Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Improvement of Mechanical Properties of Automotive Composite Material by Matrix Modification with Rubber Particles

Master's Final Degree Project

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Kaunas, 2021

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Vehicle Engineering (6211EX021)

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Study programme: Vehicle Engineering (6211EX021)

Task of the Master's Final Degree Project

Given to the student: Thirumuga Karthi Nagarajan

1. Title of the Project:

Improvement of Mechanical Properties of Automotive Composite Material by Matrix Modification with Rubber Particles.

Automobilių kompozitinių medžiagų mechaninių savybių tobulinimas, modifikuojant matricą su gumos dalelėmis

2. Aim of the Project:

The aim of the project is to improve the mechanical properties of carbon fibre reinforced polymer composites by modifying the matrix with rubber particles for automotive applications.

3. Tasks of the Project:

1. To review the scientific literature papers of composites for the transport sector and additives for the improvement of the properties.
2. To obtain the optimum concentration of pure epoxy bulk polymer and with Core-shell rubber particles
3. To test the pure Carbon fibre reinforced polymer composites and with Core-shell rubber particles to evaluate the tensile, flexural and Interlaminar shear properties.
4. To test the samples to study the impact behaviour of pure and matrix modified Carbon fibre composites.

4. Structure of the Text Part:

1. Literature review
2. Materials and methods
3. Experimental investigation
4. Results and discussion
5. Conclusion

5. Consultation of the project:

Author of the Final Degree Project	Thirumuga Karthi Nagarajan	2020-02-04
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	(abbreviation of the position, name, surname, date)	

Nagarajan Thirumuga Karthi. Improvement of Mechanical Properties of Automotive Composite Material by Matrix Modification with Rubber Particles. Master's Final degree project/supervisor assoc. prof. Daiva Zeleniakienė; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Transport Engineering (E12), Engineering Science.

Keywords: Automotive composite, Core-shell rubber particles, Carbon fibre, Impact testing, Energy absorption, Tensile and flexural

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Summary

In the current scenario, the transportation sector needs to reduce CO_2 emission, improving fuel efficiency and a faster transport network. The most important aspect is to improve fuel efficiency by reducing vehicle weight without sacrificing performance. Research and development played an important role in developing material that is lighter than the conventional materials also give better performance in the properties to make the automobiles more efficient. The composite materials are used in all modes of transport. This project presents an improvement of mechanical properties by matrix modification with the rubber particles for automotive applications. Core-shell rubber particles of Ace MX-125, 156 and 960 were used for the matrix modification. The bulk polymers of epoxy with 3, 6, 10 and 15 wt.% of three CSR particles were tested and compared to find the optimum concentration of the rubber particles for the improvement. The 6 wt.% was selected as the required concentration of the rubber particles. The static tensile test results showed that the Carbon fibre composite with CSR particle (6 wt.%) performs better than the traditional pure epoxy composite. The tensile strength was increased by 38%. The flexural and interlaminar shear properties were tested according to the respected standards. The CSR particles with 6 and 10 wt.% were used. The addition of CSR particles gradually enhances the bending strength and Interlaminar behaviour. In this case, the Ace MX-125 at 6 wt.% slightly affects the bending and ILSS due to the adhesion effect. The other composition with all the three CSR particles improved flexural strength up to 48%. The drop weight impact test was performed. The amount of CSR particles usage was similar to the bending tests. The 10 wt.% of CSR particles modified composite absorbs more than 50% energy absorbed by the pure epoxy composite.

Nagarajan Thirumuga Karthi. Automobilių kompozitinių medžiagų mechaninių savybių tobulinimas, modifikuojant matricą su gumos dalelėmis. Magistro baigiamasis projektos/Vadovė doc. Daiva Zeleniakienė; Kauno technologijos universitetas, Mechanikos inžinerojos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Transporto inžinerija (E12), Inžinerijos mokslai.

Reikšminiai žodžiai: Automobilių Kompozitai, gumos dalelės, anglies pluoštas, smūgio bandymas, energijos absorbcija, tempimas ir lenkimas.

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Santrauka

Pagal dabartinį scenarijų reikalingas CO_2 ir degalų emisijos mažinimas bei greitesnis transporto tinklas. Svarbiausias aspektas yra pagerinti degalų efektyvumą mažinant transporto priemonės svorį, neprarandant mechaninių savybių. Šiam tikslui, tyrimai ir plėtra vaidina svarbų vaidmenį kuriant kompozitinę medžiagą, kuri yra lengvesnė už įprastas ir suteikiant geresnių savybių, kad automobiliai taptų pranašesni. Kompozitinės medžiagos yra vis labiau naudojamos įvairioms transporto rūšims, todėl šio darbo tikslas ir rezultatai parodo, kad kompozitų mechaninės savybės pagerėja, kai jų matrica yra modifikuojama gumos dalelėmis. Matricos modifikavimui buvo naudojamos Ace MX-125, 156 ir 960 šerdies gumos dalelės (anlg. core-shell rubber particles, CSR). Buvo tiriami epoksidinės dervos polimerai su 3, 6, 10 ir 15 masės % trijų CSR dalelių ir palyginti, kad būtų nustatyta optimali gumos dalelių koncentracija medžiagos pagerinimui. Reikiama gumos dalelių koncentracija buvo pasirinkta 6%. Statiniai tempimo bandymo rezultatai parodė, kad anglies pluošto kompozitas su CSR dalelėmis (6%) yra stipresnis nei kompozitas su įprasta epoksidine derva – stiprumas tempiant padidėjo 38%. Lenkimo ir tarpsluoksninės šlyties savybės buvo įvertintos pagal standartus, naudojant bandinius su 6 ir 10% CSR dalelių kiekiais. Buvo gauta, kad kartu su CSR dalelių kiekiu, palaipsniui didėja lenkimo jėga ir atsparumas tarpsluoksninei šlyčiai. Tuo tarpu, naudojant 6% Ace MX-125 daleles, lenkimas ir šlytis buvo paveikti nežymiai, dėl sukibimo efekto. Kitas mišinys su visomis trimis CSR dalelėmis padidino lenkimo jėgą iki 48%. Taip pat buvo atliktas smūgio bandymas. CSR dalelių naudojimas buvo panašus į lenkimo bandymus: modifikuotas kompozitas su 10% CSR dalelėmis absorbavo daugiau kaip 50% smūgio energijos, lyginant su įprastu epoksidinės dervos kompozitu.

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List of abbreviations and terms

CFRP – Carbon fibre reinforced polymer composite

CSR – Core-shell rubber

CTBN – Carboxyl-terminated poly acrylonitrile-butadiene rubber

SBR – Styrene butadiene rubber

PBd – Polybutadiene

1. Introduction

The global energy crisis became worsened. Some of the most pressing issues facing the automotive industry were the fuel usage and emission of CO_2. In modern vehicles, most of the parts are manufactured from iron and steel.

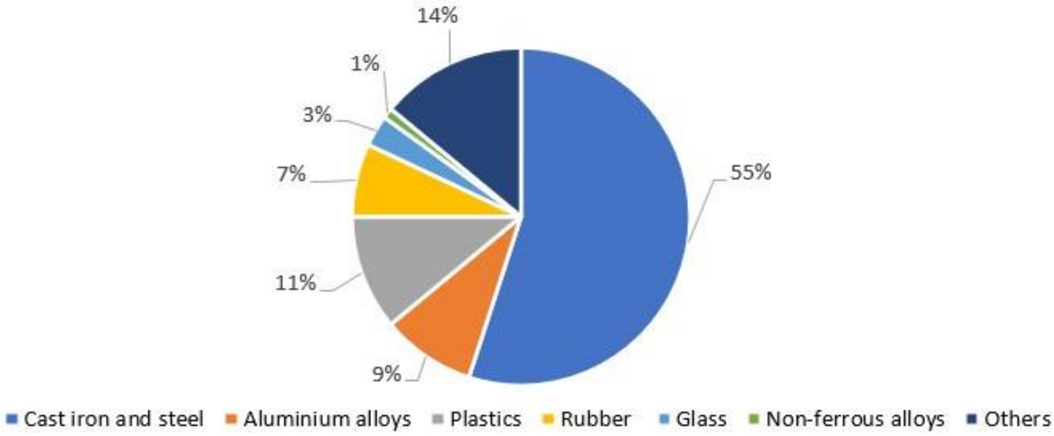

Fig. 1. Types of materials used for manufacturing of automobile parts

The various parts of a vehicle can be replaced with some alloys and some materials to increase the energy efficiency in the transport sector. If we reduce 10 kg weight of any vehicle, it will reduce the fuel consumption and 1 g/km reduction in the carbon emission. Composites emerged as a key for the factor. Carbon fibre-based composites emerged in 1960s and the usage is not only in the transport sector also in Defence, construction, aerospace application and sports etc., The ultimate reason for the usage of composites in the automotive sector is lightweight. It offers high strength to weight ratio, durability, resistance to vibration and corrosion, directional stability and less heat conduction. For example, Carbon fibre reinforced polymer composites (CFRP) are 1/5th of the weight of 1020 steel, but it is 5 times stronger than steel. Aluminium is a lightweight material, but the composite density is 2 times lesser than aluminium. FRPs are used in the automotive industry mainly to reduce weight. CFRPs are being increasingly used for body construction. It promotes sustainability. A high degree of safety is from the FRPs stable structure. The lightweight makes the vehicle more fuel-efficient, and it can minimize greenhouse gasses and other emissions if the movement towards carbon fibre begins. FRPs are useful as metal replacements in luxury car bodies as well as in truck and trailer sidings. Such solid, rigid, and light materials also increase fuel consumption while increasing the speed with higher fracture points than steel [1].

Currently, the transport sector moving towards the CFRP for manufacturing various parts. The Carbon fibre composites are in the current trend and it grows enormously. If the properties of the composites will be improved means that will be useful in many ways.

This work is a part of a large international project. Czech company SYNPO, developing new composites to use in the transport industry (Automotive, Aviation and shipbuilding). My aim of the work is to modify the epoxy matrix with CSR particles and using carbon fibre as reinforcement to enhance the mechanical behaviour of composites for automobile applications.

The novelty of the work

This work researches and compared the epoxy and matrix modified composites. This research sector is actively investigating the application of composites in the transport sector. The results provide data that can be used to make lightweight composites with improvement in the properties.

The aim of the project is to improve the mechanical properties of carbon fibre reinforced polymer composites by modifying the matrix with the rubber particles for automotive applications

The tasks:

1. To review the scientific literature papers of composites for the transport sector and additives for the improvement of the properties.
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2. Literature review

2.1. Impact of Caron fibre reinforced polymer composites in the Transport sector

Over the past decades, the usage of CFRP in the transport sector emerged relentlessly. The first car which used a carbon fibre composite chassis was McLaren MP4/1. Because of their strength, stiffness and low weight, the signature was shown up in all modes of transport.

Fig. 2. Fully modified Carbon fibre composite Koenigsegg Regera, wheel and Speed tail [1].

From 2021 to 2025, the carbon fibre and CFRP market are expected to expand at a rate (CAGR) of 12.4% (32 billion by 2025).

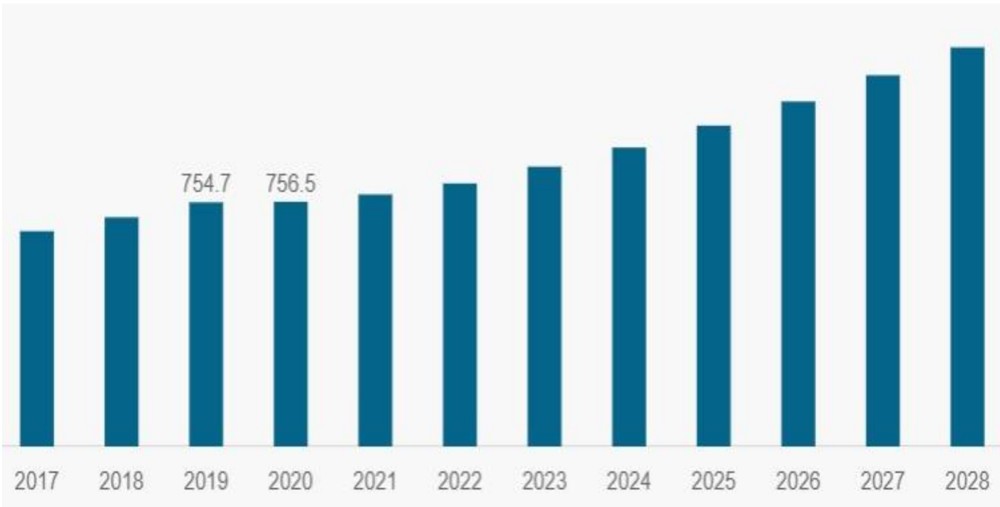


Fig. 3. European carbon fibre market size, 2017-2028(USD million) [2**]**.

Automobile parts production along with the need for lightweight materials is to fuel the market growth. The manufacturers increased the demand to manufacture various parts like bumpers, pillars, chassis, fenders, wings and drive shafts etc., The EU project (HIVOCOMP) for developing advanced materials which enable to produce a large amount of composite structural parts to transport applications to bring the composite technology closer to the mass production for the automotive applications [4]. Road transport sector moving towards the electric vehicle side. The European Commission for 'Sustainable and smart mobility strategy' guided towards by at the end of next 19 years, at least 0.03 billion emission-free cars on the European roads. The Ev's sector thrives to reduce the vehicle weight. We can achieve it through the CFRP components. Automobile companies like BMW, Audi, Volkswagen. Mercedes Benz and McLaren collaborating with the composite suppliers for manufacturing their parts [2].

Fig. 4. SGL Carbon’s - Carbon fibre-based battery enclosure for NIO electric vehicles [5].

All the vehicles in the transport industry are needed to drive for longer duration cause corrosion and it needs frequent maintenance. Naturally, the composites are corrosion-free materials. The composites are not only used in road transportation, but it also uses in the aerospace sector, both in rail and water transport and in defence vehicles.

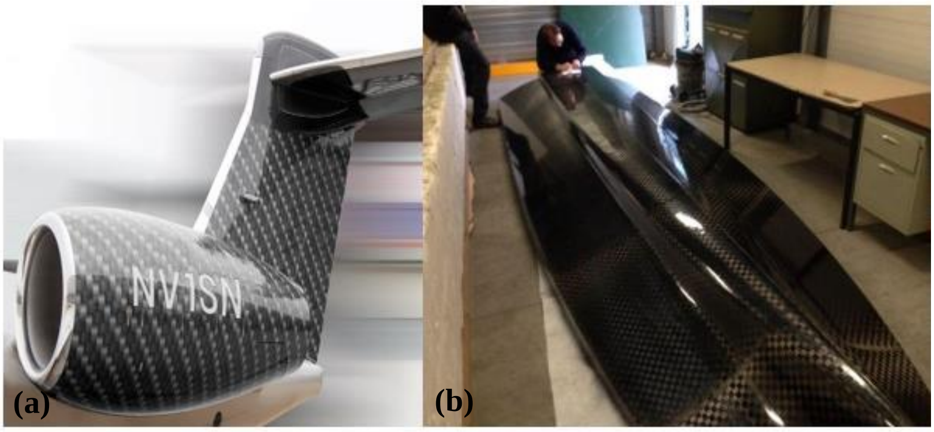


Fig. 5. (a) Carbon fibre G650 Gulfstream envision (b) Carbon fibre boat [6]

By the end of 2030, at least a 55% reduction in greenhouse gas emission. Greening mobility is the key for the transport sector growth in the future. The automakers are surge to make the vehicle in less weight to make them more energy-efficient. Engineers are jumped into making it affordable and easier to manufacture. The global carbon emission insists the Automobile manufacturers to make things in greenway. Through carbon fibre composites, Aircraft manufacturers can get good surface finish parts to optimise the performance on aerodynamics. In Boeing 787 Dreamliner, the wing and the fuselage were manufactured from the CFRPs [7].

The composites behave differently when compared with conventional metals. The metallic structures undergo deformation and heat propagated. Composites, on the other hand, are subject to brittle fracturing and energy transfer due to friction between laminates, material compressive cracking, and composite splitting, implying that composite structures can absorb energy better than metallic structures. The different natures of energy absorption of metal and composite fibres can be deduced, where metal structures on the impact the substrate folds to a certain distance providing initial absorption crashing but the material limits the dissemination of the energy, the brittleness of the composite helps in the propagation of energy within the material, reducing total damage to the parts.

Fig. 6. Metal and FRP under crash [8].

The materials various requirements, such as energy absorption, fracture durability, and structural deformation, are used to evaluate the performance of a vehicle's structure during a crash. These criteria can be met with composite materials, such as energy absorption, studied extensively by scientists and automotive enthusiasts for decades.

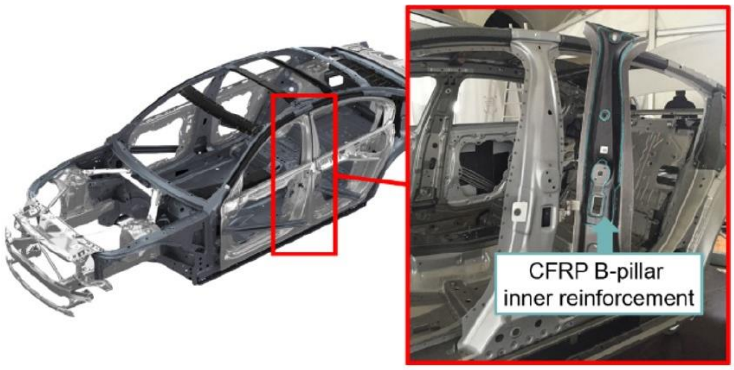


Fig. 7. A hybrid carbon composite-steel pillar assembly in BMW 7 series (G12) [9].

The B-pillar assembly of the BMW 7 series was reinforced by carbon composite in 2015 by rivet bonding shown in Fig. 7. The hybrid assembly of Cfrp with steel increased the crashworthiness of a car body. It reduced the weight by 40% and increased the crashworthiness by 10% [10].

Now the research is going on to improve the properties of the CFRP. There are various types of fillers are available to enhance the properties. Some of the fillers are CNTs, clay, Mxenes, graphene rubber and micro fillers. The rubber particles play a major role in toughening the epoxy polymers. There are two types of rubber particles available for matrix modification.

1. Carboxyl-terminated poly Acrylonitrile-Butadiene rubber (CTBN)
2. Core-shell Rubber (CSR)

Comparatively the CSR particles offer excellent properties. They are very small particles evenly distributed in the resin to terminate the cracks. The core polymer relieves inherent stress generated during curing. The CFRP trend is already in the automotive sector, if the properties get improved it will be helpful to increase the strength of their parts.

2.2. An overview of possibilities of the improvement of mechanical properties of CFRP composites

2.2.1. Graphene

Graphene is a pure carbon element (2-dimensional allotrope), in which the atoms are hexagonal in a one-atom-thick tightly packed board. That structure is the base for many carbon-based materials.

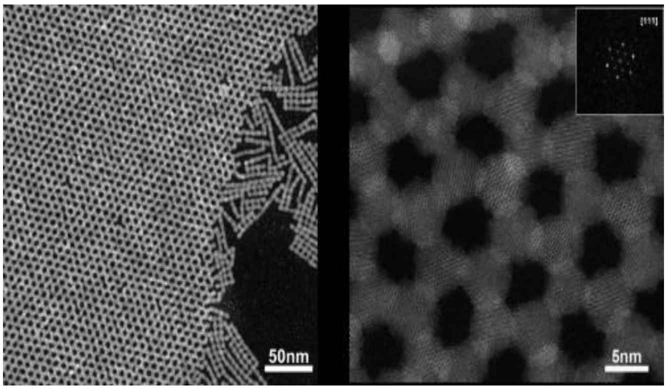


Fig. 8. Graphene (Microscopic image) [11]

Depositing the CNTs and GO separately on the carbon fibre (CF) surface by the Electrophoretic technique improved the interfacial behaviour of CF. It made a huge morphological difference in the carbon fibre. The content of the carbon gradually decreased, and the content of Oxygen increased to around 21%, the O/C ratio increased double the value 14 percentage (CNTs/CF). The GO coating creates bonding between the chemicals. It increases the area of intersection which decreased the concentration of stress and CNTs/CF interfaces shear strength increased [12]. Through the process of in-situ exfoliation, it becomes easier to make graphene reinforced polymer matrix composite in a thermoplastic polymer matrix. By shearing, the graphite into exfoliating graphene sheets enhanced the bulk polymer properties. The graphite particles need to grinded to micron size particles. When these particles dispersed in the molten polymer phase as a single layer or multi-layer, it can enhance the mechanical properties [13].

