CRANFIELD UNIVERSITY

SAYYAM KHURANA

LOAD INTRODUCTION IN BOLTED UD-SMC HYBRID COMPOSITE STRUCTURES

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MSc AEROSPACE MATERIALS

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Academic Year: 2019 - 2021

Supervisor: Andrew Mills
Associate Supervisor: David Ayre
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Supervisor: Andrew Mills
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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc Aerospace Materials
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

There is a growing need for lightweight composite parts that can be mass produced for the automotive industry. Conventional continuous fibre composites are too expensive, and Sheet Moulding Compound (SMC) parts have very high variability. Hybrid composites made of Uni-directional (UD) Tapes and SMC lie in the goldilocks zone to fulfil this market.

A suspension arm of a multi-link suspension system is chosen as a target part for the project. A complex I-beam with a cross-section similar to a suspension arm is moulded using hybrid composites. An original UD placement layout is designed to increase the net tensile strength of the part.

Six inserts are designed, manufactured, and embedded into hybrid I-beams to reduce the stress concentration and increase the bearing strength of the parts. Pin-bearing tests are performed on the parts to evaluate the impact of insert shape, projected area, and texture. The resultant hybrid parts have a higher strength than Aluminium but have lower stiffness.

Keywords:

Compression Moulding, SMC, UD, Insert, Automotive, Suspension Arm

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UD	Uni Directional
SMC	Sheet Moulding Compound
RoHM	Rule of Hybrid Mixtures

1 Introduction

Climate change is the biggest threat to modern humans. It is crucial that we reduce our greenhouse emissions through every avenue. Transport emissions account for 30% of EU's total CO_2 emissions, majority of which is caused by road transport.[1] One of ways to reduce emissions is to reduce the weight of the vehicles in turn leading to higher energy efficiency.

Most structural parts of the automobiles are made from metals. It is possible to reduce the weight of these parts by replacing them with continuous fibre composites. While this strategy has worked for the aerospace industry, continuous fibre composites are expensive and have high manufacturing cycle times. Short fibre composites on the other hand are price competitive, low production times, but have lower strength, stiffness, and reliability. Hybrid composites with short and continuous fibres combined synergistically utilises the advantages of both composites. While, the strength and stiffness of hybrid composites has been investigated in lab conditions, load transfer in real world applications occurs using bolted joints. Therefore, this report investigates the load transfer using bolted joints in hybrid composites.

The project is defined in Chapter 2. Chapter 3 presents the literature study and points out the knowledge gap. The design, manufacturing and testing method is presented in Chapter 4. Chapter 4.3 displays the results of the testing followed by their discussion in Chapter 6. The conclusion of the project is presented in Chapter 7 followed by recommendations for future work in Chapter 8.

[1]https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics

2 Project Definition

The aim of the project is to establish design rules for hybrid bolted composite joints. Amongst the various structural components in an automobile, the rear suspension arm of Porsche Panamera is chosen for redesign with hybrid composites. Currently, the arm is produced using forged Aluminium. A render of the suspension arm is shown in Figure 1.

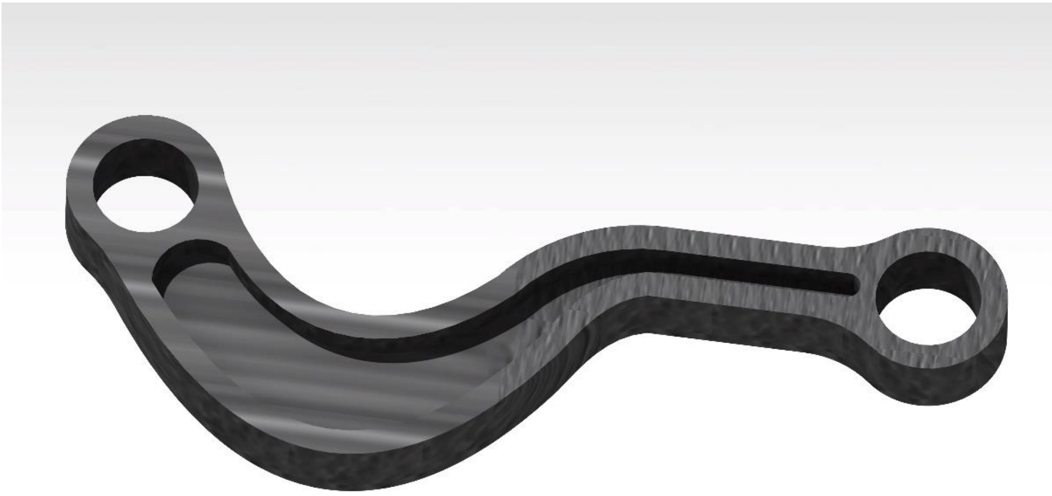


Figure 1: Render of a multi-link rear suspension arm

The car uses a multi-link suspension system, which provides design flexibility, improved comfort, and simple loading on the arms. The location of the suspension arm is displayed in Figure 2. The design requirements for a consumer car state a minimum travel distance of 200,000 km. Apart from simulating “stop brakes” and “bends”, the suspension arm also must withstand misuse scenarios such as car travelling at 50 km/hr over an obstacle 100 mm high and 100 mm long.

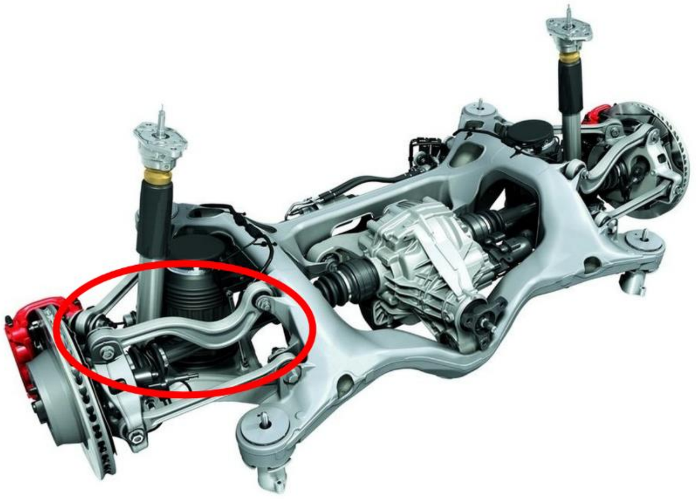


Figure 2: Location of Suspension arm

In a multi-link suspension system, the suspension arm is limited to tensile and compressive loading.[2] The loading is applied via a bushing shown in Figure 3. As a sudden catastrophic failure is unacceptable, a gradual bearing failure of the suspension arm is desired.

Figure 3: Bushings in a Suspension Arm

Every manufacturer has their own in-house loading criteria and safety factors for the suspension system. Therefore, to design a useable component, the hybrid suspension arm must meet the same technical criteria as the aluminium one.

[2] http://www.multibody.net/teaching/msms/students-projects-2020/multi-link-suspension/

To minimize design variables, an I-beam was chosen as a simplified model of a suspension arm because of its similar cross-section.

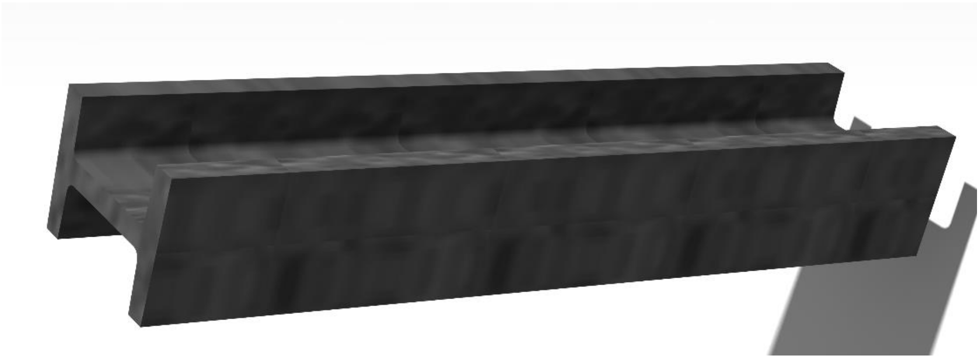


Figure 4: Render of an I-Beam

The objectives of the project are to:

- Develop a compression moulding technique for complex I-section test elements using hybrid composites.
- Develop a change in the failure mode of a SMC specimen from net tension to bearing using UD fibre tapes and shaped inserts.
- Determine the influence of insert shape on the failure of hybrid part bolted joints.
- Design a hybrid Suspension Arm with 30 % weight reduction with less than 3x the cost of forged aluminium.

The risk assessment and mitigation plan can be found in Appendix D.

