benzersiz bir numune numarası (ID) atanmıştır. Bu benzersiz numaralar, sonraki tüm test çalışmalarını raporlamak için tutarlı bir şekilde kullanılmış ve test süreci boyunca izlenebilirlik ve organizasyon sağlamıştır.

Parçacık astar paneli imalatında kullanılacak metal kalıp CATIA V5 Bilgisayar Destekli Tasarım (CAD) yazılımı kullanılarak tasarlanmıştır. Kalıp malzemesi olarak alüminyum alaşımı Al 5083 seçilmiştir. Kalıbın boyutları, 500x500 mm nihai numune boyutlarının üretimine izin verecek şekilde dikkatlice belirlenmiştir. Ayrıca, 4 mm ve 5 mm olmak üzere farklı kalınlıklarda numuneler üretmek için kalıp tasarımında maça plakalarının kullanımına uygun modifikasyonlar yapılmıştır. Daha sonra kalıp tasarımının bütünlüğünü ve üretim sürecindeki etkinliğini sağlamak için ANSYS Bilgisayar Destekli Mühendislik (CAE) yazılımı kullanılarak kapsamlı bir yapısal analiz gerçekleştirilmiştir.

Numuneler RTM yöntemi kullanılarak üretilmiştir. Bu yöntem, yüksek fiber hacim oranlarına ve üstün mekanik özelliklere sahip kompozitler üretmek için kullanılmaktadır. Kompozit parçacık astar panelleri %40, %50 ve %60 fiber hacim oranlarında üretilmiştir. Balistik test kuponları doğrudan kalıptan çıktığı gibi kullanılırken, mekanik test numuneleri 4x500x500 mm plakalardan su jeti kesim sistemi kullanılarak her test için belirtilen boyutlarda kesilerek elde edilmiştir. Su jeti kesiminin kullanılması, hassas test sonuçları elde etmek için gerekli olan numunelerdeki olası hasar veya değişiklik riskini daha da azaltmıştır.

Hazırlanan mekanik test numuneleri, Instron 8803 test cihazı kullanılarak ASTM D3039/D3039M standardına uygun olarak 2 mm/dak sabit kafa yer değiştirme hızında çekme testine tabi tutulmuş, böylece tutarlı gerilme hızları ve doğru çekme özelliği ölçümleri sağlanmıştır. Çekme testleri sonucunda, Karbon Fiber Takviyeli Epoksi (CFR-E) kompozitler en yüksek çekme mukavemetini sergilemiş, uzama azalmasına rağmen daha yüksek V_f ile önemli ölçüde iyileşmiştir. Aramid Fiber Takviyeli Epoksi (AFR-E) kompozitler, CFR-E'den daha düşük gerilme mukavemeti göstermiş, ancak daha yüksek V_f ile benzer şekilde artmıştır. Cam Fiber Takviyeli Epoksi (GFR-E) kompozitler en düşük çekme mukavemetine sahip olmasına rağmen artan V_f ile değerler iyileşmiştir. Vinilester matrisler için, Karbon Fiber Takviyeli Vinilester (CFR-V) kompozitler en yüksek çekme mukavemetine sahip olup ardından sırasıyla Aramid Fiber Takviyeli Vinilester (AFR-V) ve Cam Fiber Takviyeli Vinilester (GFR-V) kompozitler gelmektedir ve hepsi daha yüksek V_f ile gelişme eğilimi göstermiştir. Polyester matrislerde, Karbon Fiber Takviyeli Polyester (CFR-P) kompozitler yine en yüksek çekme mukavemetine sahipken, Aramid Fiber Takviyeli Polyester (AFR-P) ve Cam Fiber Takviyeli Polyester (GFR-P) kompozitler daha yüksek V_f ile aynı artan mukavemet eğilimini izlemiştir. Genel olarak, çekme mukavemeti tüm fiber türleri için daha yüksek V_f ile artmış, karbon fiber takviyeli numuneler en yüksek mukavemeti sağlamış, bunu aramid ve cam fiber takviyeli numuneler takip etmiştir.

Kayma testleri ASTM D3518/D3518M standardına göre Instron 8803 test cihazı kullanılarak gerçekleştirilmiştir. Sonuçlar, tüm fiber türleri için kesme mukavemetinin daha yüksek V_f ile arttığını göstermiştir. AFR, epoksi matrislerde kesme mukavemetinde en önemli artışı sağlamış, bunu sırasıyla CFR ve GFR izlemiştir. Vinilester ve polyester matrisler için de benzer eğilimler gözlenmiş, AFR kesme mukavemetinde en yüksek iyileşmeyi göstermiş, onu sırasıyla CFR ve GFR izlemiştir.

Basma testleri ASTM D6641/D6641M standardına göre Instron 5892 basma test cihazı kullanılarak gerçekleştirilmiştir. Sonuçlar, tüm fiber türleri için daha yüksek V_f ile basınç dayanımının arttığını göstermiştir. Sırasıyla CFR-E en yüksek basınç dayanımını sergilemiş, onu sırasıyla CFR-V ve CFR-P izlemiştir. GFR ve AFR kompozitler, daha yüksek V_f ile artan basınç mukavemeti ile benzer eğilimler göstermiştir.

Üç nokta eğme testleri ASTM D7264/D7264M standardına göre Instron 5982 test cihazı kullanılarak gerçekleştirilmiştir. Sonuçlar, tüm fiber türleri için eğilme mukavemetinin daha yüksek V_f ile arttığını göstermiştir. CFR-E en yüksek eğilme mukavemetini göstermiş, onu sırasıyla AFR-E

ve GFR-E izlemiştir. Benzer eğilimler vinilester ve polyester matrisler için de gözlenmiş, CFR kompozitler en yüksek eğilme mukavemetini gösterirken, bunu sırasıyla AFR ve GFR kompozitler izlemiştir.

Balistik testler, %50 penetrasyon olasılığını temsil eden V_{50} değerlerini belirlemek için gerçekleştirilmiştir. Balistik testler, kompozit numunelerin darbe enerjisi emme kapasitesini ve penetrasyon direncini değerlendirmek için kullanılır. Testler 7.62x51 NATO M80 mühimmatı kullanılarak gerçekleştirilmiştir. Balistik testler sonucunda aramid fiberler sürekli olarak en yüksek V_{50} balistik limitlerini sağlayarak aramid fiberlerin üstün enerji emilimini ve tokluğunu ortaya koymuştur. Bu, reçine türünden bağımsız olarak aramid fiberin üstün balistik performansını kanıtlamaktadır. Buna ek olarak, maksimum balistik performans elde etmek için en uygun konfigürasyon, aramid fiberler ve vinilester matris ile yüksek V_f olarak tanımlanmıştır. Bu kombinasyon sürekli olarak en yüksek V_{50}, en yüksek mekanik özellikler ve en az hasar miktarını sağlayarak üstün balistik dirence işaret etmektedir.

Bu çalışmada elde edilen sonuçlar, balistik uygulamalar için kompozit malzemelerin optimizasyonuna değerli bilgiler katmaktadır. Fiber tipi, matris tipi ve fiber hacim oranı arasındaki etkileşimi sistematik olarak analiz eden bu çalışma, zırhlı araçların ve personelin beka kabiliyetini artırabilecek gelişmiş kompozit parçacık astarlarının tasarımı ve geliştirilmesi için bir çerçeve sunmaktadır.

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SYMBOLS AND ABBREVIATIONS

3D : Three Dimensional
AEP : Allied Engineering Publication
AFR-E : Aramid Fiber-Reinforced Epoxy
AFR-P : Aramid Fiber-Reinforced Polyester
AFRP : Aramid Fiber-Reinforced Polymer
AFR-V : Aramid Fiber-Reinforced Vinylester
ASTM : American Society for Testing and Materials
A_w : Areal Density of Ply
BAD : Behind Armour Debris
CAD : Computer Aided Design
CFR-E : Carbon Fiber-Reinforced Epoxy
CFR-P : Carbon Fiber-Reinforced Polyester
CFRP : Carbon Fiber-Reinforced Polymer
CFR-V : Carbon Fiber-Reinforced Vinylester
CP : Complete Penetration
d : Thickness of Composite Spall Liner Panel
dB : Decibel
DOE : Design of Experiments
E_c : Compressive Modulus
E_f : Flexural Modulus
E-Glass : Electrical Grade Glass
E_t : Tensile Modulus
FMJ : Full Metal Jacket
FRC : Fiber Reinforced Composite
G : Shear Modulus
GFR-E : Glass Fiber-Reinforced Epoxy
GFR-P : Glass Fiber-Reinforced Polyester
GFRP : Glass Fiber-Reinforced Polymer
GFR-V : Glass Fiber-Reinforced Vinylester
GPa : Gigapascal
IED : Improvised Explosive Device
IR : Infrared
J : Joule
m/s : Meter per Second
MIL-STD : Military Standard

MPa : Megapascal

n : Number of Plies

NATO : North Atlantic Treaty Organization

OEM : Original Equipment Manufacturer

PP : Partial Penetration

RTM : Resin Transfer Moulding

S2-Glass : High-Strength Structural Grade Glass

STF : Shear Thickening Fluid

UD : Uni-Directional

UHMWPE : Ultra-High-Molecular-Weight Polyethylene

V_{01} : Velocity at which there is a 1% Probability of Penetration

V_{100} : Velocity at which there is a 100% Probability of Penetration

V_{50} : Velocity at which there is a 50% Probability of Penetration

V_{99} : Velocity at which there is a 99% Probability of Penetration

VARTM : Vacuum-Assisted Resin Transfer Moulding

V_f : Fiber Volume Fraction

V_{proof} : Proof Velocity

ZMR : Zone of Mixed Results

γ : Maximum Shear Strain

ε_f : Strain-to-Failure

ρ_f : Density of Fiber

σ : Standard Deviation

σ_c : Compressive Strength

σ_f : Flexural Strength

σ_t : Tensile Strength

τ : In-plane Shear Stress

1. INTRODUCTION

Throughout history, it has been demonstrated in various examples that the safeguarding of every life is invaluable, with no machine capable of replicating its significance during times of conflict and peacekeeping. Strategies intended to increase survivability within the defence sector consist of a diverse selection of tactics aimed at securing both personnel and equipment from a variety of potential threats. In modern warfare, it is vital that soldiers and highly mobile vehicles are prepared with adequate and efficient ballistic protection to prevent any detrimental impact on the operational efficacy of tactical maneuvers. Nations worldwide have invested substantial resources in research and development endeavors over the years to maintain a competitive edge. The utilization of lightweight materials is paramount in defence applications as they enable components to achieve a reduced weight without sacrificing their strength.

The importance of ballistic protection systems has grown significantly in the industry as a result of the increasing complexity and advancement of threats. With the continuous acceleration of global security issues, there is an increased demand for cutting-edge materials that can provide exceptional protection while maintaining the crucial characteristics of being lightweight and durability to ensure optimal operational efficiency.

1.1. Advances in the Defence Industry and Armoured Vehicles

The defence sector has observed significant technological advancement [Figure 1.1 (Anonymous 1)] in recent decades, primarily due to the increasing complexity and sophistication of global security challenges. These advancements encompass a range of areas, such as electronics, armaments, communication networks, and protective equipment. A significant development in this evolution is the emergence of advanced materials that offer improved performance characteristics. FRCs are considered a pivotal advancement, offering substantial improvements in terms of strength-to-weight ratios, durability, exceptional energy absorption capacities, and flexibility in design and application when compared to conventional materials.

The motivating factor driving advancements in defence technologies originates from the necessity to tackle emerging threats while enhancing the resilience and effectiveness of defence systems. Recent data indicates that global defence budgets have increased to around $1.98 trillion in 2023, reflecting a 2.6% rise from the previous year. This upward trend underscores the continuous investment in the development of state-of-the-art technologies to combat complex threats. Contemporary conflicts and security challenges demand materials that offer not only durable protection but also contribute to the agility and efficiency of military operations (Deloitte, 2023).

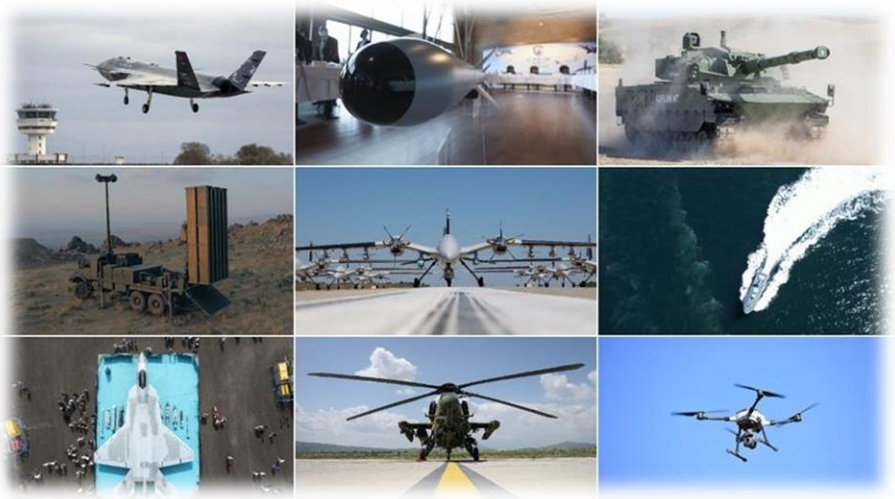


Figure 1.1. Scope and advancements in defence industry

Therefore, there is a consistent effort to develop materials that offer increased ballistic protection, upgraded mechanical properties, and reduced weight. FRCs, acknowledged for their advanced structural characteristics, have been a central focus in the quest for superior materials. As the defence sector prioritizes lightweight, high-strength solutions for ballistic protection, the ongoing progress in FRCs is set to redefine the standards for survivability and operational efficiency. The incorporation of high-performance fibers, nanomaterials, and advanced manufacturing methods is propelling the creation of next-generation ballistic protection systems that deliver superior safeguarding without sacrificing mobility or comfort. These advancements play a crucial role in addressing the changing threats encountered by military personnel and equipment in existing combat states.

Reinforced vehicles (Figure 1.2) have a significant impact on current defence tactics by functioning as mobile fortresses that guarantee the protection of both individuals and machinery in hostile surroundings. The key difficulty in constructing these vehicles is to maintain a balance between protection and mobility. Conventional materials such as steel and aluminum, although effective in offering ballistic resistance, often lead to vehicles that are excessively heavy and less maneuverable. This trade-off can restrict the operational flexibility and speed of military units. The embedding of fiber-reinforced composites in the development of armoured vehicles introduces a creative remedy to this obstacle. These composites are notably lighter than traditional metals, enabling the development of vehicles that combine high protection levels with agility. The exceptional tensile strength and energy absorption capacities allow them to effectively withstand ballistic impacts, thereby enhancing the survivability of the vehicles and their occupants. Moreover, the adaptability of composites allows for creative design approaches that can optimize the protective capabilities of armoured vehicles. By strategically arranging and aligning fibers, it becomes feasible to customize the mechanical properties of the composites for specific threat scenarios. This

customized approach increases the overall performance of the vehicles, ensuring their effective operation across various combat situations.

The distinctive characteristics of composites for military requirements are application-dependent and typically classified based on weight performance, multifunctionality, and part count reduction. In the context of vehicle applications, improvements in weight performance are counterbalanced with protection and payload considerations depending on the platform system and mission needs. The requirements of armoured vehicle systems and missions are steering the demand for strategic deployability and tactical mobility, both of which are enhanced by the utilization of lightweight composite materials.



Figure 1.2. Wheeled & tracked armoured vehicle examples

During the past twenty years, there has been a shift in research and development towards enhancing armoured vehicle technology with advanced composites. These measures have illustrated the capacity to achieve weight savings of up to 50% in vehicles, depending on factors such as design specifications, degree of part consolidation, and the integration of advanced composite materials. Despite these advancements, the widespread integration of composite technology into full-scale vehicle production has been blocked by concerns regarding production capacity. Currently, original equipment manufacturers (OEMs) in the automotive industry have initiated the integration of composite spall liners, add-on armour kits, and various structural components including hoods, fenders, and flooring to support weight reduction objectives. A further reduction in weight could be

achieved by integrating armour directly into the vehicle structure, a concept that has been validated by numerous technology supporters.

Table 1.1 provides a comprehensive analysis of the multifunctional performance enhancements observed in various applications of composite technology. For example, a composite vehicle achieved the necessary levels of ballistic protection comparable to an aluminum hull while simultaneously reducing weight by 27%. This improvement in ballistic survivability was mainly due to spall elimination and increased blast load capacity support. Additionally, the composite infantry fighting vehicle demonstrated significant mechanical advancements such as improved fatigue resistance, a noteworthy noise reduction of 5-10 dB, a substantial 67% decrease in heat and cooling losses, and reduced infrared, radar, and acoustic signatures (Ribeiro et al., 2021).

Table 1.1. Multifunctional performance improvements of FRCs

Criteria	Results & Remarks
Ballistics	> Equivalent ballistic protection at 27-35% reduced weight > Enhanced survivability by elimination of spall > Improved blast load capacity
Mechanical	> Noise reduction (5 - 10 dB) > Thermal reduction in heating/cooling loss (60 - 70%) > Reduced signature (IR, Radar, Acoustic) > Higher fatigue resistance
Life Cycle Cost	> Parts consolidation > Corrosion resistance > Enhanced damage tolerance and repairability

A further example was presented to demonstrate the feasibility of producing ground combat vehicles with reduced weight by using composite materials. The armoured vehicle not only fulfilled but also exceeded the operational criteria for a lightweight integrated structure and armour, strategic deployability, enhanced survivability, improved manufacturability, and cost-effectiveness. This vehicle functioned as a comprehensive display of utilizing composites and lightweight armours on a 22-ton vehicle suitable for air deployment by C-130/C-141 aircraft, focusing strongly on aspects such as manufacturability, repairability, non-destructive testing, and structural integrity. The combined weight of the vehicle's structure and armour was determined to be at least 33 percent lighter than comparable steel or aluminum configurations, depending on the selected payload options. The operational advantages of this vehicle were considerable, improving both deployability and survivability through the inherent decrease in signature offered by composite materials, the enhanced

agility from the vehicle's design, and the incorporation of structure and armour elements (Arris, 2021).

The last example of a composite vehicle study illustrated improved durability and potential weight reductions of up to 30% based on the payload requirements, all while upholding the essential protection and performance standards. The prototype of this composite tactical vehicle effectively employed structural composite technology in conjunction with a well-established manufacturing platform to showcase its versatility, longevity, and ability to withstand. The degree of weight reductions accomplished with each of these demonstration vehicles varied, depending on the level of composite material integration in their design. It was determined that even greater weight efficiencies could be achieved by originally conceiving the vehicle with composites in consideration, rather than adapting a metal-based design to include composite components (Li, Y., et al., 2023).

1.2. Survivability Strategy and Importance of Spall Liner

The primary classification of ballistic threats typically centers on bullets and fragments; however, it is essential to acknowledge that military personnel face a greater risk from fragments/spalls than from bullets. These secondary projectiles can originate from a range of threats such as missiles, grenades, mortars, artillery shells, mines, and improvised explosive devices (IEDs) impacting the platform from different attack angles, thereby generating a shockwave and inducing stress in the armour material, regardless of penetration. The significance of spall/fragments impact is often underestimated, presenting a considerable danger to the personnel within the platforms. Unfortunately, many protection systems disregard these effects, leading to inadequate protection. For example, historical documentation of ballistic casualties in prominent wars such as World War II, Korea, Vietnam, Israel, and the Falklands discloses that 59% of injuries were attributed to projectile fragments, 19% to bullets, and 22% to other factors. Moreover, casualties may occur due to secondary explosions, involving the ejection of debris and the destruction of various structures, vehicles, ships, and aircraft (Schmitt K., et al., 2019).

Over time, industry and military experts have recognized the inadequacy of relying solely on armour for protection against a variety of threats. As a result of this realization, supplementary systems have been developed to enhance protection. In recent years, numerous theoretical investigations have been carried out, with one study yielding the concept of the "Layered Survivability Concept" [Figure 1.3 (Anonymous 3)]. This concept introduces the idea of dividing armoured vehicle protection into five distinct "layers": "Don't Be There", "Don't Be Detected", "Don't Be Hit", "Don't Be Penetrated", and "Don't Be Killed". Each layer corresponds to different stages of enemy attack and necessitates the utilization of specific systems tailored to counteract various enemy actions. The first layer emphasizes the importance of avoiding being present in high-risk areas. Subsequently, if presence is unavoidable, the focus shifts to avoiding detection. If detection occurs, tactics must be employed to evade being hit. In the event of being hit, measures should be in place

to prevent penetration. Ultimately, if penetration does occur, the objective is to prevent fatalities. In the final phase of this concept, a critical aspect to consider is the utilization of spall liners, which are specifically designed to counteract the secondary consequences of ballistic impacts. These implications include spalling, fragmentation, and the propagation of shockwaves. The role of spall liners is essential in preventing secondary harm resulting from the detachment of material fragments from the interior surface of a vehicle subsequent to a ballistic attack. These liners play a vital role in protecting occupants by reducing the threat and consequences of spall generated by attacks that present a significant risk to the exterior surface.

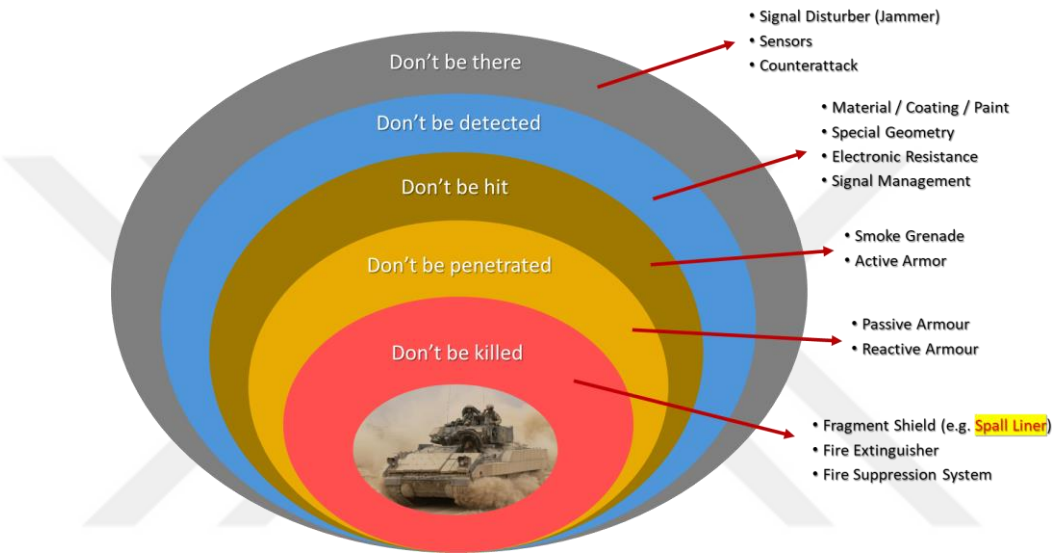


Figure 1.3. Layered survivability concept

Spall liners are composed of a FRC material utilized for lining the interiors of armoured vehicles. The purpose is to minimize the danger associated with spall generated by encounters with a dominant threat on the external surface. These liners offer safeguarding against a range of dangers, such as armour splinters discharged from the armour's rear in a ballistic scenario, as well as rigid splinters and fragments caused by explosions impacting the exterior structure, in addition to high-speed projectile fragments.

Despite the presence of a wide variety of spall liners with varying characteristics, in-depth technical research regarding their utilization and effectiveness is relatively limited in the public domain. This scarcity can be attributed to the complexities associated with testing and the confidential nature of the knowledge held by military entities and defence companies. One common application of spall liners is their positioning behind metallic targets like steel, aluminum, and titanium to improve the protection of armoured vehicle occupants by reducing the impact of "Behind Armour Debris (BAD)." The efficiency of a spall liner can be measured by its ability to decrease the number of effective fragments and control the angle at which the BAD cloud is emitted in response to an overmatch threat. Figures 1.4 and 1.5 provide a visual representation of the overmatch threat,

the integration of spall liners into armoured vehicles, and the protective mechanisms with and without the spall liners, respectively.

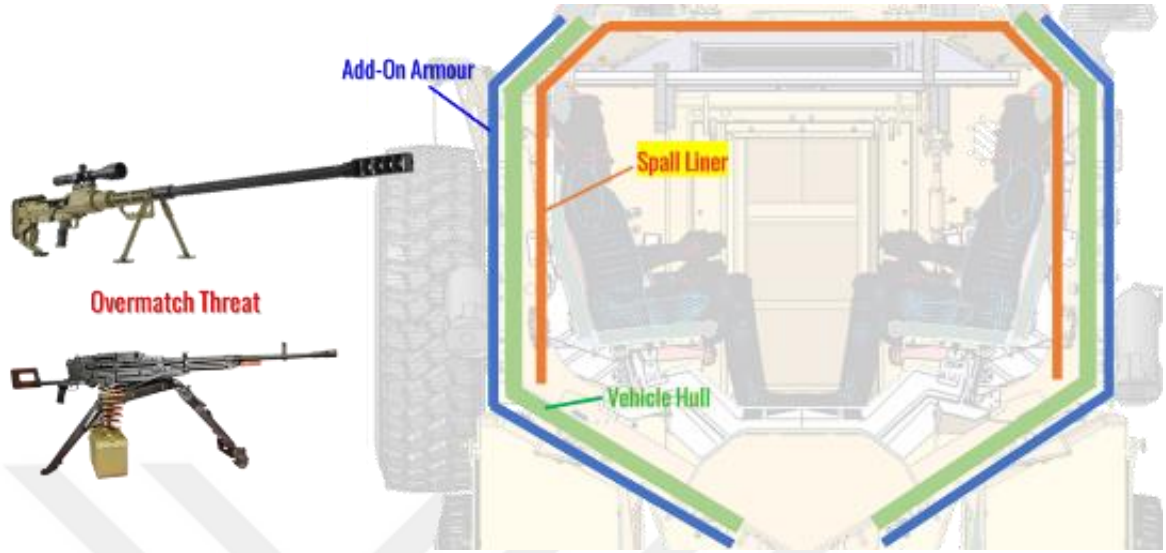


Figure 1.4. Schematic representation of overmatch threat & spall liner integration

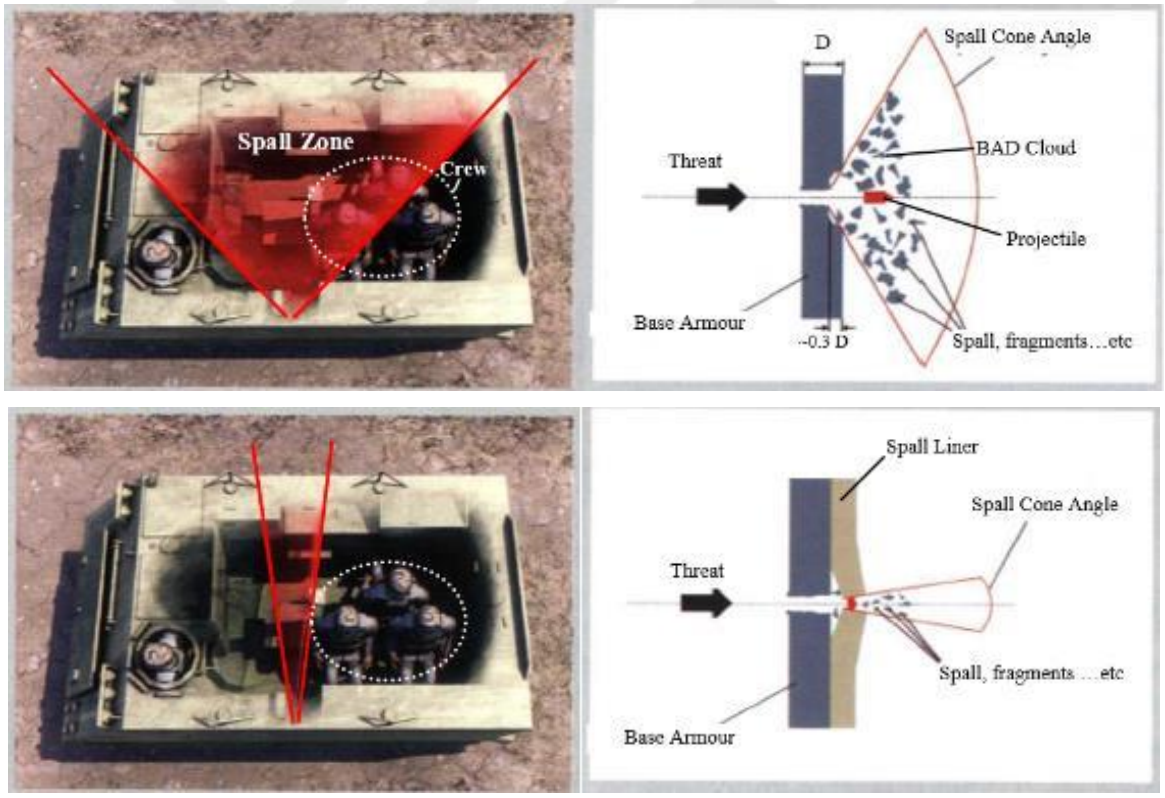


Figure 1.5. Protection phenomena with and without spall liner

The spall liner, located on the inner side of the base armour, functions as the ultimate protective layer. This essential element fulfills a dual purpose: firstly, its purpose is to prevent penetrator splinters and/or spalled armour material from entering the vehicle when the penetration capacity reaches the ballistic threshold. Secondly, should a penetrator surpass the armour's

capabilities, the spall liner aims to notably reduce the splinter cone. The effectiveness of spall liners is crucial for improving crew survivability and reducing damages primarily within the crew compartment. Therefore, the integration of spall liners is essential for enhancing the overall protection and safety of military vehicles.

1.3. Advanced Composite Design

Fiber Reinforced Composite (Figure 1.6) materials are composed of various layers of fibers, such as glass, aramid, carbon, etc. - as illustrated in Table 1.2, that demonstrate high strength and modulus. These fibers are either incorporated into or bonded to a matrix, for example, polyester, epoxy resin, etc. - as detailed in Table 1.3, with well-defined interfaces (boundaries) between them. Within this configuration, both the fibers and the matrix maintain their individual physical and chemical properties, yet collectively they exhibit a unique combination of characteristics that cannot be achieved by each component alone. Typically, the fibers serve as the primary load-bearing elements, while the matrix is responsible for maintaining their positioning and alignment, serving as a medium for transferring loads between them, and offering protection against environmental factors like high temperatures and humidity. FRCs have emerged as significant materials due to their lightweight nature, high specific stiffness, exceptional specific strength, impressive fatigue resistance, and remarkable corrosion resistance in comparison to various common metallic alloys. Moreover, FRCs provide benefits such as the capacity to customize directional mechanical properties, low thermal expansion attributes, and superior dimensional stability. The exceptional combination of physical, thermal, and mechanical properties makes composites a compelling alternative to metals in numerous applications, especially when weight reduction is a critical factor. Although FRCs have a historical background in the defence sector tracing back to the 1960s, the exploration of their efficacy for ballistic protection has experienced a surge in recent times, driven by advancements in high-performance fiber materials (Matei et al., 2024).

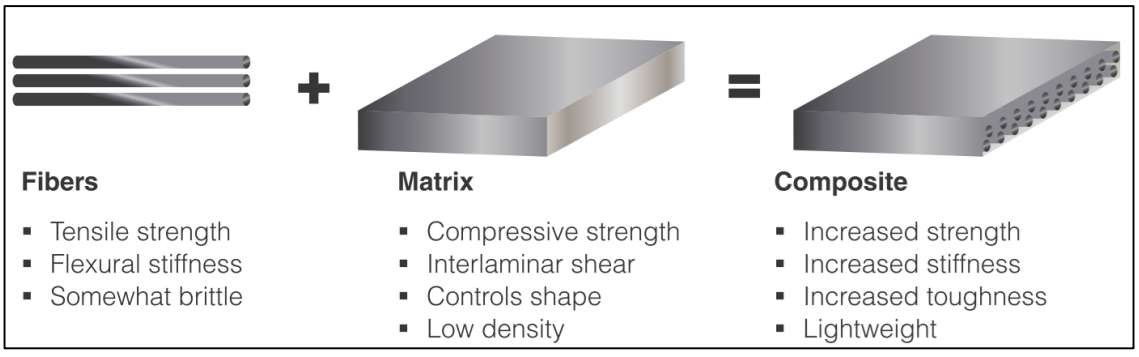


Figure 1.6. Generic representation of FRCs

FRCs can be designed in advance to meet the performance standards of a structure before the production process begins. This unique approach is made possible by the ability to achieve

desired characteristics through the selection of suitable design parameters, without any mutual influence or impact on other properties. Unlike traditional metallurgical methods, where properties are interconnected, making it difficult to modify one property without repercussions on others. In the past three decades, this specific field has made significant progress, mainly driven by the convergence of various material options and the growing need for innovative lightweight materials. A wide range of new polymeric resins and high-quality reinforcing fibers have been introduced to the market to enable the development of lightweight, high-performance materials designed for applications in the defence sector.

The precise methodology involved in the design of FRCs requires a comprehensive evaluation of various factors such as material properties, fiber arrangement, layering techniques, and more, as illustrated in Figure 1.7. The selection of different materials for the array holds great importance as it plays a vital role in determining the overall behaviour and effectiveness of the intricate structure. The manufacturing method and process parameters have a significant impact on the final performance of the composite, emphasizing the need for careful consideration and adjustment during their selection.

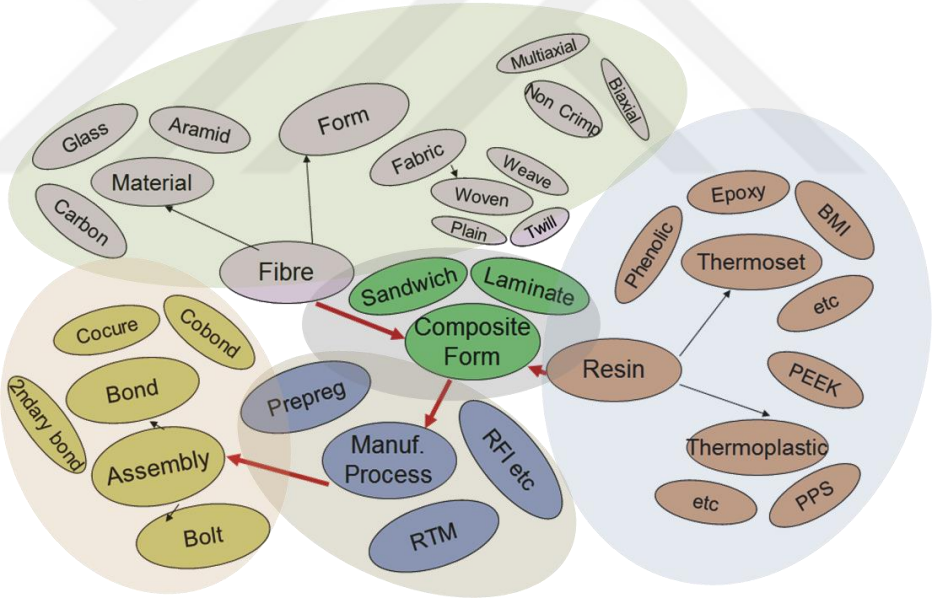


Figure 1.7. Complexity of FRCs design

Table 1.2. Properties of important high-strength fibers

Property	Carbon	Aramid	Glass
Tensile Strength	Good	Moderate	Moderate
Tensile Modulus	Good	Moderate	Poor
Compressive Strength	Good	Poor	Moderate
Compressive Modulus	Good	Moderate	Poor
Flexural Strength	Good	Poor	Moderate
Flexural Modulus	Good	Moderate	Poor
Impact Strength	Poor	Good	Moderate
In-Plane Shear Strength	Good	Moderate	Good
Low Density	Moderate	Good	Poor
Fatigue Resistance	Good	Moderate	Poor
Fire Resistance	Poor	Good	Good
Thermal Insulation	Poor	Good	Moderate
Electrical Insulation	Poor	Moderate	Good
Low Thermal Expansion	Good	Good	Good
Low Cost	Poor	Poor	Good

Table 1.3. Main thermosetting resin for defence applications

Resin Type	Advantages	Disadvantages
Polyester	• Low cost • Easy to process • Room temperature curing • Moisture resistant	• Flammable • Low mechanical properties • High styrene emissions • Low operating temperature
Vinylester	• Medium cost • Low viscosity • Good mechanical properties • Chemical resistant	• Flammable • High styrene content • Low operating temperature
Phenolic	• Medium cost • Non-Flammable • Good mechanical properties	• Toxic ingredients • Difficult to process • Can be brittle
Epoxy	• Excellent mechanical properties • Good mechanical resistance • High operating temperatures • Low cure shrinkage	• Expensive • Critical mixing • Corrosive handling • High processing temperatures

One of the intrinsic benefits of FRCs is their capability to adapt to specific applications by utilizing inventive design approaches. By adjusting the orientation of fibers and layering configurations, designers can effectively enhance the mechanical characteristics of the composites to meet the demands of various threat scenarios. For example, aligning fibers in a unidirectional manner may significantly enhance strength in a specific direction, while utilizing multidirectional alignments could offer a more uniformly distributed array of characteristics across various axes.

The alignment of filaments primarily influences the improvement of mechanical properties in a specific direction, thus enhancing the overall effectiveness of the material. In contrast to classical metallic materials, composites exhibit elasticity up to the point of rupture and are incapable of undergoing local plastic deformation. Additionally, composites are recognized for their outstanding resistance to fatigue, making them highly durable when subjected to repeated loading conditions. A comparison in Figure 1.8 (Daniel G., 2003) illustrates the differences among various materials, assisting in the selection of composite materials in the initial design stage. The comparison presented in Figure 1.8 evaluates different materials based on their volume weight, tensile strength, and tensile modulus, with a special focus on composite materials. Composite materials occupy an intermediate position in terms of weight, positioned between wood and metals like steel and aluminum. FRCs demonstrate significantly increased tensile strength in comparison to wood and plastics, approaching the levels seen in advanced materials like titanium and light alloys. This enhanced strength is particularly crucial for applications requiring materials capable of enduring significant stress. Furthermore, FRCs manifest impressive tensile modulus values, signifying stiffness and resistance to deformation under load, which are indispensable qualities in industries such as aerospace, automotive, and defence. Despite having lower density compared to metals, composite materials achieve a harmonious combination of superior strength and reduced weight, making them well-suited for structural elements where enhanced performance and efficiency are achieved through weight reduction. When combined with carbon or aramid fibers, FRCs demonstrate superior tensile strength and modulus compared to traditional materials. These high-performance FRCs play a pivotal role in high-stress applications, offering superior impact resistance and reduced weight. The ability to tailor composite characteristics by incorporating different fibers and matrices enhances their effectiveness in a wide range of engineering disciplines.