Infanta et al. studied the modified epoxy resin with a bi-axial glass cloth. When the graphene nanopowder (0.1 wt.%) is mixed with the resin, it reduces the fibre content in it. It shows improvement in tensile strength and compressive strength [14][15]. E. Mannov et al. did several FRP experiments with thermally reduced graphene oxide by matrix alteration. They prepared the CFRP (with epoxy matrix) by filament winding machine. They used thermally reduced graphene oxide (TrGO). The three-roll method is an efficient way to disperse the graphene oxide. Using this method 0.3 and 0.5 weight percentage of TrGO dispersed in the epoxy. Adding some hardening agent and insulation in GO epoxy resin to activate the matrix system and the autoclave prepreg technology homogeneously distributed the nanoparticles in the composite material. By conduced the drop weight test, the delamination size reduced by 8 percentage and in the backside delamination of the specimen reduced by 7 percentage was observed. The specimen with a 0.3 weight percentage of TrGO gives better results in increased the residual compressive strength by 19 percentage [16]

2.2.2. Boron Nitride

Boron nitride (BN) has excellent possession to enhance the properties of CFRPs. It can easily interact with polymers and offer multifunctional properties. Yuichi Tominaga et al. investigated CFRP properties with the incorporation of exfoliated h-BN. They prepared it by wet jet milling and incorporate the h-BN at 2.5 and 5.0 volume% into the matrix resin (polypropylene). After the MW irradiation, the composite was not changed. It means the thermal conductivity was formed effectively on the composite. The strength-to-weight ratio and the specific modulus were increased by 22 and 37 percentage. It means that the h-BN exfoliation enhanced the composite's mechanical strength [17]. Using the biometric approach to create the composite with small Boron nitride by coat the polydopamine. For the construction of nanocomposite, BN-F-GF was developed and integrating onto the resin mixture. It begins with the epoxy resin and curing agent $C_6H_{12}N_4$. BN-D-GF and BN/GF/epoxy composite for comparison by the previous technique and characterize the composite by SEM, differential scanning calorimeter and dynamic mechanical analysis. Hardness, thermal conductivity, dielectric test and volume resistivity test on the specimens were conducted. The dopamine treatment improved the attachment between the nano-BN and GF and increased the surface roughness, improvement in T_g. The improvement of 57% in storage modulus and 10% in hardness in the modified composite compared to the unreinforced composite and the dielectric loss got decreased.

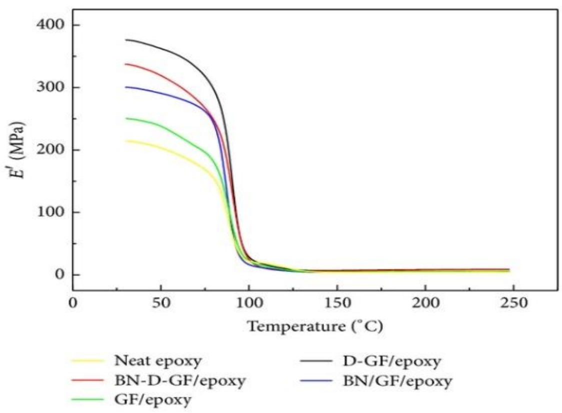


Fig. 9. The loss modulus of pure epoxy and FRP composites [18].

Also, Meysam Rahmat et al., investigated the BNNT properties for the enhancement of GFRPs. They were fabricating the fibre-epoxy/BNNT by a wet layup and VARTM method. HABS (Hydrogen assisted BNNT synthesis) method was used to produce the boron nitride nanotubes. They had used the solvent-free planetary mixing method to add the BNNT in the SC-15 composite. The dimension of the glass fabric is 17 cm * 34 cm. They conducted 3 different tests to determine the properties variation. The punch test concluded that r-BNNT addition increased specific shear strength by 8 percentage. Finally, the Charpy test concluded that a 19-percentage improvement in σ^*_{max} and increase in E. when the specimen is undergoing a three-point bending test showed a 35 – percentage improvement in the maximum stress [19]. Titanium nitride possesses some properties of chemically very inert and the service temperature up to 600^0 C. The titanium nitride coating improved the fire resistance of the CFRPs [20].

2.2.3. Carbon Nanotubes

Carbon nanotubes are widely used around the world as a filler material for strengthening composites. MWCNTs are generally in agglomerated form. The fabrication of CNT was mostly by solution bending and in-situ polymerization method [21]. The CNT was used to minimize composite density gains. When Nylon 6 is blended with polypropylene provides good processability. The properties of Carbon fibre reinforced PA6/PP composites were increased by minute particles of CNT. PP reduced the weight of the composites. The carbon fibre-reinforced Nylon 6/polypropylene composite is one of the lighter ones and the extra weight reduction was provided by pure PA6. When the number of multiwalled CNTs increased in the composite, the elastic and flexural moduli got increased.

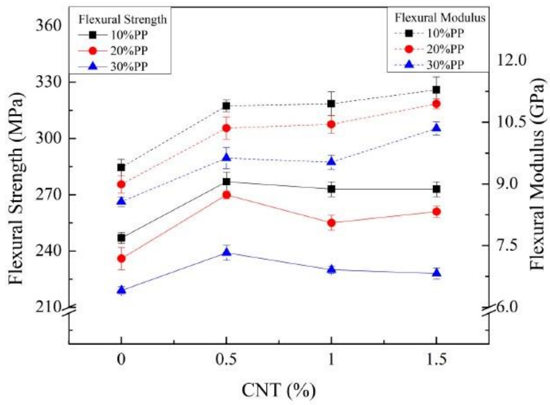


Fig. 10. Bending strength & flexural modulus of carbon fibre and CNT reinforced PA6/PP composites [22].

Kishore Kumar Pachagnula and Palaniyandi Kuppan[23] also investigated the GFRP with MWCNTs. The amount of MWCNTs was modified (0.1, 0.2, 0.3 and 0.4 wt%). High purity ethanol was added to deagglomerated the MWCNTs. For the tensile and flexural testing, the thickness of 4 mm should be maintained, (ASTM standard). The test results revealed that the 0.3% addition of MWCNTs increased tensile strength by 36%, bending strength by 39% and 128% of improvement in the optimum value of hardness. Carbon fibre was coated with MWCNTs (0.5%). During the SBS test, resulted that the carbon fibre sizing increased the delaminating resistance, increased the fibre interface bonding and fracture resistance of the composite. The polymer matrix strength increased to 18% with 50% of CNT in the fibre sizing and CNT in the matrix compared to CNT free material [24]. The carbon fibre was soaked with copper sulphate (Electroless copper plating) and adding some MWCNTs in the epoxy resin makes the composite much stronger. The surface of the specimen was rough and improved in the interfacial adhesion due to the coating. The addition of Multi-walled CNTs (1.5 wt%) increased the ultimate strain by 1.5 percentage, stiffness of 74.5 percentage, peak strength of 80.5 percentage ultimate strain of 48.8 percentage [25].

Jacob Muthu et al.,[26] functionalized the MWCNTs by the process of oxidation (HNO_3) and the CNTs was dried at three different timings (6, 8 and 48 hours). This technique energises the homogeneous distribution of CNTs within the matrix form and interfacial adhesion. Here, the resin is unsaturated polyvinyl ester resin. From the GRP hybrid composite with various fibre mass fraction (24, 32 and 40 percentage), the fibre mass fraction of 24 to 32 percentage gives a major improvement in the GRP hybrid composite. The test revealed 24hr time is the best functionalization. **6**. 0.25 percentage doping of MWCNTs 8 layer of CF laminate first and last of $0^0/90^0$ and the intermediate $+45^0/-45^0$ shows better interface bonding and good energy absorption [27][28].

2.2.4. Clay

Clay enhances the mechanical properties of the glass/carbon composites. Hand layup method produced the glass fibre composites with clay 2 wt%. The XRD (X-Ray Diffraction) results showed the formation of exfoliated structure improved tensile strength. Clay loading and the presence of the silicate layer increased the flexural strength and tensile strength [29]. Seyed Abdolwahab Hoseini and Mohammad Hossein Pol[30] investigated the addition of nano clay closite 30B within epoxy with 1, 2, 3, 5, and 7% ratio in weight concerning nano-matrix. Using Vacuum-assisted resin transfer method to manufacture the glass epoxy nano clay hybrid composite. The three-point bend flexure test shows quite an improvement in the tensile strength of 13%, failure strain of 7% and toughness of 27% with nano clay (7%).

Whenever the addition of nano clay in the GFRP, shows some improvement in the properties. Vinyl ester and epoxy/clay enhanced the tensile strength by 11.83 percentage and elastic modulus of 3.2 percentage. The alkali solution decreased the behaviour of VE/China material Nanocomposites. Adding some Montmorillonite drastically improved the ductility and the fibre-matrix interfacial bonding. Whenever comparing the Vinyl ester/Clay nano modified GFRP and the Epoxy/Clay Nano modified GFRP, TS less in the VE/China material Nano-GFRP. The addition of montmorillonite forms a layer not to allow the chemical into the matrix. With a 5-percentage addition of nano, clay had better improvement than graphene [31]. With a 2.5 wt percentage, thin layer of clay incorporated into the epoxy resin by the process called 'Slurry-compounding process'. This process uniformly distributed a few layers on the resin surface. Due to cracks between the clay, the strain increased, and fracture toughness also increased [32]

3% of nano clay in the CFRP composites shows improvement in density and hardness. The nano clay is uniformly dispersed in the epoxy composite through the milling mixing methods (TEM micrograph revealed the dispersion). The wear performance on the composite improved at 3% of nano clay. 5% of nano clay enforcement improved only the wear resistance. It improved the abrasive and adhesive wear properties.

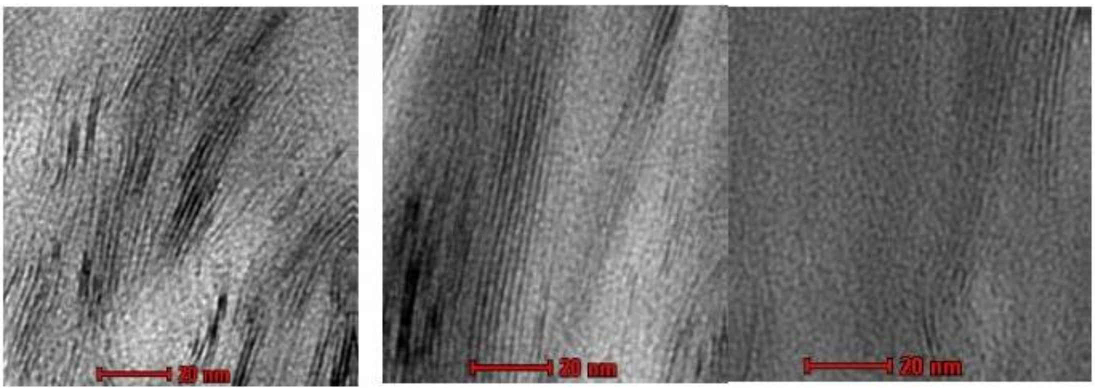


Fig. 11. 1, 3 and 5 percentage of nano clay modified CFRP [33].

Mulugeta et al.,[34] investigated the montmorillonite nano clay filled SC-15 epoxy matrix. They add 1, 2, 3 and 4 wt.% of clay in it. Nano-phased matrix is generally an organic polymer. The Dynamic mechanical analysis(DMA) revealed a 58% improvement in storage modulus up to the addition of 2 percentage of clay. According to the ASTM D790-86, the three-point flexural test revealed improvement in tensile strength (11%) and flexural strength (22%) and Nano silica particles improved the Fracture toughness up to 22%.

2.2.5. MXenes

They are not organic compounds that consists of metal carbides, nitrides and carbo nitrides. They are made from bulk crystal by an etching process.

$M_{n+1}AX_n$

M - early transition metal
A - group A element
X is either carbon or nitrogen
n = 1, 2 or 3

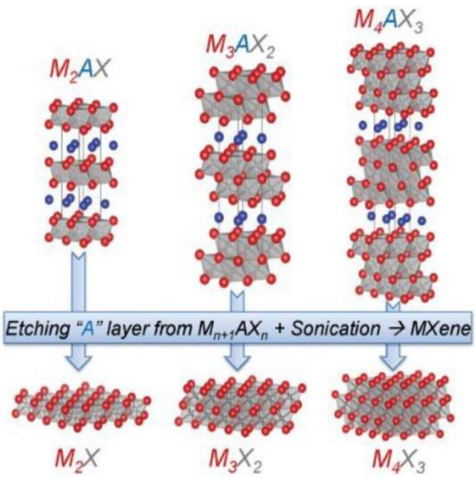


Fig. 12. MXenes structure [35].

The A atoms needs to selectively etch from the MAX phase. Etching Aluminium from Ti_3AlC_2, O, OH and F replaced with the Al atoms. The procedure of extraction is shown in Fig. 5. Modified MXenes were used to improve the interfacial effects. When Ti_2C sheets from Ti_2AlC was modified with $C_9H_{23}NO_3Si$ (Aminosilane), it improves the bonding between the epoxy and CF and chemical interlocking between them shown in Fig. 13 (b) and extraction is shown in Fig. 13 (a).

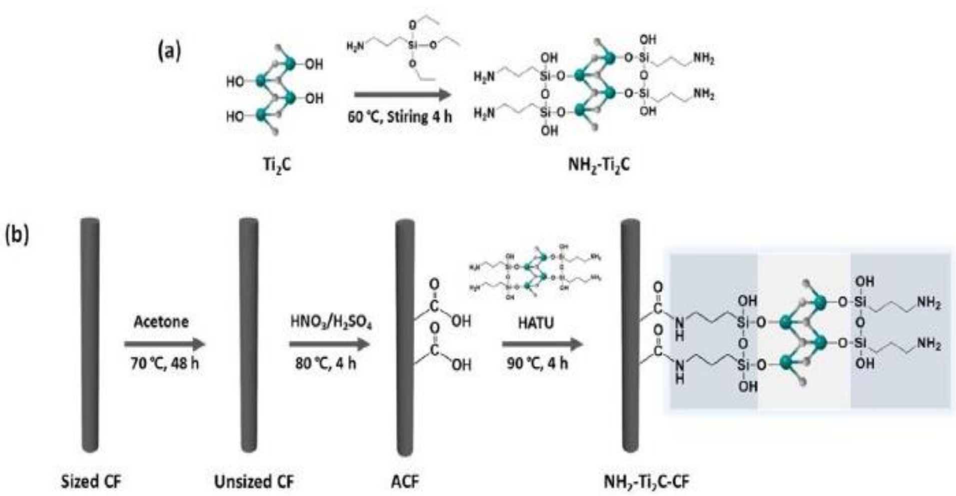


Fig. 13. (a) Ti2C modification and (b) Grafting process [35]

Due to the oxidation process, the IFSS increased up to 77.9% and ILSS up to 27%, boosted the transfer of the load capacity between the fibre and matrix resin [36]. Ti_3C_2 MXene were prepared from Ti_3AlC_2 powder, the CFs were immersed in the colloidal solution. The colloidal solution increased the atomic contents of titanium, fluoride and chloride to attach the MXene with the carbon fibre. By increased the wettability of CFs, it enhanced the performance of the composite. After reached 1 mg/mL thickness will vary. 1 mg/mL is enough to cover the CFs. The IFSS strength by 186% due to the functionalization [37]. The etching of Al from Ti_3AlC_2, with 40 wt% of HF solution. The NH_2-CF/EP composites and NH_2-Carbon Fibre/MXene/EP composite performs improvement of 74% in impact, 40% in tensile, 45% in bending and 38% in shear strength category [38].

2.2.6. Rubber and Micro-fillers

Rubber particles play a significant role in the improvement section. Mainly there are two types of rubber particles used in the toughening process.

1. Core-shell rubber (CSR)
2. Carboxyl-terminated Acrylonitrile-butadiene rubber (CTBN)

Any resin with core-shell rubber and phase separating rubber increased the toughness in FRP. The silica particles or CSR particles mixed with an epoxy polymer resin (DGEBA), increased their toughness and fracture energy. The hybrid resin (addition of silica nanoparticles and toughening by combining rubber) can be formulated. Also, the Carboxyl-terminated butadiene-acrylonitrile (CTBN) increased mechanical properties. The addition of CTBN and nanoparticles increased the tensile modulus, glass transition temperature and fracture toughness at a certain point of the level. If the addition of CTBN and nanoparticles exceed a certain limit, it affects the mechanical properties and some quiet improvement in the fatigue [39][40]. DGEBA epoxy resin with SiO_2 particles produced the hybrid-toughened epoxy polymers results in increasing the toughness of CFRP [41].

CNF and PZT (dopant) were a supplement to improve the fracture and damping properties. Here, an epoxy matrix is modified by the additive particles. The cantilever beam (double) method and 3-point end notched flexure methods were used for the fracture properties evaluation of CFRP. CNF alone increased the fracture energy. CNF and PZT particles in the matrix drastically reduced the properties. The energy-absorbing mechanisms improved the CNF and PZT particles and it improved the fracture properties [42][43]. Also, the ATBN and polypropylene oxide act as a toughening agent through the toughening process. The rubbery particles make the matrix to improve the shear yielding [44]. Rubber particles (MX – 125, 156 and 960) and hydro CTBN with DGEBA resin increased the fracture energy. Comparatively the CTBN gave greater fracture energy than the CSR particles. Bisphenol f type epoxy resin with MX-136 rubber particle as a latex agent with (3, 7, 11, 15 and 19.4 wt.%) of CSR in the mixture gives much improvement in tensile strength at 11 wt.% and tensile modulus at 19 wt% and 87% improvement in the impact behaviour when compared with an epoxy sample.

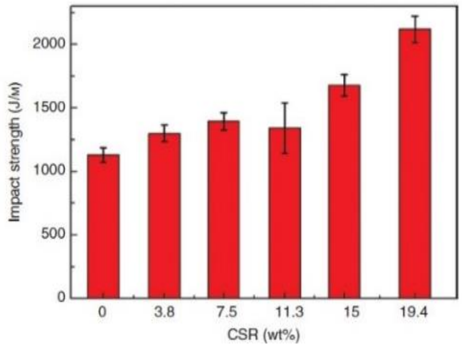


Fig. 14. Impact strength of CFRPs with varying CSR content [45].

If the number of polysiloxane based rubber particles increased in the DGEBA resin, the glass transition temperature gets slightly decreased. When increasing the CSR content, the tensile strength linearly decreased because of stress concentration. Also, the compressive stress gets decreased when the amount of CSR particles increased.