3 Literature Study

This chapter provides a comprehensive review of the hybrid composites, metal inserts in composites, and effective ways to transfer loads through them. The aim of the chapter is to present and analyse the problem, probe the work that has previously been undertaken and identify the knowledge gap and potential challenges.

3.1 Automobile Parts vs Aerospace Parts

Composites have a significant flight heritage in the aerospace sector. However, there are some key differences in aerospace and automobile requirements that must be considered when designing composite parts as outlined in Table 1.

Table 1: Differences in Aerospace and Automotive Design

	Aerospace	Automotive
Design Safety Factors	~1.5	~3
Handling	Certified Technician	Garage Mechanic
Maintenance checks	Regular scheduled checks	Irregular checks
Operating Conditions	Narrow operational envelopes with specific operational limits	Broad operational envelopes
Right to Repair	Can require custom tooling for repair	Should be repairable/ replaceable using standard tooling

3.2 Composites

Composites in this report are used to define fibre reinforced polymers. There are two broad categories of composites namely continuous and discontinuous fibre composites.

3.2.1 Continuous fibre composites

Continuous fibre composites utilize long fibres that encompass the entire structure. They can be uni-directional (UD) tapes, woven fabrics, knitted fabrics, braided shells, etc. While each type of continuous fibre has its own advantages, UDs are the simplest form of composites with the highest specific strength and stiffness.

UDs are anisotropic composites which comprise of continuous glass or carbon fibres aligned in one direction and are held together using a polymer. They are relatively expensive. Resin can be injected in them during moulding or can be pre-impregnated in the case of pre-pregs.

3.2.2 Discontinuous fibre composites

SMCs (Sheet moulding compounds) are made from discontinuous fibre composites. They are planar isotropic and can be easily moulded in complex shapes using high pressure. The relationship between strength of composites and fibre length is demonstrated in Figure 5.

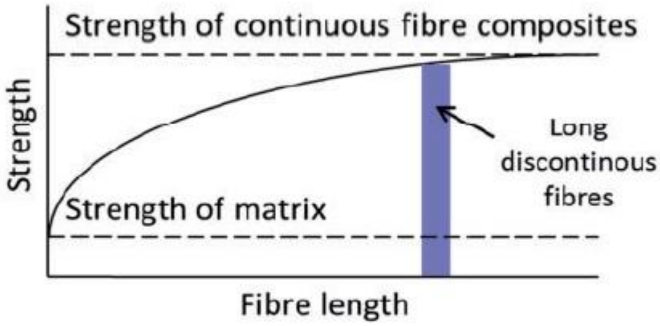


Figure 5: Composite strength as a function of fibre length (Visweswaraiah et al., 2018)

As the length of the fibres is shorter, SMCs are relatively less strong and stiff. The fibres in SMC are randomly oriented in the X-Y plane as displayed in Figure 6. SMC's gain their relative isotropicity from the random orientation of fibres. The level of isotropicity is dependent on the mould and the processing characteristics.

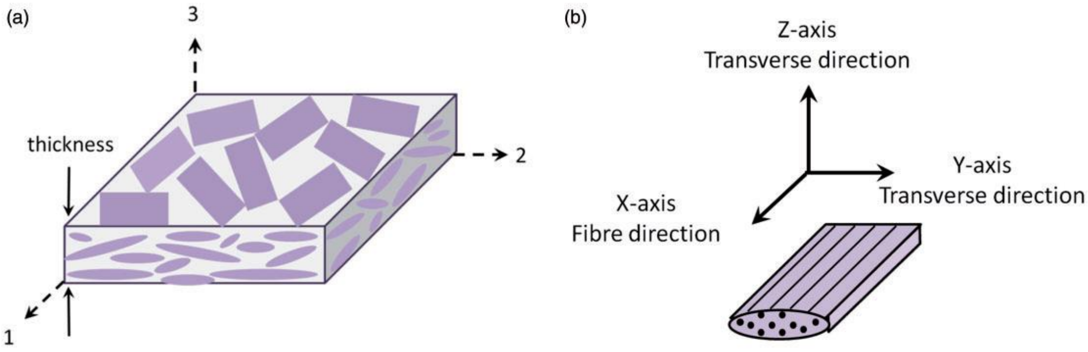


Figure 6: Orientation of discontinuous fibres in the x-y plane (Visweswaraiah et al., 2018)

Figure 7 demonstrates the different types of discontinuous fibre architectures. Long discontinuous fibres (LDF) are made from continuous fibre pre-pregs. This provides with long fibres, higher wetting (better adhesion) and higher cost. Short discontinuous fibre architectures are made using tows of dry fibre and resin sheet. They have relatively lower mechanical properties but are significantly cheaper.

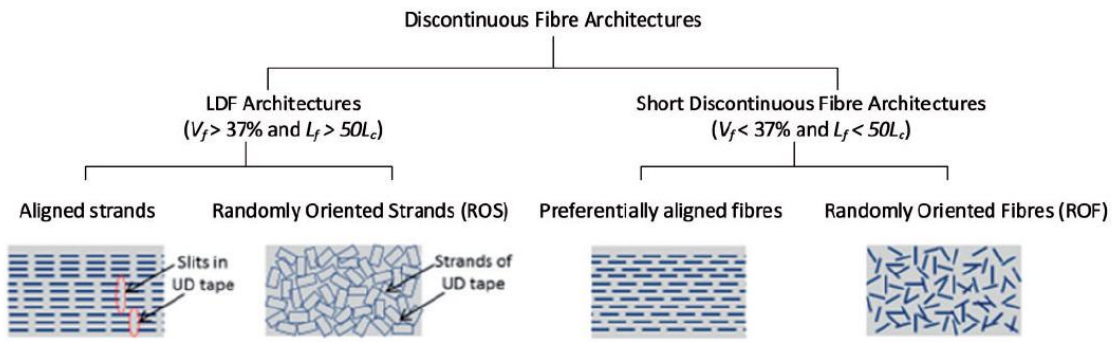


Figure 7: Classification of discontinuous fibres (Visweswaraiah et al., 2018)

SMCs are significantly cheaper than UDs which makes them viable for automotive applications. The cost of UD and SMC along with other materials is displayed in Figure 8.

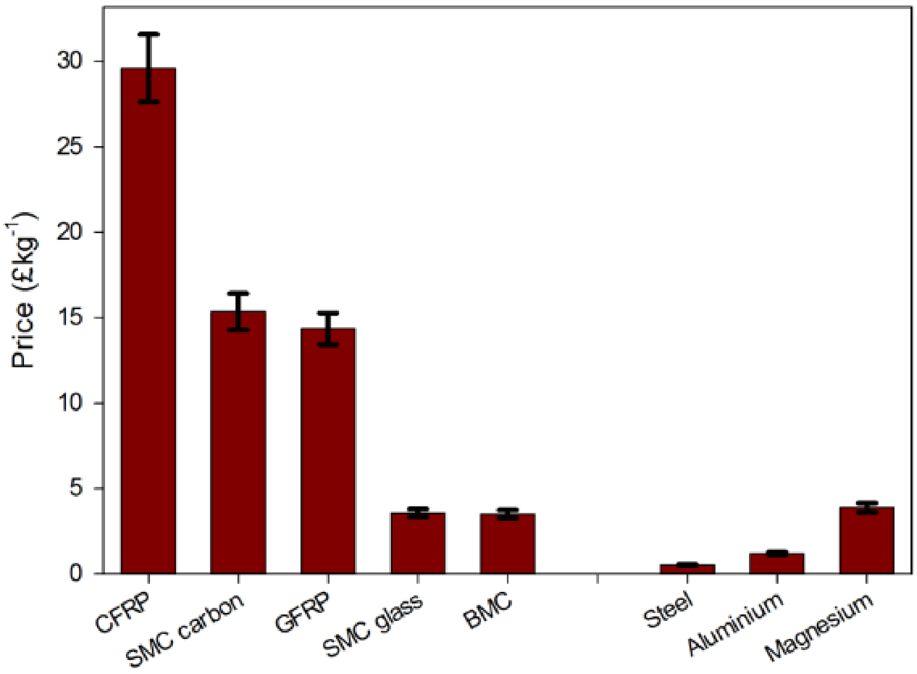


Figure 8: Cost of materials (Granta design, 2020)

SMCs are compression moulded. Compression moulding is a relatively low-cost process suitable for medium to high production batches. The final cost of any part is dependent on both the material cost and the process cost. A comparison of processing parameters and process cost of different manufacturing methods for composites and metals is presented in Table 2.