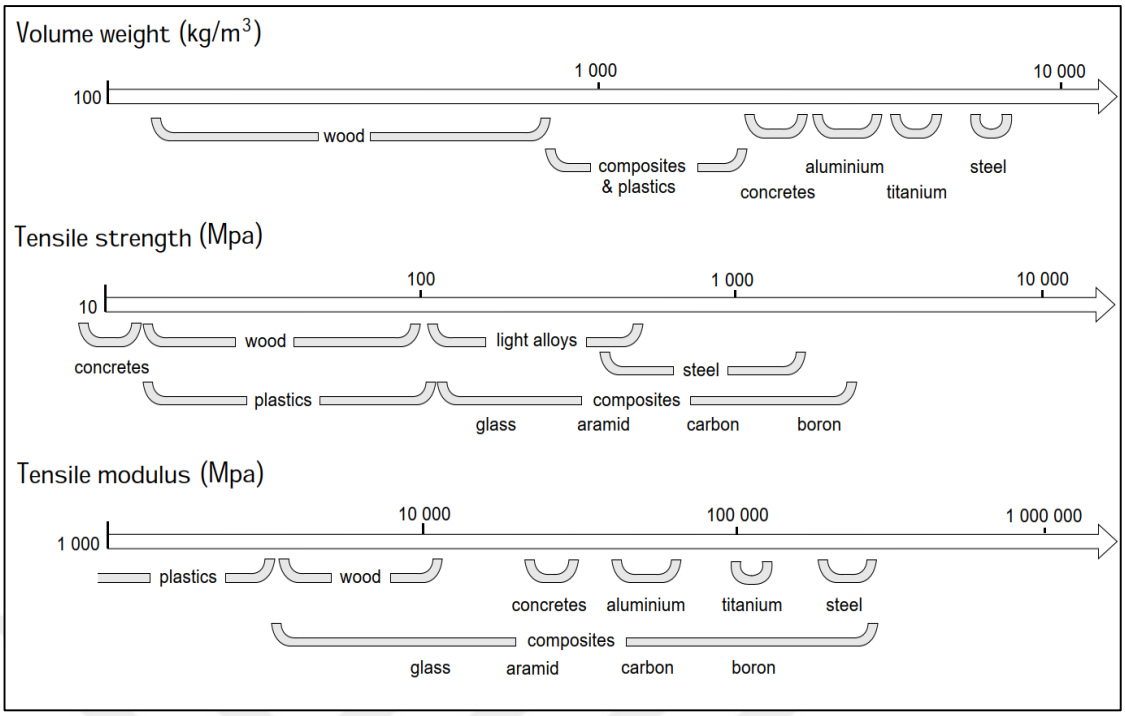


Figure 1.8. Comparison of characteristics of different materials

Moreover, Figure 1.9 (Daniel G., 2003) allows for the comparison of key specific characteristics of fibers utilized in the plies, emphasizing the specific modulus and strength to highlight the attributes of lightweight materials. The chart depicts the specific modulus and tensile strength of different materials, like aluminum alloys, E glass, Kevlar 49, high-strength carbon, high-modulus carbon, and boron. Specific modulus indicates the relationship between modulus of elasticity and density, while specific tensile strength is described as the relationship between tensile strength and density. In contrast to advanced composites, aluminum alloys exhibit lower specific modulus and tensile strength. E-glass exhibits exceptional characteristics in contrast to aluminum, which renders it appropriate for applications necessitating elevated rigidity and strength-to-weight proportions. Kevlar 49, recognized as an aramid fiber, displays significantly higher specific tensile strength, making it suitable for uses such as ballistic protection and aerospace components. The specific modulus and tensile strength of high-strength carbon fibers exceed those of other materials, leading to widespread use in the aerospace, automotive, and sporting goods sectors. The highest specific modulus can be found in high-modulus carbon fibers, rendering them suitable for applications with limited tolerance for deformation, such as precision instruments. While less common, boron fibers exhibit the highest specific modulus and tensile strength, proving to be beneficial for specialized applications despite their higher cost. On the whole, FRCs such as Kevlar 49, high-strength carbon, and high-modulus carbon shine above traditional materials, providing superior performance in weight-sensitive applications.

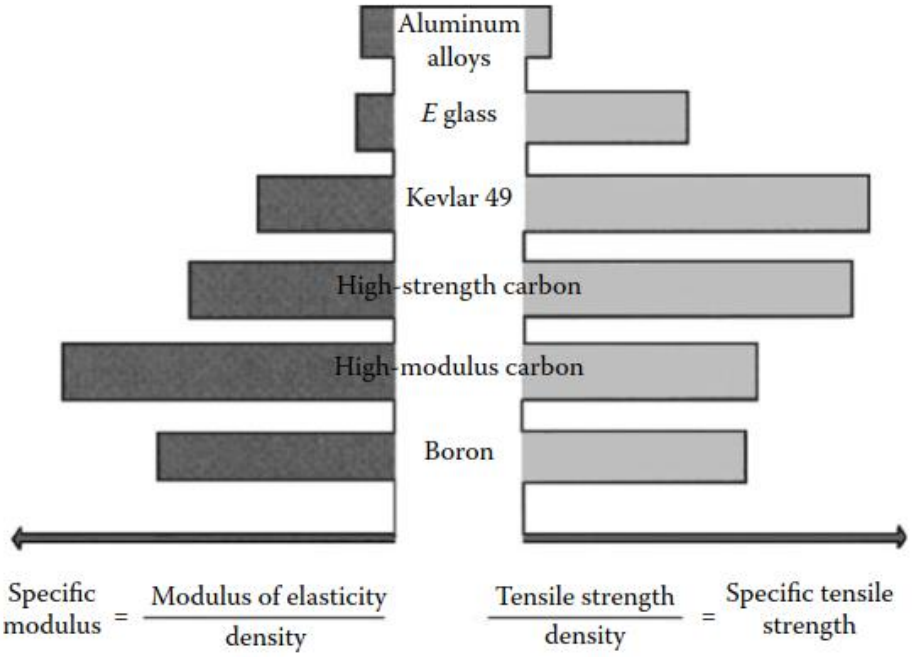


Figure 1.9. Specific characteristics of different fibers

When considering the development of cutting-edge composite materials, it is vitally important to consider a range of safety factors to ensure the reliability and efficiency of the final product. These considerations play a crucial role in minimizing any potential uncertainties and risks that may arise from the mechanical properties of the material and the overall design process. The safety factors are specifically formulated to address uncertainties related to various key aspects: i) the exact mechanical properties of both the reinforcement and matrix, ii) the presence of stress concentrations, iii) any imperfections in the calculation assumptions, iv) the complexities of the fabrication process, and v) the effects of material deterioration. In practice, these safety factors are typically categorized based on their respective levels of importance and impact, as detailed in Table 1.4 (Daniel G., 2003) provided below for reference and guidance.

Table 1.4. Safety factors for different applications

Type of Composite		**Factor of Safety**
High Volume Composites		
Static Loading	short duration	**2**
	long duration	**4**
Intermittent Loading over Long Term		**4**
Cyclic Loading		**5**
Impact Loading		**10**
High Performance Composites		**1.3** to **1.8**

1.4. Mechanical Tests of Advanced Composites

When high-strength composites were initially introduced in the 1960s, the testing methodologies employed reflected those utilized for homogeneous and isotropic metals. Nevertheless, given the nonhomogeneous (layered) and anisotropic (orthotropic) properties of composite materials, it became essential to develop specialized testing procedures to accurately evaluate their characteristics. Additionally, as the early advancement of composites was predominantly limited to aerospace companies, each firm established its individual testing protocols. Consequently, standardized testing methods for composites were established. The American Society for Testing Materials (ASTM) stands out as one of the most prominent organizations with established test standards in this particular field.

Mechanical testing plays a crucial role in the progression and validation of advanced composites. Such tests provide valuable information regarding the characteristics of the material and its behaviour under various loading scenarios, thereby guaranteeing adherence to the stringent requirements of applications like ballistic protection. Key mechanical assessments encompass analyses on tensile, compressive, and flexural strength, in addition to impact and fatigue testing [Figure 1.10 (Hexcel, 2005)].

Tensile testing is a fundamental method employed to assess the composite material's resistance to external forces attempting to induce separation within its structure, thereby providing invaluable insights into its strength and deformability characteristics. Conversely, compression testing serves as an essential technique aimed at analyzing the material's reaction when subjected to compressive forces, playing a pivotal role in elucidating its performance under protective conditions. Furthermore, flexural testing constitutes a critical examination that delves into the composite's capacity to endure bending stresses, furnishing indispensable information regarding its inherent stiffness and resistance to deformation. Impact testing holds particular significance in ballistic protection applications as it replicates the effects of high-velocity impacts on the composite materials. This particular test serves the purpose of assessing the energy absorption capacity of the material as well as its ability to resist penetration and spalling. In contrast, fatigue testing involves a detailed examination of the composite's durability and longevity when subjected to cyclic loading conditions, thereby ensuring its reliability over extended periods of use.

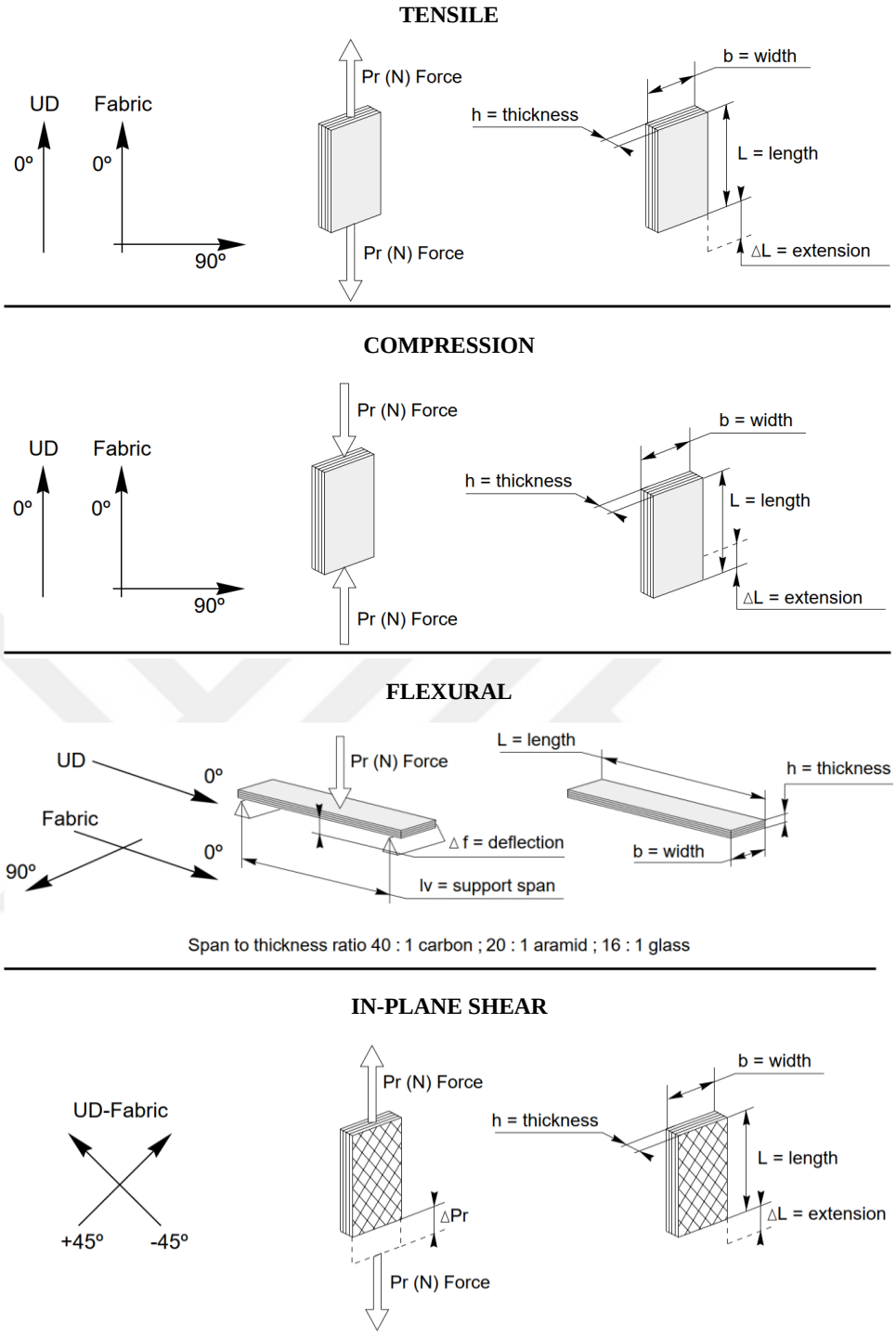


Figure 1.10. General specimen test configurations for mechanical tests

1.5. Ballistic Test of Advanced Composites

When attempting to understand armour materials or innovate new ones, there is no better starting point than conducting a reasonable ballistic impact test with an actual projectile. However, the chaotic conditions of modern battlefields present significant obstacles in obtaining an updated assessment of the current threats and establishing a defined threat spectrum against which armour technologists and engineers can design an appropriate armour system. The complexity of this challenge is further heightened by the necessity to navigate the varied and dynamic nature of contemporary combat scenarios. The ballistic test process is crucial in evaluating the protective properties of advanced composites. It involves subjecting materials to controlled impacts to assess their resistance to penetration, spalling, and fragmentation. Findings from these tests provide vital data on the performance of spall liners, aiding in the improvement of material composition and structural design for enhanced protection capabilities.

Among the various test methodologies that exist, the V_{50} (ballistic limit) test is distinguished as the most valuable, practical, and relevant technique, thus explaining its enduring popularity. Displayed in Figure 1.11 are standard probability curves illustrating the penetration characteristics of armour materials. As the velocity increases gradually from zero, the frequency of projectiles penetrating the target increases progressively until a certain velocity threshold is reached, at which point all projectiles breach the armour. Typically, the chance of defeat can be portrayed by a normal distribution, with the scope of probabilities shown by a standard deviation, symbolized as σ. The zone recognized as the zone of mixed results (ZMR) includes the span from V_{01} at -3σ to V_{99} at +3σ, incorporating a wide array of potential outcomes. Importantly, the population median, denoted by V_{50}, corresponds with the mean in a normal distribution, highlighting its importance in statistical analysis (Crouch, I. G., 2016).

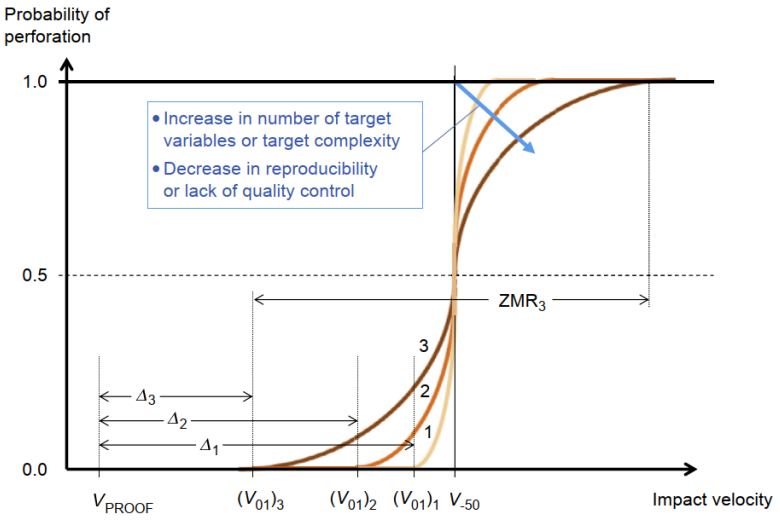


Figure 1.11. A set of probability curves for the defeat of armour materials

Various methodologies are employed in the development of these probability curves. It is crucial to ensure accurate measurement of V_i, which signifies the impact velocity. Ideally, a V_{50} calculation should involve a considerable number of shots, with at least four shots necessary for accuracy. Typically, six to eight shots are used in practice, with up to 12 rounds preferred for a more precise and representative V_{50}. A higher number of shots results in a more accurate V_{50} measurement. The probit method involves conducting 10 shots for each velocity value ranging from V_{01} to V_{50}. Each velocity increment provides the failure percentage, contributing to a point on the probability curve. While this approach offers a theoretically precise curve, it requires a significant amount of ammunition and range time for implementation.

The fundamental principle of ballistic limit testing is centered on the concept that a specific armour plate contains a range of results within a relatively narrow velocity span. All projectiles are expected to be stopped by the armour below a designated velocity threshold known as V_{proof}, as depicted in Figure 1.11. When 10 shots are fired at $V=V_{proof}$, it is predicted that all projectiles will be effectively stopped. Conversely, beyond a slightly higher velocity identified as V_{100}, all projectiles are expected to penetrate the target. In a scenario where $V = V_{100}$, out of 10 shots, all are expected to result in perforation. Between V_{proof} and V_{100}, a combination of results is expected, where some projectiles are stopped by the armour while others penetrate. It is worth noting that both "MIL-STD-662F" and "NATO AEP-2920 Edition A" provide specific guidelines regarding velocity adjustments for subsequent firings, along with additional pertinent details.

The progress in ballistic testing facilities and methodologies has been essential in improving the effectiveness and reliability of ballistic protection solutions. The use of high-speed cameras, specialized equipment, and diagnostic instruments has enabled a thorough examination of how materials react to ballistic impacts, providing valuable insights into the processes of energy absorption and dissipation, as depicted in Figure 1.12 (NATO AEP-55 Volume 1, 2014). This data plays a critical role in refining the design and performance of composite spall liners, ensuring that they deliver optimal protection levels in real-world scenarios.

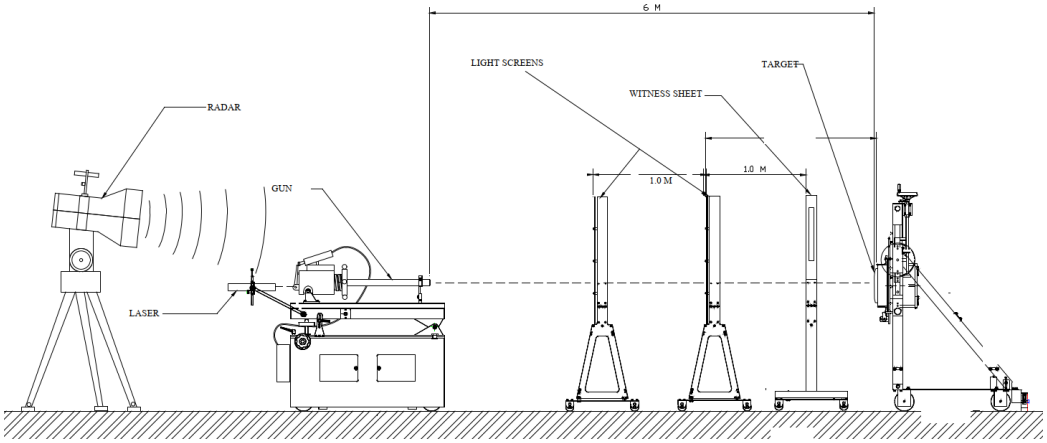


Figure 1.12. Typical ballistic testing arrangement

1.6. Research Objectives

Ballistic protection materials, such as metals and ceramics, often come with restrictions in terms of both weight and flexibility. Despite their admirable resistance to penetration, their unwieldy characteristics may hinder mobility and amplify the overall load of protective systems. Nonetheless, FRCs offer a more lightweight option without sacrificing the efficacy of protection. Furthermore, the continuously evolving landscape of threats necessitates a persistent pursuit of innovation in the field of material science to ensure that protective measures remain capable of mitigating new and emerging forms of ballistic hazards. The primary goal of this study is to establish a correlation that bridges the gap between the current functionalities of materials and the upcoming requirements of safeguarding mechanisms while analyzing advanced composite materials.

Understanding the intrinsic characteristics of FRCs and their reaction to ballistic impact is crucial in the progression of effective spall liners. The process of selecting fibers, the characteristics of the matrix, the dynamic interaction between these components, and the percentage of fiber volume all play a crucial role in clearly defining the efficacy of these materials in delivering protective capabilities. It is imperative to delve into the intricate details of these factors to enhance the performance and reliability of spall liners in various applications.

The primary objective of this study is to develop an innovative FRC spall liner, which is crucial in reducing the secondary effects of ballistic impacts like spalling, fragmentation, and shockwave propagation. This will be accomplished through the utilization of mechanical and ballistics experiments demonstrating exceptional ballistic performance, all while maintaining a lightweight and cost-effective nature. The process entails a thorough evaluation of material selection, composite construction, and fabrication techniques. Simultaneously, a secondary aim is to investigate a method to expedite this procedure and reduce costs, leveraging mechanical testing to efficiently and economically achieve this goal. This could potentially lead to significant advancements in the field of ballistic protection technology.

The specific objectives of the study include;

- studying the mechanical properties of different FRC design alternatives to identify the most efficient ones,
- evaluating the performance of different spall liner designs in withstanding ballistic impacts through a series of meticulous examinations, and
- integrating advanced materials and methodologies to enhance the overall effectiveness and functionality of the spall liners.

The investigation of FRC spall liners for ballistic protection represents a pivotal area of research with significant implications for the defence industry. The utility of these materials extends

beyond military uses to encompass civilian domains like aerospace, law enforcement, personal protective gear, and the protection of essential infrastructure.

2. PRELIMINARY WORK

2.1. Development of Advanced Ballistic Composites

Rajeshkumar and Manikandan (2020) evaluated the ballistic performance of natural fiber-reinforced composite laminates for potential use in protective applications. Natural fibers such as jute and flax were embedded in a polymer matrix to fabricate the composite laminates using hand lay-up and compression molding techniques. Ballistics tests were conducted using a gas gun to fire 7.62 mm projectiles at the composite targets with an impact velocity of approximately 850 m/s. High-speed cameras captured the impact events, and the damage mechanisms were analyzed. The results showed significant energy absorption capabilities by the natural fiber-reinforced composites. The jute fiber composites absorbed up to 150 J of energy, reducing the penetration depth of the projectiles by 30%. In comparison, the flax fiber composites absorbed around 120 J of energy.

Pandya, Parmar, and Sharma (2020) summarized the recent advancements in hybrid composites used for ballistic applications and investigated the effects of hybridization on their ballistic performance. Various hybrid composites combining different fibers such as carbon, glass, and aramid were discussed, along with their performance in ballistics tests. Techniques like Vacuum-Assisted Resin Transfer Molding (VARTM) and autoclave curing were used to fabricate the hybrid composites. Ballistic impact tests were conducted using standard military projectiles with impact velocities ranging from 500 to 900 m/s. High-speed cameras and post-impact examination were used to analyze the energy absorption, penetration depth, and damage patterns. The review highlighted that improved ballistic performance was offered by hybrid composites compared to single-fiber composites. For instance, a hybrid composite with 60% carbon and 40% aramid fibers demonstrated a 25% increase in energy absorption, reaching values up to 220 J, compared to pure carbon fiber composites. The combination of high-strength fibers like carbon with tough fibers like aramid enhanced energy absorption and resistance to penetration, making hybrid composites highly effective for ballistic protection due to their balanced properties.

Sarasini et al. (2018) investigated the impact behaviour of Carbon Fiber-Reinforced Polymer (CFRP) composites for use in ballistic protection systems. Different lay-up configurations, including unidirectional and cross-ply arrangements, were used to fabricate the CFRP composites using vacuum bagging and autoclave curing. High-velocity impact tests were conducted using a ballistic pendulum setup to measure the energy absorption and damage tolerance of the composites. Projectiles with a diameter of 7.62 mm were fired at velocities of approximately 900 m/s. The results indicated that higher energy absorption, approximately 180 J, was exhibited by CFRP composites with cross-ply lay-up configurations compared to unidirectional lay-up configurations, which absorbed around 140 J. The cross-ply composites demonstrated better ballistic performance, with less penetration depth and more distributed damage. The primary failure mechanisms included fiber breakage, matrix cracking, and delamination.

In the study conducted by Asim and Ahmed (2021), the performance of aramid fiber-reinforced composites for use in ballistic armour applications was evaluated. Aramid fibers and a thermosetting resin were used to fabricate the composites through a VARTM process. Ballistics tests were conducted using 9 mm and 7.62 mm standard ammunition to assess the protective capabilities of the composites. The impact velocities were maintained at approximately 400 m/s and 850 m/s, respectively. High-speed cameras and post-impact analysis were used to study the damage mechanisms and energy absorption. Excellent ballistic resistance was demonstrated by the aramid fiber composites, with an average energy absorption of 220 J for 9 mm projectiles and 280 J for 7.62 mm projectiles. Minimal deformation and high resistance to penetration were shown by the composites, with primary failure modes being fiber breakage and matrix cracking.

Rajasekaran et al. (2019) investigated the ballistic impact resistance of Glass Fiber-Reinforced Polymer (GFRP) composites for potential use in protective applications. Different fiber orientations, including unidirectional and woven configurations, were used to manufacture the GFRP composites, along with various resin systems. The composites were fabricated using hand lay-up and vacuum bagging techniques. Ballistic impact tests were performed using a gas gun to fire 7.62 mm projectiles at the composite samples with an impact velocity of approximately 850 m/s. The damage and energy absorption were analyzed using high-speed cameras and post-impact examination. The GFRP composites with woven fiber orientation exhibited higher impact resistance, absorbing up to 160 J of energy, compared to unidirectional fiber orientation, which absorbed around 130 J. The choice of resin system also significantly influenced the ballistic performance, with epoxy-based GFRP composites performing better than polyester-based ones.

In the research conducted by Maheswaran and Venkatesan (2018), the dynamic response of Kevlar fiber-reinforced composites when subjected to ballistic impact was investigated, aiming to enhance their use in protective applications. Kevlar fiber composites were fabricated using a hand lay-up process followed by vacuum bagging and autoclave curing. Ballistic impact tests were conducted using 7.62 mm projectiles fired at a velocity of approximately 900 m/s. High-speed cameras were used to capture the deformation and failure mechanisms during impact. Post-impact analysis included examining the damage patterns and measuring the energy absorption. Excellent energy absorption, with values up to 200 J, and high resistance to ballistic impact were demonstrated by the Kevlar composites. The primary failure mechanisms observed were fiber pull-out, matrix cracking, and delamination. Minimal back-face deformation and high energy absorption efficiency was exhibited by the composites.

Ramakrishna and Mayer (2015) compared the ballistic performance of different hybrid composites designed for protective applications, aiming to identify the most effective combinations of fibers. Hybrid composites combining carbon, glass, and aramid fibers were fabricated using VARTM and autoclave curing. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 900 m/s. High-speed cameras and post-impact analysis were used to

evaluate the performance based on energy absorption, penetration resistance, and damage patterns. Superior ballistic performance compared to single-fiber composites was demonstrated by the hybrid composites. For instance, a hybrid composite with 50% carbon and 50% aramid fibers absorbed up to 250 J of energy, while single-fiber composites absorbed around 180 J. The combination of different fibers provided a balance of strength, toughness, and energy absorption, resulting in reduced penetration depth and distributed damage.

Thakur and Thakur (2014) evaluated the ballistic resistance of hybrid composites made from natural and synthetic fibers for potential use in protective applications. Hybrid composites were fabricated using a combination of natural fibers (jute, sisal) and synthetic fibers (carbon, Kevlar) through hand lay-up and vacuum bagging techniques. Ballistics tests were conducted using 9 mm and 7.62 mm projectiles fired at velocities of approximately 400 m/s and 850 m/s, respectively. High-speed cameras and post-impact analysis were used to assess the performance based on energy absorption, penetration depth, and damage patterns. Enhanced ballistic resistance was exhibited by the hybrid composites, with energy absorption values up to 170 J for 9 mm projectiles and 220 J for 7.62 mm projectiles. The combination of fibers improved energy absorption and damage tolerance, with primary failure modes being fiber breakage, matrix cracking, and delamination.

In the study conducted by Alderliesten (2008), the ballistic performance of Fiber-Metal Laminate composites (FMLs) for protective applications was investigated, aiming to leverage the benefits of both fiber and metal layers. FMLs were fabricated using layers of fiber-reinforced polymers (carbon, glass) and metal sheets (aluminum, titanium) through hand lay-up and autoclave curing. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 900 m/s. High-speed cameras and post-impact analysis were used to evaluate the impact resistance and energy absorption capabilities of the composites. Excellent ballistic performance was shown by the FMLs, with the metal layers providing additional protection and the fiber layers absorbing up to 190 J of impact energy. The combination of fiber and metal layers resulted in reduced penetration depth and distributed damage.

Faruk et al. (2012) developed eco-friendly ballistic composites using natural fibers, aiming to create sustainable alternatives for protective applications. Natural fibers such as flax and hemp, combined with a biodegradable resin, were used to fabricate the composites through hand lay-up and vacuum bagging techniques. Ballistics tests were performed using 9 mm and 7.62 mm projectiles fired at velocities of approximately 400 m/s and 850 m/s, respectively. High-speed cameras and post-impact analysis were used to assess the impact resistance and energy absorption of the composites. Promising ballistic performance was demonstrated by the eco-friendly composites, with energy absorption values up to 150 J for 9 mm projectiles and 200 J for 7.62 mm projectiles. The primary failure mechanisms included fiber breakage, matrix cracking, and delamination.

Brown and Hu (2012) investigated the use of shear thickening fluids (STFs) in enhancing the performance of fiber-reinforced spall liners. Various STFs were integrated with high-

performance textiles such as Kevlar and Twaron, and the spall liners were fabricated using vacuum infusion techniques. Ballistics tests were conducted using a gas gun to fire 7.62 mm projectiles at velocities of 850 m/s. High-speed cameras captured the impact events, and post-impact analysis included examining the deformation and energy absorption. The ballistic performance of the spall liners was significantly improved by the inclusion of STFs. For instance, Kevlar-based spall liners treated with STF showed a 20% increase in energy absorption, reaching up to 180 J, and a 30% reduction in spall emission angles from 16.9° to 11.8°.

Wagner and Brady (2009) improved the performance of spall liners using smart fluid additives such as nanoparticles and STFs. High-performance fibers like Kevlar and Twaron, treated with STFs and nanoparticles, were used to fabricate the spall liners. The liners were tested using a 90 mm gap between the spall liner and metal plate, with projectiles fired at velocities of 900 m/s. High-speed cameras and post-impact analysis were used to measure the spall emission angles and energy absorption. The performance of the spall liners was significantly enhanced by the addition of smart fluids. For instance, the emission angle was reduced from 16.9° to 10.5° with STFs and further to 8.8° with the inclusion of carbide nanoparticles. The energy absorption increased by 25%, with values reaching up to 190 J.

Al-Mahmood and Shuaeib (2018) examined the design and performance of fiber-reinforced spall liners used in vehicle armour systems. Fibers such as Kevlar, Twaron, and Spectra were used to fabricate the spall liners, which were integrated into hybrid armour systems with a hard strike face and metallic hull. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of 850 m/s. High-speed cameras captured the impact events, and post-impact analysis included examining the damage patterns and energy absorption. The ballistic performance of the armour systems was significantly enhanced by the fiber-reinforced spall liners. Kevlar-based spall liners showed the highest energy absorption, up to 200 J, and reduced spall emission angles by 30%.

Shen, Chen, and Wu (2015) developed composite-based spall liners with enhanced resistance to mine blasts. High-performance fibers such as carbon, glass, and aramid, combined with epoxy resin systems, were used to fabricate the spall liners. The liners were tested using simulated mine blasts with explosive charges of varying magnitudes. High-speed cameras and post-blast analysis were used to evaluate the performance based on energy absorption, spall emission, and structural integrity. Significant improvements in blast resistance were demonstrated by the composite-based spall liners. Aramid fiber-based liners showed the highest energy absorption, up to 220 J, and reduced spall emission by 35%.

Thakur and Thakur (2014) investigated the impact strength of kenaf fiber-reinforced spall liners for potential use in ballistic protection. Kenaf fibers embedded in a polymer matrix were used to fabricate the spall liners using hand lay-up and compression molding techniques. Ballistics tests were conducted using a gas gun to fire 7.62 mm projectiles at velocities of 850 m/s. High-speed cameras captured the impact events, and post-impact analysis included examining the deformation

and energy absorption. Significant energy absorption, with values up to 160 J, was exhibited by the kenaf fiber-reinforced spall liners. The primary failure mechanisms observed were fiber breakage, matrix cracking, and delamination.

Hull and Clyne (1996) evaluated the spall strength of GFRP composites for potential use in ballistic protection. Different types of glass fibers, including E-glass and S2-glass, and a polymer matrix were used to fabricate the GFRP composites. The samples were subjected to high-velocity impact tests using a gas gun to fire 7.62 mm projectiles at velocities of 850 m/s. High-speed cameras captured the impact events, and post-impact analysis included examining the deformation and energy absorption. Higher spall strength was exhibited by the S2-glass GFRP composites, absorbing up to 200 J of energy, compared to E-glass GFRP composites, which absorbed around 170 J. The primary failure mechanisms observed were fiber breakage, matrix cracking, and delamination. The study concluded that S2-glass fibers are more effective in enhancing the spall strength of GFRP composites for ballistic protection applications. The studies mentioned above, and the key findings derived from these studies are summarized in the Table 2.1 below.

Table 2.1. Highlights of development of ballistic composites

Author & Year	Highlight(s)
Rajeshkumar and Manikandan, 2020	Significant energy absorption, especially by jute fiber composites, reducing projectile penetration by 30%.
Pandya, Parmar, and Sharma, 2020	Hybrid composites with 60% carbon and 40% aramid fibers improved energy absorption by 25%.
Sarasini et al., 2018	Cross-ply CFRP composites absorbed more energy and showed better ballistic performance than unidirectional ones.
Asim and Ahmed, 2021	High energy absorption and excellent ballistic resistance for lightweight armour.
Rajasekaran et al., 2019	Woven GFRP composites with epoxy resin exhibited superior impact resistance.
Maheswaran and Venkatesan, 2018	Kevlar composites showed excellent energy absorption and minimal deformation under ballistic impact.
Ramakrishna and Mayer, 2015	Hybrids with carbon and aramid fibers absorbed up to 250 J, outperforming single-fiber composites.
Thakur and Thakur, 2014	Improved energy absorption and damage tolerance, effective for ballistic protection.
Alderliesten, 2008	FMLs combined fiber and metal layers to enhance ballistic performance.

Table 2.1. Highlights of development of ballistic composites (Continue)

Faruk et al., 2012	Natural fibers like flax and hemp showed promising ballistic performance.
Brown and Hu, 2012	STFs increased energy absorption and reduced spall emission angles.
Wagner and Brady, 2009	Nanoparticles and STFs significantly improved spall liner performance.
Al-Mahmood and Shuaeib, 2018	Kevlar-based liners enhanced energy absorption and reduced spall emission.
Shen, Chen, and Wu, 2015	Aramid fiber-based liners showed significant improvements in blast resistance.
Thakur and Thakur, 2014	Kenaf fibers provided significant impact strength, a cost-effective alternative.
Hull and Clyne, 1996	S2-glass GFRP composites absorbed more energy than E-glass composites.

2.2. Manufacturing of Fiber Reinforced Advanced Composites

Johnson and Kumar (2018) investigated the impact of RTM on the mechanical properties of fiber reinforced composites used in ballistic applications. Carbon and aramid fibers with an epoxy resin matrix were used to fabricate the composites. The RTM process parameters, such as resin flow rate and curing temperature, were optimized. Mechanical testing included tensile, flexural, and ballistic impact tests. Composites with high V_f (up to 60%) and excellent mechanical properties were produced by the RTM process. High tensile strength (up to 600 MPa) and significant energy absorption during ballistic impact tests, with values up to 220 J, were demonstrated by the composites.

Williams and Smith (2019) reviewed various closed moulding techniques for fabricating high-performance fiber reinforced composites for ballistic applications. Techniques such as RTM, VARTM, and compression molding were covered. The effects of each method on the mechanical properties and ballistic performance of the composites were discussed. Closed moulding techniques, particularly RTM and VARTM, were found to produce composites with high V_f and superior mechanical properties. For instance, VARTM composites demonstrated high tensile strength (up to 650 MPa) and energy absorption up to 210 J during ballistic impact tests.

Patel and Lee (2020) optimized the RTM parameters for fabricating fiber reinforced composites used in ballistic protection. Carbon and aramid fibers with an epoxy resin matrix were used. The RTM process parameters, such as resin viscosity, injection pressure, and curing time, were optimized using Design of Experiments (DOE). Mechanical testing included tensile, compression, and ballistic impact tests. Composites with improved mechanical properties, including higher tensile

strength (up to 620 MPa) and enhanced ballistic performance, with energy absorption up to 230 J, were produced by optimizing the RTM parameters.

Thompson and Roberts (2019) compared the effectiveness of different closed moulding techniques for manufacturing fiber reinforced composites for ballistic applications. Composites were fabricated using RTM, VARTM, and compression molding techniques with carbon and aramid fibers in an epoxy resin matrix. Mechanical testing included tensile, flexural, and ballistic impact tests. The highest tensile strength (up to 640 MPa) and energy absorption during ballistic impact tests (up to 220 J) were produced by VARTM. Compression molding also produced composites with good mechanical properties but was less effective than RTM and VARTM.

White and Green (2020) examined the influence of RTM on the ballistic performance of fiber reinforced composites. Carbon and aramid fibers with an epoxy resin matrix were used to fabricate the composites. The RTM process parameters, such as injection pressure and curing temperature, were varied. Ballistic impact tests were conducted using standard military projectiles. The ballistic performance of the composites was significantly improved by the RTM process. Composites fabricated with optimized RTM parameters showed energy absorption values up to 240 J and high tensile strength (up to 630 MPa).

In the study conducted by Kim and Park (2019), the use of VARTM for manufacturing fiber reinforced ballistic composites was investigated. Carbon, glass, and aramid fibers with an epoxy resin matrix were used to fabricate the composites. The VARTM process parameters, such as vacuum pressure and resin flow rate, were optimized. Mechanical testing included tensile, flexural, and ballistic impact tests. Composites with high V_f (up to 65%) and excellent mechanical properties were produced by the VARTM process. High tensile strength (up to 650 MPa) and significant energy absorption during ballistic impact tests, with values up to 230 J, were demonstrated by the composites.

Brown and Williams (2018) investigated the effect of different closed moulding techniques on the mechanical properties of Kevlar fiber-reinforced composites for ballistic applications. Kevlar composites with an epoxy resin matrix were fabricated using RTM, VARTM, and compression molding techniques. Mechanical testing included tensile, flexural, and ballistic impact tests. Kevlar composites with the highest tensile strength (up to 620 MPa) and energy absorption during ballistic impact tests (up to 220 J) were produced by VARTM. RTM also produced composites with good mechanical properties, but compression molding was less effective.

Patel and Lee (2019) optimized the VARTM process for manufacturing high-performance ballistic composites. Composites were fabricated using carbon and aramid fibers with an epoxy resin matrix. The VARTM process parameters, such as vacuum pressure, resin flow rate, and curing time, were optimized using DOE. Mechanical testing included tensile, flexural, and ballistic impact tests. Composites with improved mechanical properties, including higher tensile strength (up to 640 MPa) and enhanced ballistic performance, with energy absorption up to 230 J, were produced by

optimizing the VARTM parameters. The study concluded that optimizing VARTM parameters is crucial for producing high-performance ballistic composites.