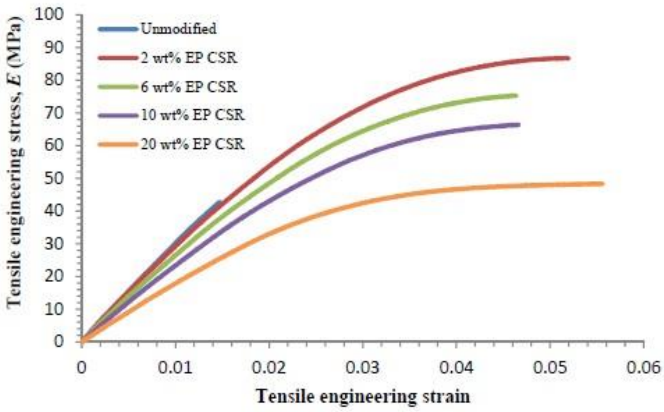


Fig. 15. Tensile stress-strain curve of varying amount of EP-CSR modified epoxies [46].

EPON 825 with MX-125, 156 and 257 shows T_g gets decreased with the increment of rubber particles and the fracture toughness increased [47]. CTBN rubber with acrylonitrile content of 18 wt.% and 40 wt.% concentration in the epoxy (Albibox 1000) was used. The fracture energy and stress intensity factor increased linearly with the increased amount of nano-Sio_2 and CTBN [48]. Dipa ray [49] investigated the toughness behaviour of composite with MX-156 in the cycom 890 epoxy resin at 1, 5 and 2 phr. To evaluate the damage tolerance of the composites, CAI tests were performed according to the standards. The storage modulus of the composites was decreased with the CSR particles. Without the rubber particles the specimens showed good flexural properties and with the CSR content flexural properties dropped by 6% at 1 phr, 14% at 3 phr and 11% at 5 phr. The compressive strength of the composites was increased up to 22% with 5 phr level of the particles.

The impact strength of Mx-960 loading in the composite was decreased from 0 to 3% but increased from 0 to 5% and plastic deformation. The increment in shear deformation and void growth improved impact strength [50]. The CSR particle PARRALOID EXL-234 of 10 wt% and 10 wt% of silica gives 82% and CSR particles alone give 100% improvement in the fracture toughness in the matrix and based on the overall mechanical performance, together with CTBN and nanoparticles [51]. The particle size also affected the toughening mechanism. The core-shell latex was prepared by the polymerization process with the particles size varying from 300 to 900 nm. At the size of 400 nm, stress and fracture level were very similar to the unmodified epoxy matrix. The cavitation decreases with the particle size [52]. When the Epikote 862 with Epikure W and another resin LY556 Dgeba with Albidur HE 600. Both the resin composition with Mx 156 and 960 at 6 wt% and the silica particles Nanopox F400 gives an improvement in fatigue and tensile properties [53]. CSR particles of Zeon 351 (Large one) and Kane Ace Mx 153 (Smaller one) with the Epoxy 828 at different volume percentage.

CSR type	L0-S0	L8-S0	L16-S0	L22-S0	L30-S0	L38-S0	L22-S16
CSR-L (vol.%)	0	8	16	22	30	38	22
CSR-S (vol.%)	0	0	0	0	0	0	16

Fig. 16. Material formulations [54**]**.

The L22-S0 gave a better improvement in fracture properties when compared to the other variations. L22-S16 gave the low fracture energy values because of the extreme optimum CSR content.

2.3. Other possibilities to improve FRP properties

Some methods are available to enhance the mechanical properties of FRP. It also improves the electrical properties. Over the past decades, fibre micro-buckling failure was a major problem in failure areas. One of the methods to decrease the sinusoidal deformation of the fibre is to wrap the fibre with fibre filament (PBO, PET and Basalt filament). It increases the compressive properties and failure mechanisms of FRP [55]. The filament cover method also improving the bending properties. The method which was used in textile industries called the cover method to add the bands to the fibre bundles. Through this method, we can increase the buckling load. If we enhance the buckling load on the fibre bundles, we can improve the bending strength. If it may be single or double-covered, the result is not a satisfactory one. It needs to be fully covered [56]. Copper oxide act as a nanofiller to enhance the mechanical behaviour of GFRP. Using the hand layup technique, the copper oxide was filled with the GFRP. Some researchers investigated the properties of GFRP with CuO powder at various percentage of weight ratio. Polystyrene resin (1 percentage), Glass fibre (38 percentage) and Nano CuO powder (2 percentage) and conducted SEM analysis and Energy-dispersive X-ray spectroscopy tests on the pate. The results demonstrated strong TS development, Compressive strength, and transverse rupture strength [57].

The pattern of axial yarns was found to have a better effect on the force of compression than axial yarns. The three-dimensional knotted composite material, however, boosts the compressive efficiency in the direction of yarn tensile properties at the expense of the biases [58]. The Euler buckling theory was used to improve the longitudinal compression power of the FRP. Euler proposed that if we decrease the buckling wavelength, we can improve the compressive buckling critical load. When the winding spacing getting shortens, the compressive strength increase. They are inversely proportional to each other. The filament winding process maximises the compressive strength around 10 to 15% [59].

Bone and nacre are some of the hardest tissue. Also, the bone microstructure is a complex one. Some biological techniques are there to improve FRP. Some researchers find a new way to manufacture the composites (a custom-developed VARTM) process. They implement the bone-inspired structure by fine-tuning the manual lamination process into the FRP composites. It gives a better improvement in fracture toughness [60].

2.4. Up-to-date materials for Automotive structures

Mostly the Automotive companies divert their way to the composites area. Through the composites, they can reduce the weight of their vehicles. For formula 1 cars, they use polymeric fibres like Aramids and Zylon. Aramids are used in the front wing endplates and wherever the aerodynamic needed. Zylon is one of the strong fibre, it is made up of a chain of P-phenlene-2, 6-benzobisaxozole and it is used in the armour panel of F1 cars [61]. KEVLAR [-CO-C_6H_4-CO-NH-C_6H_6-NH-]$_n$ is one of the strongest synthetic fibre.

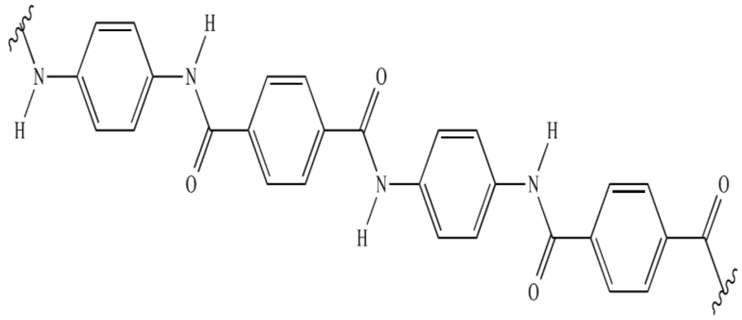


Fig. 17. KEVLAR structure [62].

It is a high strength, dimensional stabilized material. It is used in the manufacturing of gearbox, gaskets, tires, brake pads and belts. It had a special property of high resistance to scratches and has good temperature resistance and it can withstand the damage than the steel and aluminium body and it gives greater protection to the driver. Types of composite matrix materials are Ceramic, metal and polymer. Metal matrix composites had a huge impact on the Automotive sector.

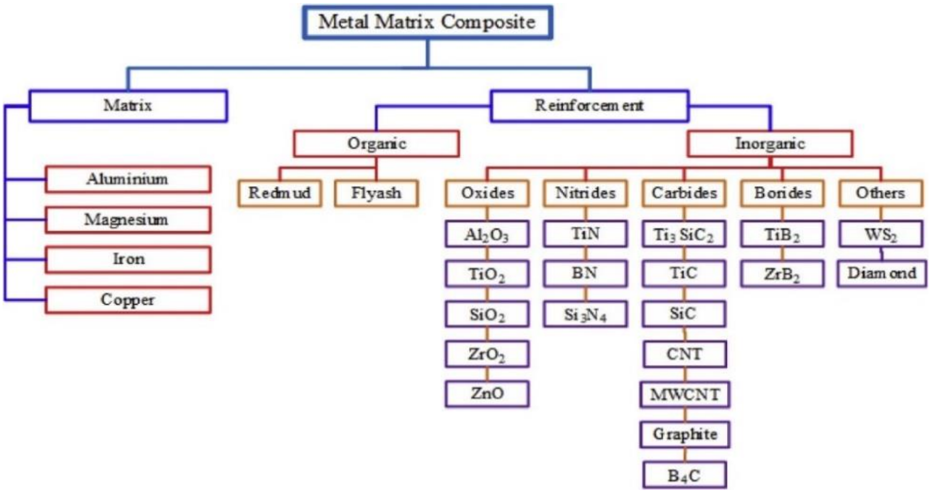


Fig. 18. Types of MMC [63]

Aluminium matrix composites are used in Brakes, engine blocks and pistons and it increased the tensile strength of the composite. AMMC'S having high strength, high stiffness and they can be used for long-term applications. Magnesium matrix composites are mainly used in the Aerospace industry. Polymer matrix connected by covalent bonds and they are resistant to atmospheric conditions and corrosion too. Ford using cellulose tree fibres in their SUVs. Ceramic matrix composites made a huge impact on the brake system [64].

3. Materials and preparation

DGEBA epoxy resin is CHS-Epoxy 582, a bisphenol-A based epoxy (Fig. 19) supplied by SYNPO a.s., Czech Republic; It is a 4,4' Isopropylidenediphenol ($C_{15}H_{16}$O2), oligomeric reaction products with 1-chloro-2, 3-epoxypropane (number average molecular weight <=700, 1, 4-bis-2, 3-epoxypropoxy butane ($C_{10}H_{18}O_4$). The EEW of 166 –179 g/mol. The molecular weight of the epoxy resin is low. It offers medium life and high-quality performance. It is recommended to use in composites, adhesives, wind energy, construction, electronics, and corrosive coatings. All the properties were given in (Table 1).

Fig. 19. CHS Epoxy 582

Table 1. CHS Epoxy 582 properties

Name	**Viscosity (25^{0}C, mPa.s)**	**Epoxy index (mol/kg)**	**Epoxy equivalent (g/mol)**	**Color (Hazen)**	**The hydrolyzed chlorine (%)**
Method	ESN ISO 12058-1	EN ISO 3001	EN ISO 3001	ISO 6271-2	ASTM D 1726
CHS EPOXY 582	640-720	5.78-6.06	165-173	Max 100	Max 0.07

There are various types of curing agent available for curing epoxy in the market. They are polymercaptan, amine (aliphatic amine, aromatic amine, cycloaliphatic), polyamide and amidoamine, phenalkamine, silane type and powder coating curing agent.

The hardener is Telalit 0420 (Fig. 20) supplied by SYNPO a.s., Czech Republic. It is an isophorodiamine. The viscosity is low and the HEW value is low. For curing, the ratio is 100:25. The properties of the hardener given in (Table 2)

Fig. 20. Telalit 0420 (Hardener)

Table 2. Hardener properties

Parameter	**Value**	**Unit**	**Method**
Colour	Max. 2	Gardener	EN ISO 4630-2
Amine vale	600 - 650	mg KOH/g	PI 627/915
Viscosity at 25^0C	10 - 25	mPa.s	EN ISO 12058-1
Hydrogen equivalent	Min. 42.5	g/mol	-

The epoxy resin is generally a brittle one. When the rubber particles get combined with the epoxy resin, the brittleness getting decreased. It increases the elasticity, strength, hardness, ductility, glass transition temperature, poisons ratio and fracture properties. The various types of rubber particles are Core shell rubber and Carboxyl- terminated-acrylonitrile-butadiene Rubber. The CSR and CTBN rubber, it has different varieties of formation. The rubber particles may be in powder form or it was pre-dispersed with the resin at some weight or volume percentage. We have three different types of CSR particles. They are Ace MX-125, 156 and 960 (Fig. 21) supplied by Kaneka, Belgium and the rubber particles are pre-dispersed in the epoxy resin at 25% concentration.

Fig. 21. CSR particles Ace MX-125, 156 and 960

They are served as an agent of toughening. The resulting coating displays increased fracture power, lap shear strength and durability without compromising the temperature of the glass transition or other thermal properties associated with the cross-link density. It is indeed free of contaminants that are ionic and natural. It is compatible with standard coating agents for cold, warm and hot curing agents. The shell diameter of the CSR particle is shown in Fig. 22 and the properties in Table. 3.

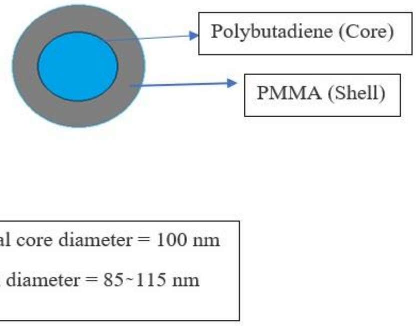


Fig. 22. Schematic diagram of Ace MX-156

Table 3. CSR particles properties

MX resin system (Unit of measures)		Dispersed CSR type	%CSR wt%	Nominal Viscosity cps	EEW g/eq	Flashpoint ^{0}C	density
Bisphenol A epoxy	Ace MX-125	SBR	25+/-1	7500@500C	243	>220^{0}C	1.1
	Ace MX-156	PBd	25+/-1	7800@500C	243	>220^{0}C	1.1
	Ace MX-960	Si	25+/-1	3000@500C	243	>220^{0}C	1.1

The reinforced carbon fibre is Plain weave Carbon fabric 160 g/m2 supplied by SYNPO a.s., Czech Republic. It used for Automotive, modelling, motorsports, marine construction and sporting equipment.

The properties are given in the following table 4.

Table 4. Carbon fabric specifications

No	Parameter	Unit	Specified fibre	Tolerance, %	Standard
1.	Density	g/cm^3	1.79	+/- 1	ISO 10119
2.	Linear density	tex	200	+/- 3	ISO 1889
3.	Filament diameter	µm	7	+/- 0.5	DIN 535811
4.	Tensile strength	MPa	3500 min.	-	ISO 10618
5.	Tensile modulus	GPa	240	+/- 2	ISO 10618

Manufacturing of pure and CSR particles modified epoxy bulk samples.

The pure resin samples are a mixture of pure epoxy and hardener. The epoxy to hardener ratio is 4:1. Epoxy mixed with hardener at 250 rpm for 10 minutes and then using the vacuum pump to be degassing the mixture. The mixture poured into tension-type silicone rubber moulds. During mixing at 10 and 15 wt.% it is quite hard to disperse and mix with the epoxy resin. The rubber particles were heated at 80^0 C for 20 to 30 minutes during the mixing. The CSR particles enforced samples are mixed first the rubber particles (3, 6, 10 and 15 wt.%) with the epoxy, it was stirred well and degassing and then the hardener is added with the mixture. Again, it needs to be degassed and poured into the moulds. To curing the samples, the mould is placed inside an oven. The curing cycle of 2 hr at 50^0C, 1 hr at 80^0C and 2 hr at 120^0C.

Fig. 23. Silicone mould

Manufacturing of Carbon fibre reinforced polymer composite

The mechanical properties of CFRP composites can be evaluated by conducting the required test on them. The main methods for the preparation of CFRP composites are,

- Resin transfer moulding.
- Hand layup method.

The hand layup method is the old one for composite fabrication. Some steps are needed to follow the process. The samples are prepared based on this method.

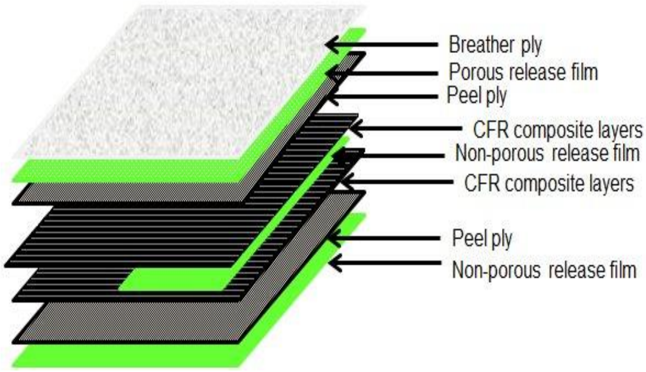


Fig. 24. Fabrication CFRP composite laminate by the hand-layup method

Figure 12 shows the sequence of arrangement. The sheets of carbon fibres are placed in the aluminium or glass plate. Before that, the plate should be applied to the releasing agent. The releasing agent must be dried. It helps to remove the final CFRP composite. We need the amount of resin is equal to the weight of the carbon fibre used. After placing the carbon fibre layer, the resin is to be applied by roller to squeeze out the air bubbles in it. The process is continued until all the layers are placed. After that, the porous release film needs to be placed. On the top, the breather ply is placed. Finally, the plastic layer is placed in connection with the vacuum pump. It needs to be sealed without any air gap. The vacuum process is to be done for around 30 minutes. The setup is shown in Fig. 25.

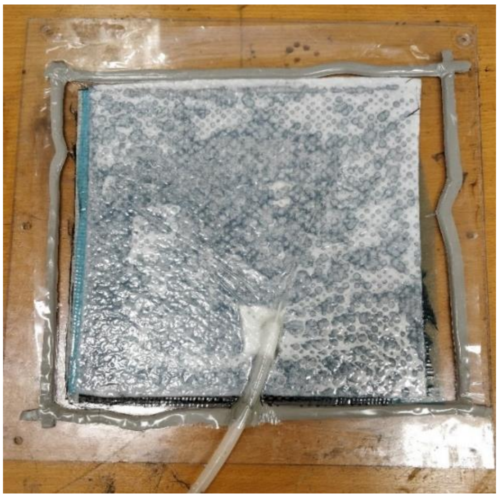


Fig. 25. Hand layup setup

4. Experimental Methods

4.1. Tensile test on bulk polymers

The samples were prepared based on the ASTM standard (ASTM D 638 – "Standard test method of plastics for tensile test". The samples containing pure epoxy and 3wt%, 6wt%, 10wt% and 15wt% of CSR particles (Ace MX – 125, 156 and 960) were prepared. Each composition of 5 samples was tested at a rate of 2 mm/min. Test conducted on Tilnius Olsen H25 KT (Universal testing machine). Doge bone-shaped specimens which are shown in Fig. 26, was employed for the test. The graph of stress vs strain plotted to calculate the tensile strength and modulus.

Fig. 26. Doge bone tensile bulk polymer

4.2. Tensile test on carbon fibre composite

The test conducted according to the 'ASTM D 3039' standard. Dimensions of the test specimens shown in Table 5.

Table 5. Dimension of the CFRP tensile specimen

Description	**Dimension in mm**
Overall length	200
Distance between the end tabs	150
Width	10
Thickness	1

All the specimens were prepared from 5 layers of carbon fabric. With the results of the bulk polymers, 6wt% to be taken for all the mixture. The test conducted on ‘Tilnius Olsen H10 KT’ Universal testing machine with 10 KN cell. The samples were pure epoxy and CSR concentration of 6 wt% of ACE MX-125, 156 and 960. 5 samples from each composition were tested and the specimen shown in Fig. 27.

Fig. 27. CFRP Tensile test specimen

4.3. Flexural test for the investigation of Bending properties

Bending test on carbon fibre composite is based on the ‘ASTM D-790’ standard. The specimens cut down from the rectangular plates. Force of compression on top of the sample and force of tension on the bottom of the sample. The specimen span needs to be long enough to break. So, the loading span to thickness ratio is 16:1. The test conducted on the ‘Tilnius Olsen HK10 KT’ machine. Two supporting rollers on the end of the specimens. The specimens of pure epoxy carbon fibre composite and CSR (Ace MX-125, 156 and 960) modified carbon fibre composites at (6 and 10 wt%) were compared. 5 specimens from each composition were tested. The dimension of the specimen is given in Table 6

Table 6. Dimension of 3 point bending test specimen

Description	**Dimension in mm**
Overall length	100
Thickness	2
Width	12
Distance between grips	32

Fig. 28. 3 point bending specimen

The Load vs displacement were recorded during the test. The sketch of 3 point bending test is shown in Fig. 29

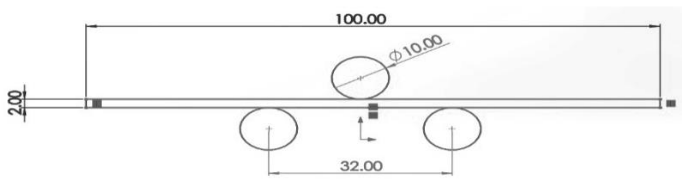


Fig. 29. Schematic diagram of 3 point bending test

4.4. Interlaminar shear strength test

To determine the matrix adhesion and quality of interfacial bonding shear strength of the carbon fibre specimens, the short beam test was conducted according to the ‘ASTM D-2344’ standard. The dimension of the specimen and span to thickness ratio is the difference from the 3-point bending test. The span to thickness ratio is 6:1. This ratio forced shear stress to attain failure before tension and compression reach their ultimate level.