Table 2: Comparison of Various Manufacturing Processes (Corbridge, 2018; Granta design, 2020)

Manufacturing Process	Pressure (MPa)	Temperature (°C)	Cycle Time (min)	Relative Cost Index (£) [3]	Economic Batch Size
Autoclave	0.3-0.7	30-350	300-600	183	1-500
Resin Transfer Moulding (RTM)	0.1-6	30-350	3-30	20.8	500-5000
Compression Moulding (SMC)	1-20	30-350	1-15	21	5000-1000000
Injection Moulding	10-100	30-350	1-2	13.1	10000-1000000
Steel Stamping	140-200	30-800	0.16	10.2	25000-250000
Sand Casting (Aluminium)	-	700	0.2-3	11.9	1000-100000
Aluminium Forging	50-130	400	0.2-6	25.1	100-10000000

The use of SMCs in structural parts is limited because of low mechanical properties and lack of repeatability in parts. A comparison of specific strength and stiffness of different materials is presented in Table 3.

[3] "The relative cost index approximates the cost of making a 'unit' or a component by the process. Its value is calculated with the 'Process Cost Model". The complexity of the part, batch size, material, manufacturing location, etc will all have an impact on the final cost, however relative cost index is a helpful tool for process comparison.

Table 3: Specific Strength and Stiffness of Different Materials (Granta design, 2020)

Material	Specific Tensile Strength (kN.m/kg)	Specific Stiffness (MN.m/kg)
Aluminium 6082	95	26.5
Aluminium 6060	60	26.5
Low Carbon Steel 1020	38	26.6
High Carbon Steel 1095	48	26.5
Stainless Steel 316L	38	24.8
Gray Cast Iron (EN GJL 350)	33	18.5
CF UD (Epoxy)	1650	105.8
CF SMC (Vinyl Ester)	77	18
GF SMC (Vinyl Ester)	104	7.4
CF HexMC (Epoxy)	193.54	24.5

Tensile loading is the critical loading for the SMCs followed by compression loading and flexural loading (Feraboli et al., 2009)**.** Compressive strength of SMCs can be up to 1.7 times higher than tensile strengths (Caprino et al., 2002). SMCs have higher fracture toughness than continuous fibre laminates and are notch insensitive. SMC parts can be designed with local thickness variation. SMCs are also more sustainable than continuous fibre composites as they can be made from recycled composite fibres.

SMCs have already found use in aerospace and automobile applications such as Boeing 787 window frame as shown Figure 9.

Figure 9: Boeing 787 window frame (Bale and others, 2015)

3.2.3 Hybrid composites

Hybrid composites is a term used for any combination of composite materials. The scope of this report is limited to a hybrid of UD-SMC thermoset composites.

Figure 10 shows that the two ways of increasing stiffness of a composite structure are by increasing the moment of inertia or intrinsic material stiffness. SMC parts can be compression moulded into complex shapes with high moment of inertia, whereas UD can add stiffness, strength, and predictability in critical load paths.

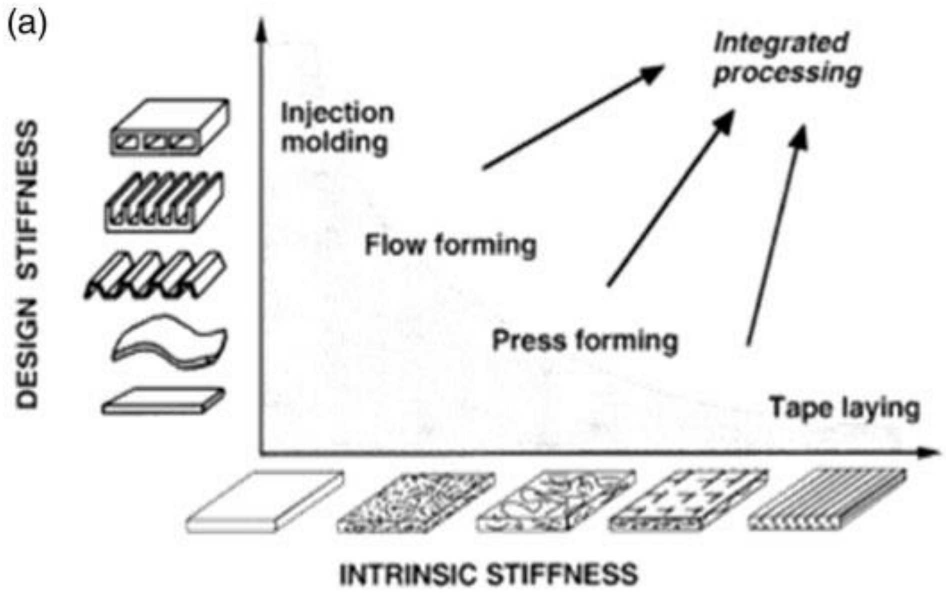


Figure 10: Ways to increase the stiffness of a composite (Visweswaraiah et al., 2018)

Therefore, hybrid composites are a way to synergistically utilise the strengths of SMC and UD. The strength and stiffness of the specimen can be tailored by changing the amount of location of the UDs. Wulfserg et al doubled flexural, tensile moduli and tensile strength through hybridization (Wulfsberg et al., 2014)**.** Hybrid composites are notch insensitive for low volume fractions of UDs (Visweswaraiah and others, 2017). Additionally, they provide higher repeatability when compared to SMCs (Akiyama, 2011). Figure 11 displays the processing and performance of different composite architectures and hybrid composites lie in the middle.

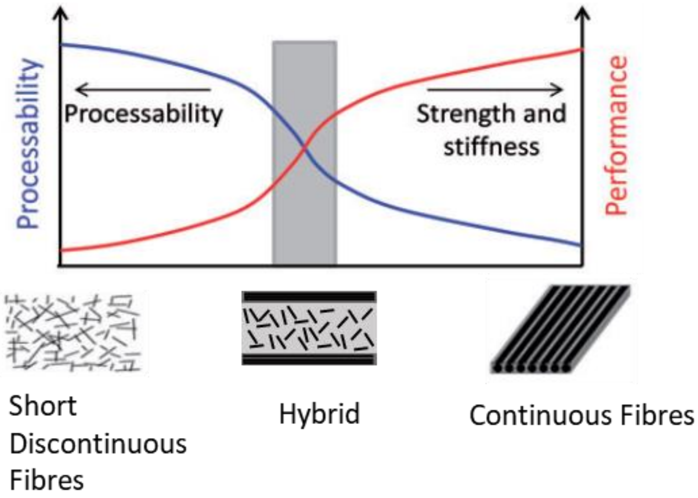


Figure 11: Processing vs performance of different composite architectures

(Selezneva and Lessard, 2016)

Hybrid composites offer a unique opportunity to reduce the cost of high performance structural composites (Hitchen and Kemp, 1996). They can be manufactured using same compression moulding technique as SMC with high production rates. An example of a single shot hybrid compression moulding can be seen in Figure 12.

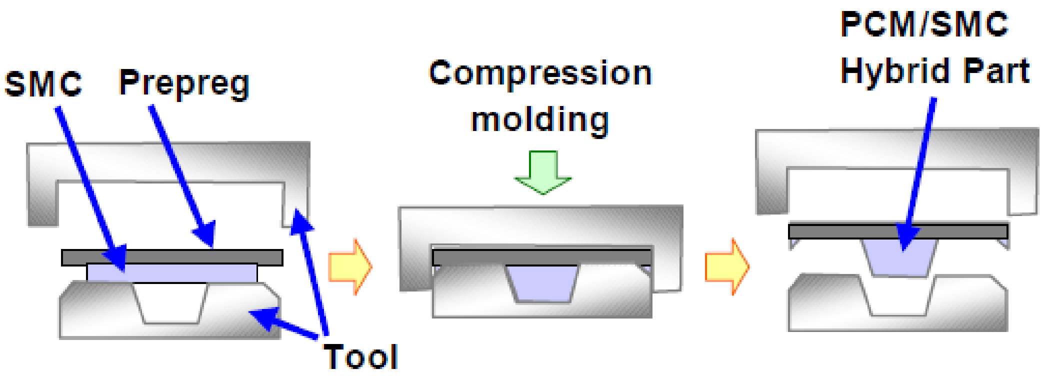


Figure 12: Net Shape Hybrid Compression Moulding

Hybrid composites have gained a lot of interest in the past few years for automotive applications as they can reduce weight of metallic parts without significantly increasing the cost. One of the earliest adoptions of hybrid composites in automobiles is the Mitsubishi Rayon hybrid structural floor displayed in Figure 13. It uses the UD to add strength and stiffness in straight paths and uses SMC to form the complex shapes.

Figure 13: Mitsubishi Rayon Hybrid Structural Floor (Corbridge, 2018)

Table 4 summarises the ways in which hybrid composites adopt advantages of SMC and UD composites.