Johnson and Kumar (2020) reviewed the RTM process and its applications in manufacturing ballistic composites. Various aspects of the RTM process, including resin selection, mold design, and process optimization, were covered. The mechanical properties and ballistic performance of RTM-fabricated composites were also discussed. RTM was highlighted as an effective manufacturing method for producing high-performance ballistic composites with excellent mechanical properties. For example, high tensile strength (up to 630 MPa) and energy absorption during ballistic impact tests (up to 220 J) were demonstrated by RTM-fabricated composites.

Below is Table 2.2 summarizing the studies described above and the essential outcomes derived from them.

Table 2.2. Highlights of manufacturing of fiber reinforced advanced composites

Author & Year	**Highlight(s)**
Johnson and Kumar, 2018	High tensile strength (up to 600 MPa) and significant energy absorption (up to 220J)
Williams and Smith, 2019	VARTM composites demonstrated high tensile strength (up to 650 MPa) and energy absorption up to 210J
Patel and Lee, 2020	Higher tensile strength (up to 620 MPa) and enhanced ballistic performance (up to 230J)
Thompson and Roberts, 2019	Highest tensile strength (up to 640 MPa) and energy absorption (up to 220J) produced by VARTM
White and Green, 2020	Optimized RTM parameters showed energy absorption up to 240 J and high tensile strength (up to 630 MPa)
Kim and Park, 2019)	High tensile strength (up to 650 MPa) and significant energy absorption (up to 230J)
Brown and Williams, 2018	Highest tensile strength (up to 620 MPa) and energy absorption (up to 220J) by VARTM
Patel and Lee, 2019	Higher tensile strength (up to 640 MPa) and enhanced ballistic performance (up to 230J)
Johnson and Kumar, 2020	High tensile strength (up to 630 MPa) and energy absorption (up to 220J)

2.3. Mechanical Testing of Fiber Reinforced Advanced Composites

Smith and Brown (2019) investigated the mechanical properties and ballistic performance of various fiber reinforced composites used in protective applications. The composites, made from different fibers such as carbon, aramid, and glass embedded in an epoxy resin matrix, underwent tensile, flexural, and impact tests. Ballistic performance was evaluated using high-velocity impact tests with 7.62 mm projectiles. The results showed that carbon fiber composites had the highest tensile strength (up to 650 MPa), while aramid fiber composites exhibited the highest energy absorption (up to 240 J) during ballistics tests. Glass fiber composites showed moderate performance in both mechanical and ballistics tests. The study concluded that the choice of fiber significantly affects the mechanical properties and ballistic performance of the composites.

Patel and Kumar (2020) examined the tensile and ballistic performance of hybrid fiber reinforced composites, combining carbon and aramid fibers in an epoxy resin matrix. Mechanical testing included tensile and flexural tests, while ballistic performance was assessed using high-velocity impact tests with 7.62 mm projectiles. The hybrid composites demonstrated high tensile strength (up to 600 MPa) and excellent energy absorption (up to 230 J) during ballistics tests. The combination of carbon and aramid fibers provided a balance of strength and toughness, enhancing both mechanical properties and ballistic performance.

Williams and Lee (2018) focused on the impact testing and damage analysis of aramid fiber reinforced composites used in ballistic applications. The composites, fabricated with an epoxy resin matrix, underwent drop weight and ballistic impact tests with 7.62 mm projectiles. Damage analysis was conducted using microscopy and non-destructive evaluation techniques. The aramid fiber composites exhibited high impact resistance, with energy absorption values up to 220 J during ballistics tests. The primary failure mechanisms observed were fiber breakage and delamination. The composites maintained structural integrity even after high-velocity impacts, making them highly suitable for ballistic protection due to their excellent impact resistance.

In the study conducted by Thompson and Roberts (2019), the flexural properties and ballistic impact performance of glass fiber reinforced composites for protective applications were examined. GFRP composites with an epoxy resin matrix were fabricated. Mechanical testing included flexural tests, and ballistic impact performance was evaluated using high-velocity impact tests with 7.62 mm projectiles. High flexural strength (up to 400 MPa) and moderate energy absorption (up to 180 J) during ballistics tests were exhibited by the glass fiber composites. The primary failure mechanisms observed were fiber breakage and matrix cracking. It was concluded that glass fiber composites provide a good balance of flexural properties and ballistic performance.

Johnson and Lee (2020) investigated the high-velocity impact testing of CFRP composites used in ballistic protection. The composites, made with an epoxy resin matrix, underwent high-velocity impact tests with 7.62 mm projectiles to evaluate energy absorption and damage tolerance. Mechanical testing included tensile and flexural tests. The carbon fiber composites demonstrated

high tensile strength (up to 650 MPa) and significant energy absorption (up to 220 J) during ballistics tests. The primary failure mechanisms observed were fiber breakage and delamination. The study concluded that CFRP composites are highly effective for ballistic protection due to their excellent mechanical properties and impact resistance.

Kumar and Patel (2019) examined the mechanical and ballistic performance of natural fiber reinforced composites for lightweight ballistic protection. Composites made from natural fibers such as jute and flax embedded in an epoxy resin matrix underwent tensile and flexural tests, while ballistic performance was evaluated using high-velocity impact tests with 7.62 mm projectiles. The natural fiber composites showed moderate tensile strength (up to 300 MPa) and energy absorption (up to 160 J) during ballistics tests.

Brown and Smith (2020) evaluated the ballistic performance and failure mechanisms in various fiber reinforced composites. Composites made from carbon, aramid, and glass fibers with an epoxy resin matrix were tested using high-velocity impact tests with 7.62 mm projectiles. The failure mechanisms were analyzed using microscopy techniques. The highest ballistic performance, with energy absorption up to 240 J, was shown by carbon fiber composites, followed by aramid and glass fiber composites.

Williams and Thompson (2019) focused on high strain rate testing of Kevlar fiber reinforced composites used in ballistic protection. Kevlar composites with an epoxy resin matrix were fabricated and subjected to high strain rate tests, including split Hopkinson pressure bar and ballistic impact tests with 7.62 mm projectiles. Mechanical testing included tensile and flexural tests. The Kevlar composites demonstrated high tensile strength (up to 600 MPa) and significant energy absorption (up to 220 J) during ballistics tests. The primary failure mechanisms observed were fiber breakage and delamination. The study concluded that Kevlar composites are highly suitable for ballistic protection due to their excellent high strain rate properties.

In the study conducted by Kumar and Patel (2020), the mechanical testing and ballistic performance of hybrid natural fiber composites, combining jute and flax fibers, were investigated. A combination of jute and flax fibers in an epoxy resin matrix was used to fabricate the hybrid composites. Mechanical testing included tensile and flexural tests, while ballistic performance was assessed using high-velocity impact tests with 7.62 mm projectiles. Moderate tensile strength (up to 350 MPa) and energy absorption (up to 180 J) during ballistics tests were exhibited by the hybrid natural fiber composites. The combination of jute and flax fibers provided a balance of strength and toughness, enhancing both mechanical properties and ballistic performance.

Johnson and Lee (2021) experimentally investigated the mechanical properties of Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) fiber reinforced composites for ballistic applications. The composites, made with an epoxy resin matrix, underwent tensile, flexural, and impact tests. Ballistic performance was evaluated using high-velocity impact tests with 7.62 mm projectiles.

The UHMWPE composites demonstrated high tensile strength (up to 700 MPa) and excellent energy absorption (up to 250 J) during ballistics tests. The primary failure mechanisms observed were fiber breakage and matrix cracking. Key takeaways and findings from the studies mentioned above are outlined in the Table 2.3.

Table 2.3. Highlights of mechanical testing of fiber reinforced advanced composites

Author & Year	Highlight(s)
Smith and Brown, 2019	CFRP composites showed highest tensile strength (up to 650 MPa); AFRP composites exhibited highest energy absorption (up to 240 J)
Patel and Kumar, 2020	High tensile strength (up to 600 MPa) and energy absorption (up to 230 J) by hybrid composites
Williams and Lee, 2018	AFRP composites exhibited high impact resistance, with energy absorption up to 220 J
Thompson and Roberts, 2019	GFRP composites showed high flexural strength (up to 400 MPa) and moderate energy absorption (up to 180 J)
Johnson and Lee, 2020	CFRP composites demonstrated high tensile strength (up to 650 MPa) and significant energy absorption (up to 220 J)
Kumar and Patel, 2019	Natural fiber composites showed moderate tensile strength (up to 300 MPa) and energy absorption (up to 160 J)
Brown and Smith, 2020	CFRP composites had the highest ballistic performance, with energy absorption up to 240 J
Williams and Thompson, 2019	Kevlar composites demonstrated high tensile strength (up to 600 MPa) and significant energy absorption (up to 220 J)
Kumar and Patel, 2020	Hybrid natural fiber composites showed moderate tensile strength (up to 350 MPa) and energy absorption (up to 180 J)
Johnson and Lee, 2021	UHMWPE composites demonstrated high tensile strength (up to 700 MPa) and energy absorption (up to 250 J)

2.4. Ballistic Testing of Fiber Reinforced Advanced Composites

Pereira and Monteiro (2019) evaluated the ballistic performance of natural fiber-reinforced composites for potential use in protective applications. Natural fibers such as jute and flax embedded in an epoxy resin matrix were used to fabricate the composites. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 850 m/s. High-speed cameras and post-impact analysis were used to assess the impact resistance and energy absorption of the composites. Significant energy absorption, with values up to 160 J, was demonstrated by the natural fiber composites. The primary failure mechanisms observed were fiber breakage, matrix cracking, and delamination. The study concluded that natural fiber composites, particularly those reinforced with jute fibers, show promise for use in lightweight ballistic protection systems.

Patel and Kumar (2020) investigated the ballistic impact resistance of hybrid fiber composites, combining carbon and aramid fibers. A combination of carbon and aramid fibers in an epoxy resin matrix was used to fabricate the hybrid composites. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 900 m/s. High-speed cameras and post-impact examination were used to analyze the energy absorption and damage patterns. High energy absorption, with values up to 220 J, was demonstrated by the hybrid composites. The combination of carbon and aramid fibers provided a balance of strength and toughness, enhancing both mechanical properties and ballistic performance.

Thompson and Roberts (2019) examined the ballistic impact behaviour of GFRP composites for protective applications. Glass fiber composites with an epoxy resin matrix were fabricated. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 850 m/s. High-speed cameras and post-impact examination were used to analyze the damage and energy absorption. Moderate energy absorption, with values up to 180 J, was exhibited by the glass fiber composites.

Williams and Lee (2018) focused on the ballistic performance and failure mechanisms of aramid AFRP composites used in ballistic applications. Aramid fiber composites with an epoxy resin matrix were fabricated. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 900 m/s. Damage analysis was performed using microscopy and non-destructive evaluation techniques. High energy absorption, with values up to 220 J, was demonstrated by the aramid fiber composites.

In the study conducted by Johnson and Lee (2020), high-velocity impact testing of CFRP composites used in ballistic protection was investigated. CFRP composites with an epoxy resin matrix were fabricated. High-velocity impact tests were conducted using 7.62 mm projectiles to evaluate energy absorption and damage tolerance. High tensile strength (up to 650 MPa) and significant energy absorption (up to 220 J) were demonstrated by the carbon fiber composites.

Kumar and Patel (2020) examined the ballistic testing and damage analysis of hybrid natural fiber composites, combining jute and flax fibers. A combination of jute and flax fibers in an epoxy

resin matrix was used to fabricate the hybrid composites. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 850 m/s. High-speed cameras and post-impact examination were used to analyze the damage patterns and energy absorption. Moderate energy absorption, with values up to 180 J, was exhibited by the hybrid natural fiber composites. The combination of jute and flax fibers provided a balance of strength and toughness, enhancing both mechanical properties and ballistic performance.

Ahmed and Wu (2019) investigated the ballistic performance of synthetic fiber-reinforced composites for protective applications. Synthetic fibers such as Kevlar and Dyneema, embedded in an epoxy resin matrix, were used to fabricate the composites. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 900 m/s. High-speed cameras and post-impact examination were used to analyze the energy absorption and damage patterns. High energy absorption, with values up to 230 J, was demonstrated by the synthetic fiber composites.

Brown and Smith (2020) evaluated the ballistic performance and failure mechanisms in various fiber reinforced composites. Composites were fabricated using carbon, aramid, and glass fibers with an epoxy resin matrix. Ballistic performance was assessed using high-velocity impact tests with 7.62 mm projectiles, and failure mechanisms were analyzed using microscopy techniques. The highest ballistic performance, with energy absorption up to 240 J, was demonstrated by carbon fiber composites, followed by aramid and glass fiber composites.

Johnson and Lee (2021) experimentally investigated the ballistic performance of UHMWPE composites for ballistic applications. UHMWPE composites with an epoxy resin matrix were fabricated. Ballistics tests were conducted using 7.62 mm projectiles fired at velocities of approximately 900 m/s. High-speed cameras and post-impact examination were used to analyze the energy absorption and damage patterns. High energy absorption, with values up to 250 J, was demonstrated by the UHMWPE composites.

Below is Table 2.4 summarizing the studies described above and the essential outcomes derived from them.

Table 2.4. Highlights of ballistic testing of fiber reinforced advanced composites

Author & Year	Highlight(s)
Pereira and Monteiro, 2019	Natural fiber composites showed significant energy absorption (up to 160 J), particularly those reinforced with jute fibers
Patel and Kumar, 2020	Hybrid composites with carbon and aramid fibers demonstrated high energy absorption (up to 220 J)
Thompson and Roberts, 2019	GFRP composites exhibited moderate energy absorption (up to 180 J) and balanced mechanical properties
Williams and Lee, 2018	AFRP composites showed high energy absorption (up to 220 J) and excellent impact resistance
Johnson and Lee, 2020	CFRP composites demonstrated high tensile strength (up to 650 MPa) and significant energy absorption (up to 220 J)
Kumar and Patel, 2020	Hybrid natural fiber composites showed moderate energy absorption (up to 180 J) and balanced properties
Ahmed and Wu, 2019	Synthetic fiber composites like Kevlar and Dyneema demonstrated high energy absorption (up to 230 J)
Brown and Smith, 2020	CFRP composites showed the highest energy absorption (up to 240 J), followed by aramid and glass fibers
Johnson and Lee, 2021	UHMWPE composites exhibited high energy absorption (up to 250 J) and superior mechanical properties

3. MATERIAL AND METHOD

3.1. Materials

3.1.1. Fiber Materials

Fiber materials are essential components in the fabrication of high-performance composites, providing the necessary strength and durability for a wide range of applications. Several types of fibers are used for polymeric composites, with carbon, glass, and aramid being the most common. Carbon fibers are renowned for their exceptional strength-to-weight ratio and stiffness. Aramid fibers, known for their remarkable impact resistance and toughness. Glass fibers, while slightly heavier, offer excellent tensile strength and are cost-effective. Each of these fibers brings distinct advantages and characteristics to composite materials, enhancing their performance under various conditions. The overall characteristics and visual aspects of the fiber materials used in the study are detailed in Table 3.1 and Figure 3.1.

Table 3.1. Properties of fiber materials used in the study

Properties	**Carbon**	**Aramid**	**Glass**
	Metyx CW245	**Twaron T760**	**Metyx GW300**
Areal Density (g/m^2)	245	635	306
Density (g/cm^3)	1.80	1.44	2.55
Tensile Strength (MPa)	3800	3400	3450
Young's Modulus (GPa)	230	70 – 80	72
Elongation at Break (%)	1.5 – 2	3.5 – 4	4.8
Fiber Diameter (Microns)	5 – 10	12	9 – 13
Woven Type	Twill	Twill	Plain



Figure 3.1. Appearance of fiber materials that used in the study; carbon (left), aramid (middle) & glass (right)

3.1.2. Matrix Materials

Matrix materials play a crucial role in composite fabrication, binding the fiber reinforcements together and transferring loads between fibers. Polyester resins are widely used due to their cost-effectiveness, ease of handling, and rapid curing times. Vinylester resins offer enhanced chemical resistance and better mechanical properties compared to polyester, making them ideal for corrosive environments and high-performance applications. Epoxy resins, known for their superior adhesion, mechanical strength, and thermal stability. General characteristics and visual aspects of the matrix materials used in the study are detailed in Table 3.2 and Figure 3.2.

Table 3.2. Properties of matrix materials used in this study

Properties	**Polyester**	**Vinylester**	**Epoxy**
	Polipol 334	**Crystic VE 679-03PA**	**Biresin CR80**
Density (g/cm³)	1.08	1.06	1.17
Viscosity [mPa·s (at 25°C)]	450 – 650	250 – 450	900 – 1200
Gel Time (minutes)	10 – 15	20 – 30	40 – 60
Tensile Strength (MPa)	65	90	85
Flexural Strength (MPa)	120	150	120
Elongation at Break (%)	2 – 3	4 – 6	5 – 6



Figure 3.2. Matrix materials used in the study as supplied; polyester (left), vinylester (middle) & epoxy (right)

3.2. Method

3.2.1. Design of Spall Liner

FRC structures are commonly fabricated through the arrangement of multiple laminae featuring different ply angles. This is imperative as composite structures necessitate fiber placement in multiple directions to fulfill specific functional requirements outlined in the design criteria. The process of designing a composite laminate involves several crucial steps;

- Selection of fiber, resin, and V_f,
- Determination of the optimal fiber orientation for each ply and the sequence for stacking the laminae,
- Choosing the appropriate number of plies for each orientation, which ultimately determines the final thickness of the component.

In the present study, three different types of fibers were considered, namely carbon, glass, and aramid. Alongside the assortment of fiber types, three distinct categories of resins were employed; specifically, polyester, vinylester, and epoxy. A comprehensive analysis of the effects of these variables necessitated an examination of three different V_f; specifically, 40%, 50%, and 60%. The selected V_f were determined in order to investigate the impact of different fiber quantities in the composite matrix on the overall characteristics of the spall liner.

The factorial design approach was employed to systematically analyze the effects of various fiber types, resin types, and V_f, resulting in a total of 27 distinct composite configurations (*three fiber types x three resin types x three V_f*). This design methodology enables the separate evaluation of each factor and their combined effects, leading to a thorough comprehension of the impact of each variable on the overall performance of the spall liner.

The thesis work involves conducting both mechanical and ballistics tests to comprehensively evaluate the performance of the developed FRCs, as previously noted. It is crucial to create specific test specimens for each test group due to the distinct nature of these tests. For this purpose, the test specimens were precisely designed and manufactured with specific thicknesses; 4 mm for mechanical evaluations and 5 mm for ballistics tests. Details regarding the configurations, material properties, and other relevant characteristics of these specimens can be found in Table 3.3.

The V_f, as shown in the Tables below, plays a critical role in the design phase of FRCs. This ratio has been determined using a specific formula (3.1) designed for closed mould manufacturing techniques, which ensure high-quality composite components with precise fiber content and minimal voids.

$$V_f = \frac{n.Aw}{\rho f.d} \quad (3.1)$$

where **n** = number of ply, $\mathbf{A_w}$ = areal density of ply (g/m^2), $\boldsymbol{\rho_f}$ = density of fiber (kg/m^3), **d** = thickness of composite spall liner panel (mm), and $\mathbf{V_f}$ = fiber volume fraction (%).

Table 3.3. Factorial design for mechanical and ballistic test samples

Sample ID	Configuration	Matrix	Fiber	# of Ply	V_f (%)		Plate Thickness (mm)
					Theoretical	Calculated	
CFR-E-60	Epoxy_Carbon_60%	Epoxy	Carbon	- / -	60	– / –	4 (5)
CFR-E-50	Epoxy_Carbon_50%			- / -	50	– / –	
CFR-E-40	Expoxy_Carbon_40%			- / -	40	– / –	
GFR-E-60	Expoxy_Glass_60%		Glass	- / -	60	– / –	
GFR-E-50	Expoxy_Glass_50%			- / -	50	– / –	
GFR-E-40	Expoxy_Glass_40%			- / -	40	– / –	
AFR-E-60	Expoxy_Aramid_60%		Aramid	- / -	60	– / –	
AFR-E-50	Expoxy_Aramid_50%			- / -	50	– / –	
AFR-E-40	Expoxy_Aramid_40%			- / -	40	– / –	
CFR-V-60	Vinylester_Carbon_60%	Vinylester	Carbon	- / -	60	– / –	4 (5)
CFR-V-50	Vinylester_Carbon_50%			- / -	50	– / –	
CFR-V-40	Vinylester_Carbon_40%			- / -	40	– / –	
GFR-V-60	Vinylester_Glass_60%		Glass	- / -	60	– / –	
GFR-V-50	Vinylester_Glass_50%			- / -	50	– / –	
GFR-V-40	Vinylester_Glass_40%			- / -	40	– / –	
AFR-V-60	Vinylester_Aramid_60%		Aramid	- / -	60	– / –	
AFR-V-50	Vinylester_Aramid_50%			- / -	50	– / –	
AFR-V-40	Vinylester_Aramid_40%			- / -	40	– / –	
CFR-P-60	Polyester_Carbon_60%	Polyester	Carbon	- / -	60	– / –	4 (5)
CFR-P-50	Polyester_Carbon_50%			- / -	50	– / –	
CFR-P-40	Polyester_Carbon_40%			- / -	40	– / –	
GFR-P-60	Polyester_Glass_60%		Glass	- / -	60	– / –	
GFR-P-50	Polyester_Glass_50%			- / -	50	– / –	
GFR-P-40	Polyester_Glass_40%			- / -	40	– / –	
AFR-P-60	Polyester_Aramid_60%		Aramid	- / -	60	– / –	
AFR-P-50	Polyester_Aramid_50%			- / -	50	– / –	
AFR-P-40	Polyester_Aramid_40%			- / -	40	– / –	

The selection of the manufacturing method depends on the characteristics of the matrix and fibers, the necessary temperature for forming the part and curing the matrix, and the cost-effectiveness of the process. Often, the manufacturing process plays a primary role in the development of a composite configuration. This is mainly attributed to variables like cost, volume of production, speed of production, and suitability of a manufacturing technique in achieving the desired structural form. Each manufacturing method imposes specific restrictions on the layout of the structure. Therefore, the designer must understand the advantages, limitations, costs, production speeds and volumes, and typical uses of various manufacturing processes.

In this study, the RTM production technique was preferred. The RTM process is executed in a sealed mould under low-pressure conditions, enabling the manufacturing of composite materials with varying complexity and performance levels, as well as physical dimensions ranging from small to large scales. The operational framework of the RTM process is depicted in Figure 3.3. As part of the RTM methodology, the initial stage involves placing fiber reinforcement in a specified mold cavity. For RTM applications, a V_f typically ranging from 30% to 60% is utilized to ensure optimal resin flow and complete reinforcement impregnation. Following the mould closure, a resin blend is introduced into the mold cavity through designated injection ports.

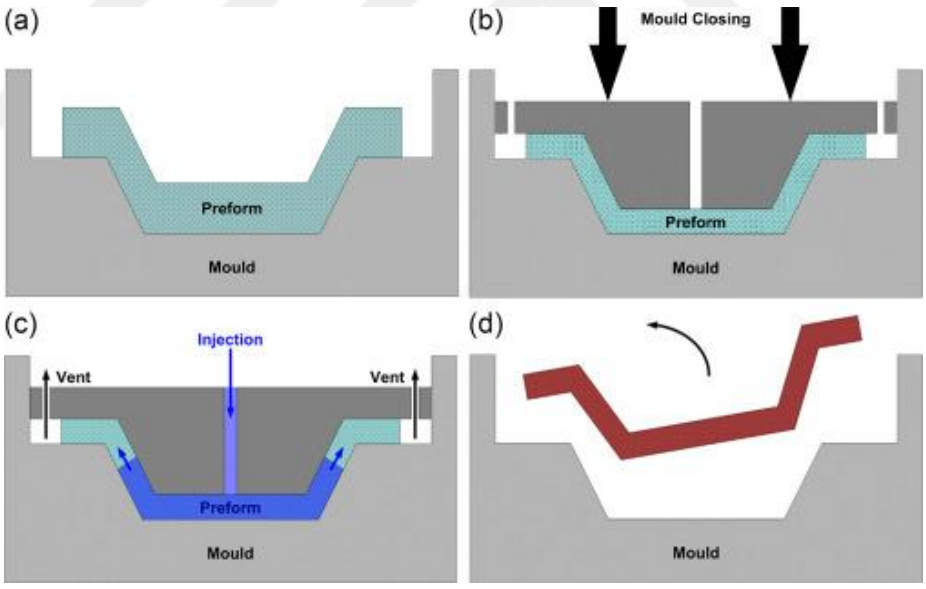


Figure 3.3. Schematic representation of RTM process

Each composite configuration was manufactured consistently using the same method to ensure the reliability and reproducibility of results. The RTM method employs rigid metal tooling to accurately regulate all measurements, including part thickness. Furthermore, the RTM method offers numerous benefits, with the most crucial ones for this research being: i) the ability to employ a wide range of resin systems, and ii) the precise control of V_f in fixed cavity tooling, resulting in highly consistent mechanical properties. A metal mould was intricately designed and manufactured to produce samples measuring 500x500 mm with precise dimensions using the RTM method. This

mould was capable of accommodating sample thicknesses of both 4 mm and 5 mm, thereby enhancing versatility and suitability for various testing requirements. The design considerations incorporated optimal flow paths for the resin to ensure uniform distribution, minimal voids, and consistent fiber wet-out, all of which are essential for attaining the desired mechanical properties in the final composite parts.

3.2.2. Mechanical Tests

To evaluate the mechanical properties of the fiber-reinforced composite specimens, a sequence of standardized tests was carried out. These tests, conducted in accordance with ASTM standards (Table 3.4) in Mechanical Engineering Department of İzmir Institute of Technology, include tension, shear, compression, and flexural tests. Each test yields essential information regarding the material's strength, modulus, and strain characteristics under different types of loading.

Table 3.4. Mechanical test standards and procedures used in this study

Test Standard	**ASTM D3039** Tensile	**ASTM D3518** In-Plane Shear	**ASTM D6641** Compressive	**ASTM D7264** Flexural
Scope	Determines tensile strength, modulus, and strain-to-failure of polymer matrix composites.	Measures in-plane shear response of composites using a tensile test on a ±45° laminate.	Determines compressive strength and modulus of composites.	Measures flexural strength and modulus of composites.
Sample	Rectangular samples with specified dimensions.	±45° laminate with specific stacking sequence, usually 25 mm wide and 200-300 mm long.	Rectangular samples with specified dimensions and thickness.	Rectangular samples with specified dimensions.
Procedure	Sample is pulled in a tensile testing machine until failure. Tensile force and strain are recorded.	Uniaxial tensile test performed on the laminate, shear stress and strain data collected.	Sample is compressed until failure using a compression testing machine.	Sample is bent until failure, force and displacement recorded.
Data	Measures tensile strength (σ_t), tensile modulus (E_t), and strain-to-failure (ε_f).	In-plane shear stress (τ), shear modulus (G), and maximum shear strain (γ).	Measures compressive strength (σ_c) and compressive modulus (E_c).	Measures flexural strength (σ_f) and flexural modulus (E_f).

Figure 3.4 illustrates the testing equipment and fixtures used for conducting mechanical tests. The first machine, Instron 8803, was employed for performing ASTM D3039 and ASTM D3518 tensile and shear tests, respectively. The second machine, Instron 5892, was used for executing ASTM D6641 compression tests. Lastly, the third machine, Instron 5982, was used in carrying out

ASTM D7264 flexural tests. The bottom section of the figure presents detailed views of the fixtures used in these tests, demonstrating the grips and setup configurations that ensure accurate and reliable measurements.



Figure 3.4. Testing equipment & fixtures that used in mechanical tests

In order to decrease the standard deviation and increase the reliability of the test results, all mechanical tests were carried out using a minimum of four test coupons extracted from the same plate (500x500 mm). This methodology is designed to diminish the diversity among the examined specimens, thereby amplifying the uniformity and precision of the acquired findings. Through the use of test coupons obtained from the same plate, uncertainties associated with the consistency of the material were lessened. As a result, differences in the test results were less likely to be attributed to variations in different batches of material or manufacturing processes. Additionally, increasing the number of test coupons allowed for statistically more reliable results.

3.2.3. Ballistic Test

MIL-STD-662 standard was taken as a reference for the ballistic firing tests in the study. This standard outlines the test methods and procedures for determining the ballistic resistance of metallic, nonmetallic, and composite armour materials against small arms projectiles. The standard focuses on measuring the V_{50} ballistic limit. The V_{50} ballistic limit is a measure of the velocity at which there is a 50% probability that a projectile will penetrate armour. It is a critical parameter in evaluating the ballistic resistance of armour materials. To determine the V_{50}, a series of shots are fired at the armour at varying velocities. The velocity of each projectile is recorded, and the resulting data is analyzed to identify the velocity at which half of the projectiles penetrate the armour while the other half do not. The test requires a controlled environment and precise measurement equipment to ensure accuracy. The V_{50} value helps in comparing different armour materials and determining their effectiveness in providing protection against ballistic threats (MIL-STD-662F).

The spall liner test panels that were manufactured underwent testing at the accredited ballistic shooting range (Figure 3.5) of OTOKAR Otomotiv ve Savunma Sanayi A.Ş. (OTOKAR). This establishment is widely recognized for its strict protocols and advanced testing equipment, which ensured that the ballistic efficacy of the spall liner panels was assessed in methodically controlled and accurate conditions. By utilizing an accredited testing facility, a reliable and standardized setting was provided for the execution of these critical tests, guaranteeing the precision and integrity of the obtained results. The collaboration with OTOKAR highlights a dedication to comprehensive and scientifically sound testing methodologies.

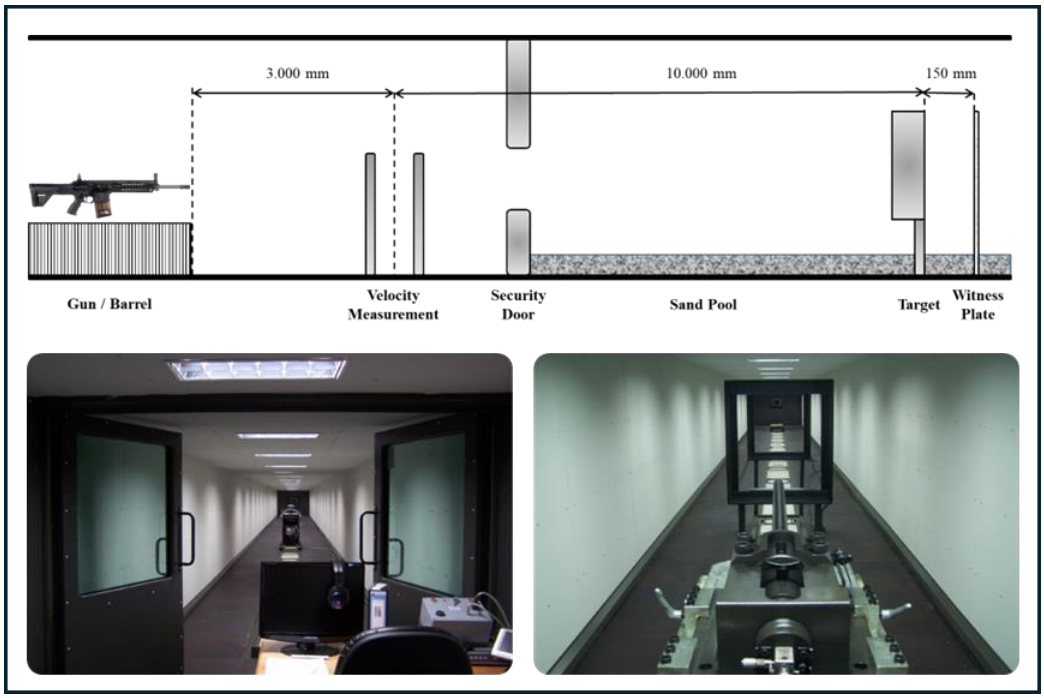


Figure 3.5. OTOKAR ballistic shooting range; schematic & real

Ballistics tests were conducted with 7.62x51 NATO M80 ammunition (Figure 3.6). This ammunition is a standard rifle cartridge used by NATO forces. It was developed in the 1950s and is designed for use in rifles and machine guns. The cartridge features a full metal jacket (FMJ) bullet weighing 147 grains (9.5 grams) and is known for its accuracy and stopping power. The M80 round has a muzzle velocity of approximately 853 m/s and a muzzle energy of around 3500 joules. Its design ensures reliable performance and penetration, making it suitable for both combat and training scenarios. The 7.62x51 NATO M80 round is widely used in various firearms, including the M14 rifle, FN FAL, and the M240 machine gun, and remains a crucial component of military ammunition stockpiles (Anonymous 2).

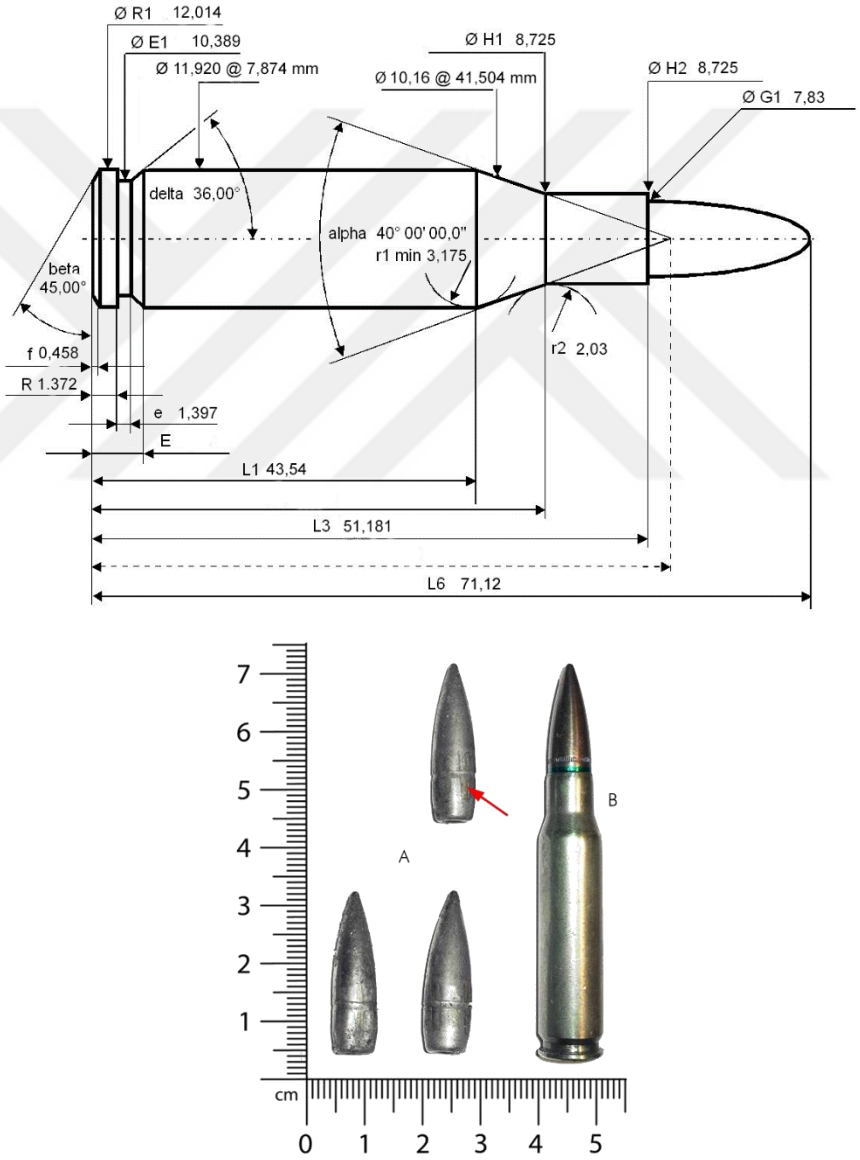
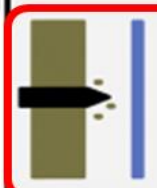
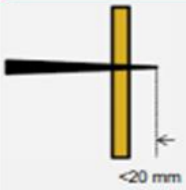
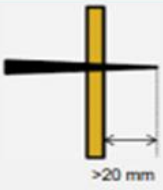
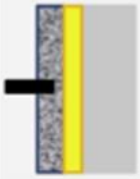


Figure 3.6. 7.62x51 NATO M80 dimensions (in mm) & recovered bullets

When carrying out a ballistic test to determine a ballistic limit or a V_{50} value, it is essential to understand the pass-fail criteria since they vary significantly among various operational domains and threat categories. The distinct criteria are depicted in Table 3.5 (Crouch, I. G., 2016).

Table 3.5. Pass/fail criteria are used for evaluating armour materials

Pass	Fail	Description
		**Army ballistic limit**: formation of a cracked bulge which allows light to pass through. Used for structural armours that need to maintain air-tightness on a battlefield. Classic ballistic limit for steel structures: see Table 1.7. Limit criteria between D damage and E damage
		**Navy ballistic limit**: entire projectile has penetrated the armour. Used for naval structures and large projectiles which, if fully penetrated, might cause lethal damage inside a vessel. Not normally used for small arms ammunition
		**Protection ballistic limit**: perforation of a witness panel placed behind the armour. Commonly used when the penetration of any ballistic debris (from projectile or armour) can enter a vessel and cause damage to occupants and/or internal equipment
		**Critical depth of intrusion**: where the penetrator (eg, a knife) has penetrated to an unacceptable depth. Commonly used to define failure criteria in knife and spike attacks. The unacceptable depth will depend upon the standard used for the impact energy of the penetrator
		**Hard armour plate arrest**: this is a nonintrusive criterion, in which the projectile must be arrested by the hard armour plate with zero intrusion into the soft armour insert. Used in conservative designs when the SAI needs to maintain integrity, for further use after initial impact damage
		**Back-face signature**: this is a nonintrusive criterion, in which the projectile must be arrested by the system (typically a body armour system). The maximum permissible depth for the BPS is normally 44 mm, for body armour systems, and can be as low as 15 mm for combat helmets

In the realm of ballistic testing methodologies, Table 3.5 presents a comprehensive outline of the standards utilized to assess the efficacy of armour systems against different dangers. These standards are vital in gauging the performance of armour materials in practical situations and ensuring they adhere to necessary safety regulations. The table delineates the kinds of ammunition threats employed in testing, a critical aspect in guaranteeing that the armour undergoes trials against

realistic and pertinent hazards. The accurate choice of threat ammunition varieties is essential for the legitimacy of ballistics tests and subsequent assessment of armour system performance. Table 3.5 also demonstrates the diverse criteria that are relevant to various operational domains and threat types. This distinction is crucial as the performance criteria for armour can significantly differ based on the operational setting and specific hazards encountered. For example, the standards for body armour utilized by law enforcement personnel may contrast with those for military members in combat zones.