Using thickness to determine the dimension of the specimen.

Span length = 6 × thickness (2) = 12 mm

The specimen with the dimension of 100×10×2 was prepared. The specimens of pure epoxy carbon composite and CSR modified carbon composites at (6 and 10 wt%) were tested and compared.

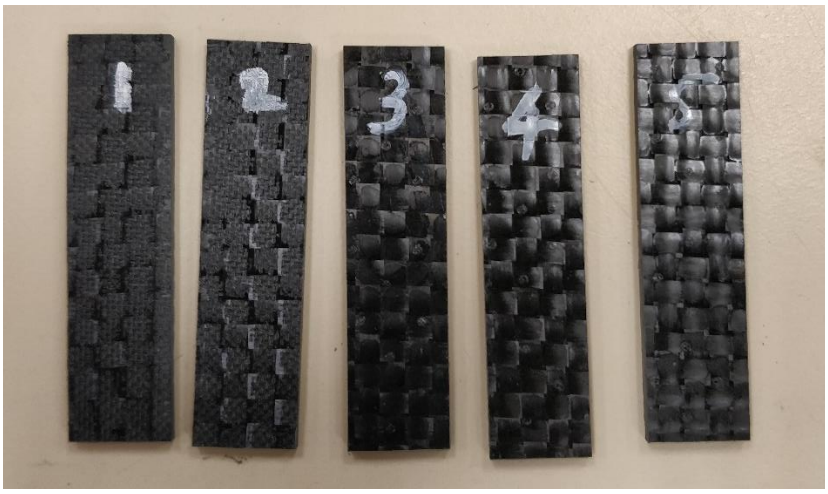


Fig. 30. Short beam test specimens

4.5. Impact test on carbon fibre composite

The test was conducted to compare the impact resistance to puncture of the pure epoxy composite with the CSR modified carbon fibre composites. The preparation was same as for the previous tests and the specimen is cut down from the rectangular plate. The dimension of the specimen is 80×80 mm and the thickness is 1 mm.

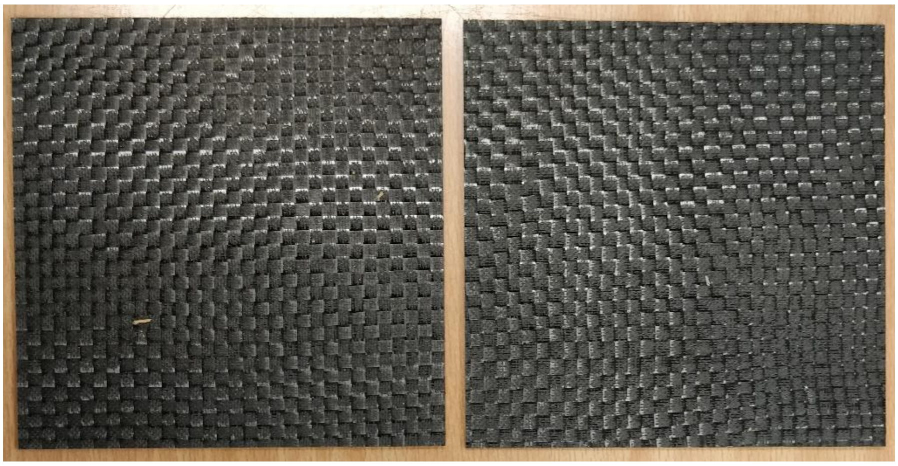


Fig. 31. Drop weight impact test specimen

The test was carried on a “Cosfield” drop weight impact tester according to the standard of ISO 6603-2 with the software. The drop weight is from the height of 400 mm and the impactor weight is 5.19 kg with a radius of 10 mm. The impact energy applied during the test was 20 J.

5. Results

5.1. Tensile test results of bulk polymers

The following graph (Fig. 32) shows the tensile test results (Stress vs Strain) of pure epoxy and CSR(3, 6, 10 and 15 wt%) modified bulk polymers.

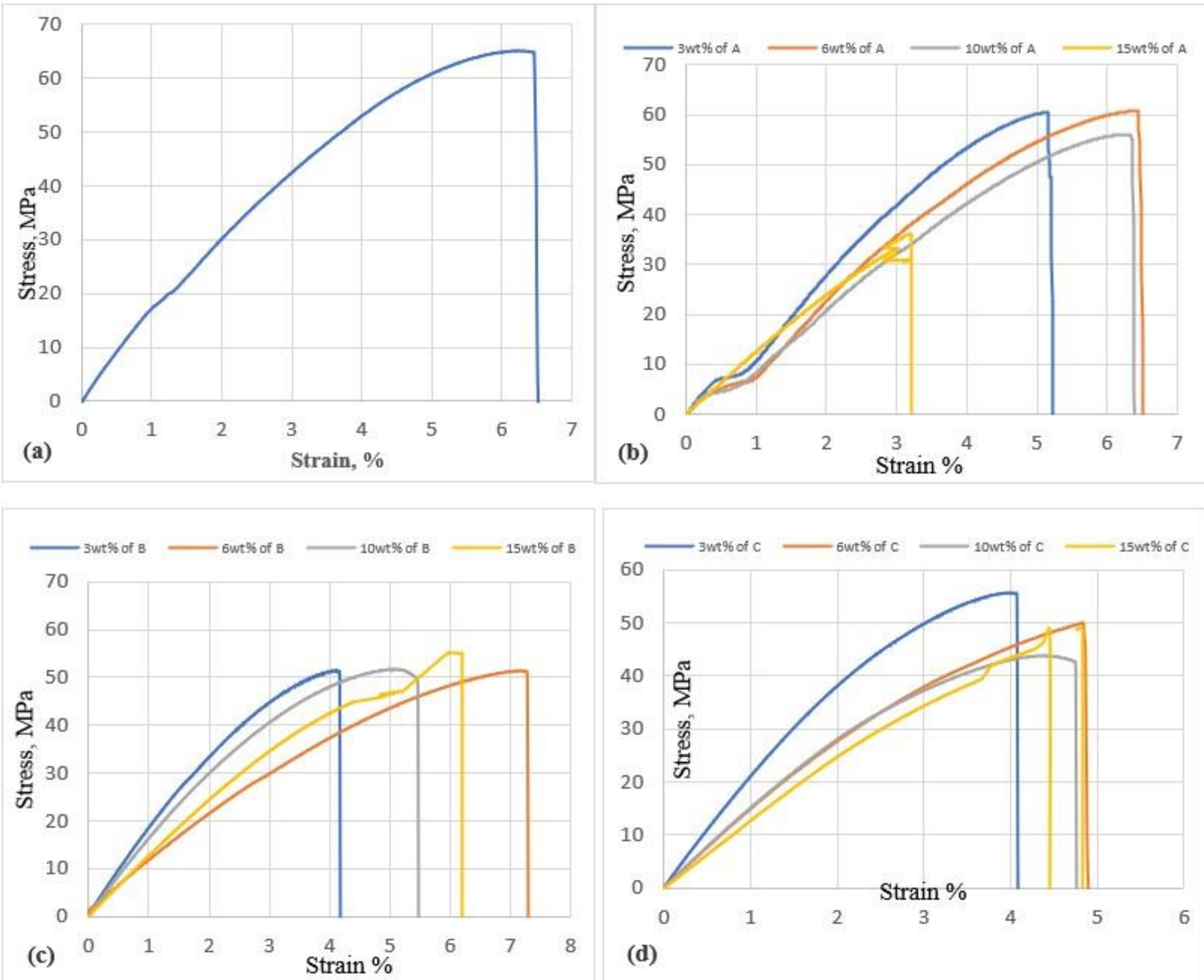


Fig. 32. (a) Stress vs strain of pure epoxy sample (b)with Ace MX-125 (c)with Ace MX-156 (d)with Ace MX-960

From graph 32, the tensile strength of the modified CSR samples is less when compared to the pure epoxy samples. This is the expected one. But the CSR particles increased the strain values. Epoxy with 6 wt% of Ace MX-156 particles increased the strain by 7.2% as compared to 6.5% of pure epoxy as shown in Fig. 32 (a), without affecting the stress. However, the Ace MX-125 and 960 reduced the stress as well as the strain of pure epoxy, as shown in Fig. 32 (b) and (d). The reduction in stress due to the increased content of rubber particles caused the plasticization effect. It can also be observed that 6 wt.% of all rubber particles increased strain in the epoxy. Further increase in the wt% on CSR particles in epoxy deteriorates the mechanical properties. Based on these results, 6 wt% of all the three CSR particles were used to modify the matrix with the carbon fibre as reinforcement.

5.2. Tensile test results of Carbon fibre composite

The output of the experiment is the max. force and displacement to the load direction. Figure 33 and 34 shows the stress-strain curve of pure epoxy carbon fibre composite and Carbon fibre composite doped with 6 wt% of Ace MX-125, 156 and 960.

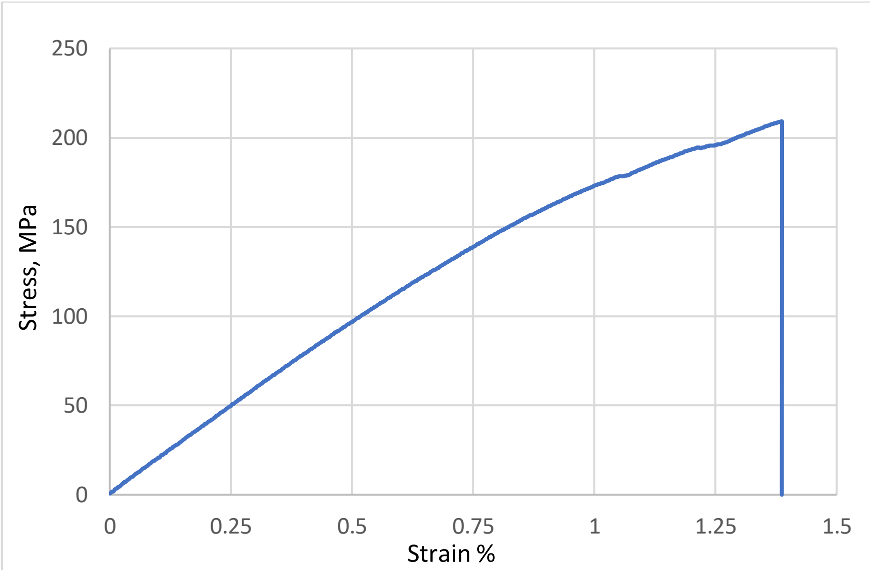


Fig. 33. Stress vs strain of pure epoxy carbon fibre composite

As we have seen from the graph (Fig. 33) maximum stress on the pure epoxy carbon fibre composite is 209 MPa.

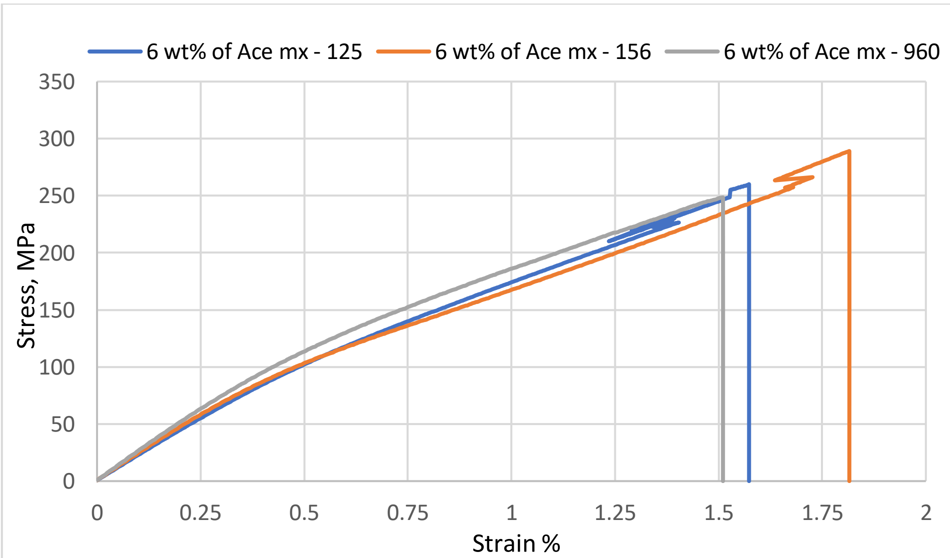


Fig. 34. Stress vs strain of CSR modified carbon fibre composite

From the graph (Fig. 34), we can see that the epoxy with 6 wt% of Ace MX-156 shows much improvement in both the stress and strain value. The stress and strain value increased by 38% and 30%.

Also, the CSR particles of Ace MX-125 and 960 modified composites increased the stress by 24% and 16% higher than the pure epoxy carbon composite. The strain values are also increased in all the three CSR particles modified composite by 12, 30 and 8%. This proves that the 6 wt% is the optimum concentration for the improvement.

Table 7. Tensile test results of pure and CSR modified CFRP

No	Specimen type	Breaking force, N	Maximum stress, MPa	Strain, %
1	Pure epoxy sample	2162	209	1.38
2	With 6 wt% of Ace MX-125	3145	260	1.57
3	With 6 wt% of Ace MX-156	3514	289	1.81
4	With 6 wt% of Ace MX-960	2893	248	1.51

From table 7, we can see the improvement in the braking force. With the addition of Ace MX-125, 156 and 960 particles braking force is increased to 45%, 62% and 33% compared with the pure epoxy carbon fibre composite.

The ultimate tensile strength is the maximum load withstand before the specimen breaks. It is also known as Tensile stress.

$$\sigma_{max} = \frac{P_{max}}{A_0}$$

where, P_{max} - Maximum load acting on the specimen and A_0 - Area of the specimen before loading

Using the obtained results, we can calculate the tensile modulus using the formula. The tensile modulus calculated from the strain values of 0.1 and 0.3% mm/mm.

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

Where, E - Tensile modulus, σ and $\mathcal{E}$ - measured stress and strain values.

The calculated values are shown in table 8.

Table 8. Tensile modulus of all the specimens

No	Specimen type	Tensile modulus, GPa
1	Pure epoxy sample	19
2	With 6 wt% of Ace MX-125	20
3	With 6 wt% of Ace MX- 156	21
4	With 6 wt% of Ace MX-960	24

5.3. Flexural test results

Figure 35 shows the Force vs displacement curve of pure and CSR modified carbon fibre composites. During the test, the specimen withstands the load acting on it. After reaching the maximum load, curves decreased due to the breakage of fibres.

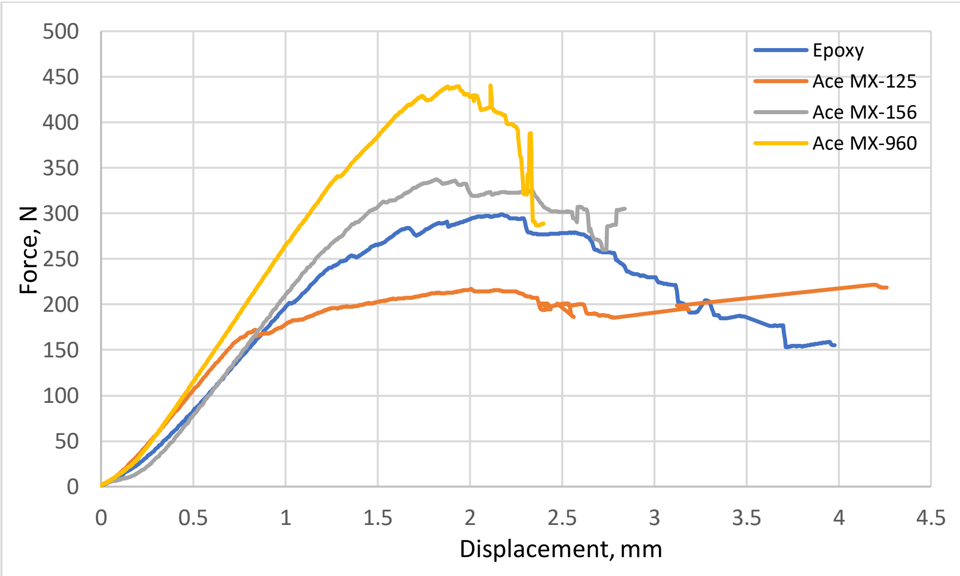


Fig. 35. Load vs displacement curve pure epoxy and CSR modified Carbon fibre reinforced polymer composite (6 wt.% of CSR particles)

As we have seen from the graph (Fig. 35), it shows linear behaviour until the breakage occurs. The maximum force on the epoxy composite is 298 N. The maximum force on CSR modified composite B and C was 336 N and 439 N. It is 12% and 47% higher than the pure epoxy composite. The matrix A only weakened the composite, the maximum force here is 217 N. It is 37% lower than the pure epoxy matrix composite.

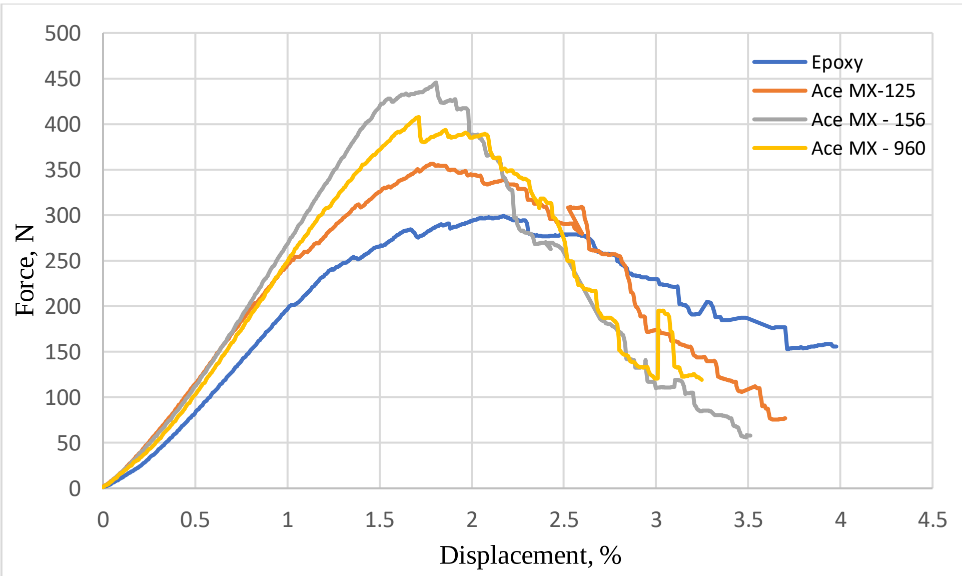


Fig. 36. Load vs displacement curve of pure epoxy and CSR modified carbon fibre reinforced polymer composite (6 wt.% of CSR particles)

Fig. 36 shows with the CSR 10 wt% modified matrix composites, there is no reduction in the force. All the three CSR modified matrix composites show improvement. It withstands the force of 354 N (18%), 445 N (49%) and 407 N (36%) more than the pure epoxy composite. The rubber particles improved the matrix structure.

From the available data Flexural strength was calculated using the formula.

$$\sigma_f = \frac{F_{max}L}{b \cdot d^2}$$

where, F_{max} – Maximum load, b – width (mm) and d – thickness (mm).