Table 4: Summary of advantages of UD, SMC, and Hybrid Composites

UD	SMC	Hybrid
High specific strength	Mouldability	Mouldability
High specific stiffness	Medium specific stiffness	Tailorable specific strength and stiffness
Repeatability	Low cost	Medium cost
Directional properties	High production rate	High production rate
	Notch insensitivity	Tailorable notch sensitivity
	Sustainable	Sustainable
	Planar isotropic	Repeatability
	Progressive failure	Progressive failure

3.3 Prepreg Compression Moulding

UD prepregs are cut and stacked in near net shape and moulded using heat and pressure as shown in Figure 14. Prepreg manufacturing is expensive, so they are generally made from carbon fibre and fast curing epoxy. The recommended compression pressure is 5-35 bars.

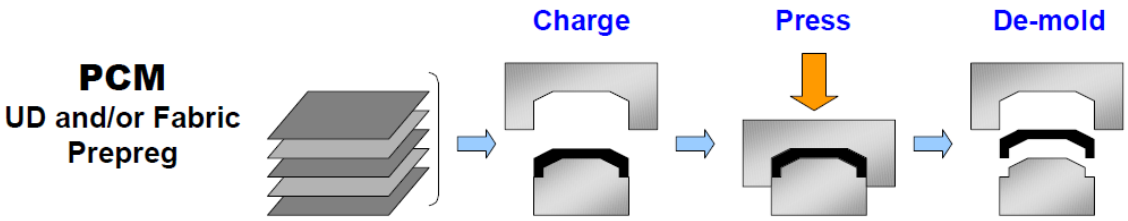


Figure 14: Prepreg Compression Moulding (Akiyama, 2011)

Prepreg compression moulding has a low cycle time, can be automated, and produces net shape parts. However, it doesn't extract voids like an autoclave. The prepregs need to be symmetric to prevent warping.

3.4 SMC Compression Moulding

3.4.1 SMC Manufacturing and Properties

SMC is manufactured by chopping carbon fibre and randomly dropping them on a layer of resin as showed in Figure 15. The manufacturing process is supposed to result in homogenous properties, but because of machine design, there is often an orientation bias in the SMC sheet.

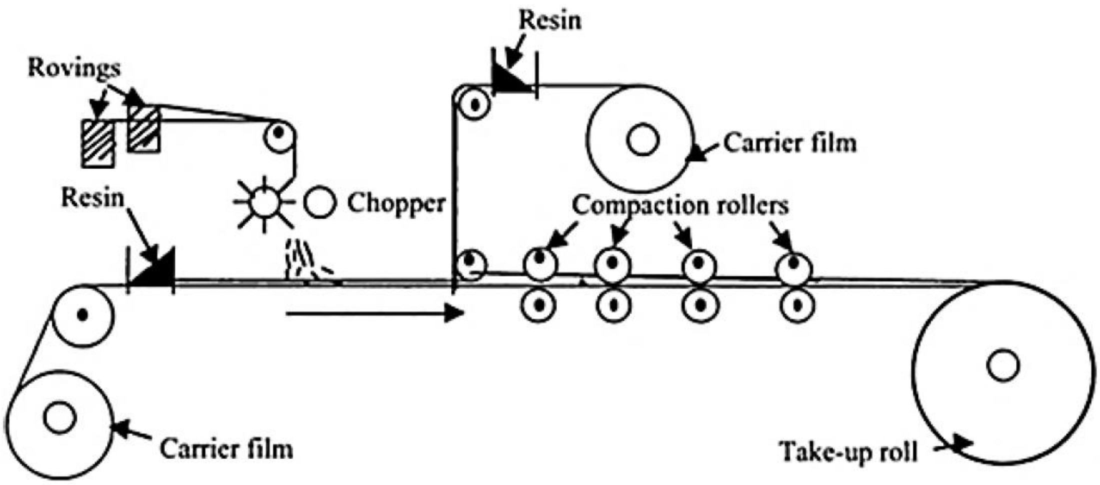


Figure 15: SMC Manufacturing Process (Mazumdar, 2001)

SMCs are notch insensitive, as the stress concentrations at the edge of fibre bundles are greater than holes. Table 5 shows the stress concentration factors in a specimen with a Diameter to Width Ratio of 0.375. It can be observed that SMCs distribute stress around a hole better than isotropic materials but has higher stress concentration at bundle ends.

Table 5: Stress Concentration Factors Around Holes in Different Materials D/W 0.375 (Bond et al., 2019)

Material	Location	Stress Concentration Factor
Metals/Isotropic	Hole	2.26
SMC	Hole	1.4
SMC	Bundle End	3.95

Figure 16 shows the width (W), diameter of the hole (D) and the edge distance (E) of a specimen.

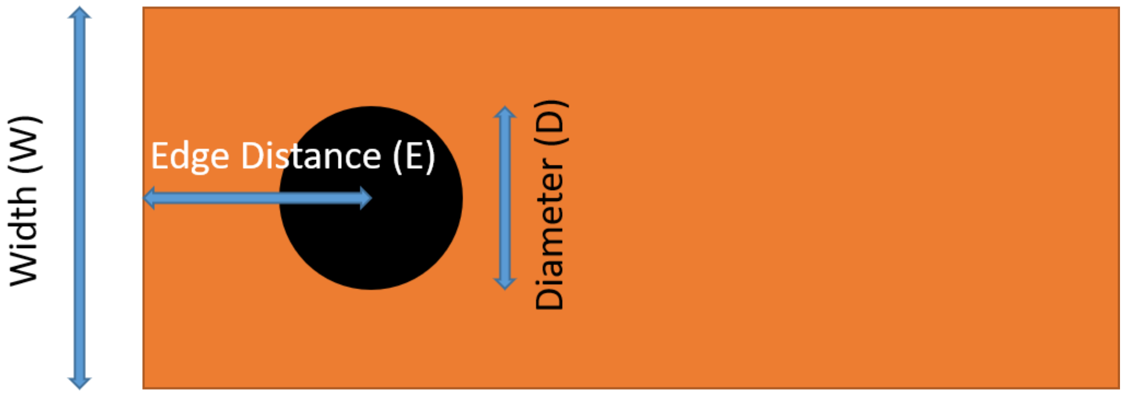


Figure 16: Diameter, Width and Edge Distance of a specimen

As the stress concentration factors depend on the dimensions of the specimen, Table 6 shows the stress concentration factors at hole of metals and composites in an infinite width scenario. It can be observed that UD [0] has high stress concentrations and UD [45] has the lowest stress concentration in continuous fibre laminates.

Table 6: Stress concentrations factors in infinite width materials (Woodhead Publishing, 2012)

Material	Location	Stress Concentration Factor
Metals	Hole	3
UD [0]	Hole	6.6
UD (45)	Hole	2
Quasi Isotropic [0/± 45/90]	Hole	3
Cross- Ply [0/90]	Hole	3.5
[0/45/0]	Hole	4.1
45/0/45	Hole	3

3.4.2 Fibres

As SMCs are relatively inexpensive, they are made with both glass fibre and carbon fibre. Glass fibre is inexpensive, strong, chemically resistant and has low galvanic potential. Carbon fibre is relatively stiff and strong but is also expensive and has high galvanic potential.

3.4.3 Resin

SMCs are manufactured with different fast curing resins for different applications. Some properties of the available resins are presented in Table 7.

Table 7: Properties of Different Resins (Bücheler, Griesbaum and Henning, 2018)

Resin	Tensile Strength in MPa	Young's Modulus in GPa	Elongation at brake in %
Epoxy	115	2.8	6
Vinyl Ester (VE)[4]	35	3.5	1.25

Epoxy is expensive and it binds well with carbon and glass fibre. It also has a high elongation at break.

VE is cheaper than epoxy. It has relatively lower strength and elongation at break. It bonds well with glass fibre but doesn't bond well with carbon fibre. Carbon fibre VE SMC has poor strength because of poor bonding but still has high stiffness. VE releases styrene during curing which is not very sustainable. Versions of VE that don't release styrene have been developed and are undergoing proliferation.

Resin in SMC needs thickening to avoid fibre matrix separation at high pressures during moulding. In epoxies, this is achieved using B-staging and in VE, thickening agents are added.

3.4.4 Charge Placement and Flow

Charge refers to the material placed in the mould before pressing. SMC is usually shipped in a roll of 1 mm sheet. Multiple sections of the sheet are cut and stacked together to make a charge for a product. Charge shape, area, location, and stacking can have an impact on the final product.

Charge area is the percent of the total cross-section area of the mould covered by the charge. A higher charge area results in low flow of material and vice versa. Different values of charge coverage ranging from 60%-95% are recommended by manufacturers. Charge flow can take place in either one, two or three dimensions as shown in Figure 17.