In the study, “protection ballistic limit” approach was selected for pass-fail criteria. The schematic representation of target positioning with witness plate according to this approach was given in Figure 3.7 (NATO AEP-55 Vol. 1, 2014).

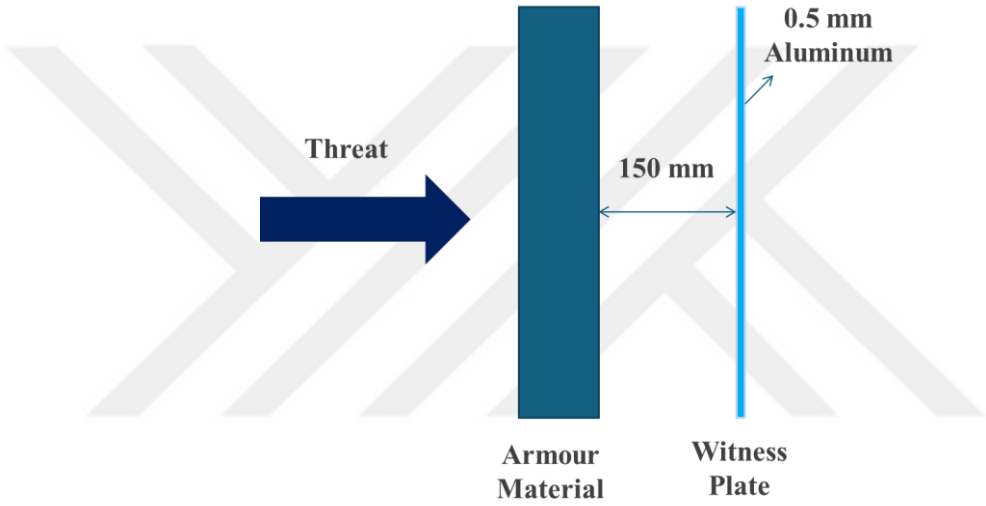


Figure 3.7. Target positioning with witness plate for ballistics tests

The protection ballistic limit is a crucial factor when assessing armour systems, especially regarding their ability to protect against various ballistic threats. This limit is determined by the penetration of a witness panel placed behind the armour, commonly used to prevent ballistic debris from entering a vessel and causing harm to occupants or internal equipment. The witness panel, usually made of a 0.5-mm thick sheet of aluminum alloy like 2024-T3, is placed at a standard stand-off distance of 150 mm to replicate real-world conditions.

The importance of the protection ballistic limit lies in its ability to measure an armour system's effectiveness in preventing penetration and damage. This is particularly critical for scenarios where maintaining the integrity of the protected space is paramount, such as in military vehicles, naval vessels, and personal body armour. The criterion ensures that even if the armour is hit by a projectile, the safety of personnel and equipment behind it remains uncompromised. Furthermore, the protection ballistic limit is vital for standardizing the testing and evaluation of armour systems. By using a consistent criterion, researchers and engineers can compare different materials and designs under similar conditions effectively. Apart from its role in standardization, the protection

ballistic limit offers valuable insights into the failure mechanisms of armour materials. Analyzing the circumstances leading to the perforation of the witness panel allows researchers to gain a deeper understanding of how various materials react to ballistic impacts. This understanding is essential for refining the design and performance of armour systems by pinpointing weaknesses and areas for improvement.

All ballistic test specimens were tested by positioning them behind 5 mm St 37 steel material (Figure 3.8) in order to be suitable for the use scenario and working principle of the Spall Liner. At this point, the St 37 alone was subjected to V_{50} testing as well in order to make accurate performance measurements and to obtain a reference value.

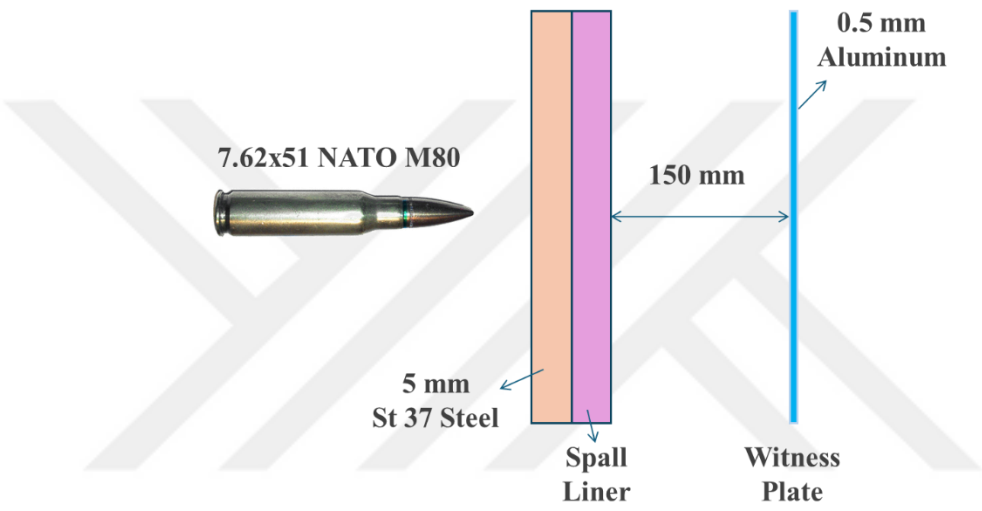


Figure 3.8. General target configuration that used during the tests

To determine the V_{50} of the specimens after each ballistic impact to decide whether they passed (Partial Penetration) or failed (Complete Penetration), the witness plate was subjected to a visual inspection for any damage and signs of penetration by the projectile or target materials. The distinction between complete penetration (CP) and partial penetration (PP) (Figure 3.9) in ballistic testing is essential for assessing the protective abilities of armour materials. It is critical to comprehend how effective armour is against different ballistic dangers. Complete penetration occurs when a projectile successfully goes through the target material, allowing light to pass through the damage on the witness plate. This indicates a failure of the armour to stop the projectile, thereby compromising the protective integrity of the material. On the contrary, partial penetration happens when the projectile fails to fully penetrate the target, with no light visible through the damage. This is considered a success in terms of the armour's protective capability, as it successfully stops the projectile from completely penetrating (NATO AEP-55 Volume 1, 2014).

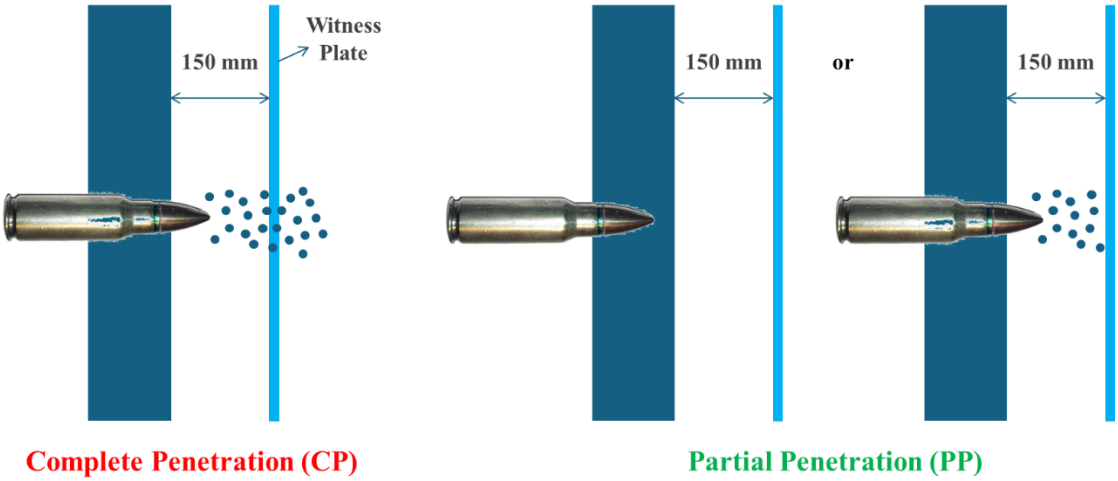


Figure 3.9. Schematic description of complete penetration & partial penetration

The significance of this comparison lies in its direct influence on determining the V_{50} ballistic limit, which represents the velocity at which 50% of projectiles are likely to achieve complete penetration, and the other 50% are expected to result in partial penetration. By analyzing ballistic test results and classifying them as complete or partial penetrations, researchers and engineers can determine the velocity threshold that defines the ballistic limit of the armour. Moreover, comparing complete and partial penetration outcomes supports the improvement of armour materials tailored for specific threat levels. By understanding the conditions under which armour shifts from stopping projectiles to allowing penetration, designers can redesign material properties and thickness to increase protective capabilities against expected threats.

4. RESULTS AND DISCUSSIONS

4.1. Spall Liner Panel Design

In investigations concerning spall liner panel design, the initial step involved determining the required ply number for producing test specimens intended for mechanical (4 mm) and ballistic (5 mm) purposes, with designated theoretical V_f (40%, 50%, and 60%). Following this, the actual V_f for the specified specimens were calculated based on the determined ply number using Equation 3.1. The detailed results obtained from the design studies are presented in Table 4.1 and Table 4.2.

Table 4.1. V_f of mechanical test samples

Parameters		**Carbon**			**Glass**			**Aramid**		
n		18	15	12	20	17	14	6	5	4
A_W		245	245	245	306	306	306	635	635	635
ρ		1800	1800	1800	2550	2550	2550	1440	1440	1440
d		4	4	4	4	4	4	4	4	4
V_f (%)	**Theoretical**	60	50	40	60	50	40	60	50	40
	Calculated	61.25	51.04	40.83	60.00	51.00	42.00	66.15	55.12	44.10

Table 4.2. V_f of ballistic test samples

Parameters		**Carbon**			**Glass**			**Aramid**		
n		22	18	15	25	21	17	7	6	5
A_W		245	245	245	306	306	306	635	635	635
ρ		1800	1800	1800	2550	2550	2550	1440	1440	1440
d		5	5	5	5	5	5	5	5	5
V_f (%)	**Theoretical**	60	50	40	60	50	40	60	50	40
	Calculated	59.89	49.00	40.83	60.00	50.40	40.80	61.74	52.92	44.10

To achieve production as close as possible to the planned V_f, the required number of plies for each configuration was meticulously determined. After finalizing the ply numbers, each configuration was assigned a unique sample designation (ID). These unique identifiers will be used consistently for reporting all subsequent test studies, ensuring traceability and organization throughout the testing process. Detailed configuration information for both mechanical and ballistic test samples is essential for accurate analysis and comparison. The final configuration details for these samples, including number of plies, matrix type, matrix type, V_f, and spall liner panel thickness, are comprehensively listed in Table 4.3 and Table 4.4

Table 4.3. Configurations of mechanical test samples

Sample ID	Configuration	Matrix	Fiber	# of Ply	V_f (%)		Spall Liner Panel Thickness (mm)
					Theoretical	Calculated	
CFR-E-60	Epoxy_Carbon_60%	Epoxy	Carbon	18	60	61.3	4
CFR-E-50	Epoxy_Carbon_50%			15	50	51.0	
CFR-E-40	Expoxy_Carbon_40%			12	40	40.8	
GFR-E-60	Expoxy_Glass_60%		Glass	20	60	60.0	
GFR-E-50	Expoxy_Glass_50%			17	50	51.0	
GFR-E-40	Expoxy_Glass_40%			14	40	42.0	
AFR-E-60	Expoxy_Aramid_60%		Aramid	6	60	66.2	
AFR-E-50	Expoxy_Aramid_50%			5	50	55.1	
AFR-E-40	Expoxy_Aramid_40%			4	40	44.1	
CFR-V-60	Vinylester_Carbon_60%	Vinylester	Carbon	18	60	61.3	4
CFR-V-50	Vinylester_Carbon_50%			15	50	51.0	
CFR-V-40	Vinylester_Carbon_40%			12	40	40.8	
GFR-V-60	Vinylester_Glass_60%		Glass	20	60	60.0	
GFR-V-50	Vinylester_Glass_50%			17	50	51.0	
GFR-V-40	Vinylester_Glass_40%			14	40	42.0	
AFR-V-60	Vinylester_Aramid_60%		Aramid	6	60	66.2	
AFR-V-50	Vinylester_Aramid_50%			5	50	55.1	
AFR-V-40	Vinylester_Aramid_40%			4	40	44.1	
CFR-P-60	Polyester_Carbon_60%	Polyester	Carbon	18	60	61.3	4
CFR-P-50	Polyester_Carbon_50%			15	50	51.0	
CFR-P-40	Polyester_Carbon_40%			12	40	40.8	
GFR-P-60	Polyester_Glass_60%		Glass	20	60	60.0	
GFR-P-50	Polyester_Glass_50%			17	50	51.0	
GFR-P-40	Polyester_Glass_40%			14	40	42.0	
AFR-P-60	Polyester_Aramid_60%		Aramid	6	60	66.2	
AFR-P-50	Polyester_Aramid_50%			5	50	55.1	
AFR-P-40	Polyester_Aramid_40%			4	40	44.1	

Table 4.4. Configurations of ballistic test samples

Sample ID	Configuration	Matrix	Fiber	# of Ply	V_f (%)		Spall Liner Panel Thickness (mm)
					Theoretical	Calculated	
CFR-E-60	Epoxy_Carbon_60%	Epoxy	Carbon	22	60	59.9	5
CFR-E-50	Epoxy_Carbon_50%			18	50	49.0	
CFR-E-40	Expoxy_Carbon_40%			15	40	40.8	
GFR-E-60	Expoxy_Glass_60%		Glass	25	60	60.0	
GFR-E-50	Expoxy_Glass_50%			21	50	50.4	
GFR-E-40	Expoxy_Glass_40%			17	40	40.8	
AFR-E-60	Expoxy_Aramid_60%		Aramid	7	60	61.7	
AFR-E-50	Expoxy_Aramid_50%			6	50	52.9	
AFR-E-40	Expoxy_Aramid_40%			5	40	44.1	
CFR-V-60	Vinylester_Carbon_60%	Vinylester	Carbon	22	60	59.9	5
CFR-V-50	Vinylester_Carbon_50%			18	50	49.0	
CFR-V-40	Vinylester_Carbon_40%			15	40	40.8	
GFR-V-60	Vinylester_Glass_60%		Glass	25	60	60.0	
GFR-V-50	Vinylester_Glass_50%			21	50	50.4	
GFR-V-40	Vinylester_Glass_40%			17	40	40.8	
AFR-V-60	Vinylester_Aramid_60%		Aramid	7	60	61.7	
AFR-V-50	Vinylester_Aramid_50%			6	50	52.9	
AFR-V-40	Vinylester_Aramid_40%			5	40	44.1	
CFR-P-60	Polyester_Carbon_60%	Polyester	Carbon	22	60	59.9	5
CFR-P-50	Polyester_Carbon_50%			18	50	49.0	
CFR-P-40	Polyester_Carbon_40%			15	40	40.8	
GFR-P-60	Polyester_Glass_60%		Glass	25	60	60.0	
GFR-P-50	Polyester_Glass_50%			21	50	50.4	
GFR-P-40	Polyester_Glass_40%			17	40	40.8	
AFR-P-60	Polyester_Aramid_60%		Aramid	7	60	61.7	
AFR-P-50	Polyester_Aramid_50%			6	50	52.9	
AFR-P-40	Polyester_Aramid_40%			5	40	44.1	

4.2. Spall Liner Panel Manufacturing

A metal mould was initially designed using CATIA V5 Computer-Aided Design (CAD) software, a crucial step in the manufacturing process of RTM as shown in Figure 4.1. Al 5083, Aluminum alloy, was chosen as the mould material. The dimensions of the mould were carefully determined to allow for the production of a final specimen size of 500x500 mm. Additionally, in order to produce specimens with two different thicknesses, namely 4 mm and 5 mm, modifications were made to the mould design to accommodate the use of caul plates. A comprehensive structural analysis of the mould design was then conducted utilizing the ANSYS Computer-Aided Engineering (CAE) software to ensure its integrity and effectiveness in the RTM process.

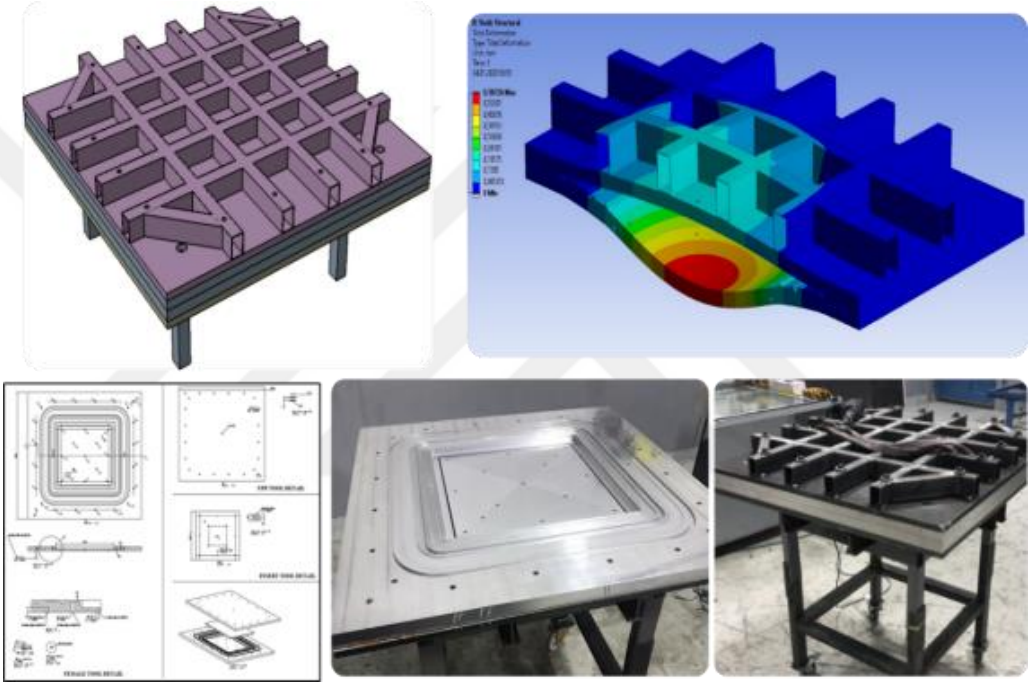


Figure 4.1. Development & manufacturing of RTM mould

Upon completion of the aforementioned procedures, a series of ballistic test specimens measuring 5 mm in thickness (refer to Figure 4.2) were methodically created using a specially designed mould. These specimens, characterized by their precise measurements of 500x500 mm, were meticulously crafted to align with the exacting standards required for conducting ballistics tests. The manufacturing process was conducted with great care to ensure that each individual specimen conformed to the specified criteria essential for obtaining accurate and reliable test results. Furthermore, apart from the creation of all configurations outlined in Table 4.3, supplementary spall liner panels were also manufactured to function as reference firing specimens during the ballistic firing trials. These reference spall liner panels play a crucial role in establishing the fundamental performance benchmarks and facilitating comparative assessments throughout the testing phase.

The comprehensive production of both the designated configurations and the reference spall liner panels plays a pivotal role in ensuring a thorough and exhaustive evaluation of the ballistic characteristics exhibited by the materials under investigation.

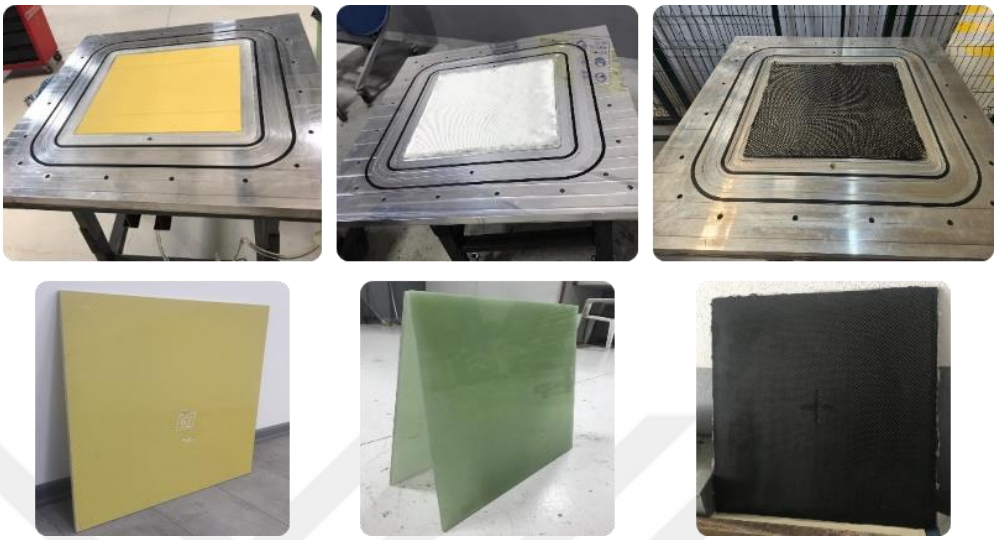


Figure 4.2. Manufacturing of ballistic test samples; aramid (left), glass (middle) & carbon (right)

Subsequently, the manufacturing of coupons (Figure 4.3) for mechanical tests was carried out. The mechanical test specimens were obtained from 4x500x500 mm plates by cutting them to the dimensions specified for each test using a water jet. This precise cutting method ensured that each specimen conformed to the required dimensions and maintained the integrity of the material properties, thereby providing reliable and consistent results during mechanical testing. The employment of water jet cutting further reduced the risk of potential damage or alterations to the samples, which is essential for acquiring precise test results.



Figure 4.3. Production of mechanical test coupons

4.3. Mechanical Test Results

The results of the tensile test, in-plane shear test, compression test, and three-point bending test are presented and evaluated in this section. These tests were conducted to evaluate the mechanical properties of composite specimens with varying fiber types, matrix type and V_f. The results and their implications are discussed in detail below.

4.3.1. Tensile Tests

As detailed in previous section, spall liner panels designed with various fiber types, resin types, and V_f were manufactured. From these spall liner panels; test coupons were prepared according to the standard procedures. The prepared specimens were subjected to tensile testing (Figure 4.4) using the Instron 8803 testing machine. According to the ASTM D3039/D3039M standard, the specimens were tested at a constant head displacement rate of 2 mm/min. This ensures a consistent strain rate, providing accurate measurements of tensile properties. The test results were analyzed and presented below, organized first by matrix, followed by fiber types, and lastly by V_f.

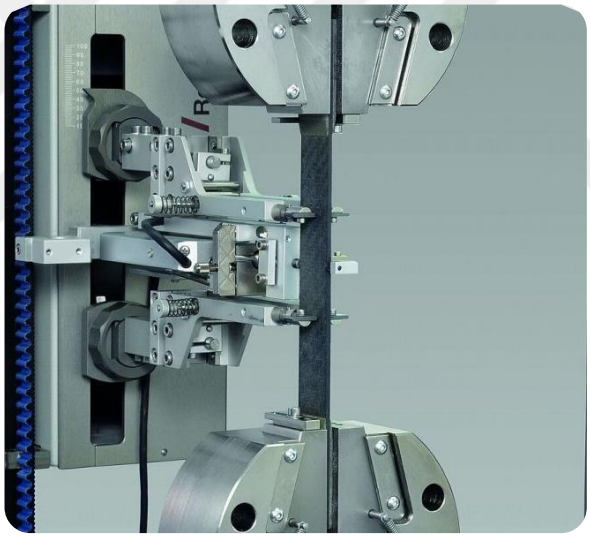


Figure 4.4. Tensile test in accordance with ASTM D3039/D3039M

Matrix Type vs Tensile Strength

Specimens with epoxy matrix having 40%, 50%, and 60% V_f using glass, aramid, and carbon fibers were subjected to tensile test, test specimens and the results are presented below in Figure 4.5 and Figure 4.6 respectively. As seen from Figure 4.6, Carbon Fiber-Reinforced Epoxy (CFR-E) composites exhibit the highest tensile strength among the tested materials. When the V_f increases from 40% to 60%, the tensile strength shows a significant improvement, rising from approximately 600 MPa to 700 MPa. This represents an approximate 16.7% increase in tensile strength. However, the elongation decreases with increasing V_f. This trend suggests that while the material becomes stronger, it also becomes less flexible. Aramid Fiber-Reinforced Epoxy (AFR-E) exhibit lower tensile strength compared to CFR-E but follow a similar trend. The tensile strength increases from about 400 MPa at 40% V_f to around 500 MPa at 60% V_f, indicating a 25% improvement. The decrease in elongation with higher V_f is observed here as well, demonstrating a decrease in ductility as the material becomes more fiber rich. Glass Fiber-Reinforced Epoxy (GFR-E) have the lowest tensile strength among the three types tested but still show significant improvements with increasing V_f. The tensile strength increases from around 300 MPa at 40% V_f to about 400 MPa at 60% V_f, indicating a 33.3% improvement. Similar to CFR-E and AFR-E, the elongation decreases as the V_f increases, indicating a reduction in flexibility. As a summary, the tensile strength increases by 16.7% for CFR-E, 25% for AFR-E, and 33.3% for GFR-E as the V_f increases from 40% to 60%.



Before test *After test*

Figure 4.5. Epoxy-based tensile test specimens, before & after test; CFR-E (left), GFR-E (middle) & AFR-E (right)

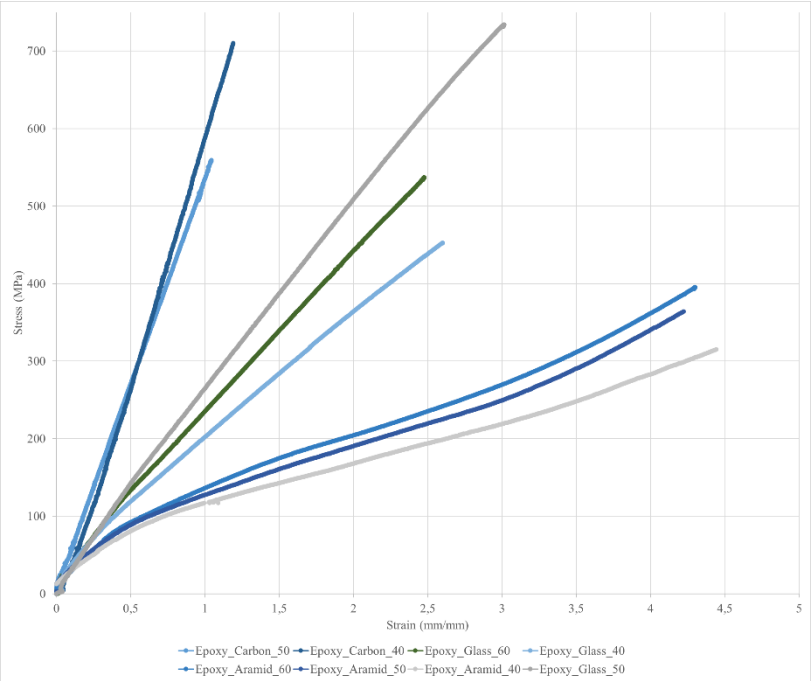


Figure 4.6. Strain – stress diagram of epoxy-based configurations

Vinylester matrix specimens having 40%, 50%, and 60% V_f using glass, aramid, and carbon fibers were subjected to tensile test, test specimens and the results are presented below in Figure 4.7 and Figure 4.8 respectively. The results indicate that Carbon Fiber-Reinforced Vinylester (CFR-V) composites exhibit the highest tensile strength among the tested materials. When the V_f increases from 40% to 60%, the tensile strength significantly improves. At 40% V_f, the tensile strength is about 500 MPa. This increases to approximately 550 MPa at 50% V_f and reaches about 600 MPa at 60% V_f. This represents a 10% increase from 40% to 50% V_f and another 9% increase from 50% to 60% V_f. Aramid Fiber-Reinforced Vinylester (AFR-V) exhibit lower tensile strength compared to CFR-V but follow a similar trend. The tensile strength increases from around 300 MPa at 40% V_f to approximately 400 MPa at 60% V_f. At 50% V_f, the tensile strength is about 350 MPa, indicating a 17% increase from 40% to 50% V_f and a 14% increase from 50% to 60% V_f. The elongation decreases as the fiber content increases, demonstrating reduced ductility at higher V_f. Glass Fiber-Reinforced Vinylester (GFR-V) present the lowest tensile strength among the three types tested, rising from approximately 200 MPa at 40% V_f to about 300 MPa at 60% V_f, with a tensile strength of around 250 MPa at 50% V_f. As a summary, the tensile strength increases by 20% for CFR-V, 33% for AFR-V, and 50% for GFR-V as the V_f increases from 40% to 60%.



Before test *After test*

Figure 4.7. Vinylester-based tensile test specimens, before & after test; CFR-V (left), GFR-V (middle) & AFR-V (right)

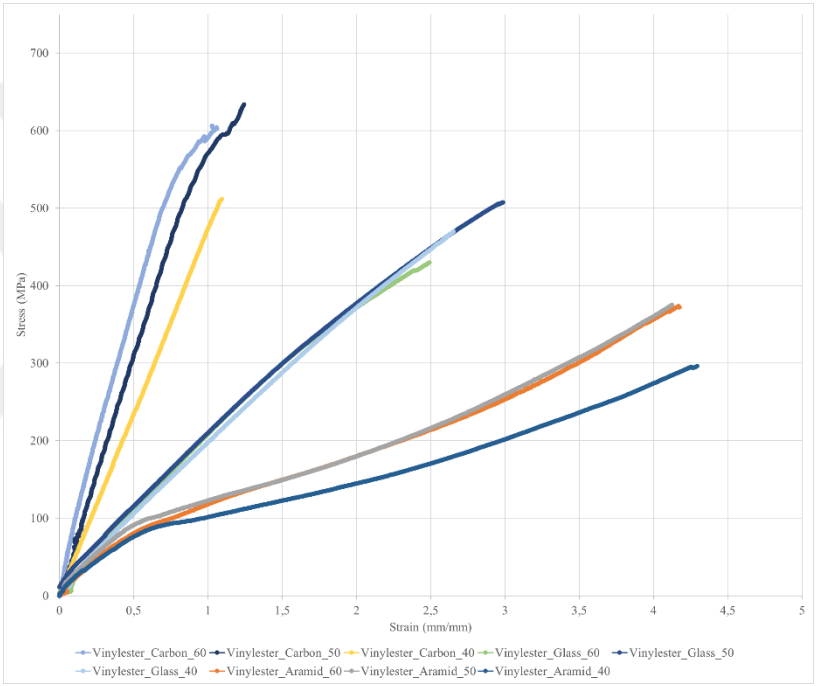


Figure 4.8. Strain – stress diagram of vinylester-based configurations

Polyester matrix specimens having 40%, 50%, and 60% V_f using glass, aramid, and carbon fibers were subjected to tensile test, test specimens and the results are presented below in Figure 4.9 and Figure 4.10 respectively. The tensile test results showed that Carbon Fiber-Reinforced Polyester (CFR-P) exhibit the highest tensile strength among the tested materials. At 40% V_f, the tensile strength is approximately 500 MPa. This increases to about 550 MPa at 50% V_f and reaches around 600 MPa at 60% V_f. This represents a 10% increase from 40% to 50% V_f and another 9% increase from 50% to 60% V_f. As with others, the elongation decreases with increasing V_f, indicating a stiffer and less ductile material at higher fiber contents. Aramid Fiber Reinforced Polyester (AFR-P) exhibit lower tensile strength compared to CFR-P but follow a similar trend. The tensile strength increases from approximately 300 MPa at 40% V_f to around 400 MPa at 60% V_f. At 50% V_f, the tensile strength is about 350 MPa, indicating a 17% increase from 40% to 50% V_f and a 14% increase from 50% to

60% V_f. Glass Fiber Reinforced Polyester (GFR-P) present the lowest tensile strength among the three types tested, increasing from 200 MPa at 40% V_f to around 300 MPa at 60% V_f, with a tensile strength of about 250 MPa at 50% V_f. Consequently, the tensile strength increases by 20% for CFR-P, 33% for AFR-P, and 50% for GFR-P as the V_f increases from 40% to 60%.



Before test *After test*

Figure 4.9. Polyester-based tensile test specimens, before & after test; CFR-P (left), GFR-P (middle) & AFR-P (right)

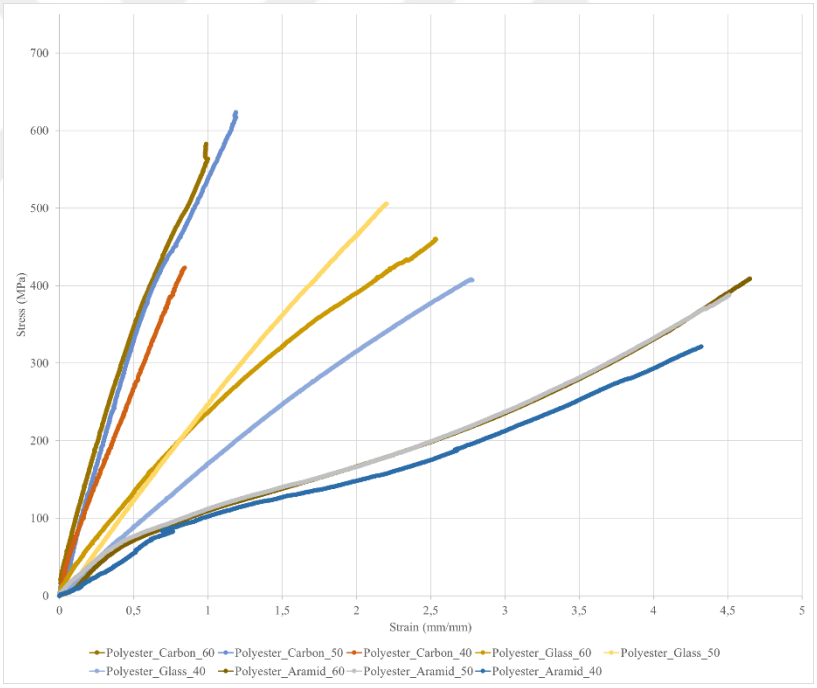


Figure 4.10. Strain – stress diagram of polyester-based configurations

Fiber Type vs Tensile Strength

Specimens with 40%, 50%, and 60% V_f of CFR using different matrix materials were subjected to tensile testing. Results in Figure 4.11 show that CFR-E exhibit the highest tensile strength. CFR-E is 600 MPa at 40% V_f, rising to 650 MPa at 50% V_f. CFR-V is around 500 MPa at 40% V_f, increasing to about 550 MPa at 50% V_f and reaching 600 MPa at 60% V_f, showing 10% and 9% increases at each stage. CFR-P also showed notable tensile strength, with values increasing from 500 MPa at 40% V_f to 600 MPa at 60% V_f. Tensile strength increased by 8.3% for CFR-E, 19% for CFR-V, and 19% for CFR-P as V_f increased from 40% to 60%, as shown in Figure 4.11.

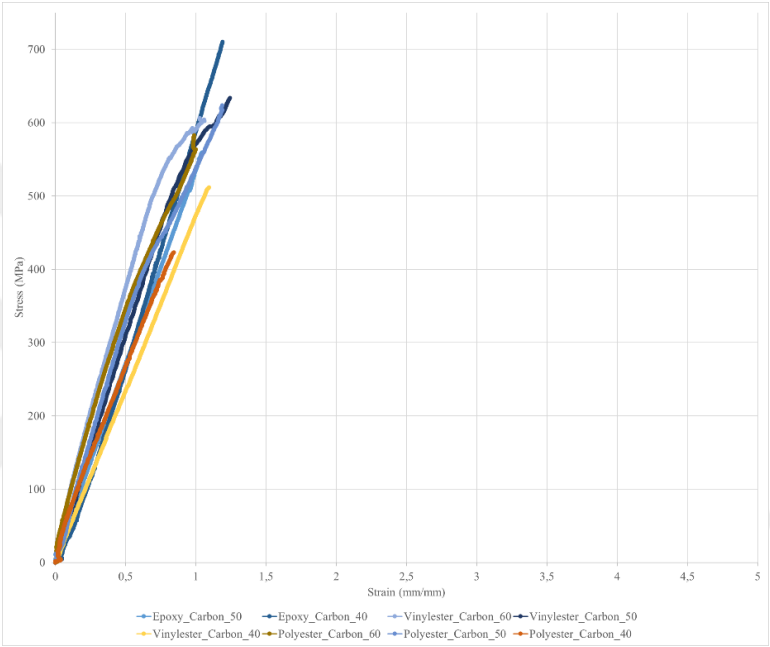


Figure 4.11. Strain – stress diagram of carbon-fiber-based configurations

Specimens with varying V_f of GFR in different matrices underwent tensile tests. Results in Figure 4.12 show that GFR-E exhibit highest tensile strength. GFR-E showed 12.5% increase from 40% to 50% V_f and 11.1% increase from 50% to 60% V_f. GFR-V has significant strength with 16.7% increase from 40% to 50% V_f and 14.3% increase from 50% to 60% V_f. GFR-P also exhibited notable strength with 20% increase from 40% to 50% V_f and 16.7% increase from 50% to 60% V_f. Overall, tensile strength increased by approximately 25% for GFR-E, 33% for GFR-V, and 40% for GFR-P from 40% to 60% V_f.

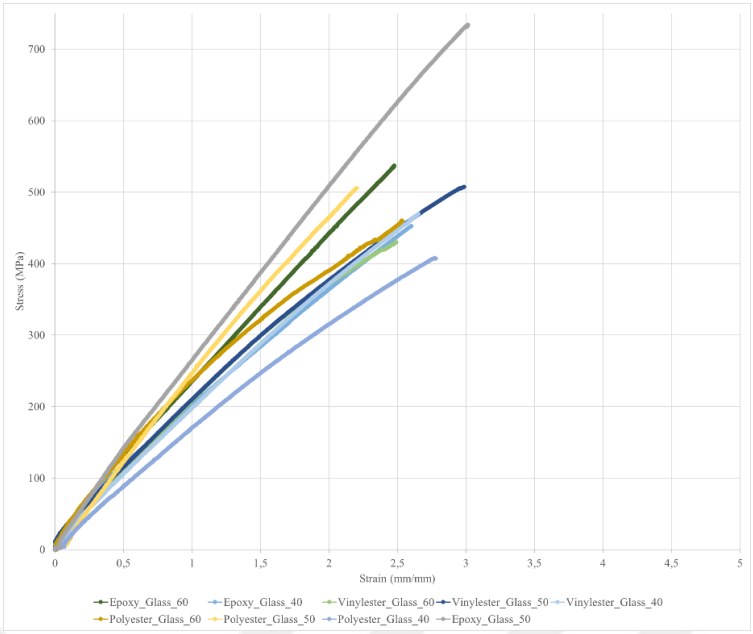


Figure 4.12. Strain – stress diagram of glass-fiber-based configurations

Specimens containing 40%, 50%, and 60% V_f of AFR using three different matrices underwent tensile test, with the outcomes depicted in Figure 4.13. The results of the tensile test demonstrated that AFR-E exhibited relatively high tensile strength. Specifically, the assessment at 40% V_f has approximately 300 MPa, subsequently increasing to nearly 350 MPa at 50% V_f and further rising to almost 400 MPa at 60% V_f. AFR-V also exhibited considerable tensile strength, showing a 20% enhancement from 40% to 50% V_f and an additional 16.7% increase from 50% to 60% V_f. Similarly, AFR-P demonstrated remarkable tensile strength. Consequently, the tensile strength increases by approximately 33% for AFR-E, 40% for AFR-V, and 50% for AFR-P as the V_f increases from 40% to 60%.