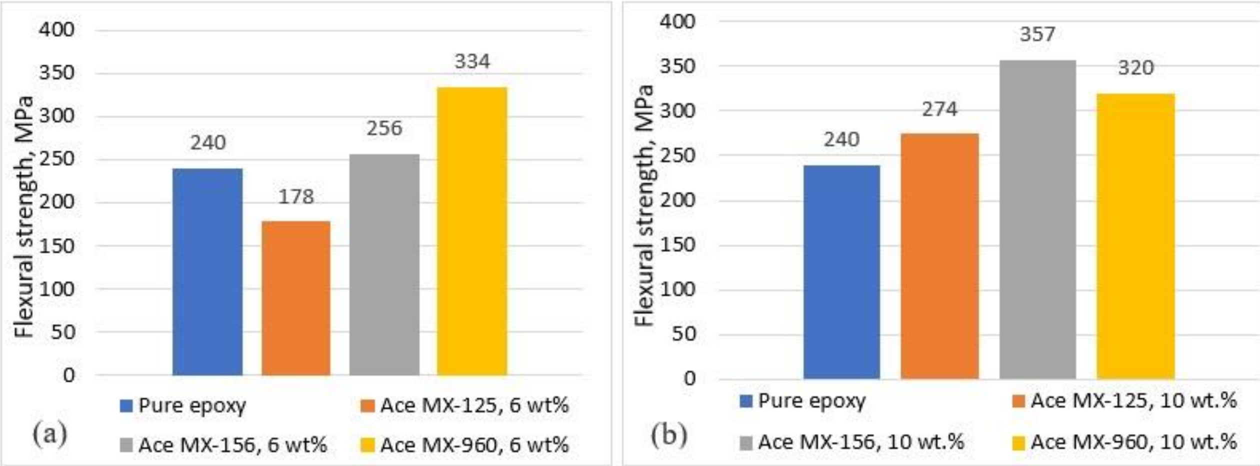


Fig. 37. Flexural strength of pure epoxy and CSR modified Carbon fibre reinforced polymer composite

From the graph (Fig. 37) we can see that the CSR particles improved the flexural strength of the composite. The strength of pure epoxy sample was 240 Mpa. It can be observed that Ace MX-960 particles improve the flexural strength by 39% whereas Ace MX-125 particles decreased the strength by 26%. The particles of Ace MX-156 marginally improve the flexural strength by 6%. When the weight percentage of rubber particles increased, the flexural properties also increased.

Likewise, with the 10 wt.%, the flexural strength gradually increased. With the 10 wt.% of CSR particles, the strength increased by 14% with Ace MX-125, 48% with Ace MX-156 and 33% with Ace MX-960.

Flexural modulus,

$$\varepsilon_f = \frac{m.L^3}{(4bd^3)}$$

where, F_{max} - maximum force, L - support span, b - width of specimen, d - specimen thickness and m - a slope of the force-displacement curve.

Table 9 below shows the flexural modulus of pure and CSR modified at 6 and 10 wt.% of carbon fibre reinforced polymer composites.

Table 9. Flexural modulus of pure epoxy and CSR modified at 6 wt.% carbon fibre composite

No	Specimen type	Flexural modulus, GPa
1	Pure epoxy sample	17.91
2	With Ace MX-125, 6 wt.%	18.24
3	With Ace MX-156, 6 wt.%	20.6
4	With Ace MX-960, 6 wt.%	24.16

Table 10. Flexural modulus of pure epoxy and CSR modified at 10 wt.% carbon fibre composite

No	Specimen type	Flexural modulus, GPa
1	Pure epoxy sample	17.91
2	With Ace MX-125, 10 wt.%	21.6
3	With Ace MX-156, 10 wt.%	24.9
4	With Ace MX-960, 10 wt.%	23.34

5.4. Dynamic testing results

During the impact test, the force (kN), contact time (ms), deflection (mm) and impact energy (J) were measured. The energy absorbed by the specimen was obtained from the force and displacement. All the samples were tested at the speed of 2.8 m/s. The impactor from the height of 400 mm. The amount of energy applied to the specimen is 20 J. According to the ISO 6603-2 standard, the force-time graph depicts force at damage, maximum force, and force at puncture of the specimens.

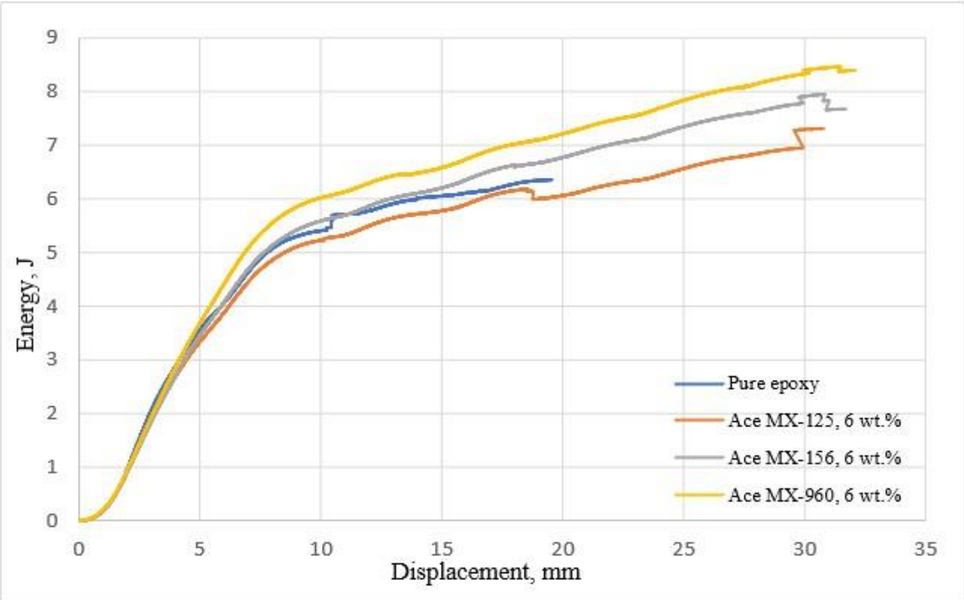


Fig. 38. Energy-Deflection graph of pure epoxy and CSR (6 wt.%) modified Carbon fibre reinforced polymer composite

Fig. 38 shows that all specimens with 6 wt% of CSR particles absorb more energy than the pure epoxy specimens. It absorbs 6.35 J of energy whereas the 3% of rubber particles makes the composite absorb more energy, the specimens with Ace MX-125, 156 and 960 absorbs 7.31 J, 7.95 J and 8.46 J of energy.

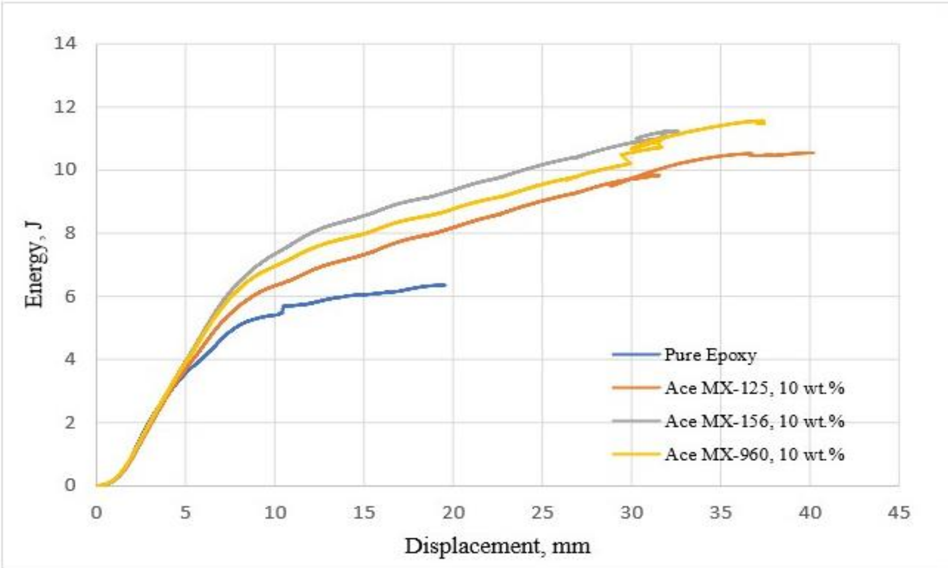


Fig. 39. Energy-Deflection graph of pure epoxy and CSR (10 wt.%) modified Carbon fibre reinforced polymer composite

Likewise, the 10 wt.% of Ace MX-125, 156 and 960 improved the composites energy absorption capability composites which are shown in Fig. 39. When the amount of rubber particles getting increased, the energy absorption increased due to the nano-sized rubber core. The specimens with Ace MX-125, 156 and 960 at 6 wt.% absorbs 10.54 J, 11 J and 11.56 J of energy which is 65%, 73% and 82% more than the pure epoxy samples.

In Fig. 40, subscript ‘d’ denotes damage initiation of the specimen. Therefore, the force required to puncture ‘F_P’ the specimen is half of the maximum force ‘F_m’. The force required to puncture the pure epoxy sample is 0.659 kN, whereas the force required for the modified composite is 0.627 kN.

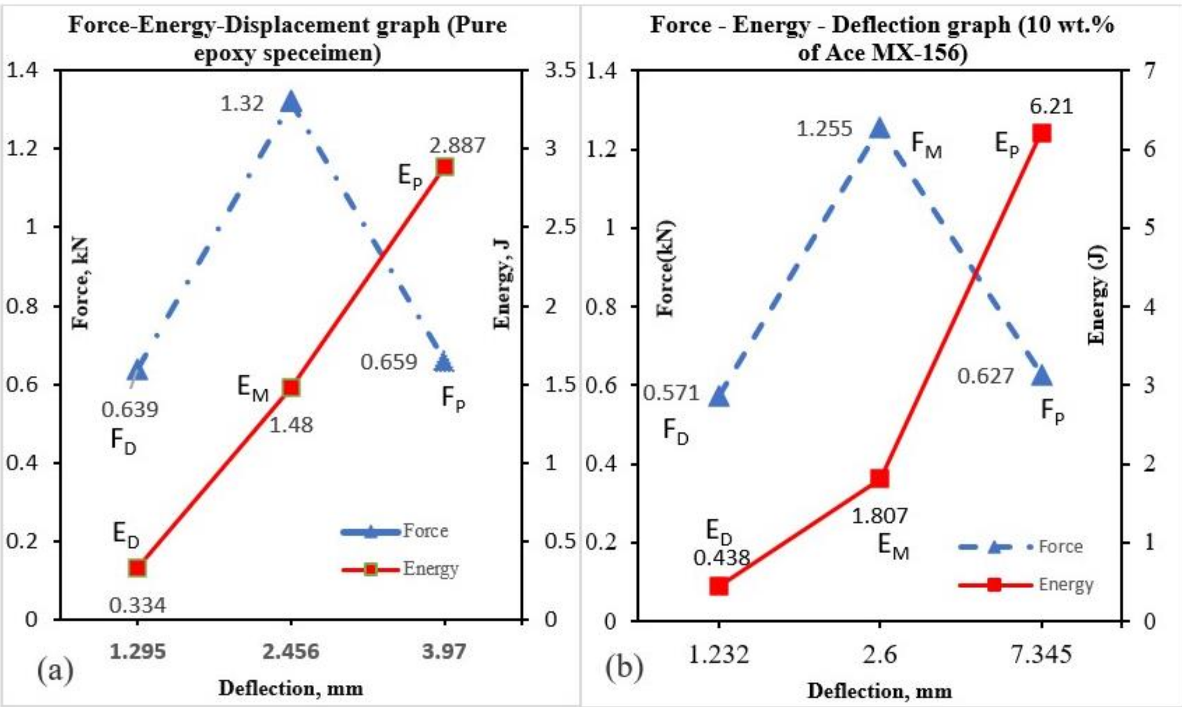


Fig. 40. Force-Energy-Displacement graph of (a) pure epoxy and (b) CSR modified (Ace MX-156, 10 wt%) Carbon fibre reinforced polymer composite

The deflection at the puncture of a pure epoxy specimen is 0.659 KN and for the CSR modified specimen is 0.627 KN. Force is a little bit different, but the energy absorbing capacity of CSR modified composites increased relentlessly.

Fig. 41. Punctured specimens of each type

Fig. 41 shows the specimens of each type, which allows us to compare them with each other. It is compared that the figure 38 and 39, it is cleared that the curves of energy were increased by adding the rubber particles up to 10 wt.%. CSR particles eliminate the damage initiation energy and improving the bonding between the matrix and carbon fibre leads to delaying the crack propagation and absorbing more energy than the pure epoxy composite.

Fig. 42. Specimens with fibre failure (a) pure epoxy composite (b) Ace MX-960 at 10 wt.% modified composite

Fig. 42 shows the damage that occurred in the specimens at the end of the drop weight test. All of the specimens with comparable damage forms are penetrated by the given impact energy (20 J) through the steel impactor. The diamond shape represents the end of failure. There was fibre pull out and edges are sharp at the breakage point. The specimen with CSR particles turns out to be more brittle than the epoxy one. The stress causes fibre damage because a large amount of load is converted into shear stress. The front and backside have the same feature, compression on the front side and high tensile stress on the opposite side.

5.5. Interlaminar shear strength test results

Using the short beam test to evaluate the fibre adhesion of the composite material. Material's fatigue behaviour is greatly influenced by ILSS. It is a simple mode II transverse shear loading test.

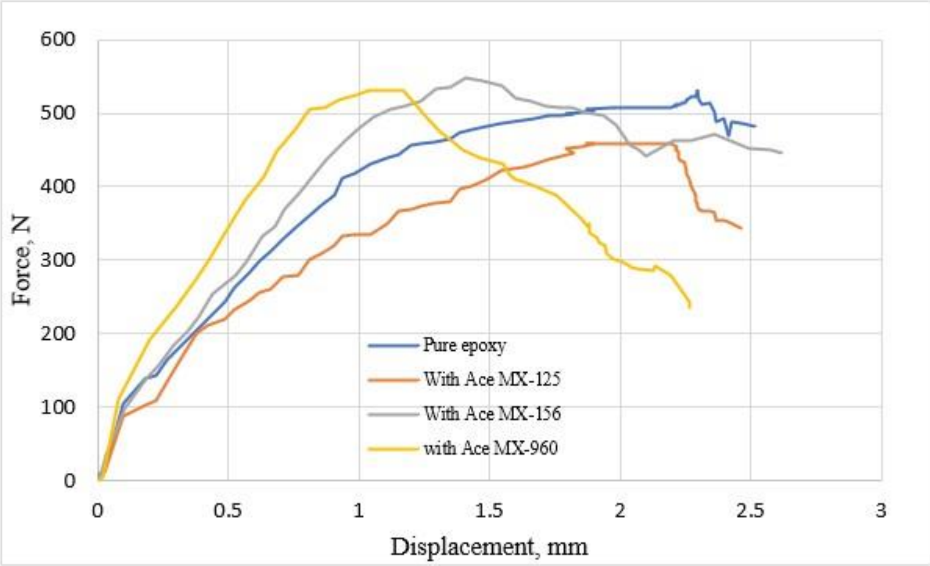


Fig. 43. Load vs Displacement curve of pure and CSR modified at 6 wt.% Carbon fibre reinforced polymer composite for ILSS

Fig. 43, the max. force on the pure epoxy composite was 530 N. Likewise in the bending test, with the Ace MX-125 at 6 wt.% the force is less when compared to the epoxy one. The Ace MX-156 and 960 need more force to get damage and the force required was 3% higher than the pure epoxy composite. With Ace MX-960 at 6 wt.%, the force was the same as the pure epoxy composite.

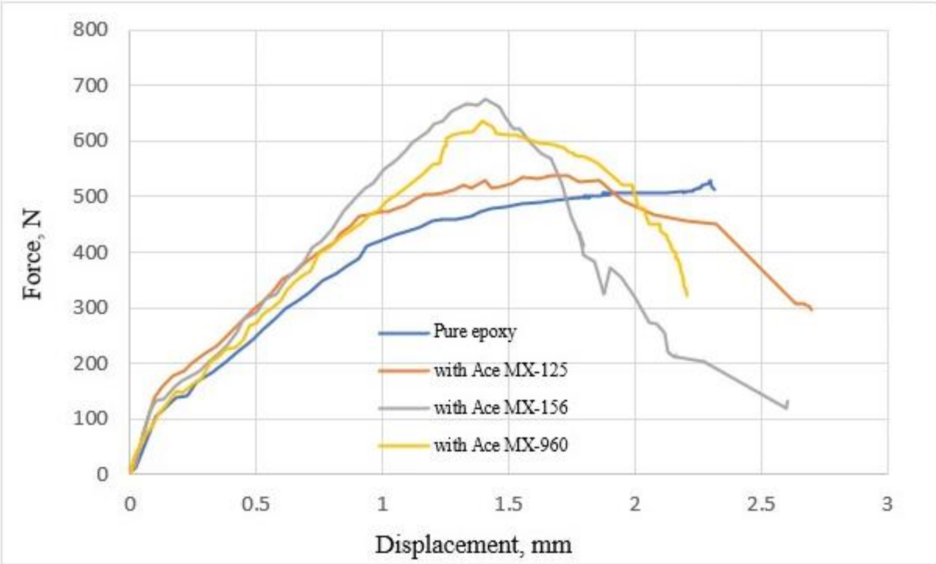


Fig. 44. Load vs Displacement curve of pure and CSR modified at 10 wt.% Carbon fibre reinforced polymer composite for ILSS

With the 10 wt.%, all the three CSR particles shows improvement. When compared with the pure epoxy composite the Ace MX-125, 156 and 960 requires 15%, 27% and 19% more force to initiate the breakage which is shown in Fig. 44. It improves the strength of composites.

ILSS calculated by using the formula,

$$F = \frac{(0.75 \times P_{max})}{b \times h}$$

where, P_{max} - Maximum force during the test in N, b – width in mm and h – thickness in mm

Table 11. ILSS results of pure and modified CFRP at 6 wt%

No	Specimen type	Interlaminar shear strength, MPa
1	Pure epoxy sample	19.76
2	With 6 wt% of Ace MX-125	16.52
3	With 6 wt% of Ace MX-156	21.36
4	With 6 wt% of Ace MX-960	24.1875

Table 12. ILSS results of pure and modified CFRP at 10 wt%

No	Specimen type	Interlaminar shear strength, MPa
1	Pure epoxy sample	19.76
2	With 10 wt% of Ace MX-125	22.35
3	With 10 wt% of Ace MX-156	26.4
4	With 10 wt% of Ace MX-960	26.5

From table 11 and 12 we can see that the Interlaminar shear strength of Ace MX-125 at 6 wt.% is getting reduced because of the adhesion effect between the modified matrix and the carbon fibre reinforcement. But with the Ace MX-156 and 960, the interlaminar strength increased by 8% and 22%. With 10 wt% of Ace MX-156 and 960 gave almost the same values of ILSS. ILSS improved by 13% with Ace MX-125 at 10 wt%. when the amount of rubber particles increased, the composites are enabled to resist the delamination damage. The interlaminar shear strength increased with the content of CSR particles.

Discussion

Unlike the metals, carbon fibre is anisotropic, properties are not the same in all directions. Carbon fibre offers 2 to 5 times more rigidity. The carbon fibre composites have a density of 1.79 gram per cubic centimetre, which in the case of Aluminium is 2.7 g/cm^3 and steel is 7.9 g/cm^3. Carbon fibre is 2 and 5 times lesser than Aluminium and steel. CFRP can absorb 120 kJ/kg whereas steel only absorbs 20 kJ/kg.