[4] From datasheet in Appendix B

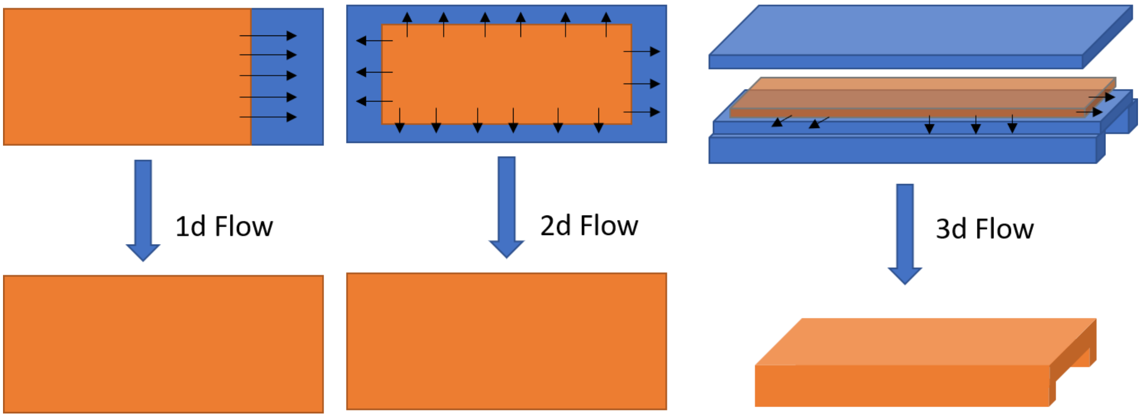


Figure 17: 1d Flow, 2d Flow and 3d Flow Scenarios

SMC flow inside a mould is often not uniform. Figure 18 shows the two non-uniform flows observed during compression moulding. Fountain flow is usually observed in thermoplastics as the polymer cools and becomes more viscous around the edges, whereas preferential flow is observed in thermosets where the heat from the edge of the tool reduces viscosity and promotes flow. Because of preferential flow, the fibre volume fractions are often higher near the edges of a tool. This can lead to high stiffness on the edges and lead to a fracture prone core (Corbridge, 2018)(Orgéas and Dumont, 2011)**.**

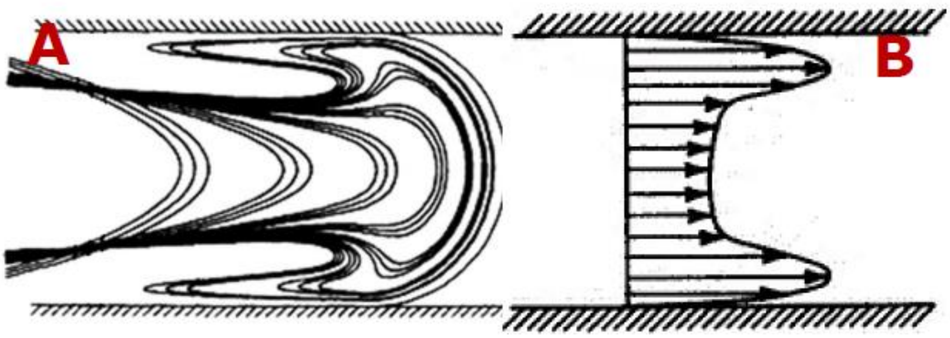


Figure 18: Flow Mechanisms: (A) Fountain flow usually observed in thermoplastic moulding;(Papathanasiou and Guell, 1997) **(B) Preferential flow usually observed in thermoset compression moulding** (Lee and Tucker, 1987)

Apart from charge coverage and charge placement, variables such as charge viscosity, fibre volume fraction, mould shape, mould surface roughness, mould temperature, mould closing speed, and dwell time of charge on the mould affect the flow and quality of the SMC.

3.4.5 Charge stacking sequence

Charge stacking sequence refers to the attribute of SMC sheets stacked in the Z-direction. Best practice guidelines suggest that small pieces of charges should be avoided when possible. Additionally, a pyramid charge structure as shown in Figure 19 should be used to avoid trapping voids.

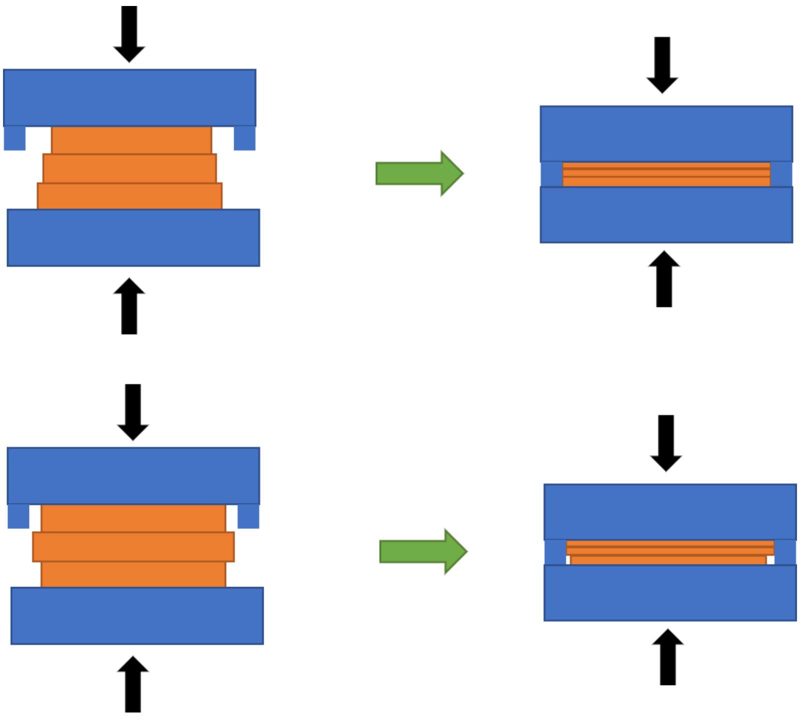


Figure 19: Pyramid Stacking Sequence to avoid voids and out of plane fibre distortion (REVELLINO, SAGGESE and GAIERO, 2000)

3.4.6 Advantages of High Flow Moulding

There are two design philosophies of SMC manufacturing: high/medium flow and low flow moulding.

3.4.6.1 Orientation of Fibres – Mechanical Properties

High amount of flow leads to preferential orientation of fibres. This can be an advantageous if desired. Extremely high flow can also lead to tangling and orientation of fibres in the z-direction, increasing loss and variability of mechanical properties.

3.4.6.2 Voids

SMC charge sheets have voids. High flow in combination with high pressures leads to low void content which increases predictability. This is because the flowing material allows the air pockets to escape.

3.4.6.3 Manufacturing Complexity

High Flow design requires charge to be placed on a smaller (and often imprecise) section of the mould. Therefore, it reduces the complexity during the moulding process.

3.4.6.4 Flow in Ribs

One of the techniques used to enhance the stiffness of polymer parts is to add ribs. Adding ribs is often not possible in a low flow design without manually placing the charge in the cavity.

However, the flow and orientation of fibres in the z directions leads to a variety of issues such as:

- Voids and resin rich regions which leads to higher shrinkage which leads to sink marks as seen in Figure 20
- Fibre matrix separation (Jeong, Kim and Im, 1996)
- Fibre bridging/entanglement

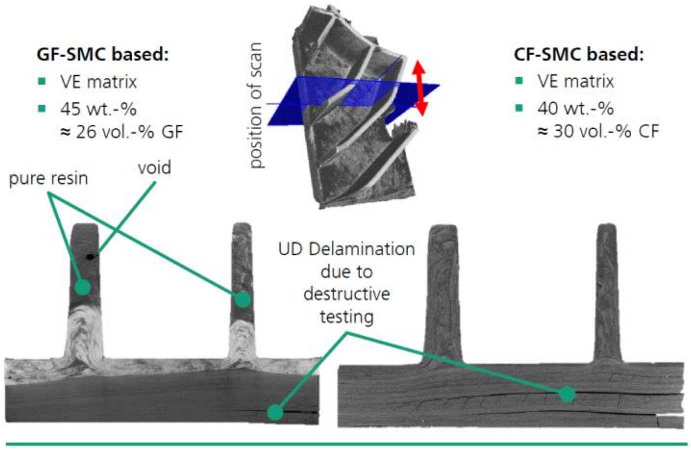


Figure 20: Defects in SMC ribs

A few strategies that have been successfully used to counter these issues:

- Increasing surface roughness at rib corners to encourage earlier rib filling (Kia, 1993)
- Increase rib thickness to prevent fibre bridging. However may lead to difference in local cure times, residual stress and consequently sink marks (Fan et al., 1989)
- Material break charge design as shown in Figure 21.