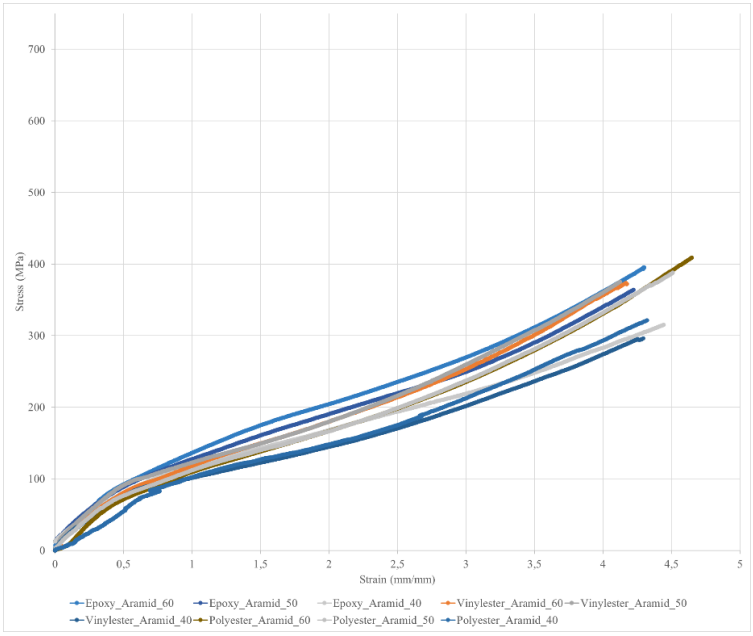


Figure 4.13. Strain – stress diagram of aramid-fiber-based configurations

4.3.2. In-plane Shear Tests

As previously stated, spall liner panels were manufactured using various fiber types, resin types, and V_f. Then, test coupons were prepared in accordance with established standard procedures. The fabricated specimens underwent in-plane shear testing on a ±45° laminate using an Instron 8803 testing machine (Figure 4.14) in compliance with the ASTM D3518/D3518M standard.

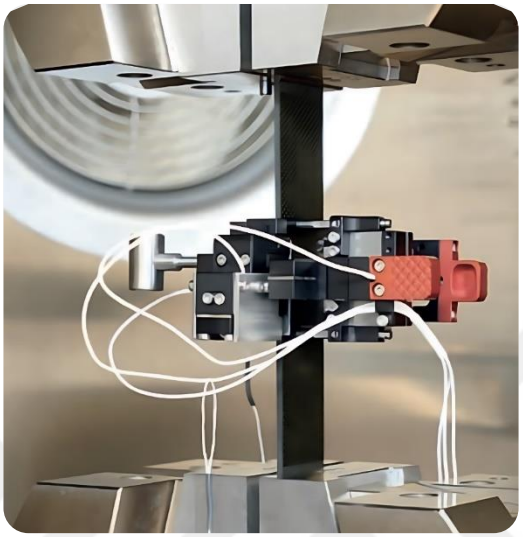


Figure 4.14. In-plane shear test in accordance with ASTM D3518/D3518M

Matrix Type vs In-plane Shear Strength

Specimens with V_f of 40%, 50%, and 60% were tested with different fiber types in an epoxy matrix. The test results for these specimens are detailed in Figures 4.15 and 4.16 successively. Figure 4.16 illustrates the relationship between V_f and Shear Strength for carbon, glass, and aramid fibers in an epoxy matrix. For CFR-E, shear strength increases to 108.52 MPa at max V_f, a surge of 37.5% from 40% V_f. GFR-E shows varying shear strength: 79.59 MPa at 40%, 81.42 MPa at 50% (2.3% increase), and 95.04 MPa at 60% V_f (19.4% increase). GFR-E has slight shear strength increases with V_f rise. AFR-E has significant shear strength changes with V_f, 78.92 MPa at 40%, 103.03 MPa at 50% V_f (30.6% increase). These findings indicate that AFR offer the most substantial enhancement in shear strength when integrated into an epoxy matrix, followed by CFR, and lastly GFR.



Before test *After test*

Figure 4.15. Epoxy-based shear test specimens, before & after test; CFR-E (left), GFR-E (middle) & AFR-E (right)

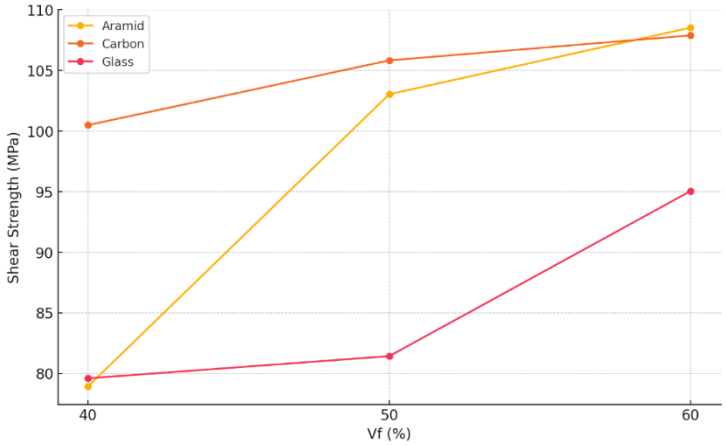
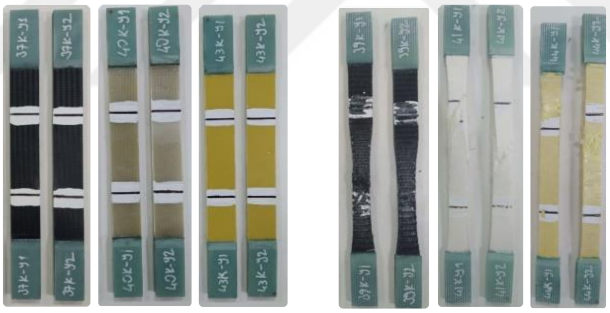


Figure 4.16. Shear strength – V_f diagram of epoxy-based configurations

Specimens containing vinylester matrix with different V_f using glass, aramid, and carbon fibers were subjected to shear testing, with the outcomes presented in Figure 4.17 and Figure 4.18. The study compares the shear strength of different fiber-reinforced composites (AFR, GFR, and CFR) at varying V_f. Results show that AFR provides the highest enhancement in shear strength in the vinylester matrix, followed by GFR and then CFR. Shear strength increases as V_f increases, with AFR showing the most significant improvements compared to GFR and CFR at 50% and 60% V_f levels.



Before test *After test*

Figure 4.17. Vinylester-based shear test specimens, before & after test; CFR-V (left), GFR-V (middle) & AFR-V (right)

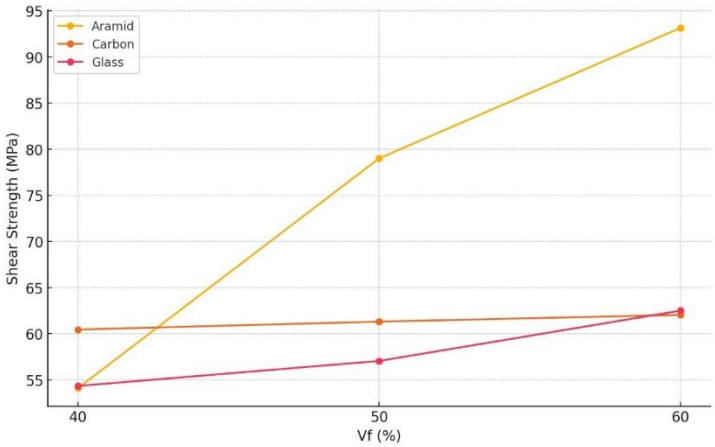
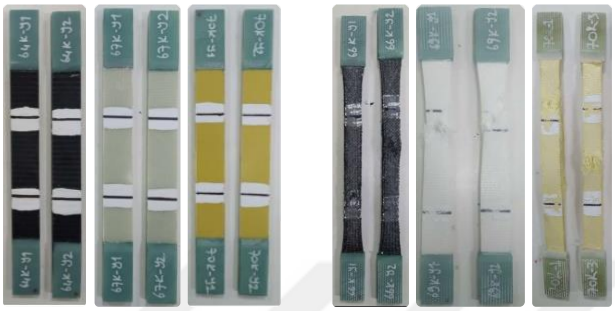


Figure 4.18. Shear strength – V_f diagram of vinylester-based configurations

Specimens with varying V_f of glass, aramid, and carbon fibers in the polyester matrix were tested for shear strength. Results, presented in Figure 4.19 and Figure 4.20 showed that CFR-P has a 12.8% increase in shear strength from 40% to 50% V_f, and a 20.5% increase at 60% V_f. GFR-P has a moderate increase, while AFR-P showed the most significant enhancement, with a 74.7% increase at 60% V_f. The findings indicate that AFR shows the highest enhancement in shear strength upon incorporation into polyester matrix, followed by CFR, and GFR exhibiting the lowest effect.



Before test *After test*

Figure 4.19. Polyester-based shear test specimens, before & after test; CFR-P (left), GFR-P (middle) & AFR-P (right)

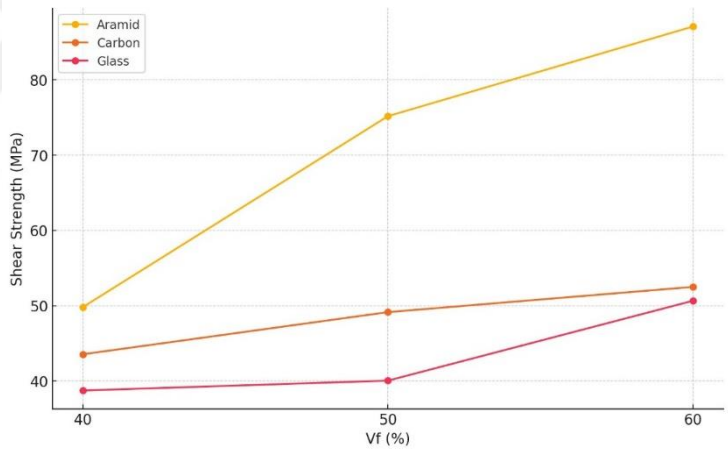


Figure 4.20. Shear strength - V_f diagram of polyester-based configurations

Fiber Type vs In-plane Shear Strength

Specimens with varying V_f percentages for CFR with different matrix materials were tested for shear strength. Results showed an increase in shear strength with higher V_f for CFR-E, CFR-V, and CFR-P (Figure 4.21). The study suggests that incorporating CFR leads to significant improvement in shear strength of the polyester matrix with increasing V_f. The impact of carbon fibers on enhancing shear strength depends on the type of matrix used, with optimal performance in an epoxy matrix, followed by polyester matrix, and least effectiveness in the vinylester matrix.

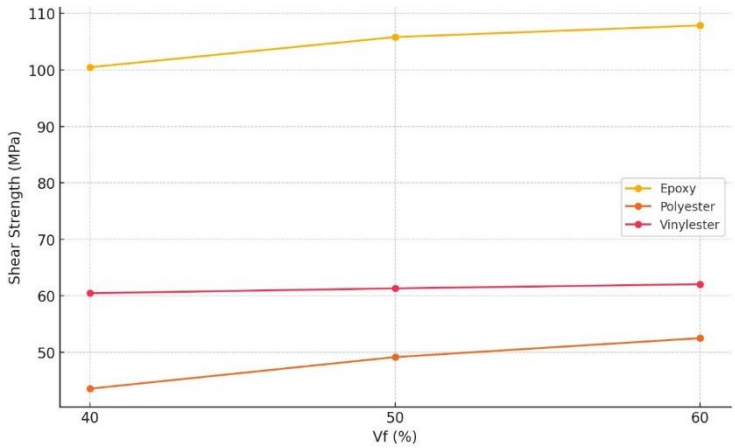


Figure 4.21. Shear strength - V_f diagram of carbon fiber-based configurations

Specimens with different V_f of GFR and matrices were subjected shear testing, with results shown in Figure 4.22. Shear strength for GFR-E increased progressively from 79.59 MPa at 40% V_f to 95.04 MPa at 60%, indicating significant reinforcement of epoxy matrix. GFR-V has shear strengths of 54.35 MPa at 40%, 57.06 MPa at 50%, and 62.51 MPa at 60% V_f. GFR-P showed shear strengths of 38.75 MPa at 40%, 41.05 MPa at 50%, and 50.66 MPa at 60% V_f, highlighting a notable enhancement in polyester matrix's shear strength. The effectiveness of GFR in enhancing shear strength varies based on the matrix material, being most effective in epoxy, followed by polyester, and least effective in vinylester.

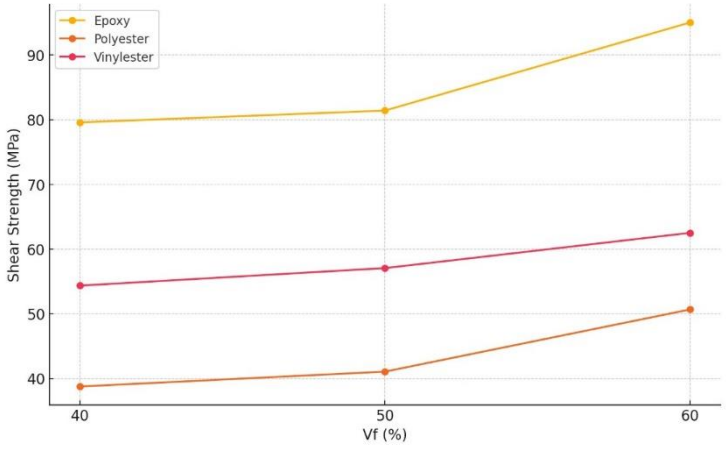


Figure 4.22. Shear strength - V_f diagram of glass fiber-based configurations

Specimens with different V_f's of AFR in various matrices were tested under shear conditions, with results shown in Figure 4.23. AFR-E showed increasing shear strength from 78.92 MPa to 108.52 MPa at 40%, 50%, and 60% V_f respectively. AFR-V displayed shear strengths of 54.11 MPa, 79.01 MPa, and 93.14 MPa at corresponding V_f levels. AFR-P exhibited shear strengths of 49.82 MPa, 75.15 MPa, and 87.05 MPa at 40%, 50%, and 60% V_f respectively. The study indicates that AFR enhances shear strength in polyester matrices based on V_f. The effectiveness of AFR in improving shear strength varies with the type of matrix, being highest in epoxy, lower in polyester, and least in vinylester.

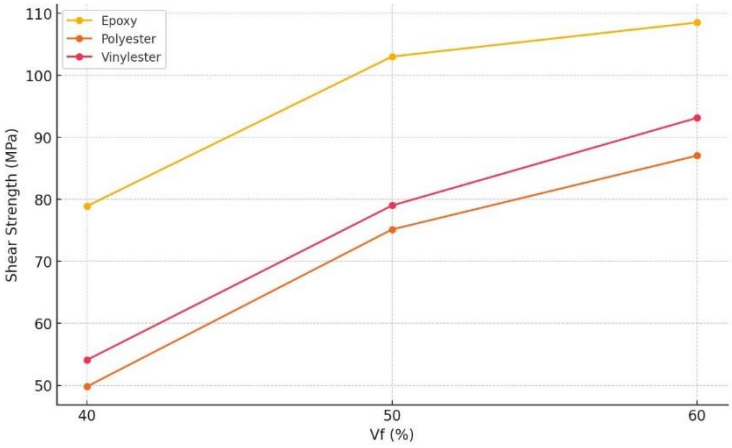


Figure 4.23. Shear strength - V_f diagram of aramid fiber-based configurations

4.3.3. Compression Tests

The test specimens were prepared following the guidelines outlined in the ASTM D6641/D6641M standard and were subjected to compression testing using an Instron 5892 Compression testing machine with a Combined Loading Compression (CLC) test fixture (Figure 4.24).



Figure 4.24. Compression test in accordance with ASTM D6641/D6641M

Matrix Type vs Compressive Strength

A series of compressive experiments were conducted to assess the performance of specimens with varying V_f when reinforced with different fiber types within an epoxy matrix. The results are presented in detail in Figures 4.25 and 4.26. The CFR-E specimen with maximum V_f exhibited a compressive strength of 520 MPa, which is slightly higher than that of the specimen with 40% V_f (510 MPa), indicating an increase in strength of 1.96%. There is a notable enhancement in compressive strength as the V_f increases from 40% to 60% for GFR-E. AFR-E demonstrates a steady compressive strength of approximately 100 MPa for all V_f percentages. These findings indicate that CFR offers the highest and most stable compressive strength when integrated into an epoxy matrix, followed by GFR, which shows notable improvements with increased V_f. AFR-E, while stable, provides the lowest compressive strength among the tested fibers.



Before test *After test*

Figure 4.25. Epoxy-based compression test specimens, before & after test; CFR-E (left), GFR-E (middle) & AFR-E (right)

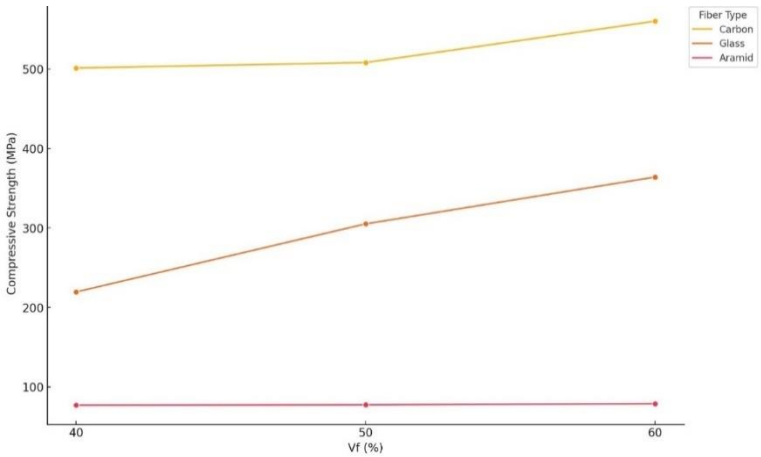
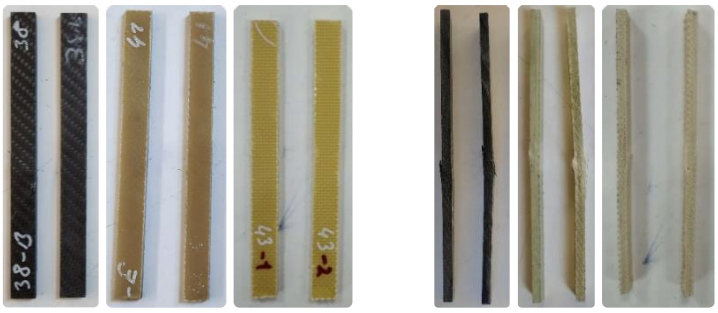


Figure 4.26. Compressive strength – V_f diagram of epoxy-based configurations

Specimens with varying V_f of 40%, 50%, and 60% were tested using different types of fibers in the vinylester matrix. Results, illustrated in Figure 4.27 and Figure 4.28, showed that CFR-V exhibited consistent high compressive strength, with a 6.67% increase from 40% to 60% V_f. GFR-V showed a significant improvement in compressive strength with increasing V_f, with increments of 25% and 62.5%, indicating a strong positive relationship between fiber content and compressive

strength. AFR-V specimens consistently have a lower compressive strength for all V_f tested, suggesting AFR provide a consistent but lower strength compared to CFR and GFR in vinylester matrices. These results suggest that CFR-V demonstrated the highest compressive strength, followed by GFR-V with notable enhancements, while AR-V presented the lowest among the fibers evaluated.



Before test *After test*

Figure 4.27. Vinylester-based compression test specimens, before & after test; CFR-V (left), GFR-V (middle) & AFR-V (right)

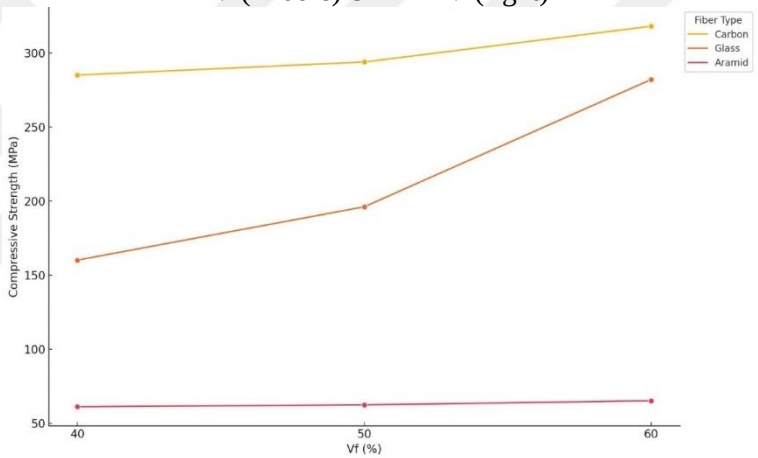
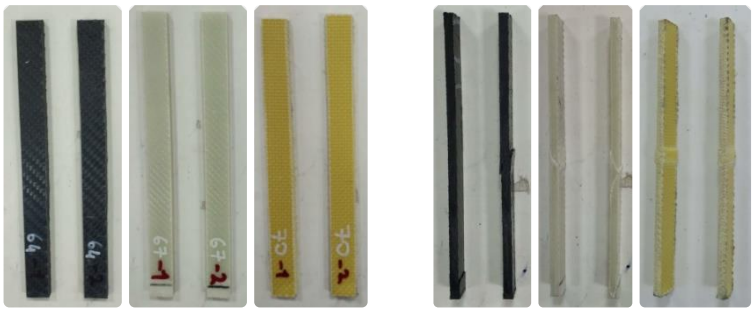


Figure 4.28. Compressive strength – V_f diagram of vinylester-based configurations

Specimens with different V_f percentages were tested using different fibers in the polyester matrix. Results are shown in Figure 4.29 and Figure 4.30. For CFR-P, compressive strength at maximum V_f is around 300 MPa, a significant increase from 250 MPa at 40%. GFR-P also shows improved compressive strength with higher V_f percentages 150 MPa at 40%, 180 MPa at 50%, and 250 MPa at 60% V_f. AFR-P consistently has a compressive strength of about 50 MPa for all V_f tested. CFR provides the most enhancement in compressive strength in polyester matrix, followed by GFR. AFR-P has the least compressive strength among the fibers tested.



Before test *After test*

Figure 4.29. Polyester-based compression test specimens, before & after test; CFR-P (left), GFR-P (middle) & AFR-P (right)

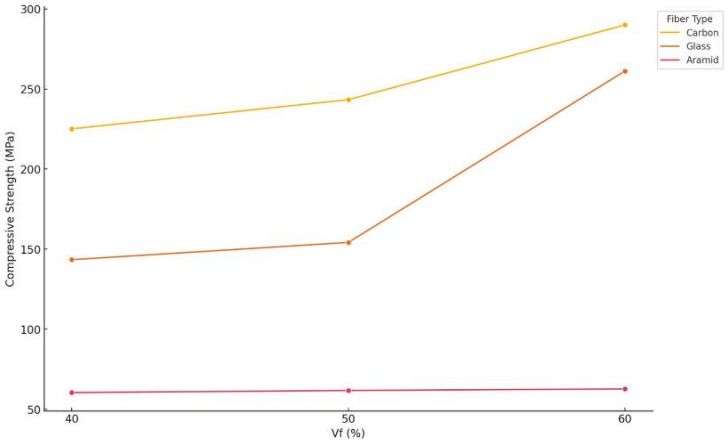


Figure 4.30. Compressive strength - V_f diagram of polyester-based configurations

Fiber Type vs Compressive Strength

Specimens with V_f of 40%, 50%, and 60% were tested with CFR for different matrix types: epoxy, vinylester, and polyester. The test specimens and their corresponding results are outlined in the Figure 4.31. CFR in an epoxy matrix demonstrates the highest compressive strength, with reaching approximately 550 MPa at maximum V_f. The compressive strength remains high for all V_f levels, showing a 5.77% increase from 40% to 60% V_f. In contrast, CFR in the vinylester matrix experiences a noticeable decline, with values dropping to around 350 MPa at 60% V_f. CFR in the polyester matrix shows even lower compressive strength values overall, with values around 300 MPa at 60% V_f. These findings suggest that epoxy matrix offer the highest compressive strength with CFR, followed by vinylester and polyester matrix.

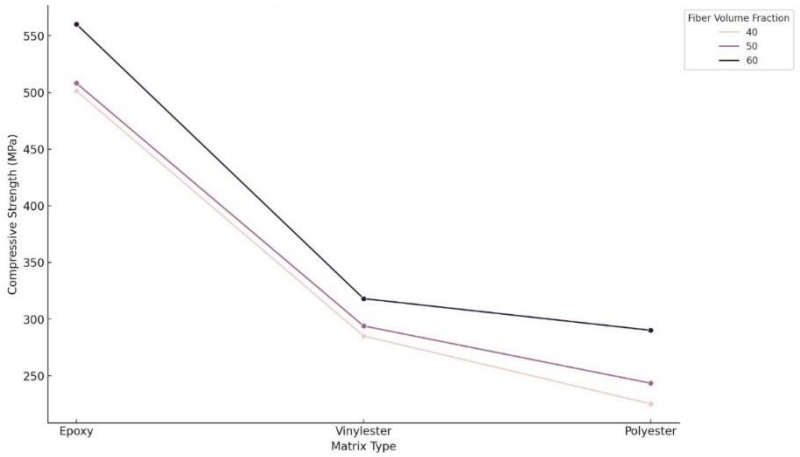


Figure 4.31. Compressive strength - V_f diagram of carbon fiber-based configurations

Specimens with varying V_f percentages were tested with GFR using different matrix types: epoxy, vinylester, and polyester, with results detailed in Figure 4.32. In GFR-E, compressive strength peaks at 60% V_f with approximately 350 MPa, showing a 75% increase from 40% V_f. GFR-V exhibits decreasing compressive strength from 60% to 40% V_f, with drops of 20% and 40% in strength, respectively. GFR-P demonstrates the lowest compressive strength values among tested matrices, showing drops of 25% and 50% from 60% to 40% V_f. These findings suggest that GFR significantly enhances compressive strength in an epoxy matrix, followed by vinylester and polyester matrices.

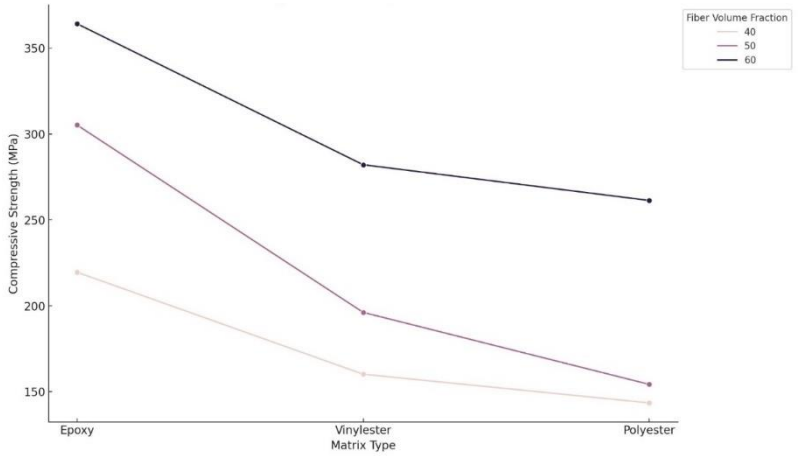


Figure 4.32. Compressive strength - V_f diagram of glass fiber-based configurations

Specimens with varying V_f of AFR were tested with epoxy, vinylester, and polyester matrices. The results are outlined in the Figure 4.33. For the maximum V_f, AFR-E exhibits compressive strength of approximately 77.5 MPa. It is around 75 MPa at 50% and about 72.5 MPa at 40% V_f. The trend indicates a 6.9% increase in compressive strength from 40% to 60% V_f, suggesting that higher V_f enhances compressive strength slightly in an epoxy matrix. In the case of AFR-V, compressive strength decreases significantly. At 60%, it is 65 MPa, reducing to about 62.5

MPa at 50%, and further to 60 MPa at 40% V_f. These values show reductions of 4% and 8%, respectively. Vinylester matrix offer moderate compressive strength with AFR but are less effective than epoxy matrix at higher fiber content levels in maintaining compressive strength. These reductions are 4.2% and 8.3%, respectively, which indicate that AFR-P displays a comparatively weaker performance in terms of compressive strength when compared to epoxy and vinylester matrices.

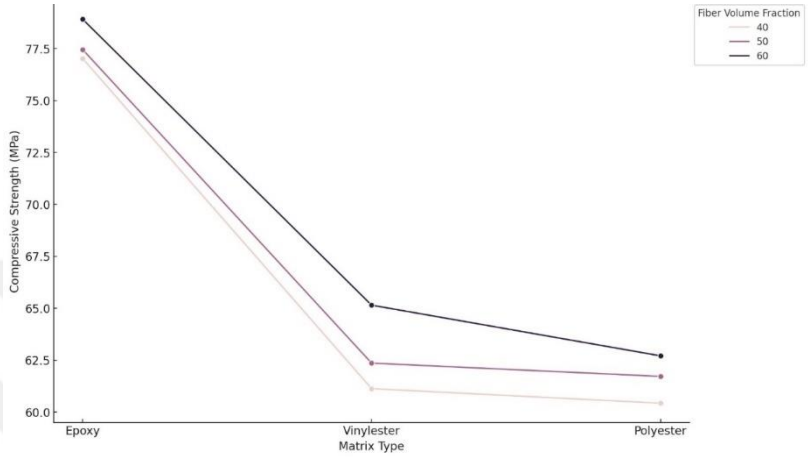


Figure 4.33. Compressive strength - V_f diagram of aramid fiber-based configurations

4.3.4. Three-Point Bending Tests

Spall liner panels were manufactured by employing a variety of fiber types, matrix types, and V_f. Subsequently, test specimens were prepared following the guideline outlined in ASTM D7264/D7264M standard. These specimens were then subjected to a flexural strength test using a three-point loading principle on an Instron 5982 testing machine (Figure 4.34). The results are firstly evaluated according to matrix type, then fiber type and finally V_f and presented below.

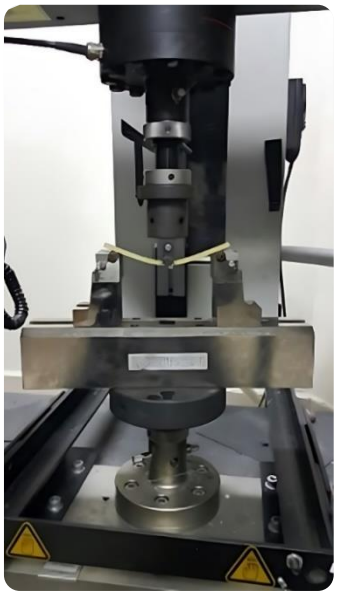


Figure 4.34 Three-point bending test in accordance with ASTM D7264/D7264M

Matrix Type vs Flexural Strength

Epoxy matrix specimens with 40%, 50% and 60% V_f values prepared by using glass, aramid and carbon fibers were subjected to flexural tests, and the test specimens and results are presented in Figures 4.35 and 4.36, respectively. CFR-E exhibited the highest flexural strength. The force demonstrated an increase from 500 N at 40% to 850 N at 60% V_f. As V_f increased, the material displayed a tendency towards greater hardness and a reduction in ductility. AFR-E specimens exhibited lower flexural strength compared to CFR-E but followed a similar trend. GFR-E presented the lowest flexural strength among the three types tested. Consequently, the flexural strength increases by 70% for CFR-E, 100% for AFR-E, and 125% for GFR-E as the V_f increases from 40% to 60%. The study shows that CFR-E has the highest flexural strength, then followed by AFR-E and GFR-E. All materials show increased flexural strength as V_f increases.



Before test *After test*

Figure 4.35. Epoxy-based flexural test specimens, before & after test; CFR-E (left), GFR-E (middle) & AFR-E (right)

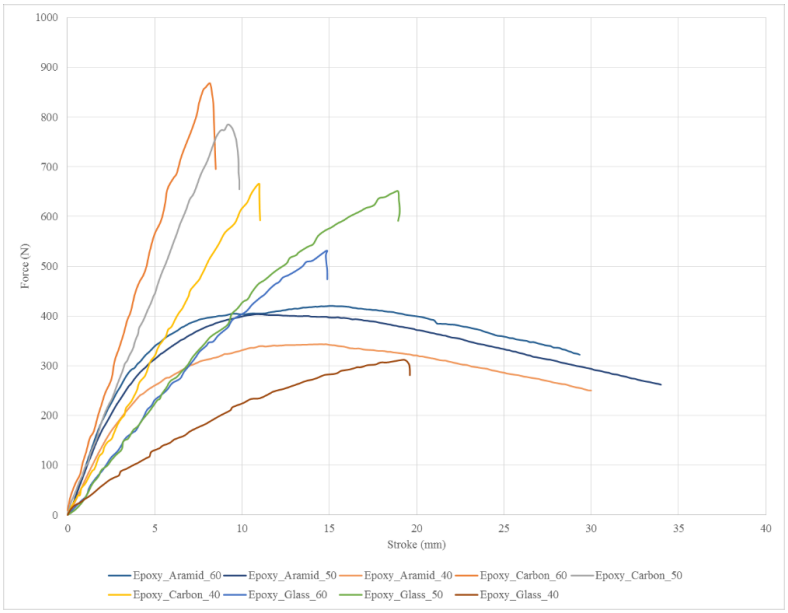


Figure 4.36. Force – stroke diagram of epoxy-based configurations

Vinylester matrix specimens with V_f of 40%, 50%, and 60% using glass, aramid, and carbon fibers were subjected to flexural tests. The test specimens and the results are presented in the Figure 4.37 and Figure 4.38. The flexural strength of CFR-V has the highest of the materials tested, reaching 350 N at 40%, 500 N at 50% and peaking at 600 N at 60% V_f. AFR-V has lower flexural strength than CFR-V but followed a similar trend, increasing from 300 N at 40% to 400 N at 50% and 550 N at 60% V_f. GFR-V showed the lowest flexural strength with a 50% increase from 40% to 50% V_f and a 16.7% increase from 50% to 60% V_f. As V_f increased from 40% to 60%, the flexural strength increased by 71.4% for CFR-V, 83.3% for AFR-V and 75% for GFR-V.



Before test *After test*

Figure 4.37. Vinylester-based flexural test specimens, before & after test; CFR-E (left), GFR-E (middle) & AFR-E (right)

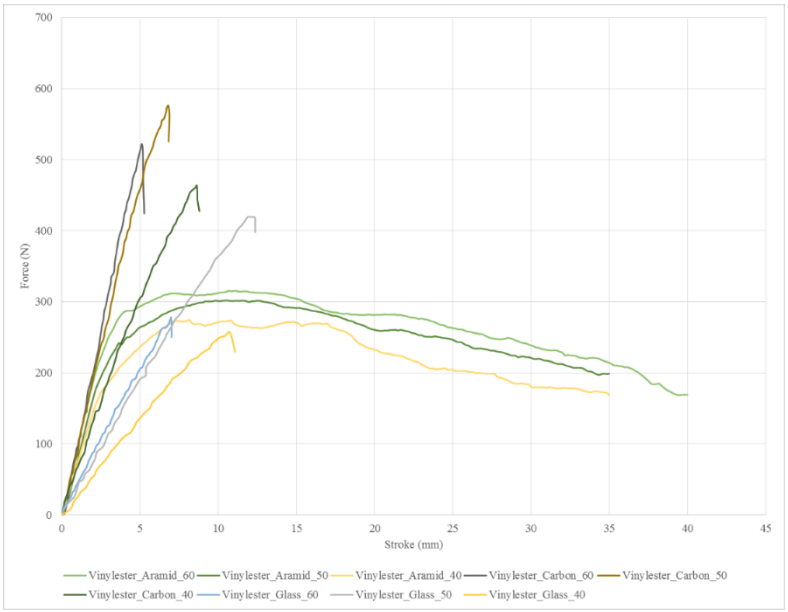


Figure 4.38. Force – stroke diagram of vinylester-based configurations

Flexural tests were conducted on polyester matrix specimens with varying V_f (40%, 50%, and 60%) reinforced with glass, aramid, and carbon fibers. The test specimens and the corresponding results are presented in Figures 4.39 and 4.40. The flexural strength of CFR-P has the highest among

tested materials. At 40% V_f, the force reached about 300 N, then increased to 500 N at 50% V_f and reached 700 N at 60% V_f. AFR-P specimens exhibited lower flexural strength compared to CFR-P but followed a similar trend. GFR-P showed the lowest flexural strength of the three types tested. The flexural strength increased from 100 N at 40% V_f to 200 N at 50% V_f and approximately 350 N at 60% V_f. Consequently, the flexural strength increases significantly with increasing V_f, CFR-P by 133.3%, AFR-P by 200%, and GFR-P by 250%. These findings indicate that CFR-P offers the highest flexural strength, followed by AFR-P and GFR-P, all materials show improved flexural strength with higher V_f.