Various types of fillers are available to toughening the epoxy matrix which is discussed in the literature section. The rubber particles with different wt.% can be used as a matrix modifier to enhance the characteristics of the composites. When the amount of rubber particles increased, the viscosity of mixtures increased, it was discussed in the material section. Also, above the certain wt.% of fillers increased the brittleness of the mixture. Mechanical tests were conducted on the composites to evaluate the effect of CSR particles. Composites with CSR particles outperformed traditional epoxy composites.

From the obtained results, the mechanical behaviour of Carbon fibre composites is upgraded with the Core shell rubber particles. It allows us to make more efficient CFRP composites for automotive applications. It helps to make the vehicles fuel-efficient, reducing weight and enhance the safety of passengers.

Conclusion

In the current automotive field, CFRP composites is a promising material. It can be used to make driveshafts, chassis, wings, pillars etc., and it outperforms traditional materials like steel and aluminium in low weight applications. Improving the strength of the composites is considered to be an important study in the composite field. In this project, the mechanical properties of pure epoxy matrix carbon fibre composites were enhanced by modifying the matrix with Ace MX – 125, 156 and 960 CSR particles for Automobile applications. By performing static and dynamic tests, the effects of CSR particles were evaluated.

1. The tensile strength of 0º degree specimens of CFRP with 6 wt.% of Ace MX – 125, 156 and 960 was enhanced up to 24, 38 and 16%. Also, the improvement in the modulus. With the addition of rubber particles, it withstands more force than traditional composites.
2. The flexural and shear properties of composites were studied with CSR particles at 6 and 10 wt.%. Adding Ace MX-125, 156 and 960 at 10 wt.% shows excellent bending strength, modulus and shear strength. In both cases, only with the addition of Ace MX-125 (6 wt.%), the properties were degraded. The shear strength is a factor for good fatigue behaviour. CSR particles improved the fibre bond between the matrix and Carbon fibre to improve the shear behaviour of the composites compared to the traditional composite. The maximum improvement is 34%.
3. The nano-sized core rubber improved the energy absorbing capacity of composites. With the CSR particles the composites able to absorb 40% more than the epoxy composites. The pure epoxy composites absorb 6 Joules of energy while the CF composites with Ace MX-125, 156 and 960 particles absorb 10.54 J, 11 J and 11.56 J of energy which is 65%, 73% and 82% more than the pure epoxy samples.

List of References

1. www.dexcraft.com/articles/carbon-fiber-composites/aluminium-vs-carbon-fiber-comparison-of-materials/#weight_and_density
2. www.koenigsegg.com/koenigsegg-produces-first-regera-uning-knc-koenigsegg-naked-carbon/
3. www.fortunebusinessinsights.com/industry-reports/carbon-fiber-market-101719
4. https://cordis.europa.eu/article/id/90405-increasing-carbon-fibre-use-in-cars
5. www.sglcarbon.com/en/company/press/press-information/press-report/nio-battery-enclosure/
6. www.envisionaviation.com/press/2015/press_11-2015.html
7. Sustainable & Smart mobility strategy. Putting European transport on track for the future. European Commission. DOI: https://ec.europa.eu/transport/sites/transport/files/2021-mobility-strategy-and-action-plan.pdf.
8. BARNES. G, COLES. I, ROBERTS. ADAMS. D. O and GARNER. D.M. Crash safety assurance strategies for future plastic and composite intensive vehicles (PCIVs). June 01, 2010; DOI: https://www.nhtsa.gov/sites/nhtsa.gov/files/dot-vntsc-nhtsa-10-01.pdf.
9. LARRY. M. A guide to carbon fiber reinforced polymer repairs. DOI: https://www.vehicleservicepros.com/collision-repair/body-shop-and-repair/article/21191679/a-guide-to-carbon-fiber-reinforced-polymer-repairs.
10. Lee. M, Seo, H and Kang. Comparison of collision test results for center-pillar reinforcements with TWB and CR420/CFRP hybrid composite materials using experimental and theoretical methods. *Composite structures*, 2017; 168, 698-709. DOI: 10.1016/j.compstruct.2017.02.068.
11. ESRF [Online]. Viewed on 10 January 2020. Available from: honeycomb-artificial-graphene-nanocrystal-structure-studied-at-the-esrf.html
12. XUMING YAO, XINYU GAO, JIANJUN JIANG, CHUMENG XU CHAO DENG & JUNBIAO WANG. *Comparison of carbon nanotubes and graphene oxide coated carbon fibre for improving the interfacial properties of carbon fibre/epoxy composites*. *Composites part B*: *Engineering,* 2018; 132:170-177. ISSN 1359-8368.
13. The state university of New Jersey. *Graphene-Reinforced Polymer matrix Composites.* Inventors: NOSKER THOMAS, LYNCH JENNIFER, KEAR BERNARD, HENDRIX JUSTIN and CHIU GORDAN. 4 February 2016. Appl: 29 July 2015. WO 2016/18995.
14. M. KAMARAJ, E. ANUSH ODSON and SHUBHATRA DATTA. Effect of graphene on the properties of flax fabric reinforced epoxy composites. *Advanced composite materials,* 2019; Doi:10.1080/09243046.2019.1709679.
15. INFANTA MARY PRIYA and BK VINAYAGAM. Enhancement of bi-axial glass fibre reinforced polymer composite with graphene platelet nanopowder modifies epoxy resin. *Advances in Mechanical Engineering,* 2018. 10(8), 1-10. Doi:10.1177%2F1687814018793261.
16. E. MANNOV, H. SCHMUTZLE, S. CHANDRASEKARAN, C. VIETS, S. BUSCHHORN, F.TÖLLE AND R. MÜLHAUPT. Improvement of compressive strength after impact in fibre reinforced polymer composites by matrix modification with thermally reduced graphene oxide. *Composites Science and Technology,* 2013; 87:36-41.
17. YUICHI TOMINAGA, DAISUKE SHIMAMOTO AND YUJI HOTTA. Improvement of thermal and mechanical properties of carbon fibre reinforced plastic composite with exfoliated hexagonal boron nitride particles. *Journal of ceramic society of Japan,* 2016; 124 [8]: 808-812.

18. XUEMEI WEN, ZAOZAO XIANO, TAO JIANG, JIAN LI, WIE ZHANG, LEI ZHANG and HUAIQI SHAO. Constructing Novel Fibre Reinforced Plastic (FRP)Composites through a Biomimetic Approach: Connecting Glass Fibre with Nanosized Boron Nitride by Polydopamine Coating. *Journal of Nanomaterials,*2013; Volume 2013, Article ID 470583, 7 pages. Doi:10.1155/2013/470583.
19. MEYSAM RAHMAT, BEHNAM ASHRAFI, ALEX NAFTEL, DRAZEN DJOKIC, YADINIKA MARTINEZ-RUBI, MICHAEL B. JAKUBINEK AND BENOIT SIMARD. Enhanced Shear Performance of Hybrid Glass Fibre−Epoxy Laminates Modified with Boron Nitride Nanotubes. *Applied nanomaterials,*2018; 1:2709-2717.
20. GANESH VENKATESAN et al., Effect of titanium nitride coating for improvement of fire resistivity of polymer composites for aerospace application. *Journal of Aerospace industry*,2018; 232(9):1692-1703. Doi:10.1177%2F0954410017703147.
21. DIMITRIOUS G. PAPAGEORGIOU, ZHELING LI, MUFENG LIU, KINLOCH, and ROBERT J. YOUNG. Mechanisms of mechanical reinforcement by graphene and carbon nanotubes in polymer nanocomposites, 13 Jan 2020; 12,2228.
22. HUU-DUC NGUYEN-TRAN, VAN-THO HOANG, VAN-TA DO, DOO-MAN CHUN and YOUNG-JIN YUM. Effect of Multiwalled Carbon Nanotubes on the Mechanical Properties of Carbon Fiber-Reinforced Polyamide-6/Polypropylene Composites for Lightweight Automotive Parts. *Materials,* 15 March 2018; 11, 429. Doi:10.3390/ma11030429.
23. KISHORE KUMAR PANCHANGULA and PALANIYANDI KUPPAN. Improvement in the mechanical properties of neat GFRPs with multi-walled CNTs. *Journal of Materials and Technology,*30 April 2018; 8(1):366-376.
24. H.W. ZHOU, L. MISHNAEVSKY JR, H.Y. YI, Y.Q. LIU, X. HU, A. WARRIER and G.M. DAI. Carbon fiber/carbon nanotube reinforced hierarchical composites: effect of CNT distribution on Shearing strength. *Composites part B,*2016; 88:201-211. Doi:10.1016/j.compositesb.2015.10.035.
25. GIA TOAI TRUONG, JIHO KIM and KYOUNG-KYU CHOI. Effect of Multiwalled Carbon Nanotubes and Electroless Copper Plating on the Tensile Behaviour of Carbon Fiber Reinforced Polymers. *Advances in Materials science and Engineering,*2018; Article ID 8264138, 13 pages. Doi:10.1155/2018/8264138.
26. JACOB MUTHU and CASIAN DENDERE. Functionalized multiwall carbon nanotubes strengthened GRP hybrid composites: Improved properties with optimum fiber content. *Composites: part B,*2014; 67(2014) 84-94. Doi: 10.1016/j.compositesb.2014.06.012.
27. PRASHANT RAWAT and KALYAN SIGH. Damage Tolerance of Carbon Fiber Woven Composite Doped with MWCNTs under Low-Velocity Impact. *Procedia Engineering,*2017; 173,440-446.
28. HAYDEN K. CORNWELL. *Tensile and interfacial properties of Radially aligned CNT grown carbon fibers.* Massachusetts: Massachusetts University of Technology, 2017. Master's thesis.
29. KUSMONO and ZAINAL ARIFIN MOHD ISHAK. Effect of Clay Addition on Mechanical Properties of Unsaturated Polyester/Glass Fiber Composites. *International Journal of Polymer Science,*2013; Volume 2013, Article ID 797109, 7 pages. Doi: https://doi.org/10.1155/2013/797109.

30. SEYED ABDOLVAHAB HOSEINI and MOHAMMAD HOSSEIN POL. Investigation of the Mechanical Properties of the Glass/Epoxy composites reinforced with nanoclay particles. *International Journal of Mechanical and Production Engineering*,2015; 3(12). ISSN 2320-2092.
31. N. DOMUN, H. HADAVINIA, T. ZHANG, T. SAINSBURY, G.H. LIAGHAT and S. VAHID. Improving the fracture toughness and the strength of epoxy using nanomaterials – a review of the current status. *Nanoscale,* 2015; 7, 10294.
32. KE WANG, LING CHEN, JINGSHEN WU, MEI LING TOH, CHAOBIN HE and ALBERT F. YEE. Epoxy Nanocomposites with highly exfoliated clay: Mechanical properties and fracture mechanisms. *Macromolecules*, 2005; 38, 788-80.
33. AIDAH JUMAHAT, NORHASHIDAH MANAP, ANIS ADILAH ABU TALOP, TG FAIZUDDIN and TG MOHD AZMI. Chopped carbon fiber reinforced polymer composites: Effect of nano clay on adhesive and abrasive wear properties, 2019. Volume-8, Issue-4. ISSN: 2277-3878.
34. MULUGETA H. WOLDEMARIAM, GIOVANNI BELINGARDI, ERMIAS G. KORICHO and DANIEL T. REDA. Effects of nanomaterials and particles on mechanical properties and fracture toughness of composite materials: a short review. *Mini review. AIMS Material science,* 2019. 6(6), 1191-1212.
35. MICHAEL NAGUIB, VADYM N. MOCHALIN, W. BARSOUM and YURY GOGOTSI. 25th Anniversary article: MXenes: A new family of two-dimensional materials. *Advanced materials*, 2014; 26, 992-1005. Doi: 10.1002/adma.201304138.
36. RUONAN DING, YAN SUN, JINWOO LEE, JAE-DO NAM and JONGHWAN SUHR. Enhancing interfacial properties of carbon fibre reinforced epoxy composites by grafting MXene sheets (Ti_2C). *Composites part B*, 2021. Vol. 207. 108580.
37. LU LIU, GUOBING YING, CONG HU, KAICHENG ZHANG, FENGHEN MA, LIN SU, CHEN ZHANG and CHENG WANG. Functionalization with MXene (Ti_3C_2) enhances the wettability and shear strength of carbon Fiber-epoxy composites. *ACS Applied nano materials*, 2019. 2, 5553-5562.
38. XIAOLI ZHAO, SHUHUA QL, JIANJUN LIU, XIAO HAN and FAN ZHANG. Preparation and mechanical performance of carbon fiber reinforced epoxy composites by Mxene nanosheets coating. *Journal of Materials Science: Materials in Electronics*, 2019; vol: 30, 10516 – 10523. DOI: 10.1007/s10854-019-01395-w.
39. DECLAN CAROLAN, A.J. KINLOCH, A. IVANKOVIC, S. SPRENGER and A.C. TAYLOR. Mechanical and fracture performance of carbon fibre reinforced composites with nanoparticles modified matrices. In: *21st conference on Fracture ECF21.* Catalonia, Italy, 20-24 June 2016.
40. A.J. KINLOCH, A.C. TAYLOR and S. SPRENGER. Fibre-reinforced composites optimized by the synergy between rubber-toughening and sio_2-nanoparticles, 2016.
41. A. J. KINLOCH, R. D. MOHAMMED, A. C. TAYLOR, S. SPRENGER and D. EGEN. The interlaminar toughness of carbon-fibre reinforced plastic composites using 'hybrid-toughened' matrices. *Journal of material science*, 2016; 41:5043-5046. DOI: 10.1007/s10853-006-0130-8.
42. V. KOSTOPOULOS, P. KARAPAPPAS, T. LOUTAS, A. LOUTAS, A. PAIPETIS and P. TSOTRA. Interlaminar fracture toughness of carbon fibre-reinforced polymer laminates with Nano- and micro-fillers. *Strain*, 2011; 47, 269-282.
43. ELENORA DAL LAGO, ELISABETTA CAGNIN, CARLO BOARETTI, MARTINA ROSO, ALESSANDRA LORENZETTI and MICHELE MODESTI. Influence of different carbon-based

fillers on electrical and mechanical properties of a PC/ABS blend. *Polymers,*2020; 12, 29. Doi:10.3390/polym12010029.

44. JITHA S JAYAN, APPUKUTTAN SARITHA and KURUVILLA JOSEPH. Innovative materials of this era for toughing the epoxy matrix: A review. *Polymer composites,*2018. Available from: <https://doi.org/10.1002/pc.24789>.
45. G. GIANNAKOPOULOS, K. MASANIA, and A. C. TAYLOR. Toughening of epoxy using core-shell particles. *Journal of Materials Science*, 2011; vol. 46, no. 2, pp. 327–338. DOI: doi.org/10.1007/s10853-010-4816-6.
46. HYEONGCHEOL PARK, HANA JUNG, JAESANG YU, MIN PARK and SOENG YUN KIM. Carbon fiber-reinforced plastics based on epoxy resin toughened with core shell rubber impact modifiers, *E-Polymers*, 2015; vol. 15, no. 6, pp. 369–375. DOI: 10.1515/epoly-2015-0068.
47. ERICH D. BAIN, DANIEL B. KNORR JR. ADAM D. RICHARDSON, KEVIN A. MASSER, JIAN YU and JOSEPH L. LENHART. Failure processes governing high-rate impact resistance of epoxy resins filled with core-shell rubber particles. *Journal of material science*, 2016; 51:2347-2370. DOI: 10.1007/s10853-015-9544-5.
48. A. J. KINLOCH, R. D. MOHAMMED and A. C. TAYLOR. The effect of silica nano particles and rubber particles on the toughness of multiphase thermosetting epoxy polymers. Journal of Materials Science, 2005.
49. DIPA RAY, ANTHONY COMER, IMGA ROSCA, WINFRED OBANDE, GEAROID CLANCY and WALTER STANLEY. *Core-shell rubber nanoparticle toughened carbon fibre/epoxy composites.*
50. H.R. BROWN, J. A. SCHNEIDER and T. L. MURPHY. Experimental studies of the deformation mechanisms of core-shell rubber modified diglycidyl ether of bisphenol- A EPOXY AT CRYOGENIC TEMPERATURES. *Journal of composite materials,* 2014; vol. 48, no. 11, pp. 1279-1296.
51. J. L. TSAI, B. H. HUANG and Y. L. CHENG. Enhancing fracture toughness of glass/epoxy composites by using rubber particles together with silica nanoparticles. Journal of Composite materials, 2009; vol. 43, no. 25, pp. 3107-3123. DOI: 10.1177%2F0021998309345299.
52. L. BÉCU-LONGUET, A. BONNET, C. PICHOT, H. SAUTEREAU, AND A. MAAZOUZ. Epoxy Networks Toughened by Core-Shell Particles: Influence of the Particle Structure and Size on the Rheological and Mechanical Properties. *Journal of Applied Polymer Science*, 1999; vol. 72, no. 6, pp. 849–858.
53. SHAMSIAH AWANG NGAH. *Static and Fatigue behaviour of fibre composites infused with rubber and silica nanoparticle-modified epoxy*. A thesis submitted for the degree of Doctor of philosophy of Imperial college and the Diploma of Imperial college. June 2013.
54. DONG QUAN and ALOJZ IVANKOVIC. Effect of core-shell rubber (CSR) nano-particles on mechanical properties and fracture toughness of an epoxy polymer. *Polymer,* 2015; 66, 16 – 28. DOI: 10.1016/j.polymer.2015.04.002.
55. Fangtao Ruan. *Improvement of compression performance of fiber reinforced polymer.* China: Shinshu University, 2016. Doctoral thesis. Shinshu University.
56. LIMIN BAO, RYO SAKURDA, DAIKI ICHIKAWA and FANGTAO RUAN. Improvement in the bending strength of FRP using the filament cover method. *The journal of the textile industry,*2020; 111(2), 183-188. ISSN 0040-5000.

57. RAJMOHAN T, KOUNDINYA U.K, ARUN PREMNATH A and HARISH G. Evaluation of mechanical properties of nano filled glass fiber reinforced composites. In: *Proceedings of the international conference on Advanced Nanomaterials & Emerging Engineering Technologies*,2013: ICANMEET-2013. New Delhi: IEEE.
58. B.N. COX, M.S. DADKHAH, R.V. INMAN, W.L. MORRIS and J. ZUPON. Mechanisms of compressive failure in 3D composites. *Acta metallurgica et materialia,* Dec 1992; 40(12), 3285-3298.
59. FANTANGTAO RUAN, ZHENZHEN XU, DAYIN HOU, YANG LI and CHANGLIU CHU. Enhancing longitudinal compressive properties of unidirectional FRP based on micro buckling compression failure mechanism. *Journal of Engineered fibers and fabrics,*2018; 13(1).
60. FLAVIA LIBONATI, ANDRE E. VELLWOCK, FRANCESCO LELMINI, DILMURAT ABLIZ, GERHARD ZIEGMANN and LAURA VERGANI *et al*. Bone-inspired enhanced fracture toughness of de novo fibre reinforced composites. *Science report 9,* 2019; 3142. Doi:10.1038/s41598-019-39030-7.
61. https://www.azom.com/article.aspx?ArticleID=8194.
62. SITI MADIHA MUHAMMAD AMIR, M.T.H. SULTAN, MOHAMMAD JAWAID, AHMAD HAMDAN ARIFFIN, SHUKRI MOHD, KHAIRUL ANUAR MOHD SALLEH, MOHAMAD RIDZWAN ISHAK and AIN UMAIRA MD SHAH. 16 - Nondestructive testing method for Kevlar and natural fiber and their hybrid composites, Editor(s): Mohammad Jawaid, Mohamed Thariq, Naheed Saba, In: *Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites,* Woodhead Publishing, 2019; Pages 367-388. ISBN 9780081022900. Available from: https://doi.org/10.1016/B978-0-08-102290-0.00016-7.
63. ER. DARAPU SRIKANTH S. KUMAR, DARAPU SWATHISRI. Kevlar® Composite materials in automobile engine parts manufacturing. In: *28th Indian Engineering Congress,* Chennai, India, 2013. Doi:10.13140/2.1.3552.6402.
64. SATHYASEELAN. P, PRABHUKUMAR SELLAMUTHU & LAKSHMANAN PALANIMUTHU. Influence of stacking sequence on mechanical properties of areca-kenaf fiber-reinforced polymer hybrid composite. *Journal of Natural fibers,* 2020; ISSN: 1544-0465.