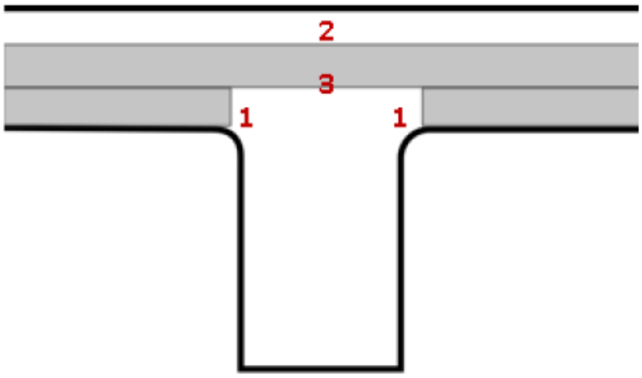


Figure 21: Material Break Charge Design (Corbridge, 2018)

3.4.6.5 Independence from manufacturing alignment bias

High flow can reduce the impact of the alignment bias in SMC charge sheets formed during SMC manufacturing.

3.4.7 Disadvantages of high flow

3.4.7.1 Fibre Matrix Separation

High flow increases the likelihood of fibre matrix separation as the fibres and resin face higher shear loads during moulding.

3.4.7.2 Weld Line

When two edges of flow meet, they can form weld lines as shown in Figure 22 which can significantly reduce mechanical properties. Weld lines should be avoided near joints.

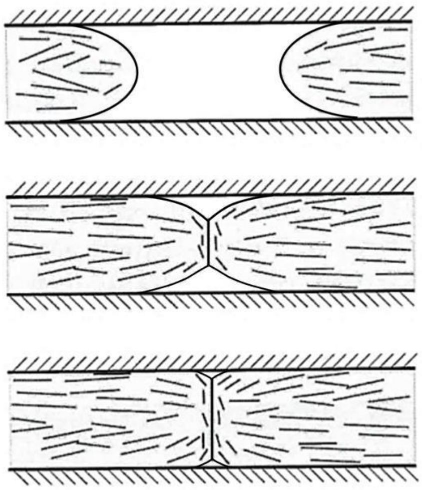


Figure 22: SMC flow creating a weld line (Sentis et al., 2017)

3.4.7.3 Fibre waviness and alignment

Higher flow leads to fibre waviness which reduces the planar properties of the composite. Additionally, variable fibre alignment reduces the predictability of the part and reduces the isotropicity of the material.

3.4.7.4 Flow around inserts

Flow around holes and inserts can form knit lines as shown in Figure 23. They can significantly reduce strength. One way to tackle knit lines is to place the charge on top of the insert avoiding flow over around the hole.

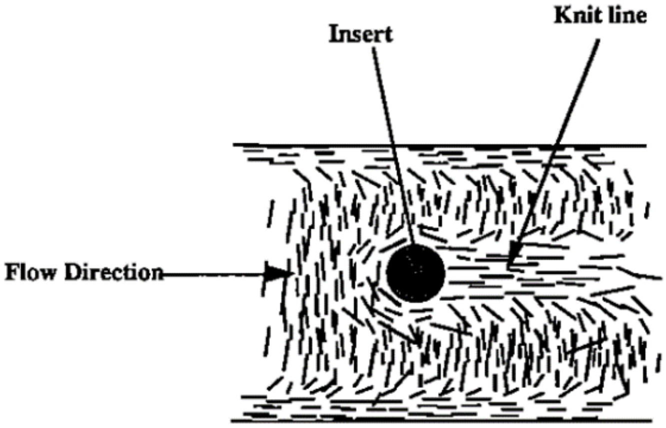


Figure 23: Knit line formed past an insert (Sasdelli, Karbhari and Gillespie, 1993)

3.4.8 Compression Pressure

The compression pressure recommended by the manufacturer is 80-120 bars. In low flow moulding, a higher pressure leads to low voids. In high flow moulding, a higher pressure doesn't have any conclusive impact on the void content.

3.4.9 Scalability

Modulus of a material is a volume averaged property and is not impacted by the size of the part. Strength on the other hand is limited by the critical load path. In a SMC part, fibre bundles oriented transversely to the load direction and ends of fibre bundles are regions of high stress concentrations as shown in Table 5. Large changes in local modulus make these locations ideal for crack initiation. Cracks propagate on the boundaries of bundle ends. Figure 24 shows that the likelihood of proximity stress concentrations increases with the size of the part. Therefore scalability of strength from small to large parts is unlikely. (Bond et al., 2019)

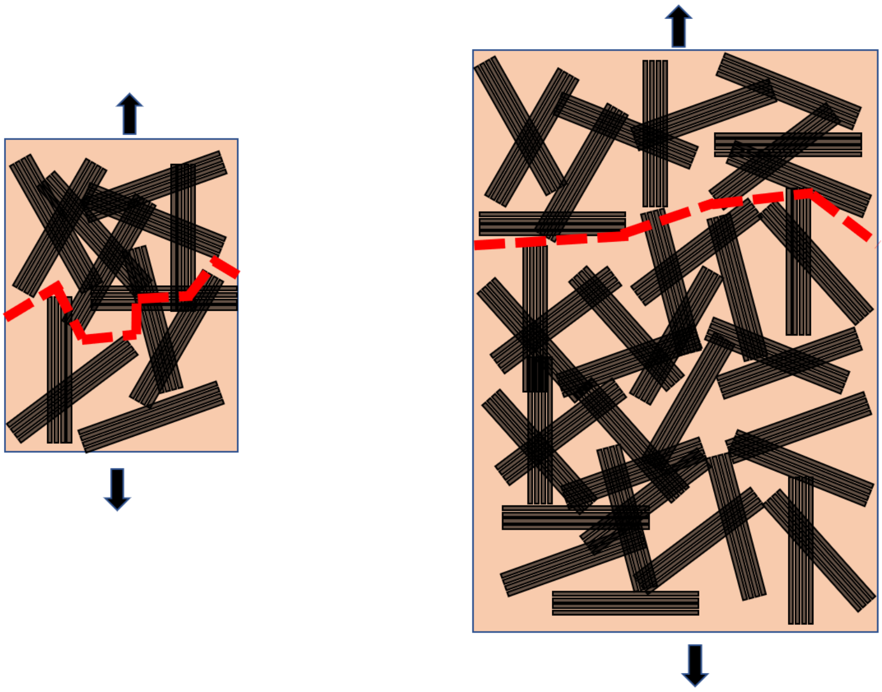


Figure 24: Increased likelihood of proximity of fibre bundle ends and transverse fibres in larger parts

3.4.10 Shrinkage

Thermoset polymers shrink when cured. The shrinkage is higher for polyester and vinyl ester resins. Fibres reduce the shrinkage, so resin rich regions often experience larger shrinkage leadings to voids and sink marks. Shrinkage also increases transversely with fibre alignment. Shrinkage of resin also leads to residual stresses which can lead to warping. Additives that expand are often added to minimize shrinkage, however this can have a negative impact on the material strength.

3.4.11 Internal Mould Release

Internal mould release is added to the SMC resin to allow for easier removal from the mould tool. During curing, the mould release diffuses through the SMC charge and collates towards the metal mould. Mould release makes it harder for metal inserts to stick to the resin. The impact of the internal mould release on co-curing of multiple composites is not known yet.

3.4.12 Temperature

Temperature during moulding has a significant impact on the final product as thermoset resins get less viscous with temperature until gelation. A higher temperature leads to a more uniform flow and preheating SMC epoxy charge to 60-65 degrees has shown promising results. On the other hands, a higher temperature increases the risk of fibre matrix separation and squish effect.

3.4.13 Dwell Time

Dwell time refers to the duration that the SMC is left on the moulding tool to heat without force. It minimises preferential flow as large parts of the SMC preheat to the same temperature. On the other hand, it reduces viscosity which may lead to fibre-matrix separation. It increases the risk of premature gelation. As SMC is heated only on the bottom surface during dwell time, it may lead to unequal flow in the z direction. This issue is more critical for thick parts (Olsson, Lundström and Olofsson, 2009). Dwell time can be reduced by using fast mould closure speed or simplifying charge placement.

3.4.14 Mould Closing Speed

A faster mould closing speed results in a more uniform fibre distribution in SMC parts (Olsson, Lundström and Olofsson, 2009). It also reduces the fibre matrix separation when moulding ribs. This is likely because faster moulding speed reduces the impact of non-uniform heating of the charge in the mould.

3.4.15 Compression under vacuum

Applying vacuum during compression moulding leads to lower void content and pressure build-up in tool from confined air (Olsson, Lundström and Olofsson, 2009)**.** It also leads to uniform flow at low closing speeds. On the other hand, it adds manufacturing cost. It is also not suitable at high temperatures when using polyester or vinyl ester because of styrene boiling.

3.5 Hybrid Compression Moulding

Hybrid compression moulding is very similar to SMC moulding with a few additional considerations.