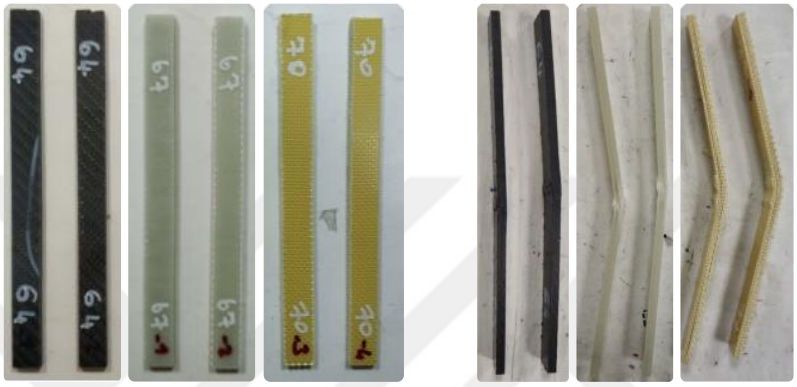


Figure 4.39. Polyester-based flexural test specimens, before & after test; CFR-E (left), GFR-E (middle) & AFR-E (right)

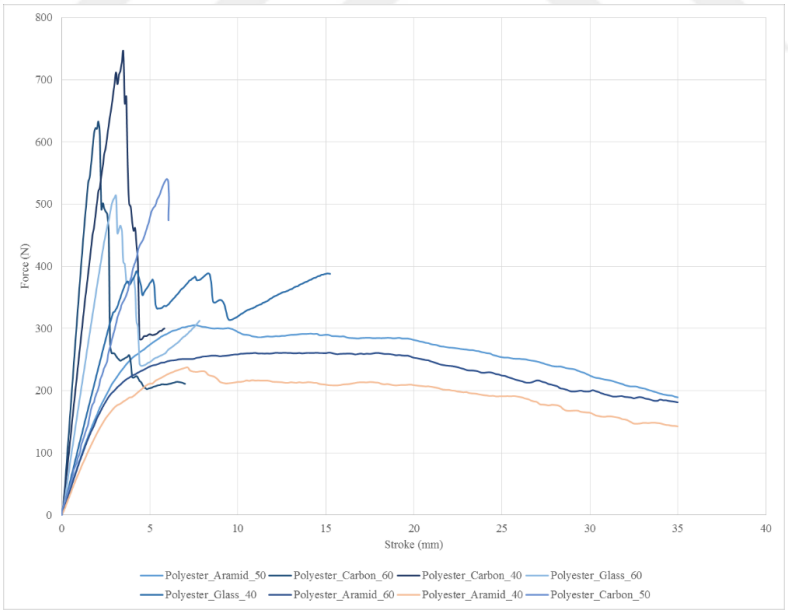


Figure 4.40. Force – stroke diagram of polyester-based configurations

Fiber Type vs Flexural Strength

Carbon fiber-reinforced composite specimens with epoxy, vinylester and polyester matrices at 40%, 50% and 60% V_f values were tested using flexural tests, and the results are shown in Figure 4.41. The flexural strength of CFR-E has highest compared to other materials tested. The maximum force at 40% V_f is 600 N, increasing to 700 N at 50% V_f, and peaking at around 800 N at 60% V_f. CFR-V specimens have lower flexural strength compared to CFR-E but has a similar trend, increasing from 300 N at 40% V_f to 500 N at 60% V_f CFR-P has the lowest flexural strength, ranging from about 200 N at 40% V_f to 450 N at 60% V_f. These findings indicate that CFR-E offers the highest flexural strength, followed by CFR-V and CFR-P.

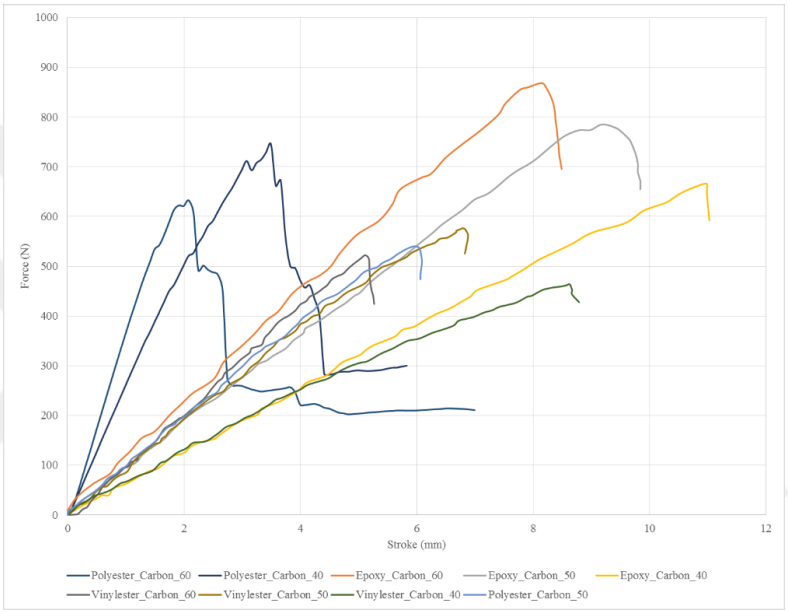


Figure 4.41. Force – stroke diagram of carbon-fiber-based configurations

Glass fiber-reinforced composite specimens with different matrix types and V_f were subjected to flexural test. Results are shown in Figure 4.42. GFR-E has the highest flexural strength with force reaching 350 N at 40%, 450 N at 50%, and 600 N at 60% V_f. GFR-V has lower strength, increasing from 200 N at 40% to 300 N at 50%, and around 400 N at 60% V_f. GFR-P exhibited the lowest strength, increasing from 100 N at 40% to 200 N at 50%, and approximately 300 N at 60% V_f. Consequently, the flexural strength increases by 71.4% for GFR-E, 100% for GFR-V, and 200% for GFR-P as the V_f increases from 40% to 60%. These findings indicate that GFR-E offers the highest flexural strength, followed by GFR-V and GFR-P, and all materials exhibit significant improvement in flexural strength with increasing V_f.

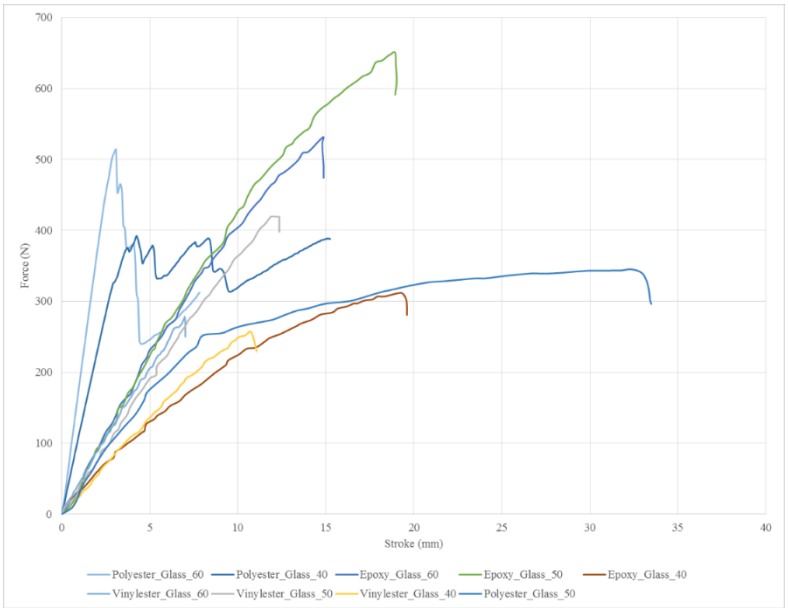


Figure 4.42. Force – stroke diagram of glass-fiber-based configurations

Aramid fiber-reinforced composite specimens with different matrix types and varying V_f percentages underwent flexural test, with results shown in Figure 4.43. AFR-E has the highest flexural strength among materials tested, with maximum forces of 350 N at 40% V_f, 375 N at 50%, and 425 N at 60%. The data indicates that increasing V_f leads to stiffer and less ductile material properties. AFR-V specimens have lower flexural strength than AFR-E but showed a similar trend, with strengths of 250 N at 40% V_f, 275 N at 50%, and around 300 N at 60%. AFR-P has the lowest flexural strength among the tested materials. Consequently, flexural strength increased by 21.4% for AFR-E, 20% for AFR-V, and 25% for AFR-P as V_f increased from 40% to 60%. These results suggest that AFR-E provides the highest flexural strength, followed by AFR-V and AFR-P.

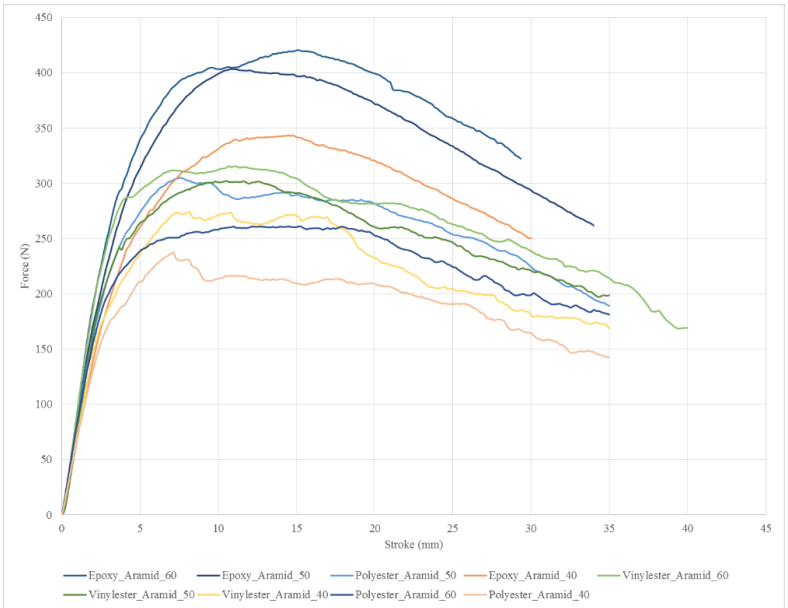


Figure 4.43. Force – stroke diagram of aramid-fiber-based configurations

4.4. Ballistics Test Results

Ballistics tests were conducted to determine the V_{50} ballistic limit of each configuration. The test included warm-up firings for constant velocity, yaw measurements, and subsequent firings to achieve a combination of partial and complete penetrations. The V_{50} ballistic limit was calculated as the arithmetic mean of the four highest partial and the four lowest complete penetration velocities.

In this section, firstly, the graphs showing the V_{50} of each configuration and the photographs of the test specimens after ballistic firing test (front and back side) are given respectively. Then the results are presented based on fiber type, matrix type, and V_f to determine the impact of each parameter on ballistic performance.

The V_{50} for the CFR-E-60 was calculated by conducting a series of ballistics tests with sixteen shots. The arithmetic mean of the four highest partial penetration velocities and the four lowest complete penetration velocities was used to determine the V_{50} is 547.27 m/s. CFR-E-60 demonstrates a significant V_{50} ballistic limit, indicative of its high impact resistance due to the robust combination of epoxy matrix and carbon fibers at a 60% V_f. The V_{50} in Figure 4.44 highlights the configuration's effectiveness in absorbing and dissipating energy from ballistic impacts. Post-test images (Figure 4.45) reveal the damage patterns on both the front and back faces, showing localized delamination and fiber breakage, typical of high-performance composites under ballistic stress.

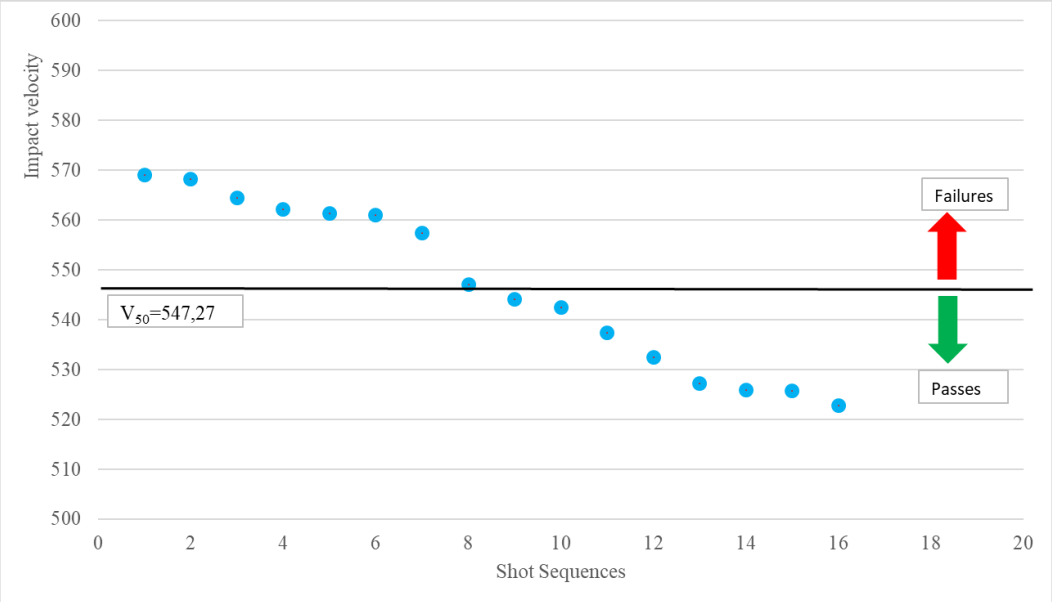


Figure 4.44. Number of shoots & V_{50} of CFR-E-60

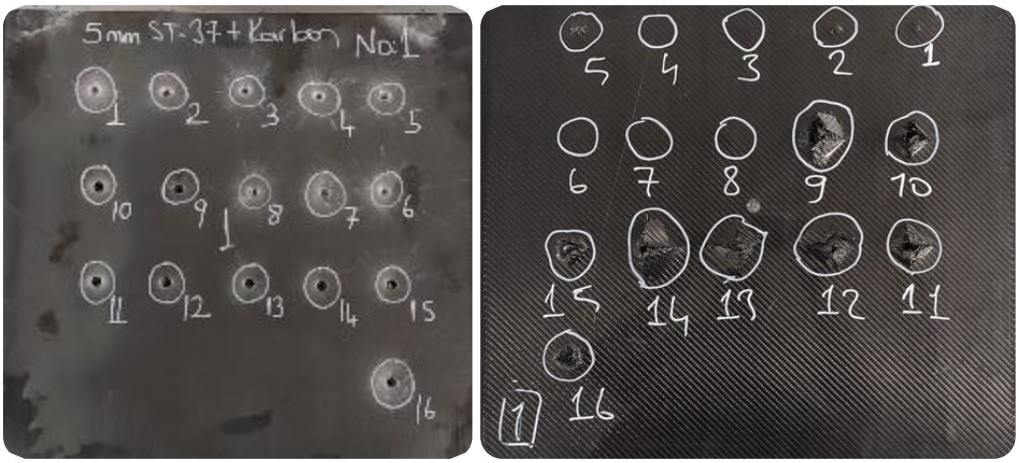


Figure 4.45. After test CFR-E-60, front-face (left) & back-face (right)

The V_{50} of CFR-E-50 is determined as 529.46 m/s through ballistics tests with ten shots. The CFR-E-50 with a 50% V_f, displays a slightly lower V_{50} compared to the 60% counterpart, as seen in Figure 4.46. This reduction in fiber content may result in diminished energy absorption and distribution capabilities. The post-test images (Figure 4.47) illustrate more pronounced damage, with larger delaminated areas and visible fiber pull-out. Despite these damages, the epoxy matrix and carbon fiber combination still provide considerable ballistic protection, but the reduced V_f translates to lower overall ballistic resistance.

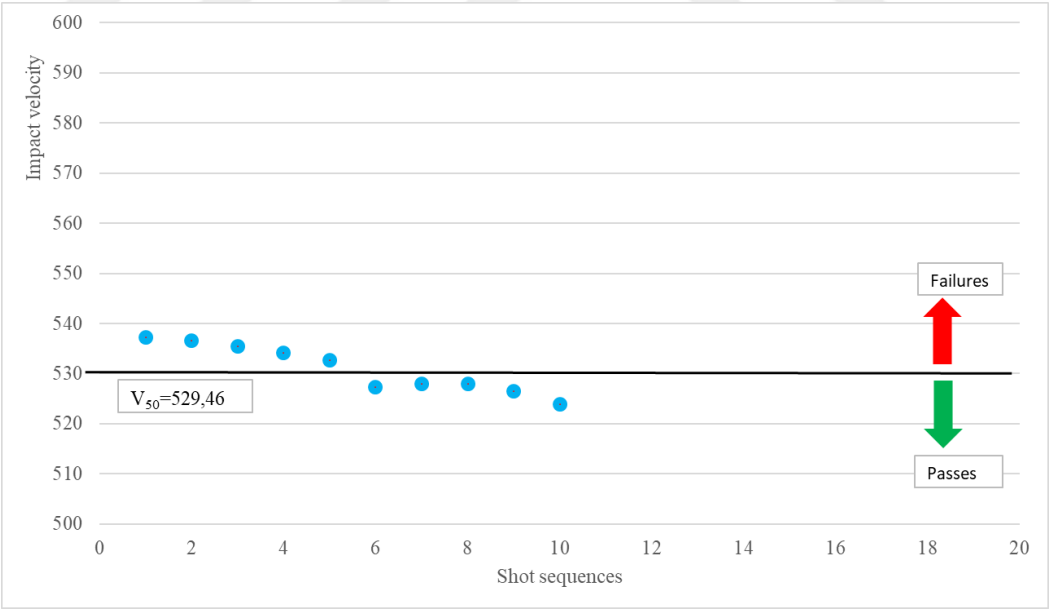


Figure 4.46. Number of shoots & V_{50} of CFR-E-50

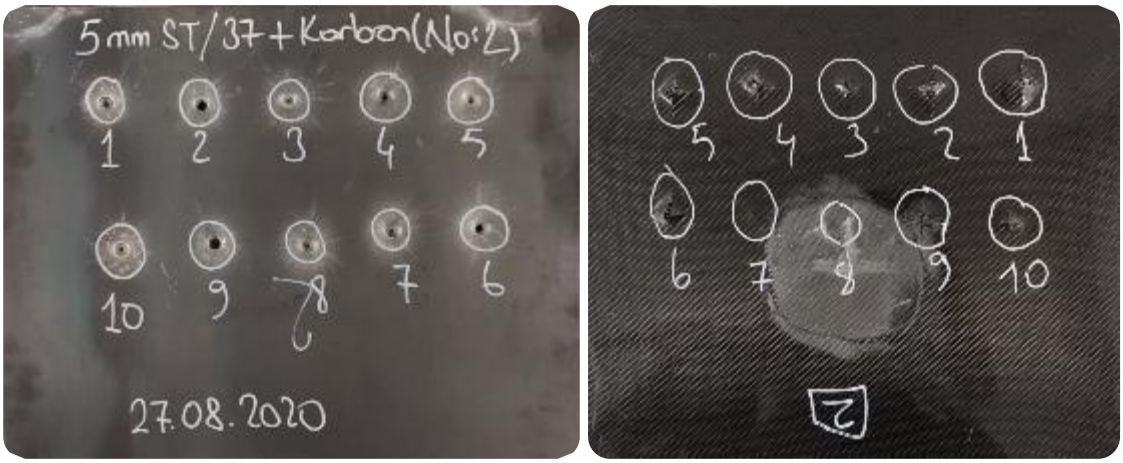


Figure 4.47. After test CFR-E-50, front-face (left) & back-face (right)

The V_{50} of GFR-E-60 is determined as 556.68 m/s through ballistics tests with thirteen shots. The GFR-E-60 features glass fibers at a 60% V_f within an epoxy matrix, offering a balanced performance as indicated by the V_{50} in Figure 4.48. The high fiber content enhances the material's ability to withstand and mitigate ballistic impacts. Post-test analysis (Figure 4.49) shows front and back face images, where the damage is more evenly distributed compared to carbon fiber configurations.

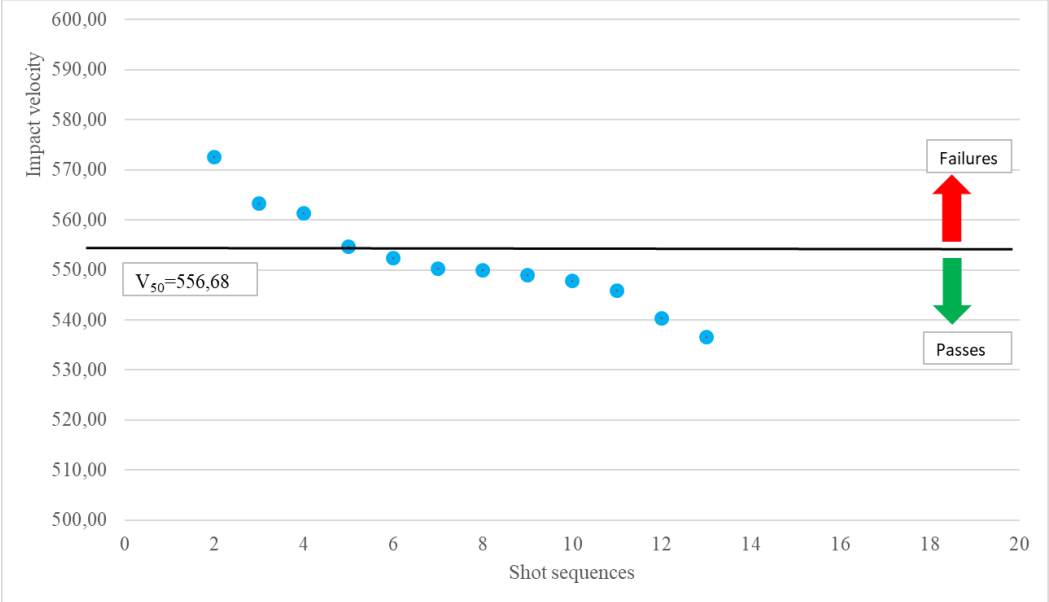


Figure 4.48. Number of shoots & V_{50} of GFR-E-60

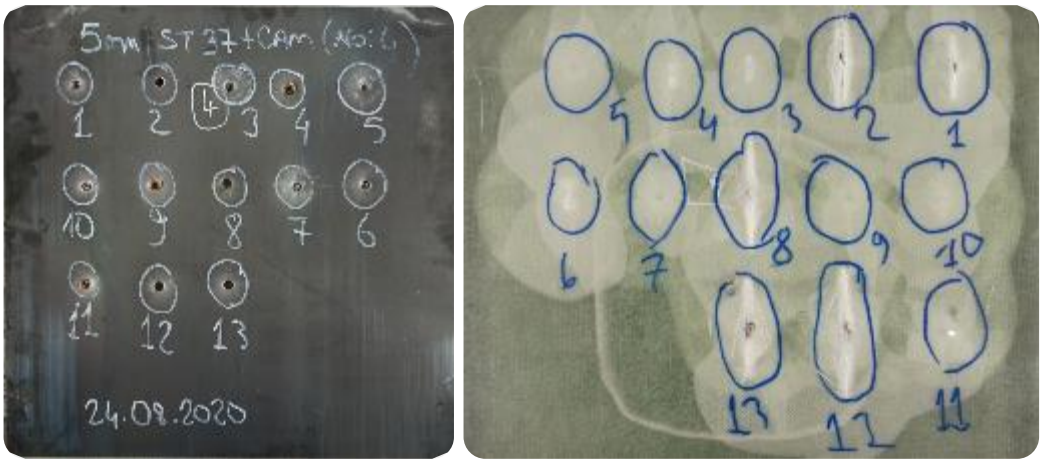


Figure 4.49. After test GFR-E-60, front-face (left) & back-face (right)

The V_{50} of GFR-E-50 is determined as 589.53 m/s through ballistics tests with eighteen shots. The GFR-E-50 presents a lower V_{50} compared to the 60% version, as shown in Figure 4.50. The post-test images (Figure 4.51) depict damage characteristics typical of glass fiber composites, including significant fiber breakage and matrix cracking. The reduction in fiber content compromises the ballistic performance, reflecting in the observed lower V_{50}.

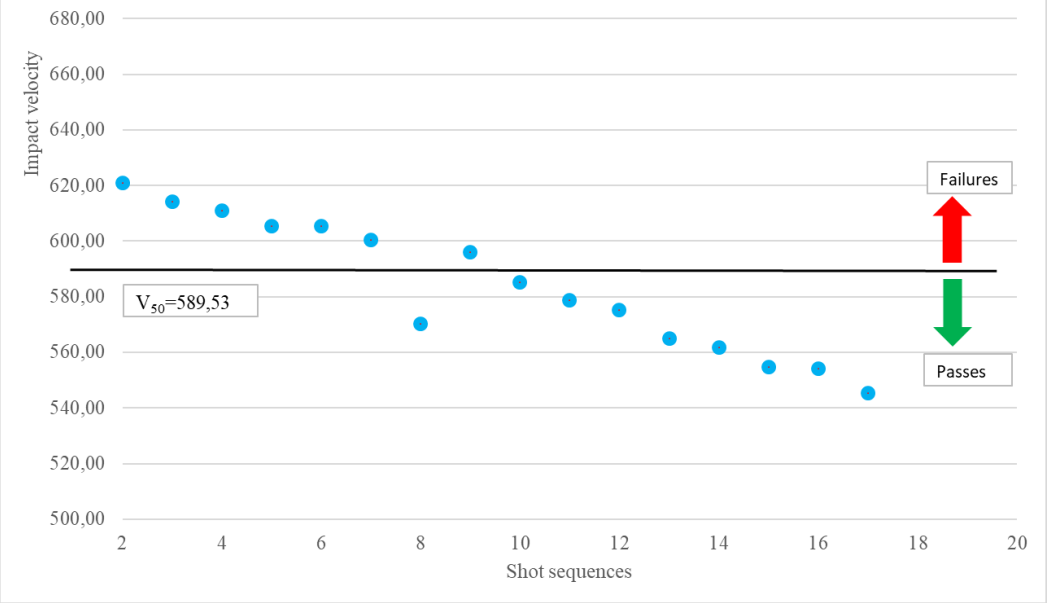


Figure 4.50. Number of shoots & V_{50} of GFR-E-50

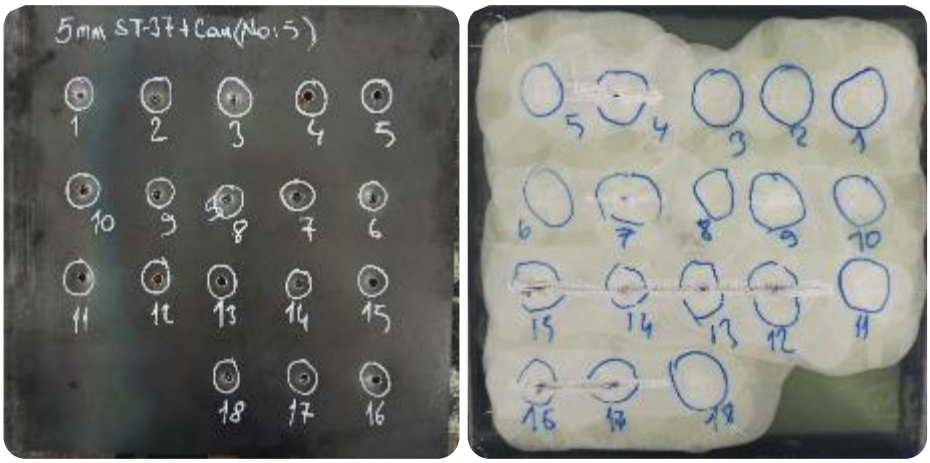


Figure 4.51. After test GFR-E-50, front-face (left) & back-face (right)

The V_{50} of GFR-E-40 is determined as 551.41 m/s through ballistics tests with fifteen shots. The GFR-E-40, with the lowest V_f among the glass fiber composites, exhibits the lowest V_{50} in this series (Figure 4.52). The test results suggest that a further reduction in fiber content significantly affects the material's ability to absorb and dissipate ballistic energy. The post-test photos (Figure 4.53) reveal extensive damage, with large areas of delamination and significant fiber-matrix separation.

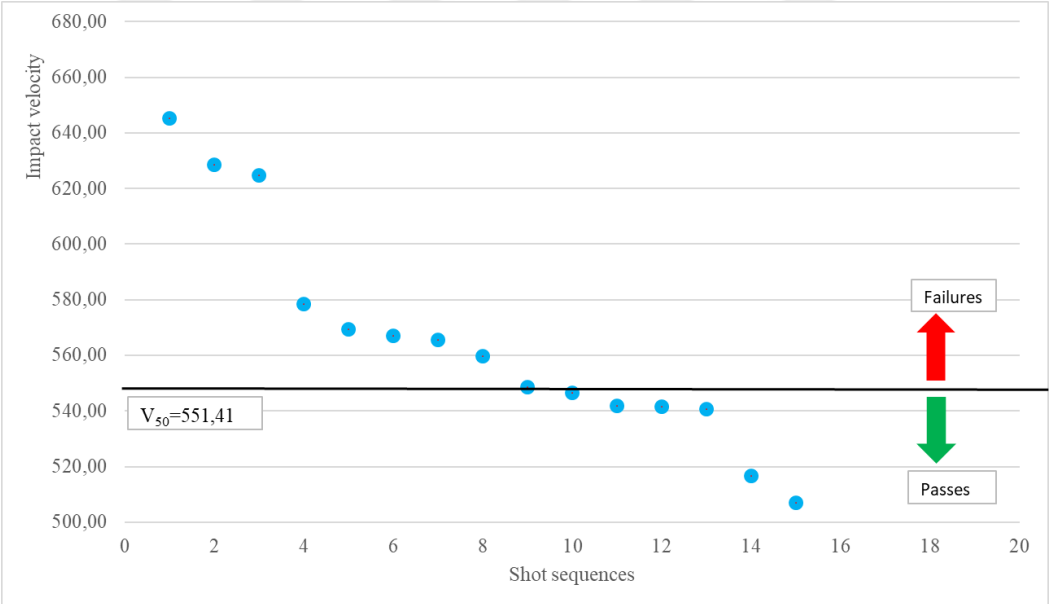


Figure 4.52. Number of shoots & V_{50} of GFR-E-40

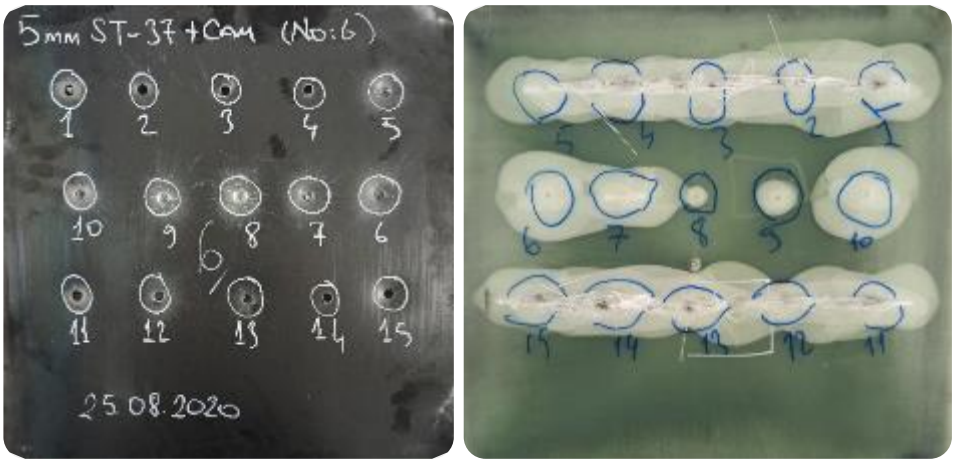


Figure 4.53. After test GFR-E-40, front-face (left) & back-face (right)

The V_{50} of AFR-E-60 is determined as 626.61 m/s through ballistics tests with eighteen shots. The high V_{50} (Figure 4.54) reflects the excellent ballistic resistance of aramid fibers, known for their high toughness and energy absorption capabilities. Post-test images (Figure 4.55) indicate limited damage, with minor delamination and fiber damage.

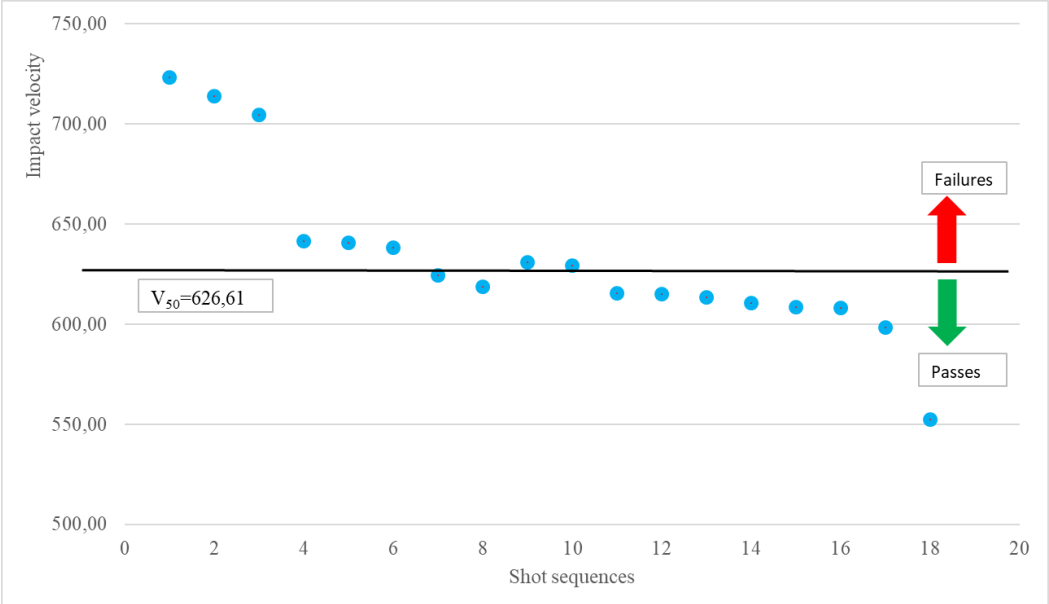


Figure 4.54. Number of shoots & V_{50} of AFR-E-60

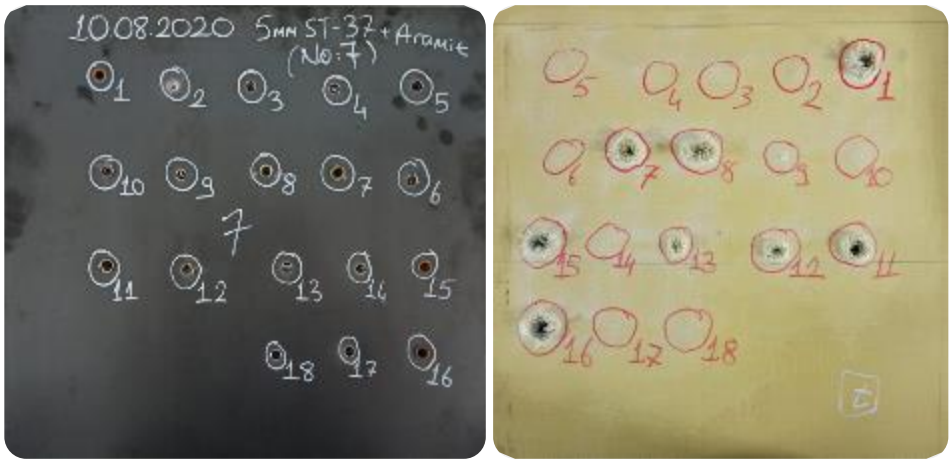


Figure 4.55. After test AFR-E-60, front-face (left) & back-face (right)

The V_{50} of AFR-E-50 is determined as 559.75 m/s through ballistics tests with sixteen shots. The V_{50} (Figure 4.56) is slightly lower than the 60% variant, indicating a reduction in ballistic resistance due to decreased fiber content. The post-test images (Figure 4.57) show moderate damage with some delamination and fiber pull-out.

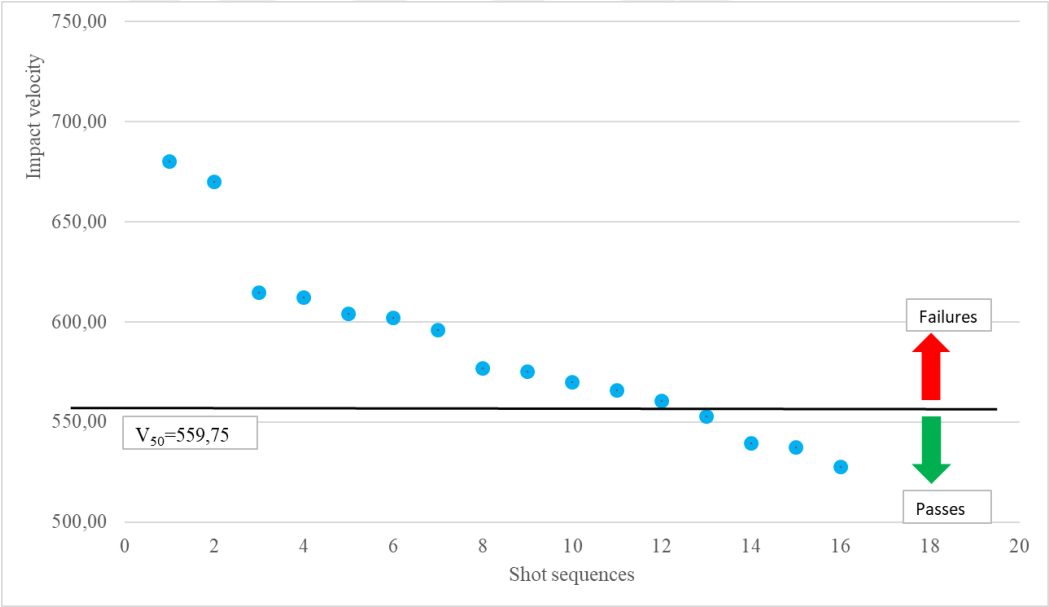


Figure 4.56. Number of shoots & V_{50} of AFR-E-50

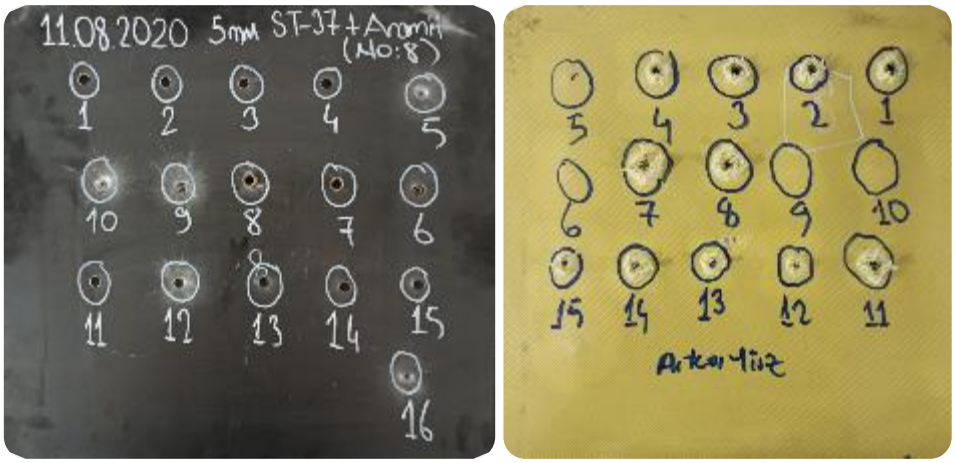


Figure 4.57. After test AFR-E-50, front-face (left) & back-face (right)

The V_{50} of AFR-E-40 is determined as 556.10 m/s through ballistics tests with twenty-three shots. The AFR-E-40, with the lowest V_f among the aramid composites, demonstrates a further decrease in V_{50} (Figure 4.58). The post-test images (Figure 4.59) reveal more extensive damage, including larger delaminated areas and significant fiber breakage.