Appendices

Appendix 1. Tensile test results

Carbon fibre, Pure epoxy composite								
No	L	L_t	t	b	F	σ	ε	E
	mm	mm	mm	mm	N	MPa	%	GPa
1	200	150	1.01	10.45	1552	147.109	2.05	23.7
2	200	150	1.05	10.40	1480.5	134.75	0.904	21.22
3	200	150	1.02	10.45	3052	286.57	1.38	26.1
4	200	150	1.05	10.40	2350	215.20	1.45	19.2
5	200	150	1.02	10.50	2382.5	222.45	1.50	21.39
Mean					2163	200.8	1.45	18.5
Std. deviation					654.41	55.25	0.40	2.64

Carbon fibre, with Ace MX-125 at 6 wt.% composite								
No	L	L_t	t	b	F	σ	ε	E
	mm	mm	mm	mm	N	MPa	%	GPa
1	200	150	1.02	10.45	3772	314.33	2.96	23
2	200	150	1.01	10.35	3188	265.66	2.6	22.6
3	200	150	1.05	10.50	2912	242.66	2.29	22.5
4	200	150	1.02	10.45	2736	228	2.09	21.67
5	200	150	1.01	10.40	3120	260	2.36	23.83
Mean					3145.6	261.8	2.45	22.6
Std. deviation					392.80	32.73	0.33	0.78

Carbon fibre, with Ace MX-156 at 6 wt.% composite								
No	L	L_t	t	b	F	σ	ε	E
	mm	mm	mm	mm	N	MPa	%	GPa
1	200	150	1.01	10.45	3688	241.66	1.86	20.01
2	200	150	1.02	10.5	3136	261.33	1.792	22.66
3	200	150	1.01	10.35	3962	261.33	2.09	22.3
4	200	150	1.02	10.45	2796	233	1.43	22.3
5	200	150	1.01	10.40	3932	327.66	2.07	22.3
Mean					350.8	264.49	1.84	21.91
Std. deviation					522	37.14	0.26	1

Carbon fibre, with Ace MX-960 at 6 wt.% composite								
No	L	L_t	t	b	F	σ	Ɛ	E
	mm	mm	mm	mm	N	MPa	%	GPa
1	200	150	1.02	10.45	3292	300.02	2	24.7
2	200	150	1.01	10.50	3048	279.12	1.66	26.1
3	200	150	1.01	10.44	3068	269.4	1.67	23.1
4	200	150	1.02	10.52	2200	200.47	1.34	22.33
5	200	150	1.01	10.40	2800	250.21	1.7	21.3
Mean					2881.6	259.98	1.674	23.5
Std. deviation					418.95	37.73	0.23	1.90

Appendix 2: Flexural test results

Carbon fibre, pure epoxy composite									
No	L	Ls	t	b	F	σ	Ɛ	σ_f	E_f
	mm	mm	mm	mm	N	MPa	%	MPa	GPa
1	100	32	1.9	12.5	339.6	361.23	4.92	226	19.38
2	100	32	1.9	12.5	347.2	369.31	3.58	231.46	12.06
3	100	32	1.9	12.5	324.8	345.49	3.42	216.5	18.26
4	100	32	1.9	12.5	356	378.68	3.55	237.33	15.61
5	100	32	1.9	12.5	266.4	283.373	3.28	177.6	20.21
6	100	32	1.9	12.5	363.8	386.34	3.28	242.53	15.89
Mean					332.96	354.07	3.66	221.90	16.90
Std. deviation					37.63	37.42	0.62	23.51	2.74

Carbon fibre, with Ace MX-125 at 6 wt.% composite									
No	L	Ls	t	b	F	σ	Ɛ	σ_f	E_f
	mm	mm	mm	mm	N	MPa	%	MPa	GPa
1	100	32	1.9	12.5	280.8	298.69	4.74	187.2	21.33
2	100	32	1.9	12.5	217.25	231.091	3.02	144.83	8.88
3	100	32	1.9	12.5	263.32	279.969	2.32	175.46	17.63
4	100	32	1.9	12.5	237.75	252.898	3.25	158.5	10.71
5	100	32	1.9	12.5	221	235.08	3.705	147.33	18.82
6	100	32	1.9	12.5	183	194.659	1.83	122	15.75

Mean					233.895	248.73	3.14	155.88	1.52
Std. deviation					31.92	37.1762	1.02	23.29	4.82

Carbon fibre, with Ace MX-156 at 6 wt.% composite									
No	L	Ls	t	b	F	σ	Ɛ	σ_f	E_f
	mm	mm	mm	mm	N	MPa	%	Mpa	GPa
1	101	32	1.9	12.5	346	368.044	3.05	230.66	19.8
2	102	32	1.9	12.5	338	359.960	2.87	225.6	17.07
3	99.65	32	1.9	12.5	331.6	352.726	3.16	221.06	16.31
4	101	32	1.9	12.5	352.8	375.27	3.10	235.2	18.61
5	101	32	1.9	12.5	358.8	381.65	2.94	239.2	23.63
6	100	32	1.9	12.5	358	380.80	3.16	238.66	20.14
Mean					287.73	369.74	3.04	231.73	19.26
Std. deviation					11.05	11.68	0.11	7.32	2.61

Carbon fibre, with Ace MX-960 at 6 wt.% composite									
No	L	Ls	t	b	F	σ	Ɛ	σ_f	E_f
	mm	mm	mm	mm	N	MPa	%	Mpa	GPa
1	101	32	1.9	12.5	502.5	534.51	2.57	335	21.95
2	102	32	1.9	12.5	412.5	438.78	2.60	275	23.44
3	100	32	1.9	12.5	461	490.37	2.57	307.33	22.65
4	101	32	1.9	12.5	512.25	544.88	2.67	341.5	22.74
5	101	32	1.9	12.5	479	509.51	2.58	319.33	23.75
6	100	32	1.9	12.5	352.8	375.27	2.34	235.2	24.46
Mean					453.34	482.22	2.55	302.22	23.165
Std. deviation					60.63	64.49	0.11	40.42	0.89

Carbon fibre, with Ace MX-125 at 10 wt.% composite									
No	L	Ls	t	b	F	σ	Ɛ	σ_f	E_f
	mm	mm	mm	mm	N	MPa	%	Mpa	GPa
1	100	32	1.9	12.5	386	478.51	4.04	257.33	26.40
2	100	32	1.9	12.5	348.4	375.81	3.30	232.66	25.09
3	100	32	1.9	12.5	378.8	478.91	3.50	252.53	25.89
4	100	32	1.9	12.5	393.2	423.70	3.61	262.13	20.76

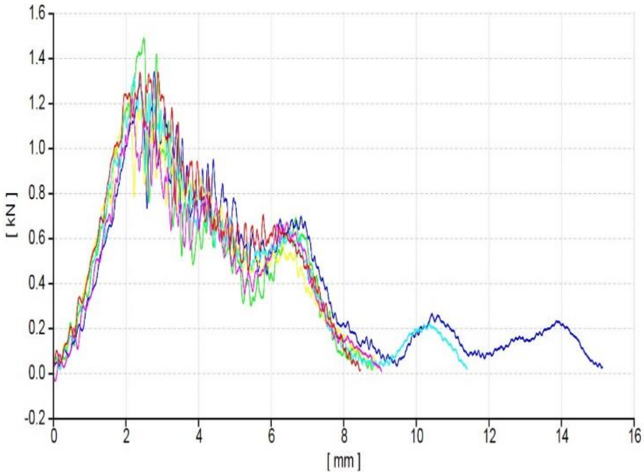
5	101	32	1.9	12.5	400.5	434.08	3.18	267	16.69
6	100	32	1.9	12.5	324.8	382.50	4.50	216.53	24.92
Mean					371.95	428.91	3.68	248.03	23.29
Std. deviation					29.28	44.69	0.49	19.46	3.80

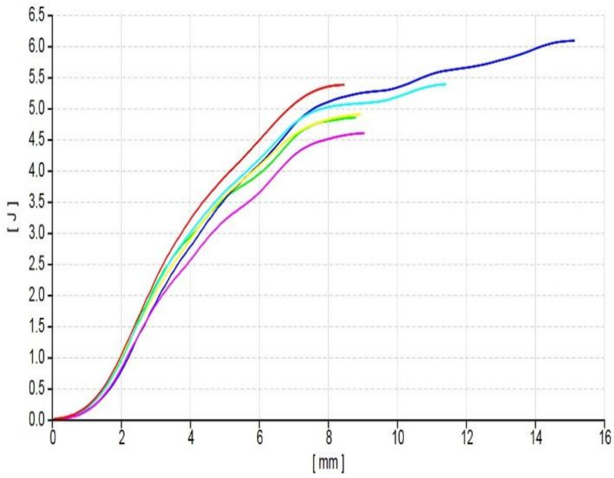
Carbon fibre, with Ace MX-156 at 10 wt.% composite									
No	L	Ls	t	b	F	σ	ε	σ_f	E_f
	mm	mm	mm	mm	N	MPa	%	Mpa	GPa
1	100	32	1.9	12.5	490.5	564.61	3.75	327	21.40
2	100	32	1.9	12.5	442	505.95	3.31	294.66	24.19
3	100	32	1.9	12.5	477.5	548.77	3.14	318.3	26.07
4	100	32	1.9	12.5	564	651.82	1.79	376	32.24
5	100	32	1.9	12.5	506.25	537.2148	2.77	337.5	21.77
6	100	32	1.9	12.5	420.5	481.72	3.72	280.33	23.24
Mean					483.45	548.34	3.08	322.2	24.8
Std. deviation					50.54	58.87	0.73	33.69	4.01

Carbon fibre, with Ace MX-960 at 10 wt.% composite									
No	L	Ls	t	b	F	σ	ε	σ_f	E_f
	mm	mm	mm	mm	N	MPa	%	Mpa	GPa
1	100	32	1.9	12.5	401.5	475.09	3.17	267.66	26.43
2	100	32	1.9	12.5	438	515.81	3.17	292	25.56
3	100	32	1.9	12.5	372.8	440.42	3.42	248.53	22.91
4	100	32	1.9	12.5	552.75	654.58	2.49	368.5	31.43
5	100	32	1.9	12.5	406.5	481.39	2.69	271	23.28
6	100	32	1.9	12.5	436.5	516.09	3.42	291	18.11
Mean					434.67	513.89	3.06	289.78	24.62
Std. deviation					62.73	74.51	0.38	41.82	4.41

Appendix 3: Impact test results

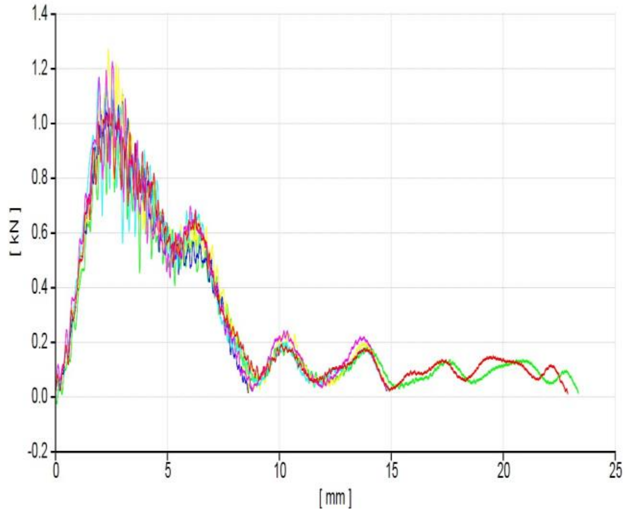
Pure epoxy composite

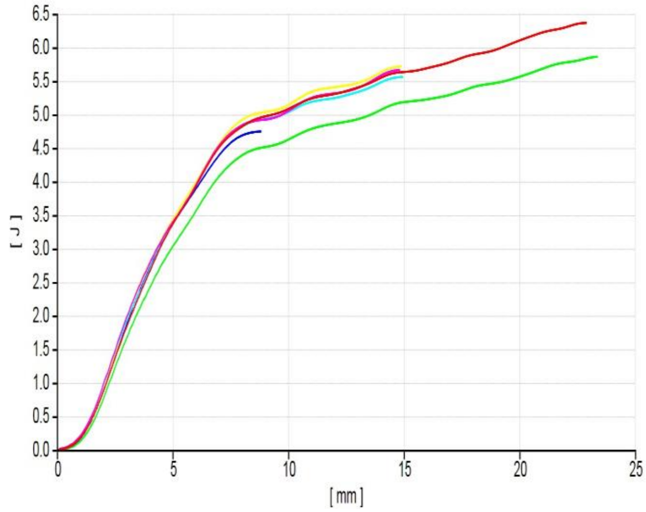




Sample	T	I_d	F_d	E_d	I_m	F_m	E_m	I_p	F_p	E_p	F_oT_m	E_oT_m	V_o	B_i	T_s
	mm	mm	kN	J	mm	kN	J	mm	mm	J	kN/m	J/mm	m/s		^oC
1	1.070	1.284	0.689	0.373	2.871	1.332	2.106	4.339	0.666	3.476	1.245	1.969	2.039	0	11.9
2	1.070	1.118	0.548	0.243	2.482	1.484	1.595	3.257	0.739	2.421	1.387	1.490	2.04	0	11.9
3	1.070	1.535	0.654	0.405	2.767	1.335	1.639	3.988	0.666	2.770	1.247	1.532	2.041	0	12.0
4	1.070	1.332	0.725	0.402	2.098	1.224	1.132	4.751	0.612	3.439	1.143	1.058	2.041	0	12.0
5	1.070	1.309	0.697	0.361	2.363	1.329	1.411	3.926	0.664	2.945	1.242	1.318	2.039	0	12.0
6	1.070	1.192	0.504	0.219	2.153	1.215	1.000	3.560	0.607	2.271	1.135	0.934	2.041	0	12.0
Mean	1.070	1.295	0.636	0.334	2.456	1.320	1.480	3.970	0.659	2.887	1.233	1.384	2.040		
Std. Dev	0.000	0.142	0.089	0.082	0.316	0.098	0.397	0.534	0.048	0.503	0.091	0.371	0.001		
Var. Coeff	0.00%	10.98%	14.06%	24.46%	12.86%	7.4%	26.81%	13.45%	7.28%	17.42%	7.40%	26.81%	0.05%		

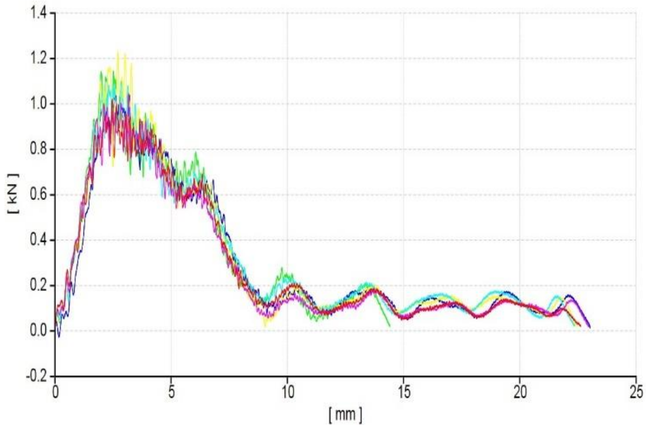
Carbon fibre, with Ace MX-125 at 6 wt.% composite

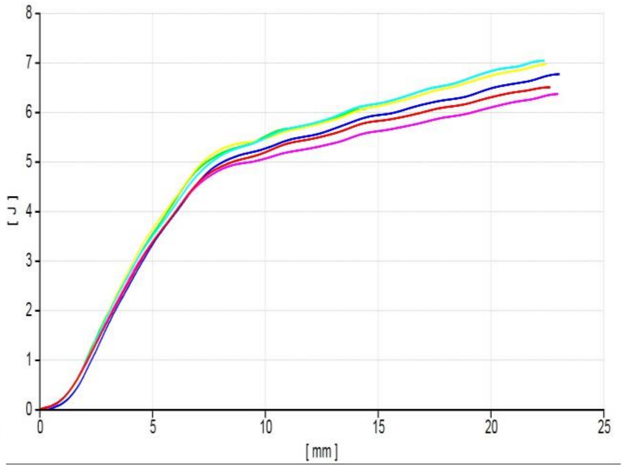




Sample	T	I_d	F_d	E_d	I_m	F_m	E_m	I_p	F_p	E_p	F_oT_m	E_oT_m	V_o	B_i	T_s
	mm	mm	kN	J	mm	kN	J	mm	mm	J	kN/m	J/mm	m/s		^oC
1	1.070	1.077	0.499	0.226	2.380	1.051	1.274	5.230	0.525	3.506	0.982	1.191	2.042	0	12.1
2	1.070	1.178	0.462	0.213	2.717	1.003	1.442	3.723	0.500	2.238	0.937	1.347	2.040	0	12.1
3	1.070	1.118	0.515	0.235	2.969	1.101	1.861	4.599	0.550	3.142	1.029	1.740	2.040	0	12.1
4	1.070	1136	0.523	0.253	2.337	1.266	1.274	3.886	0.632	2.732	1.183	1.191	2.041	0	12.1
5	1.070	0.962	0.430	0.183	1.898	1.159	0.899	2.964	0.579	1.912	1.083	0.840	2.041	0	12.1
6	1.070	1.070	0.573	0.256	2.514	1.220	1.516	4.058	0.609	2.841	1.140	1.417	2.042	0	12.1
Mean	1.070	1.090	0.500	0.228	2.469	1.133	1.378	4.077	0.566	2.729	1.059	1.288	2.041		
Std.Dev	0.000	0.074	0.050	0.027	0.365	0.100	0.319	0.775	0.050	0.582	0.094	0.298	0.001		
Var.Coeff	0.00%	6.81%	10.01%	11.87%	14.77%	8.86%	23.12%	19.01%	8.89%	21.33%	8.86%	23.12%	0.04%		

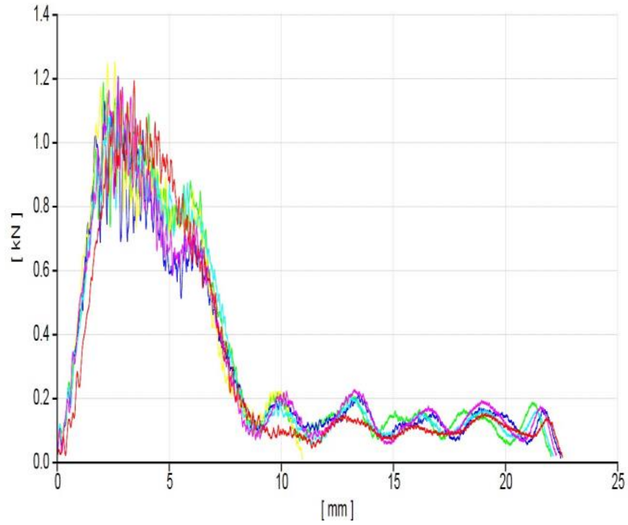
Carbon fibre, with Ace MX-156 at 6 wt.% composite