3.5.1 UD Flow

One of the key issues with moulding UD and SMC together is that UD can flow and result in fibre waviness, wrinkling, buckling and fibre distortion as seen in Figure 25 (Dhakal et al., 2013). UD flow is very low in the longitudinal direction and higher in the transverse direction. UD does suffer from resin bleed in the longitudinal direction.

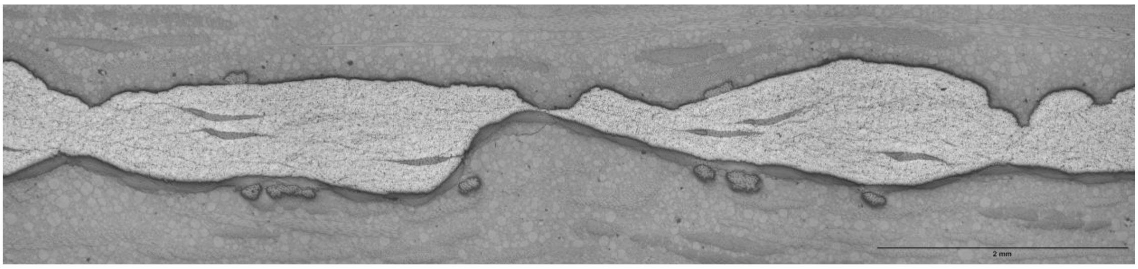


Figure 25: UD waviness inside hybrid

One way to alleviate UD flow is partial curing/staging of UD. It involves partially curing the UD before adding the SMC as shown in Figure 26.

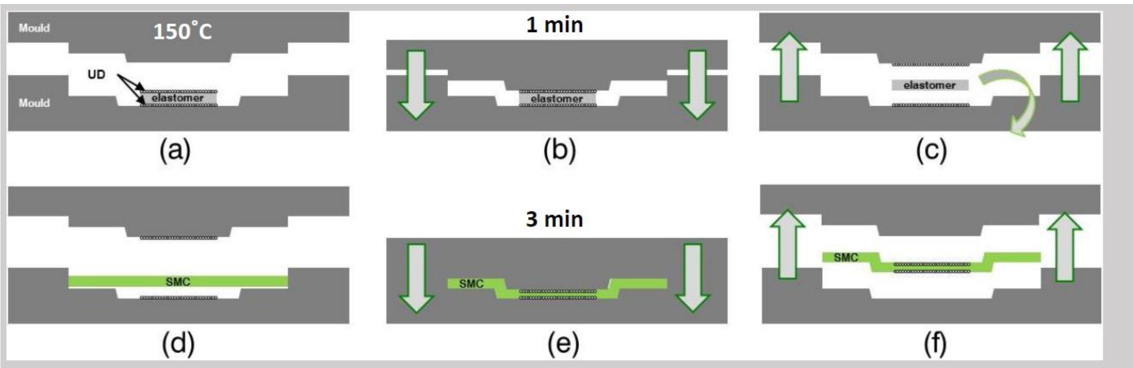


Figure 26: Two stage hybrid compression moulding

Due to fast curing times, partial curing needs to be precise. Low partial curing results in UD flow. High partial curing results in loss of tackiness and adhesion between SMC and UD. Potential downsides of partial curing are dry regions on SMC under the UD and SMC ripples near the UD-SMC interface. Corbridge looked at different amounts of curing/staging from 25-75% and found 50% to be ideal.

Resin bleed at UD-SMC interface has been observed in hybrid composites. This leads to slight increase in the fibre volume fraction of the UD and may lead to dry spots. Additionally, as the resin bleed is not uniform, it may lead to variability in local modulus.

Debulking UD plies can improve adhesion of pre cured UD plies and SMC and leads to a lower void content. However, debulking is not practical for high volume manufacturing.

3.5.2 Adhesion of UD and SMC

The adhesion at the interface of the UD and the SMC is a critical part of the composite. Same resin for the UD and SMC should be used when possible. It is critical for the resins to have similar curing times and temperatures.

However, a lot of SMCs in the market use Vinyl Ester and prepregs use epoxy. Co-curing of lightly cross-linked epoxy and vinyl ester results in good interfacial shear strength. Lightly cured epoxy has been used to improve adhesion of vinyl ester to carbon fibre (Xu and Drzal, 2001). Additionally, Polyester based gel coats have been known to adhere well to epoxy in the marine industry.

3.5.3 Difference in Compression Pressure

Prepreg UD compression pressure is 5-35 bar whereas SMC compression pressure 80-120 bar. Higher pressure on prepreg can lead to resin bleed and fibre rich edges of UD. It may also cause fibre fracture and distortion. As higher pressure is necessary in SMC to reduce void content, hybrids are moulded at higher pressures.

3.5.4 Stacking of UD and SMC

UDs and SMCs can be stacked in many ways. Figure 27 shows the different orientations that have been tested. UD-SMC-UD sandwich orientation has resulted in good results in stiffness, strength, and flexural modulus. It is also easier to mould as the UDs can be placed on mould surfaces.

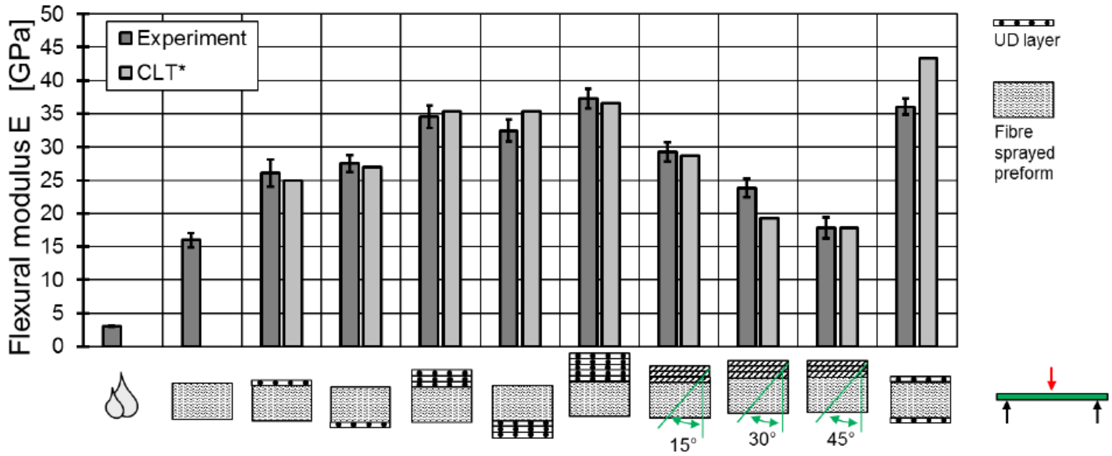


Figure 27: Flexural modulus of different UD-SMC orientations (Hopmann et al., 2017)

3.5.5 Charge Placement

If multiple layers of UD are used, they should be tapered to prevent stress concentrations. Interface angle should be less than 7 degrees to reduce the peel stress. (Evans et al., 2017)

A low flow moulding is preferred in hybrid composites as it reduces the risk of UD flow and increases part predictability. Figure 28 shows that there is a significant difference in the mechanical properties of SMC composites in the charge region and the flow region. However, in hybrid composites, the difference is negligible.

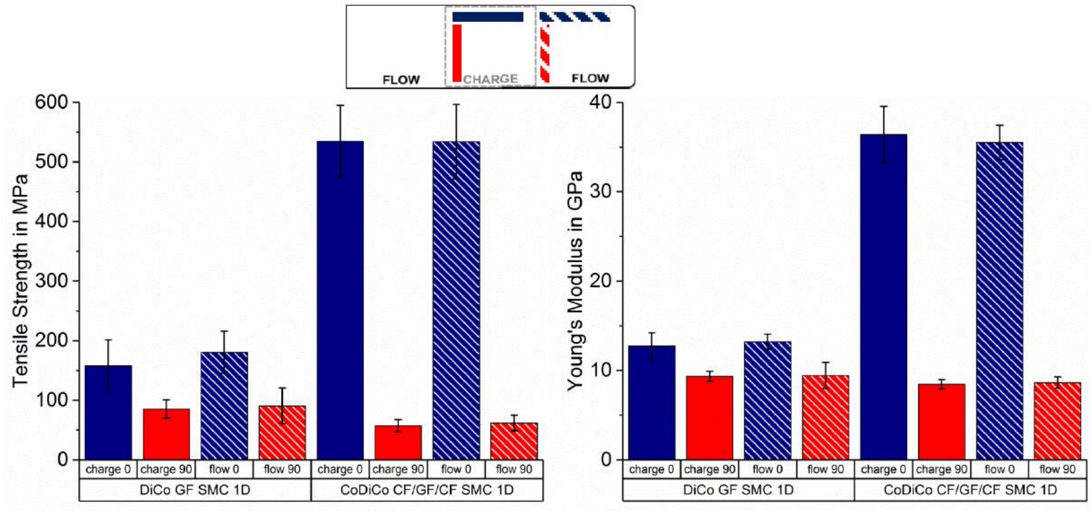


Figure 28: Difference in mechanical properties of SMC and hybrid composite sections in charge region and flow region

3.5.6 Predictability and Testing

Predictability of hybrid composites is higher than that of SMCs but lower than continuous fibre composites. Most hybrid strength prediction techniques are destructive and use a fibre angle-based approach. Vibration based models are being developed to predict fibre orientations but there has been no success in predicting failure location or load using them.