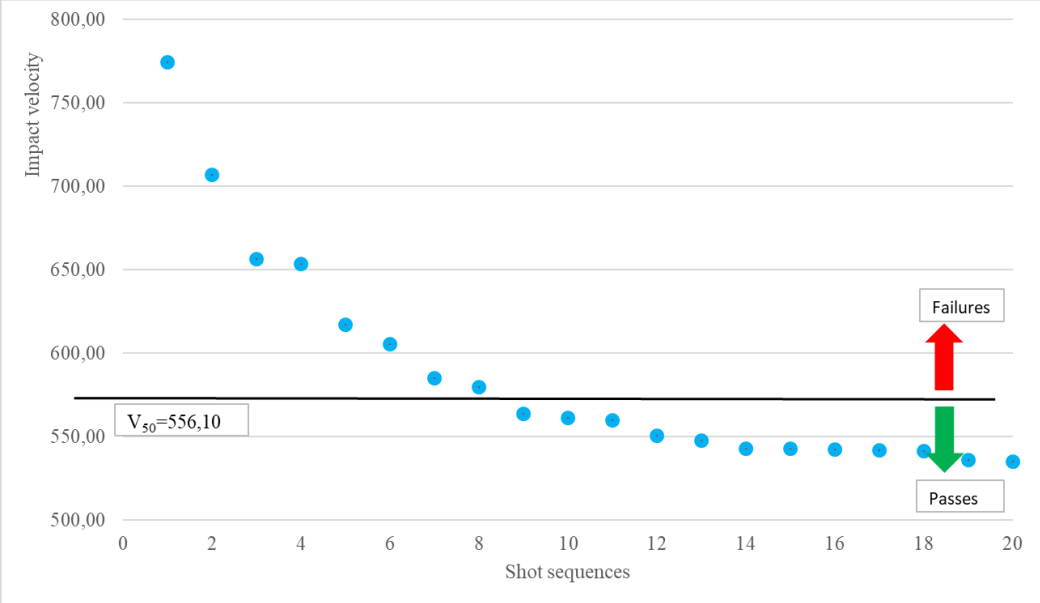


Figure 4.58. Number of shoots & V_{50} of AFR-E-40

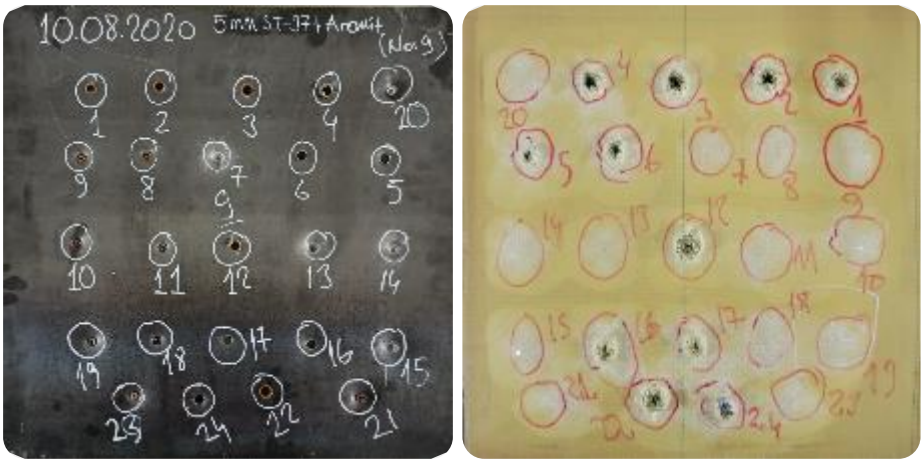


Figure 4.59. After test AFR-E-40, front-face (left) & back-face (right)

The V_{50} of CFR-V-60 is determined as 536.21 m/s through ballistics tests with eight shots. The CFR-V-60, utilizing vinylester resin with a 60% V_f, displays a notable V_{50} as shown in Figure 4.60. This combination benefits from the high tensile strength and stiffness of carbon fibers along with the durability and chemical resistance of vinylester resin. The post-test images (Figure 4.61) reveal minimal damage, indicating excellent energy absorption and distribution capabilities.

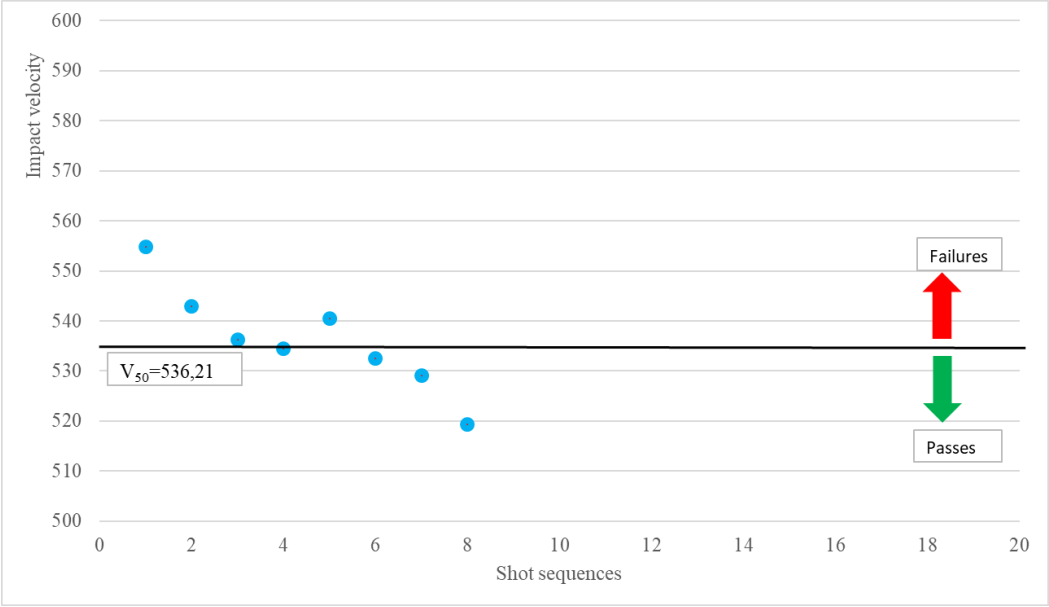


Figure 4.60. Number of shoots & V_{50} of CFR-V-60

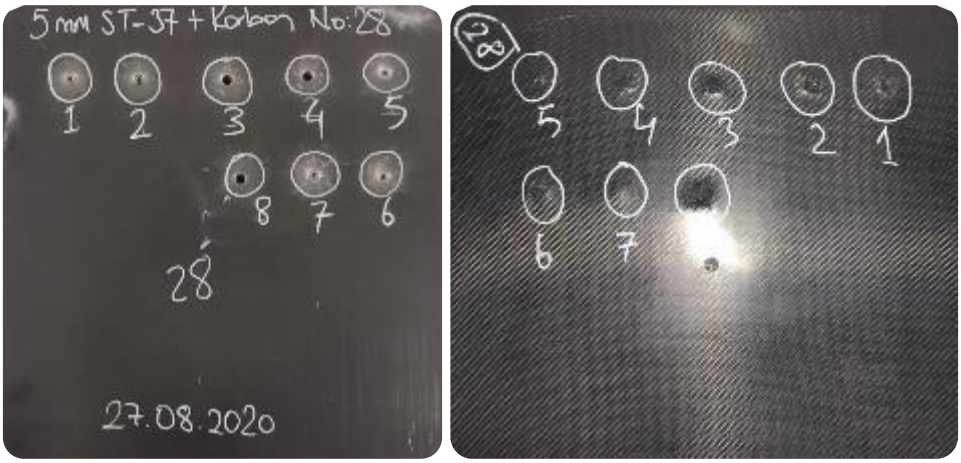


Figure 4.61. After test CFR-V-60, front-face (left) & back-face (right)

The V_{50} of CFR-V-50 is determined as 547.65 m/s through ballistics tests with fifteen shots. The V_{50} (Figure 4.62) is slightly reduced compared to the 60% variant due to the lower V_f. This reduction results in a slight decrease in ballistic resistance. The post-test images (Figure 4.63) show more evident damage, including greater delamination and fiber breakage.

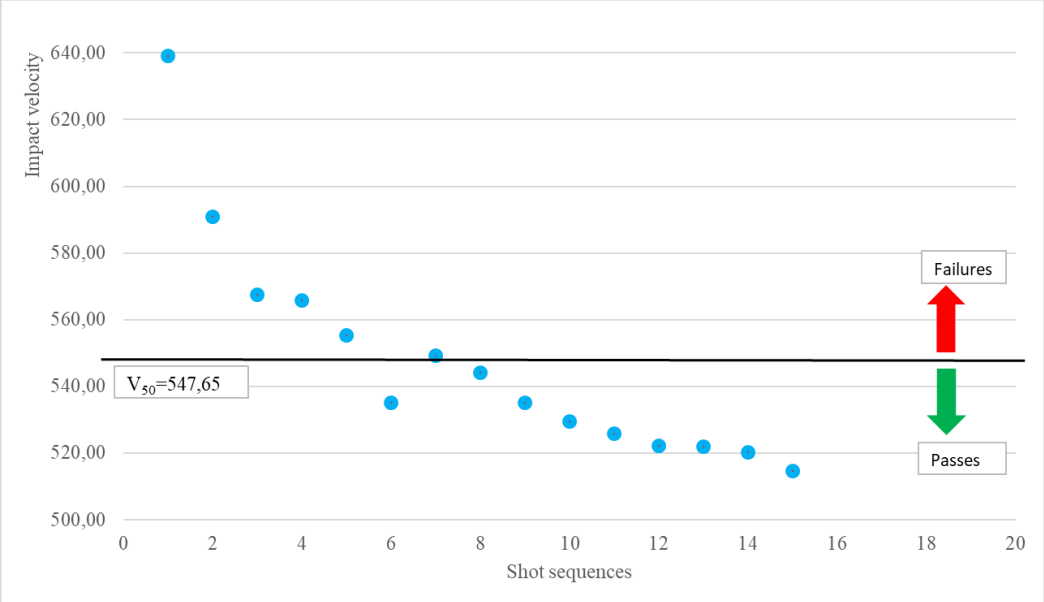


Figure 4.62. Number of shoots & V_{50} of CFR-V-50

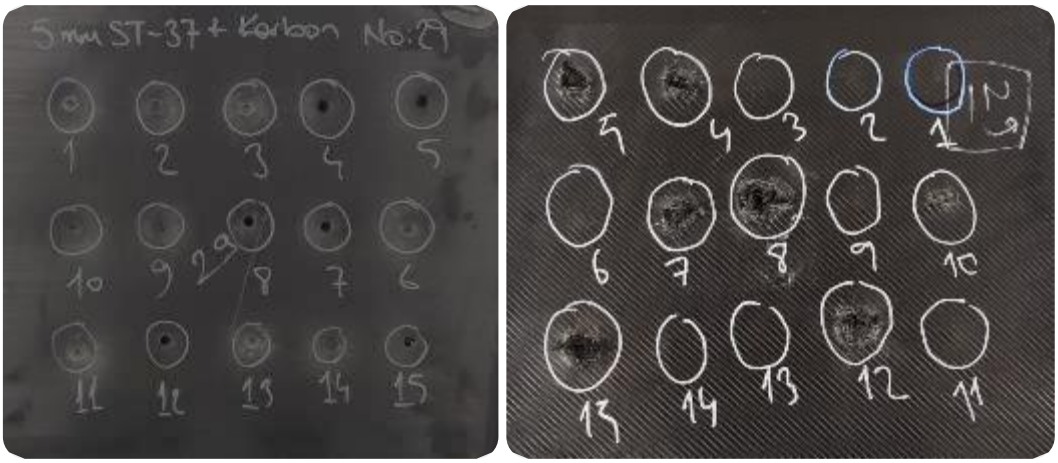


Figure 4.63. After test CFR-V-50, front-face (left) & back-face (right)

The V_{50} of GFR-V-60 is determined as 575.84 m/s through ballistics tests with fourteen shots. The GFR-V-60 features glass fibers at a 60% V_f within the vinylester matrix, achieving a moderate V_{50} as illustrated in Figure 4.64. Glass fibers offer good energy absorption, while the vinylester matrix provides chemical resistance and durability. The post-test images (Figure 4.65) exhibit distributed damage with limited delamination, showing the material's capacity to manage ballistic impacts effectively.

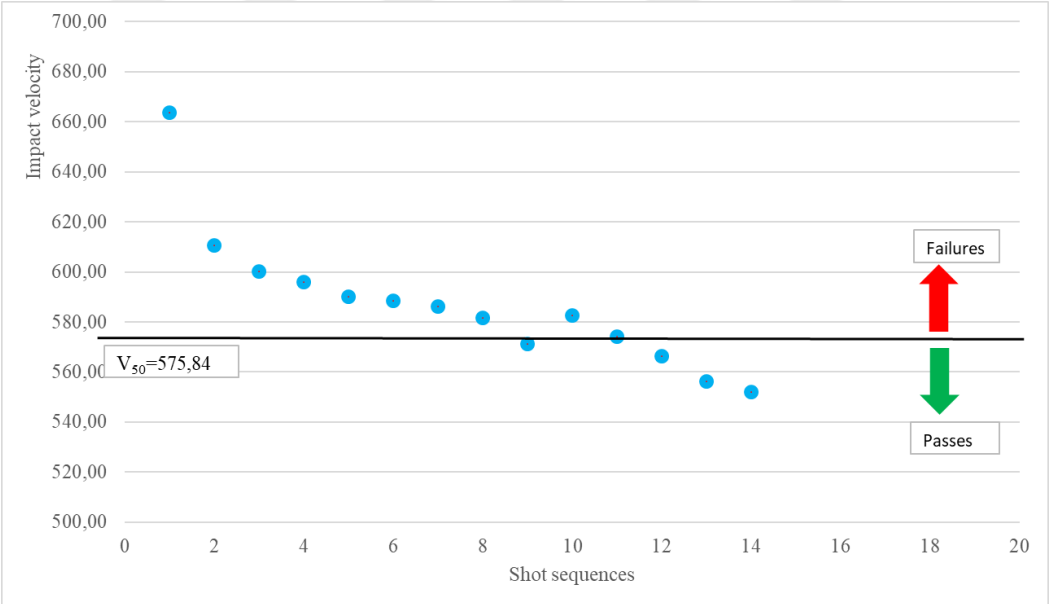


Figure 4.64. Number of shoots & V_{50} of GFR-V-60

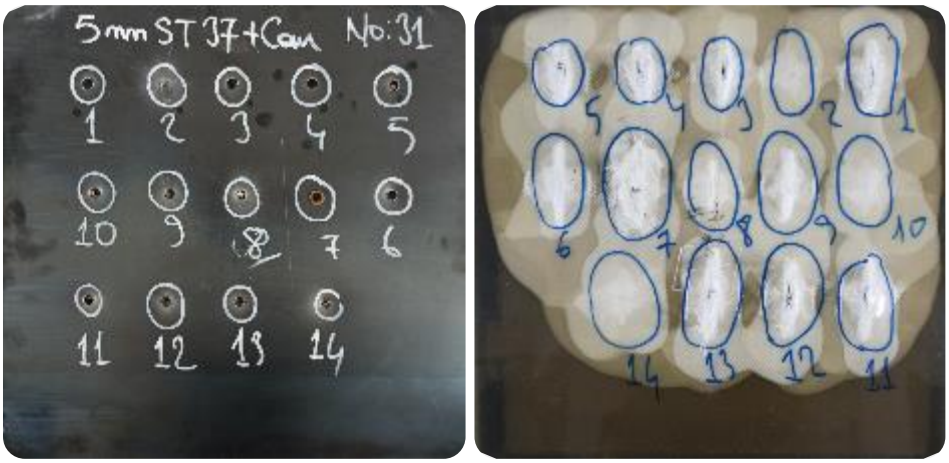


Figure 4.65. After test GFR-V-60 sample, front-face (left) & back-face (right)

The V_{50} of GFR-V-50 is determined as 596.77 m/s through ballistics tests with fourteen shots. The GFR-V-50 shows a lower V_{50} compared to its 60% counterpart, as seen in Figure 4.66. The reduced fiber content affects the overall ballistic performance, resulting in more significant damage upon impact. The post-test images (Figure 4.67) reveal increased delamination and fiber breakage.

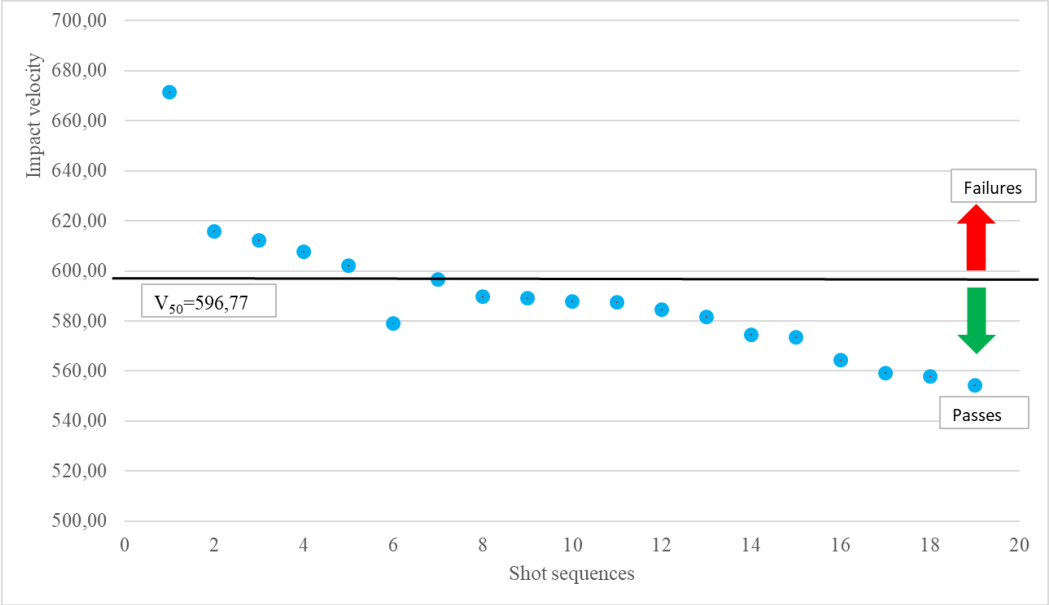


Figure 4.66. Number of shoots & V_{50} of GFR-V-50

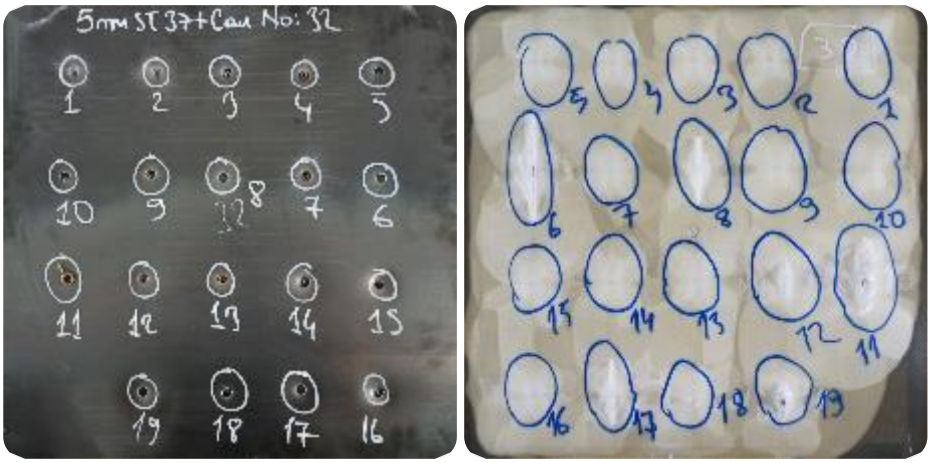


Figure 4.67. After test GFR-V-50, front-face (left) & back-face (right)

The V_{50} of GFR-V-40 is determined as 549.36 m/s through ballistics tests with twenty shots. In the GFR-V-40, the lowest V_f among the glass fiber composites results in the lowest V_{50} (Figure 4.68). The post-test images (Figure 4.69) indicate extensive damage, with significant delamination and fiber-matrix separation.

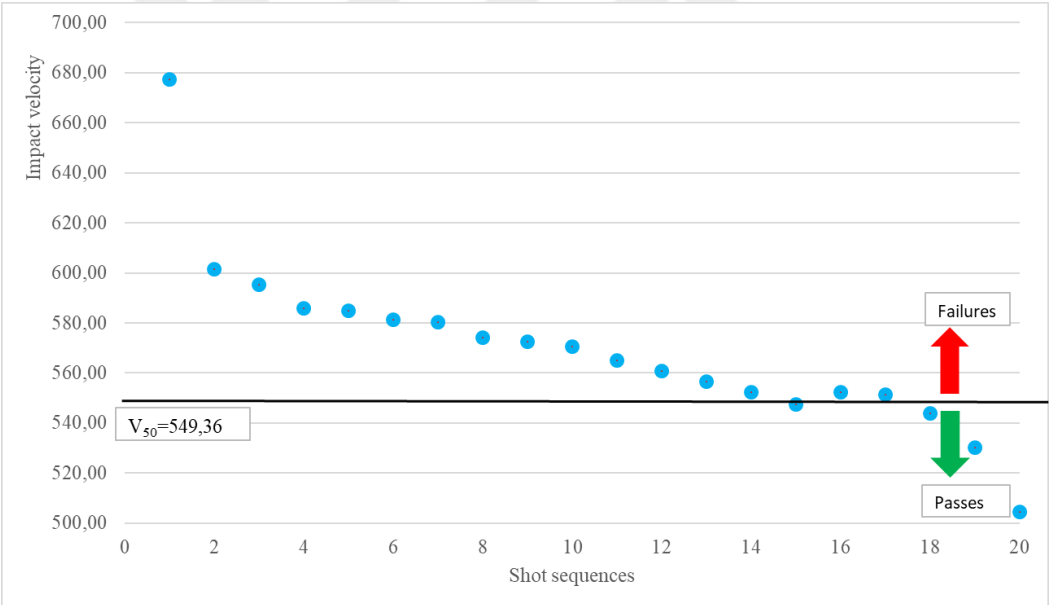


Figure 4.68. Number of shoots & V_{50} of GFR-V-40

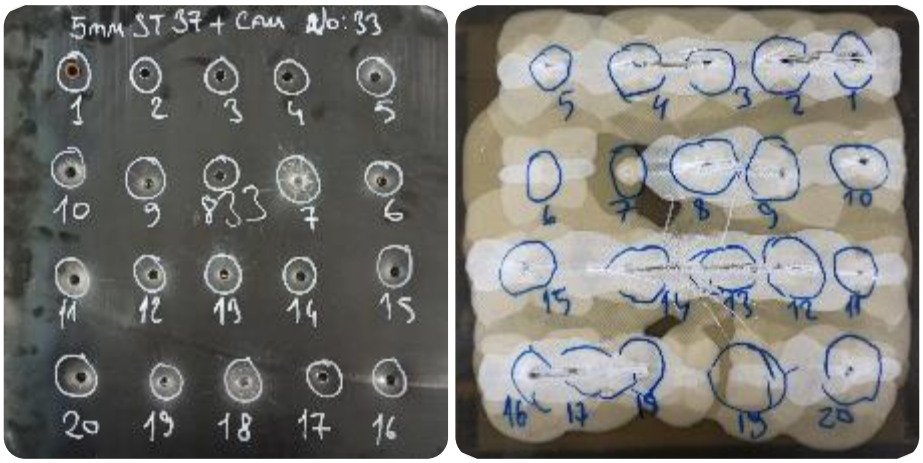


Figure 4.69. After test GFR-V-40, front-face (left) & back-face (right)

The V_{50} of AFR-V-60 is determined as 630.47 m/s through ballistics tests with twenty-four shots. The AFR-V-60 employs aramid fibers at a 60% V_f within the vinylester matrix, achieving a high V_{50} (Figure 4.70). Aramid fibers' toughness and energy absorption capabilities, combined with the durability of the vinylester matrix, result in excellent ballistic resistance. Post-test images (Figure 4.71) reveal minimal damage, showcasing the material's effectiveness in managing high-impact stresses.

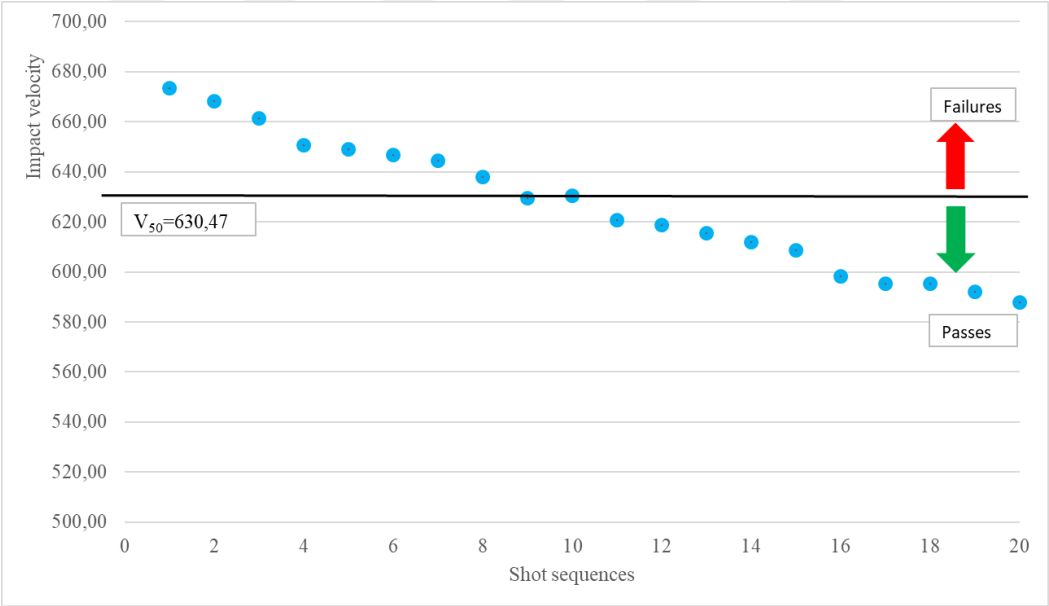


Figure 4.70. Number of shoots & V_{50} of AFR-V-60

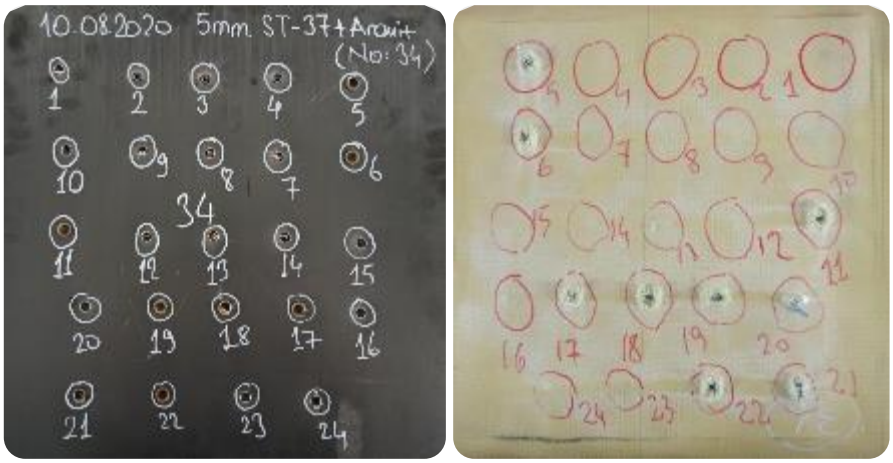


Figure 4.71. After test AFR-V-60, front-face (left) & back-face (right)

The V_{50} of AFR-V-50 is determined as 575.59 m/s through ballistics tests with eleven shots. The AFR-V-50, with a 50% V_f, exhibits a slightly lower V_{50} compared to the 60% version (Figure 4.72). This reduction affects the ballistic performance, but the material still provides substantial protection due to the inherent toughness of aramid fibers. The post-test images (Figure 4.73) display moderate damage, with some delamination and fiber pull-out, indicating effective energy absorption and distribution.

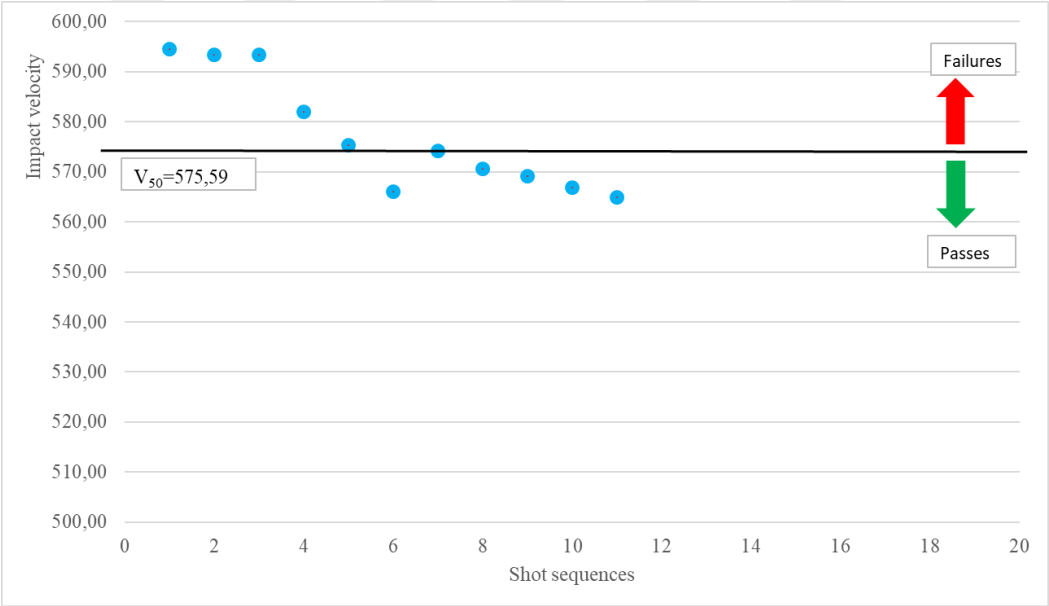


Figure 4.72. Number of shoots & V_{50} of AFR-V-50

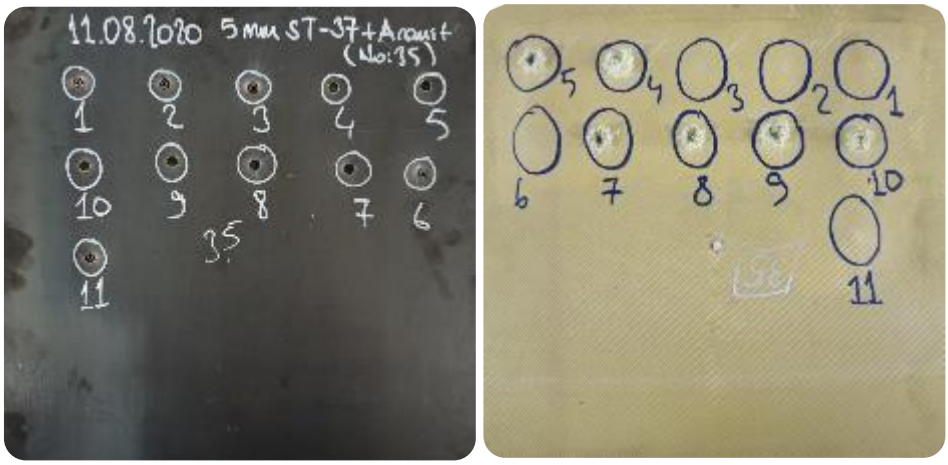


Figure 4.73. After test AFR-V-50, front-face (left) & back-face (right)

The V_{50} of AFR-V-40 is determined as 571.03 m/s through ballistics tests with fifteen shots. The AFR-V-40, with the lowest V_f among the aramid composites, shows a further decrease in V_{50} (Figure 4.74). The post-test images (Figure 4.75) reveal more significant damage, including larger delaminated areas and considerable fiber breakage.

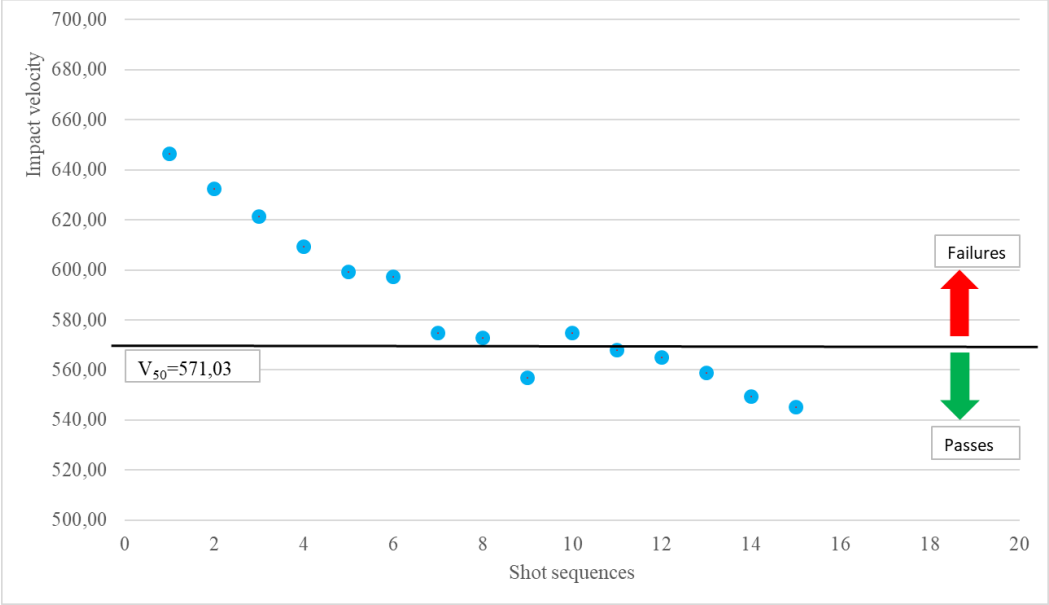


Figure 4.74. Number of shoots & V_{50} of AFR-V-40

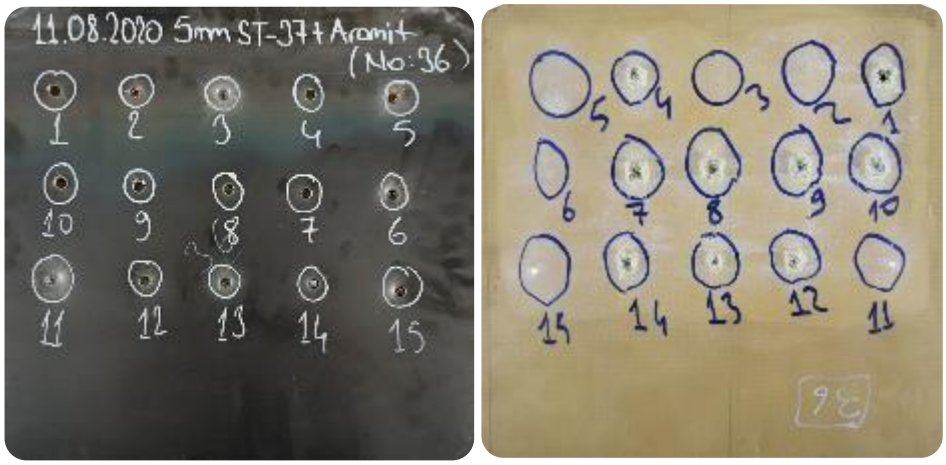


Figure 4.75. After test AFR-V-40, front-face (left) & back-face (right)

The V_{50} of CFR-P-60 is determined as 544.39 m/s through ballistics tests with nineteen shots. The CFR-P-60, featuring polyester resin and 60% carbon V_f, achieves a significant V_{50} as depicted in Figure 4.76. The combination of carbon fibers' high strength and stiffness with the flexibility of polyester resin results in a composite with excellent impact resistance. The post-test images (Figure 4.77) show minimal damage, indicating effective energy absorption and distribution.

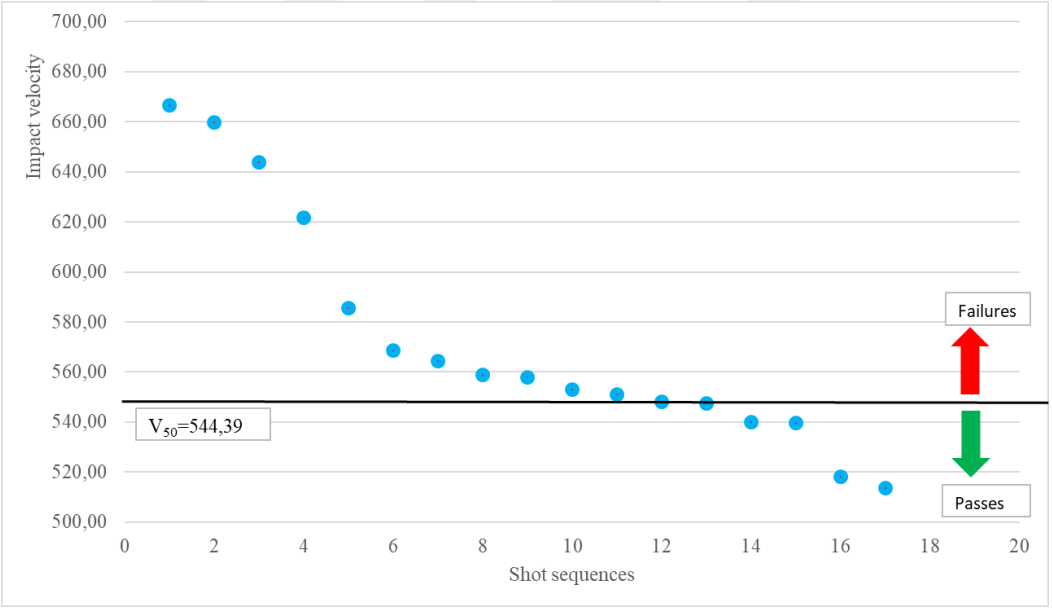


Figure 4.76. Number of shoots & V_{50} of CFR-P-60

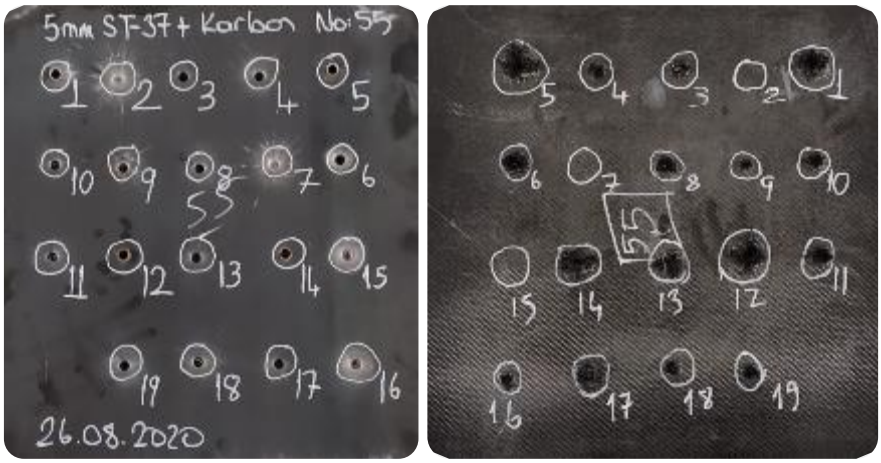


Figure 4.77. After test CFR-P-60, front-face (left) & back-face (right)

The V_{50} of CFR-P-50 is determined as 543.49 m/s through ballistics tests with fourteen shots. The CFR-P-50, with a 50% V_f, shows a slightly lower V_{50} compared to the 60% variant, as seen in Figure 4.78. The reduced fiber content affects the overall ballistic resistance, resulting in more evident damage upon impact. The post-test images (Figure 4.79) reveal increased delamination and fiber breakage.