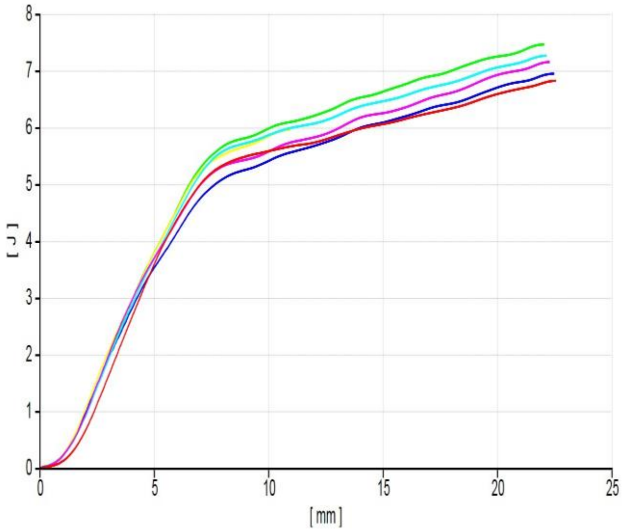




Sample	T	I_d	F_d	E_d	I_m	F_m	E_m	I_p	F_p	E_p	F_oT_m	E_oT_m	V_o	B_i	T_s
	mm	mm	kN	J	mm	kN	J	mm	mm	J	kN/m	J/mm	m/s		°C
1	1.070	0.872	0.390	0.163	2.439	1.015	1.275	6.843	0.507	4.484	0.949	1.192	2.040	0	12.1
2	1.070	1.083	0.529	0.238	2.498	1.139	1.450	6.653	0.569	4.658	1.064	1.355	2.043	0	12.1
3	1.070	1.539	0.638	0.365	2.593	1.058	1.290	7.034	0.529	4.579	0.988	1.205	2.040	0	12.1
4	1.070	1.133	0.501	0.252	2.688	1.225	1.603	5.072	0.612	3.693	1.145	1.498	2.041	0	12.1
5	1.070	1.089	0.502	0.238	2.827	1.093	1.726	6.729	0.547	4.583	1.022	1.613	2.042	0	12.1
6	1.070	1.111	0.561	0.264	3.152	1.041	1.951	6.575	0.520	4.313	0.973	1.823	2.041	0	12.3
Mean	1.070	1.138	0.520	0.253	2.699	1.095	1.549	6.484	0.547	4.385	1.023	1.448	2.041		
Std.Dev	0.000	0.218	0.081	0.065	0.261	0.077	0.264	0.710	0.039	0.359	0.072	0.246	0.001		
Var.Coeff	0.00%	19.17%	15.66%	25.66%	9.68%	7.02%	17.02%	10.95%	7.04%	8.20%	7.02%	17.02%	0.05%		

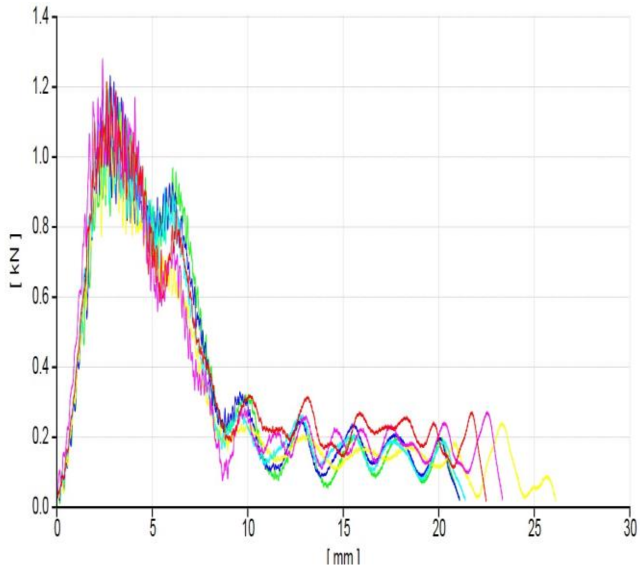
Carbon fibre, with Ace MX-960 at 6 wt.% composite

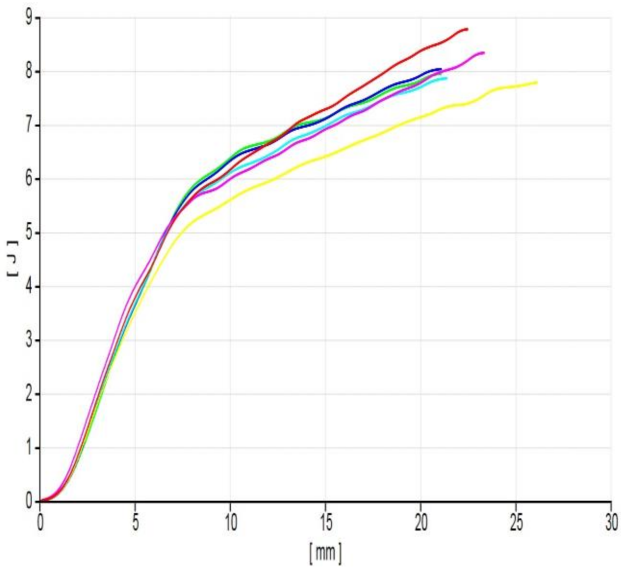




Sample	T	I_d	F_d	E_d	I_m	F_m	E_m	I_p	F_p	E_p	F_oT_m	E_oT_m	V_o	B_i	T_s
	mm	mm	kN	J	mm	kN	J	mm	mm	J	kN/m	J/mm	m/s		°C
1	1.070	1.501	0.574	0.331	3.417	1.189	2.061	6.354	0.594	4.622	1.111	1.926	2.041	0	12.3
2	1.070	0.945	0.452	0.199	2.033	1.183	1.003	6.743	0.591	5.136	1.105	0.938	2.041	0	12.3
3	1.070	1.037	0.525	0.240	2.694	1.203	1.665	4.807	0.601	3.411	1.124	1.556	2.041	0	12.3
4	1.070	1.153	0.640	0.323	2.547	1.247	1.632	6.614	0.623	5.018	1.165	1.525	2.040	0	12.3
5	1.070	1.093	0.515	0.260	3.099	1.096	2.029	7.074	0.548	5.211	1.024	1.896	2.040	0	12.3
6	1.070	1.043	0.522	0.243	2.694	1.194	1.680	5.123	0.596	3.788	1.116	1.570	2.041	0	12.3
Mean	1.070	1.128	0.538	0.266	2.747	1.185	1.678	6.119	0.592	4.531	1.107	1.568	2.041		
Std. Dev	0.000	0.195	0.064	0.051	0.475	0.049	0.381	0.929	0.025	0.759	0.046	0.356	0.001		
Var. Coeff	0.00%	17.28%	11.82%	19.28%	17.29%	4.16%	22.73%	15.18%	4.16%	16.76%	4.16%	22.73%	0.03%		

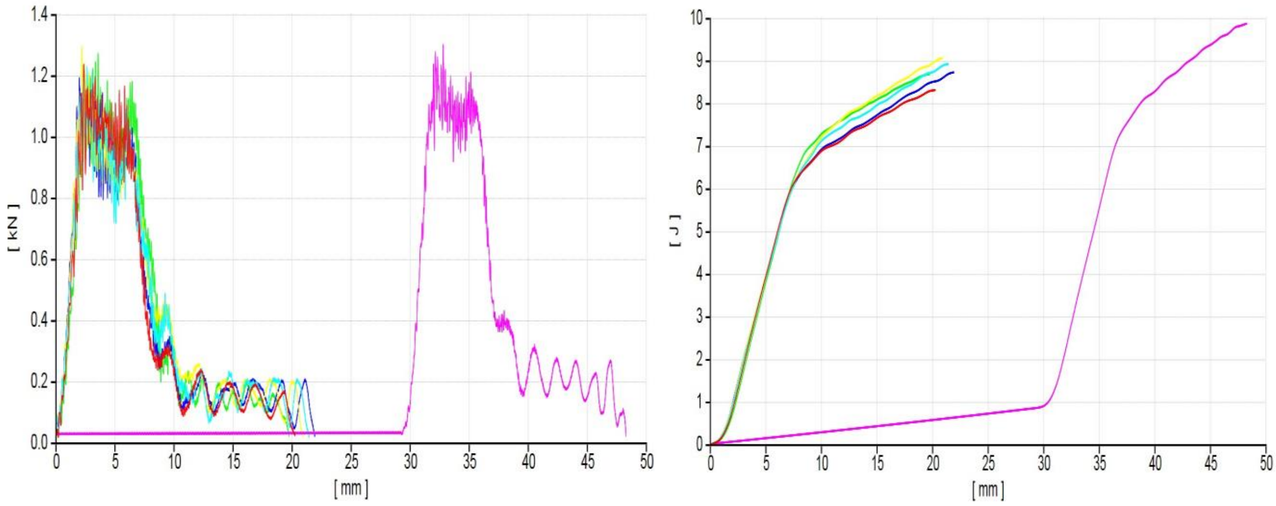
Carbon fibre, with Ace MX-125 at 10 wt.% composite





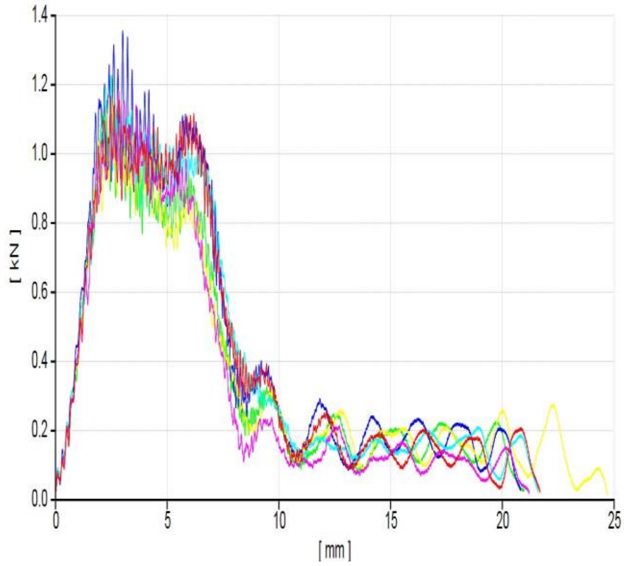
Sample	T	I_d	F_d	E_d	I_m	F_m	E_m	I_p	F_p	E_p	F_oT_m	E_oT_m	V_o	B_i	T_s
	mm	mm	kN	J	mm	kN	J	mm	mm	J	kN/m	J/mm	m/s		^{o}C
1	1	1.618	0.795	0.525	2.582	1.209	1.464	5.361	0.605	4.033	1.209	1.464	1.996	0	14.8
2	1	1.064	0.408	0.171	2.675	1.190	1.404	7.265	0.595	5.471	1.190	1.404	1.997	0	14.9
3	1	1.150	0.409	0.204	2.769	1.227	1.586	7.096	.613	5.326	1.227	1.586	1.996	0	14.9
4	1	1.074	0.427	0.180	2.617	1.208	1.411	6.019	0.304	4.203	1.208	1.411	1.996	0	14.9
5	1	1.193	0.517	0.250	2.607	1.181	1.480	6.876	0.590	5.137	1.181	1.480	1.996	0	15.0
6	1	1.194	0.615	0.333	2.371	1.274	1.428	4.880	0.636	3.908	1.274	1.428	1.996	0	15.0
Mean	1.000	1.216	0.529	0.277	2.604	1.215	1.462	6.250	0.607	4.680	1.215	1.462	1.996		
Std. Dev	0.000	0.205	0.153	0.135	0.132	0.033	0.068	0.986	0.016	0.706	0.033	0.068	0.000		
Var. Coeff	0.00%	16.87%	29.03%	48.77%	5.07%	2.73%	4.63%	15.77%	2.68%	15.09%	2.73%	4.63%	0.02%		

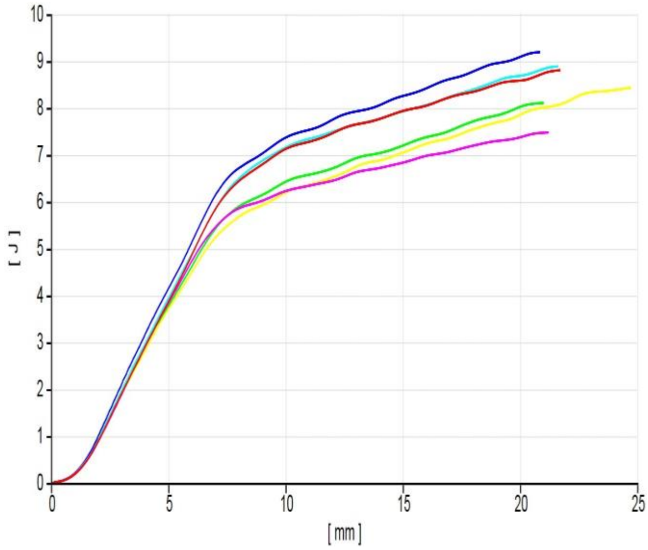
Carbon fibre, with Ace MX-156 at 10 wt.% composite



Sample	T	I_d	F_d	E_d	I_m	F_m	E_m	I_p	F_p	E_p	F_oT_m	E_oT_m	V_o	B_i	T_s
	mm	mm	kN	J	mm	kN	J	mm	mm	J	kN/m	J/mm	m/s		^oC
1	1.000	1.618	0.795	0.525	2.582	1.209	1.464	5.361	0.605	4.033	1.209	1.464	1.996	0	14.8
2	1.000	1.064	0.408	0.171	2.675	1.190	1.404	7.265	0.595	5.471	1.190	1.404	1.997	0	14.9
3	1.000	1.150	0.409	0.204	2.769	1.227	1.586	7.096	.613	5.326	1.227	1.586	1.996	0	14.9
4	1.000	1.074	0.427	0.180	2.617	1.208	1.411	6.019	0.304	4.203	1.208	1.411	1.996	0	14.9
5	1.000	1.193	0.517	0.250	2.607	1.181	1.480	6.876	0.590	5.137	1.181	1.480	1.996	0	15.0
6	1.000	1.194	0.615	0.333	2.371	1.274	1.428	4.880	0.636	3.908	1.274	1.428	1.996	0	15.0
Mean	1.000	1.216	0.529	0.277	2.604	1.215	1.462	6.250	0.607	4.680	1.215	1.462	1.996		
Std.Dev	0.000	0.205	0.153	0.135	0.132	0.033	0.068	0.986	0.016	0.706	0.033	0.068	0.000		
Var.Coeff	0.00%	16.87%	29.03%	48.77%	5.07%	2.73%	4.63%	15.77%	2.68%	15.09%	2.73%	4.63%	0.02%		

Carbon fibre, with Ace MX-960 at 10 wt.% composite





Sample	T	I_d	F_d	E_d	I_m	F_m	E_m	I_p	F_p	E_p	F_oT_m	E_oT_m	V_o	B_i	T_s
	mm	mm	kN	J	mm	kN	J	mm	mm	J	kN/m	J/mm	m/s		°C
1	1.000	0.951	0.389	0.172	2.446	1.161	1.361	7.428	0.580	6.152	1.161	1.361	1.997	0	14.9
2	1.000	1.086	0.542	0.245	2.504	1.220	1.471	6.905	0.610	5.369	1.220	1.471	1.998	0	15.0
3	1.000	1.167	0.608	0.309	2.988	1.350	2.122	7.074	0.675	6.209	1.350	2.122	1.997	0	15.0
4	1.000	1.138	0.516	0.263	2.565	1.153	1.475	6.960	0.575	5.220	1.153	1.475	1.997	0	15.0
5	1.000	1.217	0.587	0.320	2.459	1.223	1.415	7.577	0.611	6.277	1.223	1.415	1.997	0	15.0
6	1.000	1.100	0.508	0.246	2.813	1.175	1.717	6.846	0.588	5.373	1.175	1.717	1.997	0	15.0
Mean	1.000	1.110	0.525	0.259	2.629	1.214	1.593	7.132	0.606	5.767	1.214	1.593	1.997		
Std.Dev	0.000	0.091	0.077	0.053	0.221	0.073	0.286	0.300	0.037	0.493	0.073	0.286	0.000		
Var.Coeff	0.00%	8.19%	14.74%	20.47%	8.42%	6.03%	17.97%	4.21%	6.05%	8.55%	6.03%	17.97%	0.02%		

Appendix 4: Interlaminar shear strength test results

Carbon fibre, pure epoxy composite						
No	L	L_s	t	b	F	ILSS
	mm	mm	mm	mm	KN	MPa
1	40.62	12	1.90	10.50	0.5172	19.95
2	40.80	12	1.85	10.48	0.5362	20.15
3	40.60	12	1.90	10.50	0.5533	20.80
4	40.80	12	1.90	10.45	0.5306	19.94
5	40.80	12	1.90	10.47	0.4296	16.15
Mean					0.51338	19.398
Std. deviation					0.048592	1.849262

Carbon fibre, with Ace MX-125 at 6 wt.% composite						
No	L	L_s	t	b	F	ILSS
	mm	mm	mm	mm	KN	MPa
1	40.70	12	1.98	10.30	0.4995	18.85
2	40.65	12	1.96	10.45	0.5022	19
3	40.62	12	2	10.42	0.4965	18
4	40.67	12	2	10.45	0.4899	17.35
5	40.52	12	2	10.43	0.4999	18.32
Mean					0.4976	18.304
Std. deviation					0.004758	0.668079

Carbon fibre, with Ace MX-156 at 6 wt.% composite						
No	L	L_s	t	b	F	ILSS
	mm	mm	mm	mm	KN	MPa
1	40.65	12	1.85	10.43	0.6631	24.28
2	40.62	12	1.90	10.46	0.5272	19.8
3	40.66	12	1.85	10.39	0.518	19.47
4	40.60	12	1.80	10.43	0.512	19.24
5	40.13	12	1.94	10.48	0.6323	23.77
Mean					0.6631	24.28
Std. deviation					0.071497	2.491138

Carbon fibre, with Ace MX-960 at 6 wt.% composite						
No	L	L_s	t	b	F	ILSS
	mm	mm	mm	mm	KN	MPa
1	40.60	12	1.98	10.38	0.7332	27.56
2	40.64	12	1.98	10.27	0.6381	23.98
3	40.63	12	1.85	10.46	0.7047	26.49
4	40.64	12	1.96	10.46	0.6009	22.59
5	40.68	12	1.96	10.43	0.5493	20.65
Mean					0.64524	24.254
Std. deviation					0.07499	2.817895

Carbon fibre, with Ace MX-125 at 10 wt.% composite						
No	L	L_s	t	b	F	ILSS
	mm	mm	mm	mm	KN	MPa
1	40.64	12	1.97	10.28	0.6464	24.30
2	40.67	12	2	10.40	0.6165	23.17
3	40.68	12	2	10.29	0.5535	20.80
4	40.63	12	2	10.49	0.5773	21.70
5	40.66	12	2	10.26	0.4584	17.23
Mean					0.57042	21.44
Std. deviation					0.072074	2.70988

Carbon fibre, with Ace MX-156 at 10 wt.% composite						
No	L	L_s	t	b	F	ILSS
	mm	mm	mm	mm	KN	MPa
1	40.63	12	1.91	10.48	0.7228	27.17
2	40.63	12	1.77	10.48	0.6452	24.25
3	40.68	12	1.82	10.48	0.7115	26.74
4	40.54	12	1.74	10.46	0.7278	27.36
5	40.67	12	1.75	10.53	0.7167	26.94
Mean					0.7048	26.492
Std. deviation					0.033881	1.274939

Carbon fibre, with Ace MX-960 at 10 wt.% composite						
No	L	L_s	t	b	F	ILSS
	mm	mm	mm	mm	KN	MPa
1	40.66	12	1.80	10.51	0.7768	29.20
2	40.64	12	1.80	10.47	0.6384	24
3	40.65	12	1.80	10.52	0.7234	27.19
4	40.65	12	1.90	10.45	0.7408	27.84
5	40.68	12	1.80	10.40	0.6627	24.91
Mean					0.70842	26.628
Std. deviation					0.056881	2.136462