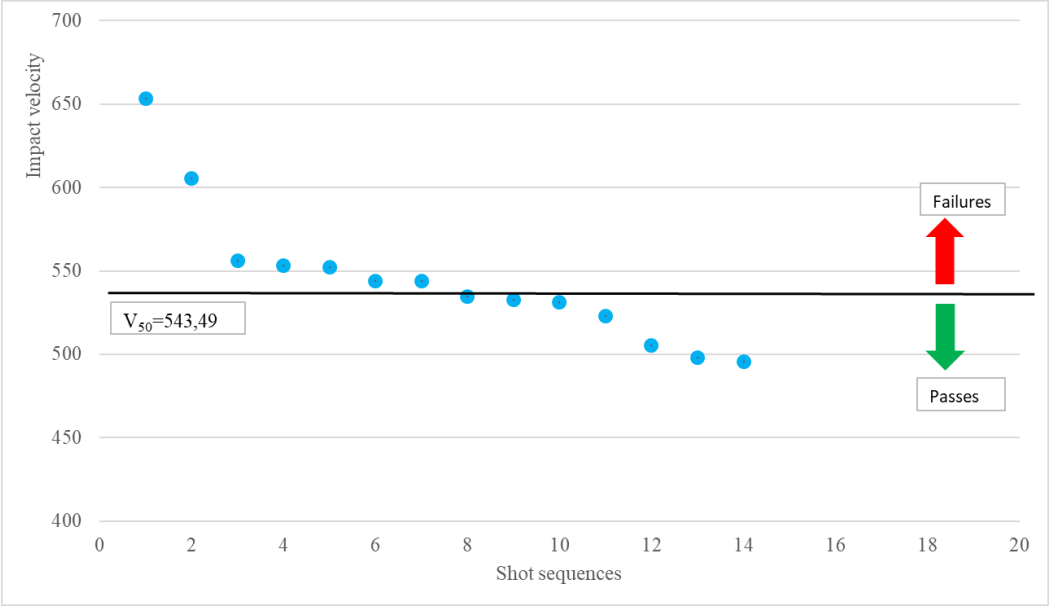


Figure 4.78. Number of shoots & V_{50} of CFR-P-50

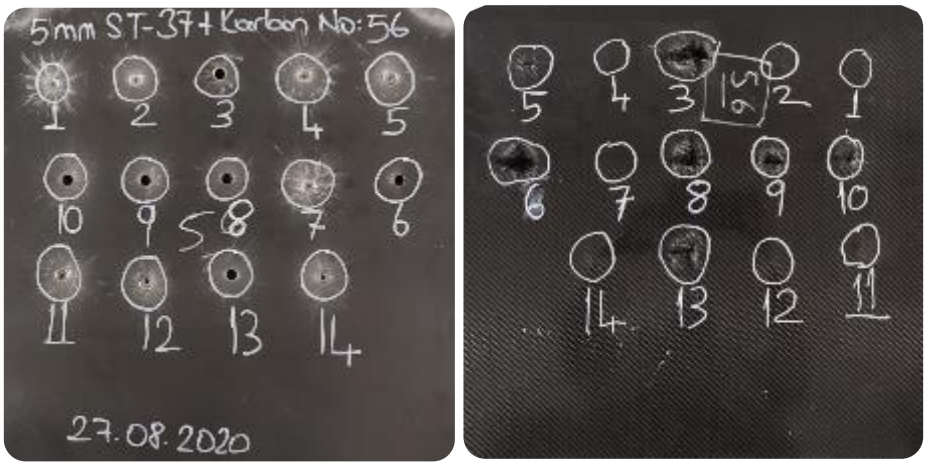


Figure 4.79. After test CFR-P-50, front-face (left) & back-face (right)

The V_{50} of CFR-P-40 is determined as 535.69 m/s through ballistics tests with twenty shots. In the CFR-P-40, the lowest V_f among the carbon fiber composites results in the lowest V_{50} (Figure 4.80). The post-test images (Figure 4.81) indicate extensive damage, with significant delamination and fiber-matrix separation.

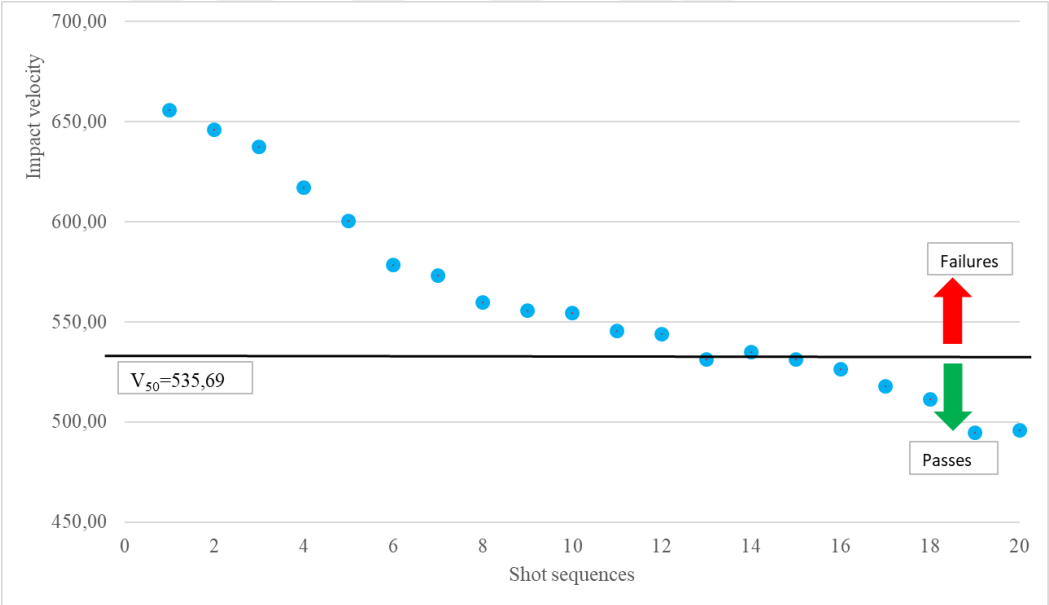


Figure 4.80. Number of shoots & V_{50} of CFR-P-40

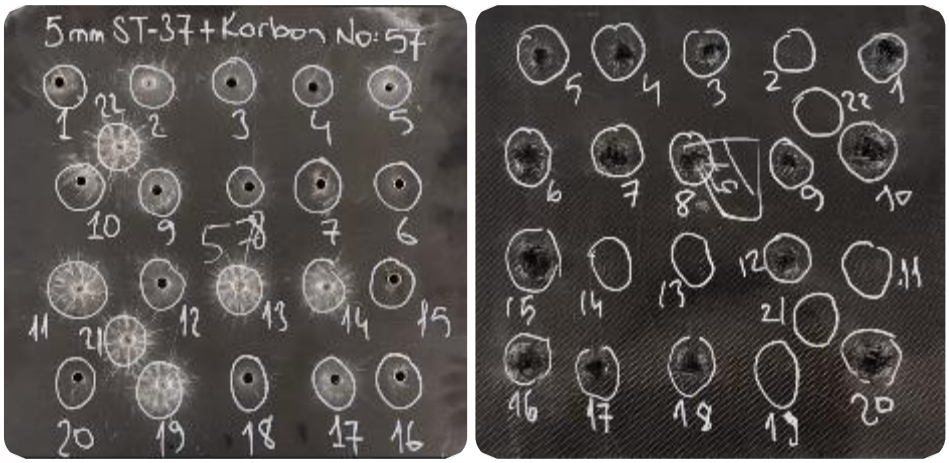


Figure 4.81. After test CFR-P-40, front-face (left) & back-face (right)

The V_{50} of GFR-P-60 is determined as 553.36 m/s through ballistics tests with fifteen shots. The GFR-P-60, featuring glass fibers at a 60% V_f within the polyester matrix, demonstrates a moderate V_{50} as shown in Figure 4.82. Glass fibers offer good energy absorption, while the polyester resin provides flexibility and cost-effectiveness. The post-test images (Figure 4.83) exhibit distributed damage with limited delamination, showing the material's capacity to manage ballistic impacts effectively.

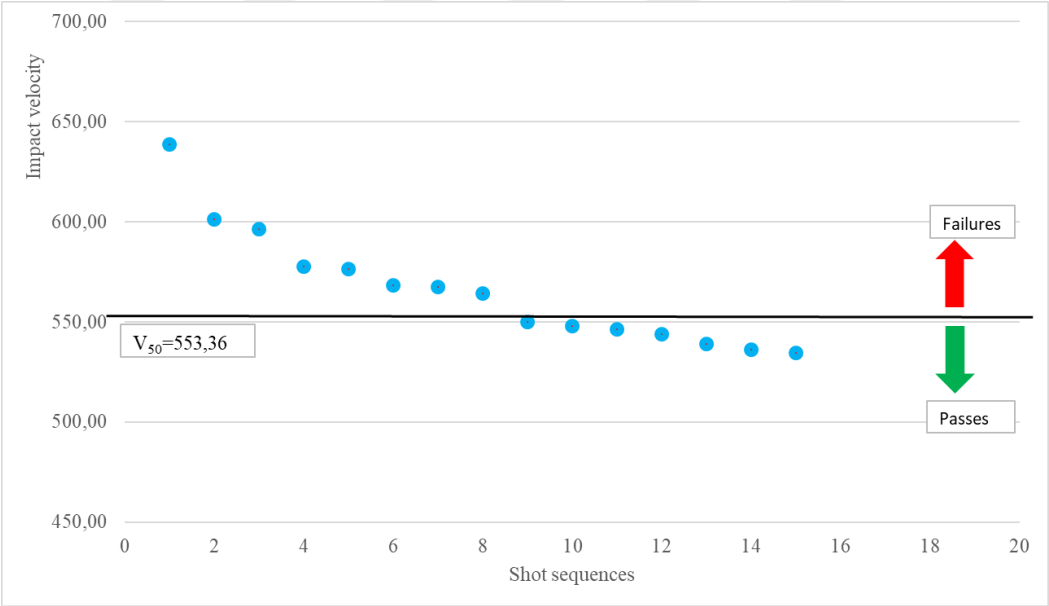


Figure 4.82. Number of shoots & V_{50} of GFR-P-60

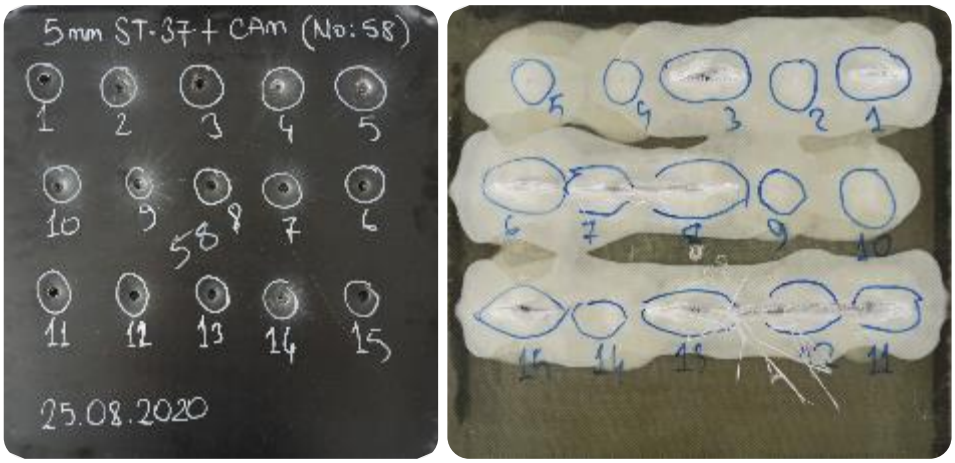


Figure 4.83. After test GFR-P-60, front-face (left) & back-face (right)

The V_{50} of GFR-P-50 is determined as 543.80 m/s through ballistics tests with sixteen shots. The GFR-P-50, with a 50% V_f, shows a lower V_{50} compared to its 60% counterpart, as seen in Figure 4.84. The reduced fiber content affects the overall ballistic performance, resulting in more significant damage upon impact. The post-test images (Figure 4.85) reveal increased delamination and fiber breakage.

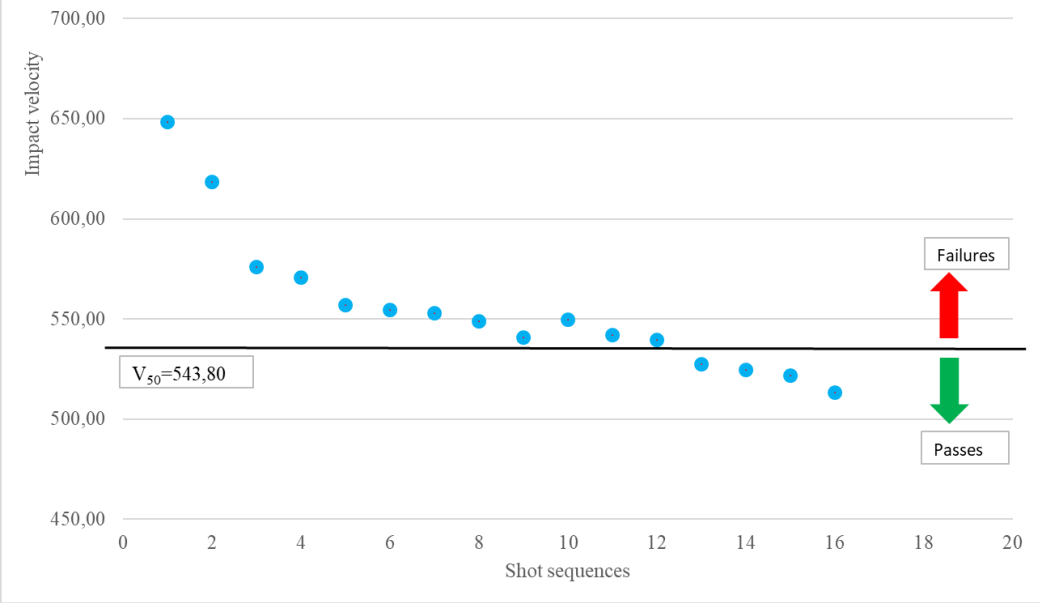


Figure 4.84. Number of shoots & V_{50} of GFR-P-50

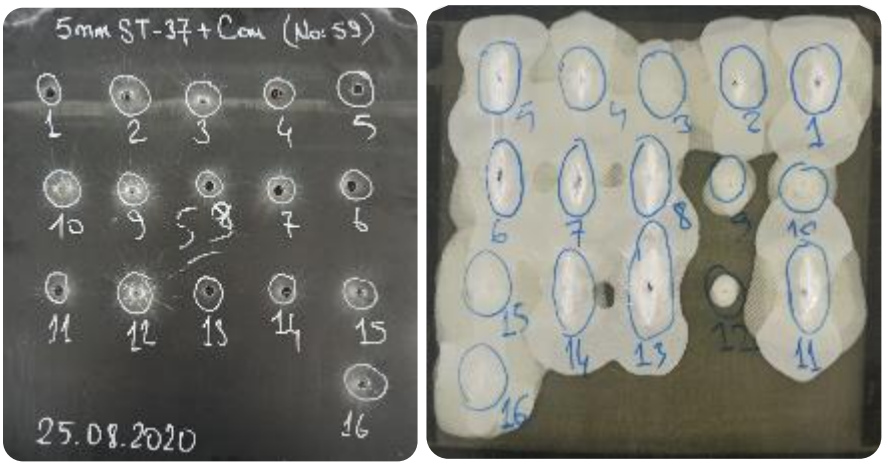


Figure 4.85. After test GFR-P-50, front-face (left) & back-face (right)

The V_{50} of GFR-P-40 is determined as 551.90 m/s through ballistics tests with sixteen shots. In the GFR-P-40, the lowest V_f among the glass fiber composites results in the lowest V_{50} (Figure 4.86). The post-test images (Figure 4.87) indicate extensive damage, with significant delamination and fiber-matrix separation.

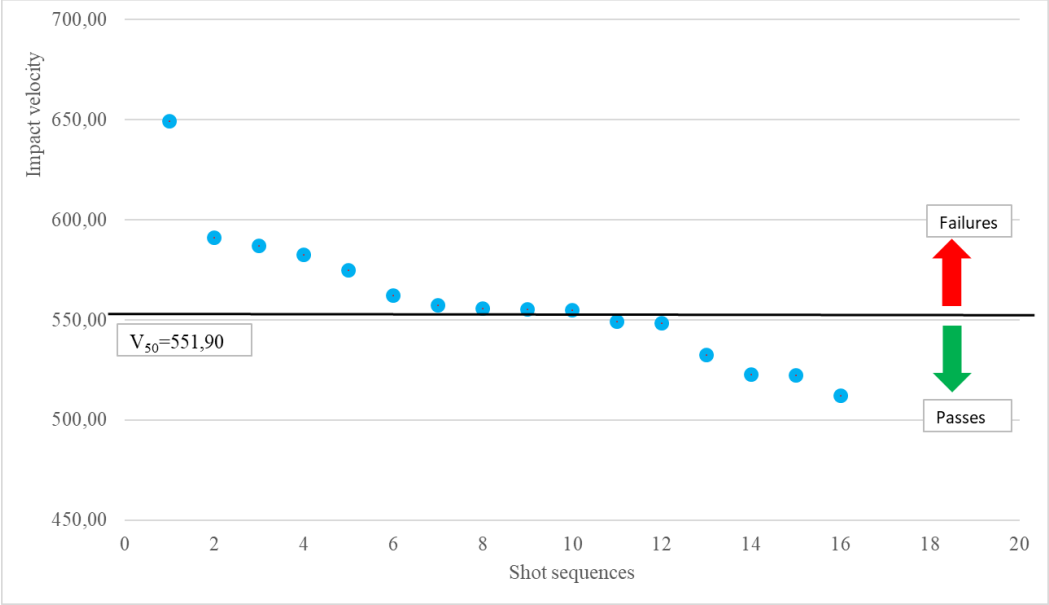


Figure 4.86. Number of shoots & V_{50} of GFR-P-40

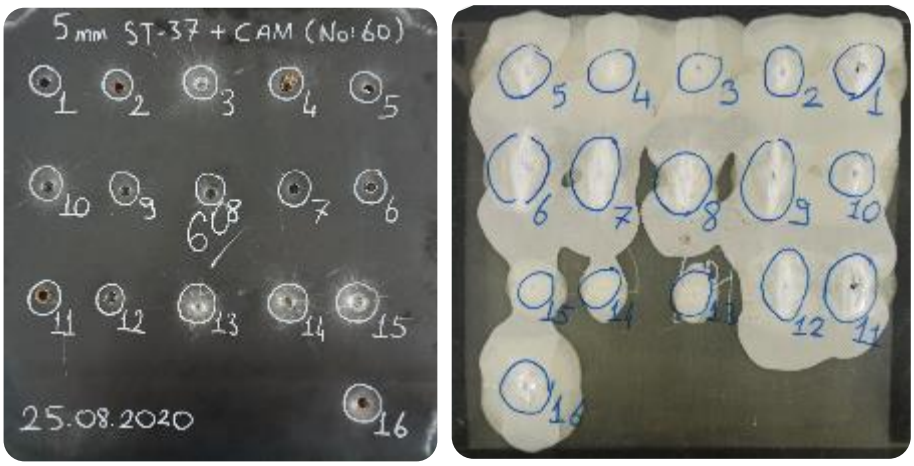


Figure 4.87. After test GFR-P-40, front-face (left) & back-face (right)

The V_{50} of AFR-P-60 is determined as 630.97 m/s through ballistics tests with nineteen shots. The AFR-P-60 employs aramid fibers at a 60% V_f within polyester matrix, achieving a high V_{50} (Figure 4.88). Aramid fibers' toughness and energy absorption capabilities, combined with the flexibility of the polyester matrix, result in excellent ballistic resistance. Post-test images (Figure 4.89) reveal minimal damage, showcasing the material's effectiveness in managing high-impact stresses.

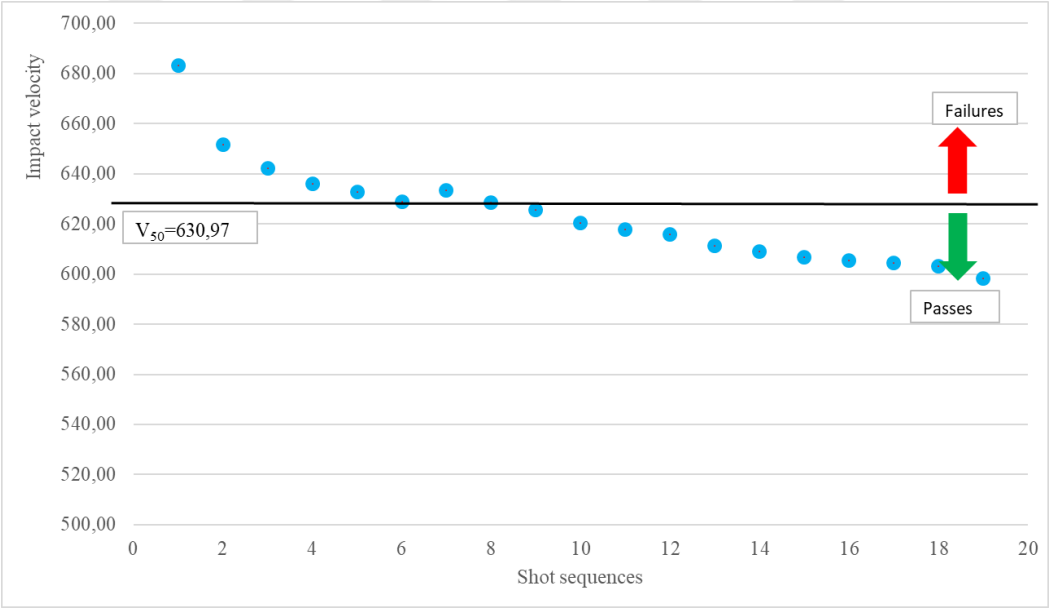


Figure 4.88. Number of shoots & V_{50} of AFR-P-60

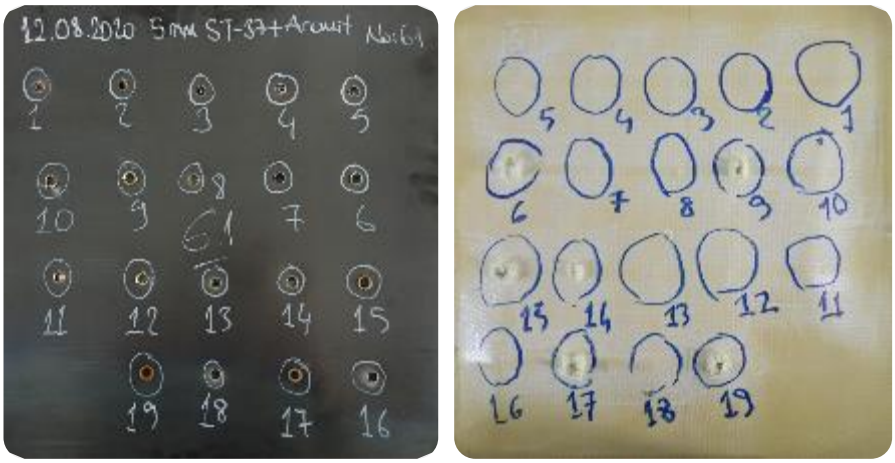


Figure 4.89. After test AFR-P-60, front-face (left) & back-face (right)

The V_{50} of AFR-P-50 is determined as 604.72 m/s through ballistics tests with seventeen shots. The AFR-P-50, with a 50% V_f, exhibits a slightly lower V_{50} compared to the 60% version (Figure 4.90). This reduction affects the ballistic performance, but the material still provides substantial protection due to the inherent toughness of aramid fibers. The post-test images (Figure 4.91) display moderate damage, with some delamination and fiber pull-out, indicating effective energy absorption and distribution.

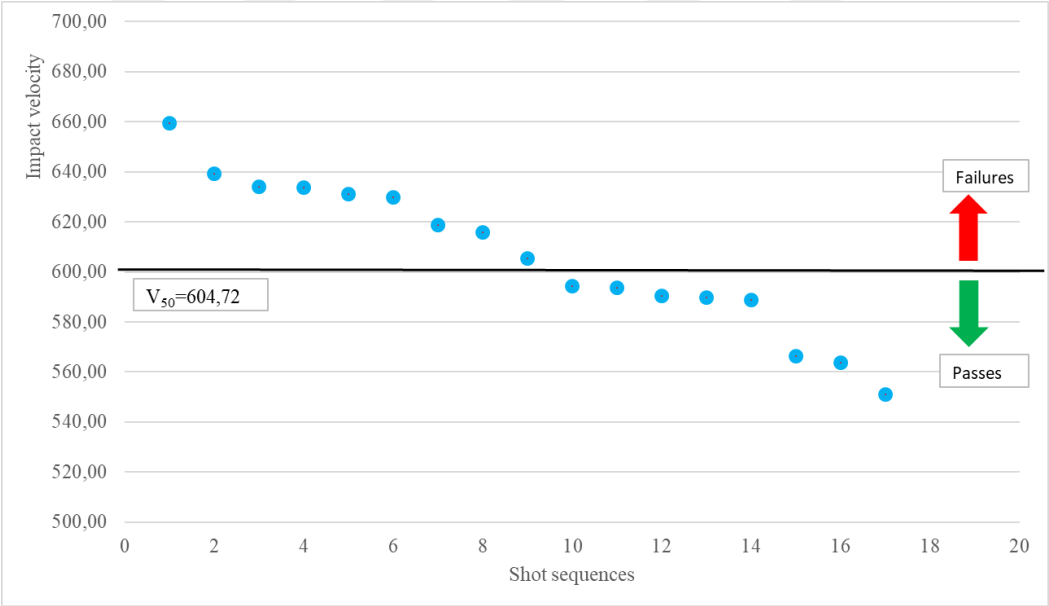


Figure 4.90. Number of shoots & V_{50} of AFR-P-50

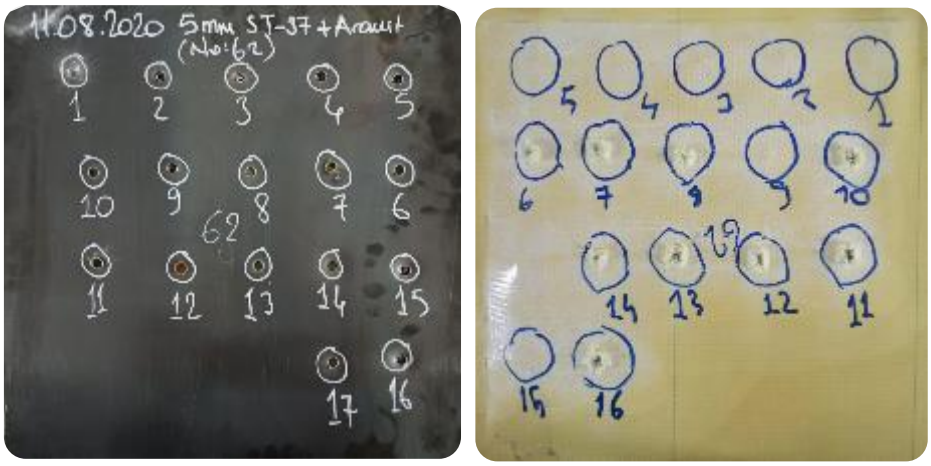


Figure 4.91. After test AFR-P-50, front-face (left) & back-face (right)

The V_{50} of AFR-P-40 is determined as 579.91 m/s through ballistics tests with sixteen shots. The AFR-P-40, with the lowest V_f among the aramid composites, shows a further decrease in V_{50} (Figure 4.92). The post-test images (Figure 4.93) reveal more significant damage, including larger delaminated areas and considerable fiber breakage.

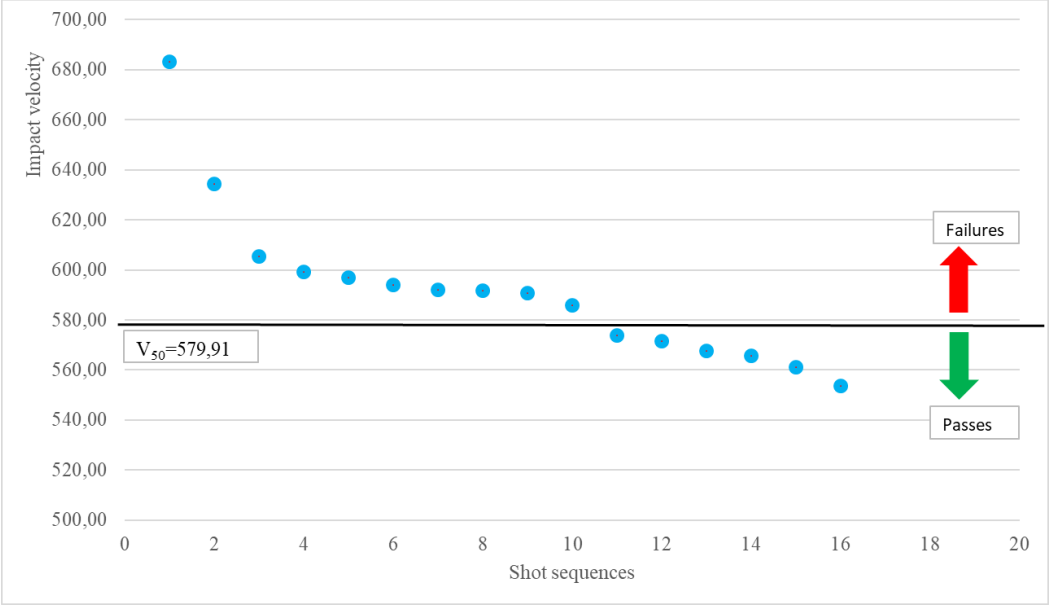


Figure 4.92. Number of shoots & V_{50} of AFR-P-40

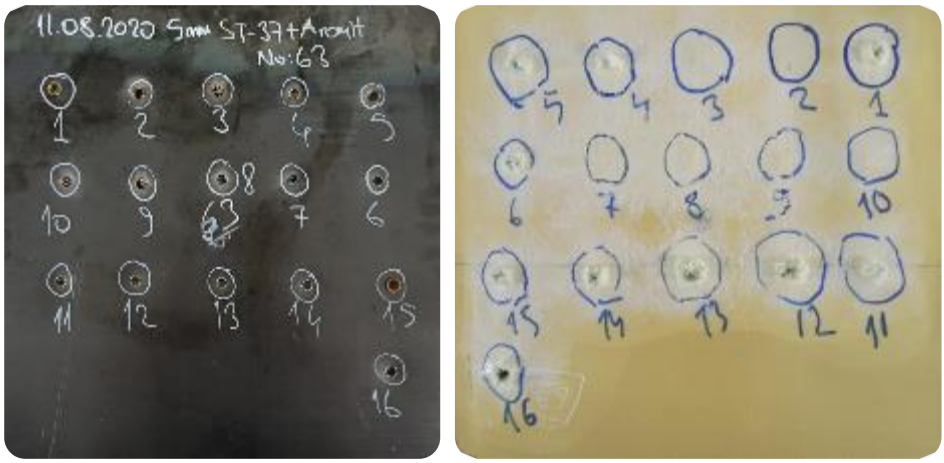


Figure 4.93. After test AFR-P-40, front-face (left) & back-face (right)

As a results of ballistics tests, among the fiber types tested, AFRs consistently exhibited superior ballistic performance for all matrix types and V_f. This superiority is attributed to the inherent toughness and excellent energy absorption capabilities of aramid fibers, resulting in higher V_{50} values and minimal post-test damage. CFRs also showed high ballistic resistance, particularly at higher V_f, due to their high tensile strength and stiffness. However, CFRs displayed more pronounced damage patterns upon impact compared to aramid fibers. GFRs, while providing good energy absorption, generally resulted in lower V_{50} values and more extensive damage, making them less effective for high-performance ballistic applications.

The type of matrix used played a crucial role in determining ballistic performance. Epoxy resin, known for its excellent mechanical properties and strong adhesion to fibers, resulted in the highest V_{50} values for all fiber types and V_f. Vinylester resin, with a good balance of mechanical properties and chemical resistance, showed moderate ballistic performance. Polyester resin, generally yielded the lowest V_{50} values, indicating lower ballistic resistance compared to epoxy and vinylester matrices.

Increasing V_f from 40% to 60% consistently improved the V_{50} values for all configurations. This trend underscores the importance of higher fiber content in enhancing the material's ability to absorb and dissipate ballistic energy. Configurations with 60% V_f demonstrated the highest V_{50} values and the least amount of damage, indicating superior ballistic performance. Conversely, configurations with 40% V_f exhibited the lowest V_{50} values and more extensive damage, highlighting the critical role of fiber content in achieving optimal ballistic protection.

Post-test images provided valuable insights into the damage mechanisms in different configurations. AFR configurations exhibited minimal delamination and fiber breakage, reflecting their superior energy absorption and toughness. CFR configurations showed localized delamination and fiber breakage, with more pronounced damage in lower V_f. GFR configurations displayed significant delamination and fiber-matrix separation, particularly at lower V_f, indicating lower overall ballistic resistance.

When examining V_{50} values for different matrix types for aramid, carbon, and glass fibers, aramid fibers demonstrated superior ballistic performance in all matrices, with the highest V_{50} observed in the epoxy matrix, achieving an increase of 13.8% as the V_f increased from 40% to 60%. This is followed by the vinylester and polyester matrices, which also showed significant improvements. Carbon fibers exhibited moderate ballistic performance, with the highest V_{50} in the vinylester matrix, followed by the epoxy and polyester matrices. The increases in V_{50} for carbon fibers were more modest, with the highest being a 4.7% increase in the vinylester matrix. Glass fibers displayed variable performance, with the epoxy matrix providing the highest V_{50} values, followed by vinylester and polyester matrices. Notably, the ballistic performance of glass fibers in the vinylester matrix peaked at a V_f of 50%, indicating a non-linear relationship between V_f and performance.

Overall, aramid fibers provided the highest ballistic resistance for all matrix types. Carbon fibers offered moderate resistance, particularly in the vinylester matrix, while glass fibers showed the most variability but still outperformed carbon fibers at lower V_f. Aramid fibers consistently provided the highest ballistic resistance for all matrices and V_f, making them the preferred choice for high-performance applications.

5. CONCLUSIONS

The primary objective of this study was to develop and evaluate FRC spall liners for enhanced ballistic protection. By investigating the impact of different fibers, matrix materials, and V_f on the ballistic performance of FRCs, this study aims to identify the optimal configurations that offer higher protection. The methodology involves the design and fabrication of different composite spall liner panels using the RTM method. These spall liner panels were subjected to mechanical and ballistics tests, including tensile, compression, in-plane shear, flexural, and V_{50} ballistic limit tests. Post-test analyses were conducted to evaluate the damage mechanisms and validate the effectiveness of different configurations.

The results highlight several key findings:

- The RTM manufacturing method has been used for the production of spall liner panels and subsequent specimens with high V_f, consistent mechanical properties, and improved ballistic performance.
- Mechanical tests revealed that the tensile, shear, compressive, and flexural strengths improved with higher V_f. However, an increase in V_f also leads to a decrease in elongation, highlighting the trade-off between strength and flexibility. Carbon fiber composites displayed the highest tensile and flexural strengths, followed by aramid and glass fibers.
- The aramid fibers demonstrated the highest V_{50} ballistic limit across all configurations, showcasing their superior energy absorption and toughness. This indicates that aramid fibers are highly effective for dissipating ballistic energy, making them an ideal choice for spall liners.
- Among the matrices tested, vinylester-based composites exhibited the best performance in terms of both mechanical properties and ballistic resistance. The epoxy-based composites exhibited superior tensile strength but did not surpass the vinylester in ballistics tests. Polyester-based composites, while cost-effective, offered the least ballistic protection compared to other matrices.
- Higher fiber volume fractions are generally correlated with an enhanced ballistic performance. Composites with a V_f of 60% consistently exhibited the highest V_{50} values, indicating that increasing the fiber content within the composite matrix improves its ability to resist ballistic impacts.
- Post-test damage analysis revealed that the aramid fiber configurations exhibited minimal delamination and fiber breakage. In contrast, carbon fiber configurations show more noticeable damage patterns, particularly at lower V_f, and glass fibers demonstrate significant delamination and fiber-matrix separation.

- It is understood that the designed CFR composites are not suitable for spall-liner applications, although they exhibit high values in terms of mechanical properties.
- The optimal configuration for achieving the maximum ballistic performance is identified as a high V_f with aramid fibers and a vinylester matrix. This combination yields the highest V_{50}, the highest mechanical properties and the least amount of damage, indicating superior ballistic performance.

The developed advanced composite spall liners are highly suitable for defence and aerospace applications, providing enhanced protection owing to their low weights. Integrating these composites into military vehicles can lead to weight reduction while maintaining or improving ballistic protection levels. Extensive empirical data on the mechanical properties and ballistic performance of various fiber types and composite configurations are provided, enriching the scientific database and aiding future research and development. The empirical data and insights into the performance of various FRCs provide a substantial foundation for future innovations in composite materials for ballistic protection. Comparative analyses and detailed performance metrics serve as reference points for ongoing and future studies in this field.

The developed FRC spall liners can be directly applied in military vehicles and personal protective equipment to enhance protection against ballistic threats. Additionally, lightweight and high-strength composites can be used in aerospace applications for protective gear and structural components, improving both safety and performance. These advancements will also benefit law enforcement by enhancing the safety of officers during high-risk operations. Furthermore, the development of advanced protective gear for civilians, including body armour and helmets, could be valuable for use in conflict zones or high-risk professions.

In future studies, novel fiber and matrix combinations, including hybrid composites with nanomaterials, could be used to enhance ballistic protection and mechanical performance beyond current capabilities. Additionally, the integration of additional functionalities into ballistic composites, such as self-healing properties, embedded sensors for damage detection, and improved thermal management, could be explored. In-depth studies on the dynamic impact behavior of advanced composites under varying projectile velocities and angles could be conducted to better understand their performance in real-world scenarios. Furthermore, the long-term durability of ballistic composites under different environmental conditions, including extreme temperatures, humidity, and UV exposure, could be assessed to ensure reliability in diverse operational environments. Advanced computational models and simulations could be developed to predict the behavior of ballistic composites under impact, aiding in the design and optimization of new materials and structures.

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CURRICULUM VITAE

Yılmaz ERBİL, spent his childhood in different cities because of his father’s duty. He enrolled in Çukurova University Mechanical Engineering Department in 1995, and he graduated with a bachelor's degree and MSc degree in the same in 2000 and 2003 respectively. He resides in Eskişehir, TÜRKİYE as of date of thesis completion, has accumulated over two decades of experience in the defence and automotive sectors. He is currently the General Manager of SECANT Savunma ve Havacılık A.Ş., which specializes in survivability systems and advanced composites.