3.6 Mechanical Properties of Hybrid Composites

3.6.1 Modulus

The modulus of the hybrid composite can be predicted using Rule of Hybrid Mixtures (RoHM) as shown in Equation 3-1. It assumes that constant strain can be applied to both materials without any interaction.

Equation 3-1: Rule of Hybrid Mixtures

$$E = E_{UD}V_{UD} + E_{SMC}V_{SMC}$$

Where:

E_{UD} is the modulus of the UD

V_{UD} is the volumetric ratio of the UD in the hybrid composite

E_{SMC} is the modulus of the SMC

V_{SMC} is the volumetric ratio of the SMC in the hybrid composite

RoHM generally leads to slight overestimation of modulus (Venkateshwaran, Elayaperumal and Sathiya, 2012) (MIR et al., 2007). The potential reasons for variation in modulus are the orientation of fibres in UD and SMC. The impact of orientation of fibres in SMC is described in Equation 3-2.

Equation 3-2 Modulus of Random Fibre Composites

$$E_{SMC} = \eta_0 E_f V_f + E_m V_m$$

Where:

η_0 is the Krenchel efficiency factor

E_f , E_m are the modulus of the fibre and matrix respectively

V_f , V_m are the volume fraction of the fibre and matrix respectively

η_0 is assumed to be 0.375 when fibres are randomly oriented in a 2d plane. However, if the fibres flow in the z direction, the efficiency factor reduces. η_0 is 0.2 for the randomly oriented fibres in a 3d plane (Matthews and Rawlings, 1999).

Misalignment of the UD due to placement or flow can cause significant reduction in stiffness and strength as well. The impact of the UD angle on UD strength can be predicted using the classical laminate model.

3.6.2 Strength

While RoHM works well for predicting the modulus, it isn't equally accurate at predicting the strength of hybrid composites. This is because specimen strength is highly dependent on the UD-SMC interaction and interface properties. Any region of imperfection or location of multiple fibre bundle edges can lead to stress build-up which cannot be predicted using the RoHM equation. However, it is the most accessible way to predict the strength and has been found to be accurate in cases such as Figure 29.

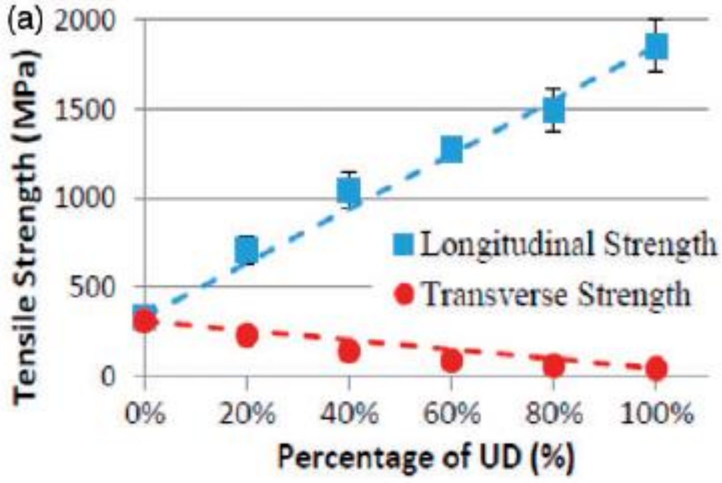


Figure 29: Difference in longitudinal and Transverse strength as a function of UD
(Evans et al., 2017)

3.7 Composite Joining Methods

Composites can be joined with metals in three key ways: (Jahn et al., 2016)

1. Adhesive Bonding
2. Mechanical Interlocking – using bolts, rivets or clinching
3. Adhesive bonding and Mechanical Interlocking

Table 8 summarises the advantages and disadvantages of the three methods. A combination of adhesive bonding and mechanical interlocking seems to be ideal for high loads.

Table 8: Advantages and Disadvantages of different composite joining methods

Joining Method	Advantages	Disadvantages
Adhesive bonding	• Uniform (fibre friendly) load introduction (Jahn et al., 2016) • No galvanic corrosion for dissimilar materials • Cost effective • Lightweight	• High material thickness can require high overlapping length • Durability and material degradation over time • Surface treatments • Long curing times • Humidity and Temperature constraints • Difficulty of Inspection • No Disassembly
Mechanical interlocking	• Higher load transfer(Jahn et al., 2016) • Reliable-measurable-high TRL • Easier maintenance/recycling • Easy Assembly • Relatively inexpensive • Easy Inspection • Ease of Regulatory Approval	• Weakness from Drilling – fibre damage, load transmission break, • Weakness from hole – load transmission break • Fibre Damage, yielding of matrix, loss of bolt clamp load impacts strength and fatigue (Caccese et al., 2009) • Relatively heavy

		• Risk of galvanic Corrosion • Stress Concentration at hole • Fibre Discontinuity
Adhesive bonding and Mechanical interlocking	• Better load distribution due to increased contact area (Kunc, Erdman and Klett, 2004) • Decreased stress concentration (Kunc, Erdman and Klett, 2004) • Higher joint rigidity (Kunc, Erdman and Klett, 2004) • Corrosion resistance • Water tightness • Easy Inspection	Expensive Time consuming Weakness from Hole Weakness from Drilling Limited Knowledge No disassembly

3.8 Inserts

As rivets and clinching have high potential for fibre damage and residual stresses, bolts are a better option. Bolts can be attached to composites using co-moulded inserts resulting in adhesive bonding and mechanical interlocking. The key benefit of a co-moulded insert is avoiding the drilling damage as shown in Figure 30.

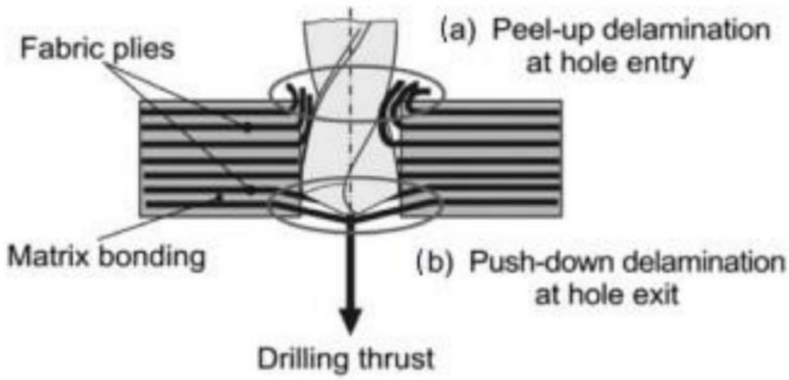


Figure 30 : Damage due to drilling (Faraz, Biermann and Weinert, 2009)

Figure 31 shows co-moulded inserts that reduce stress concentrations and introduce relatively fibre friendly loads. They also shield the hole from repeated attachment of fasteners. A joint strength increase of up to 24% has been observed between samples with and without cylindrical inserts. (Camanho and Matthews, 2000)

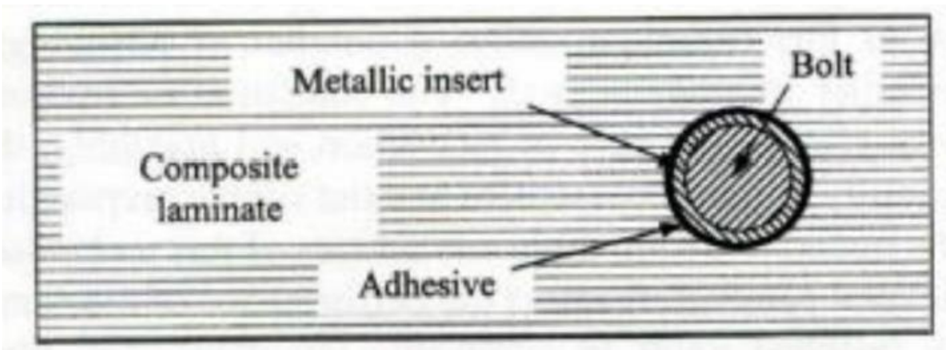
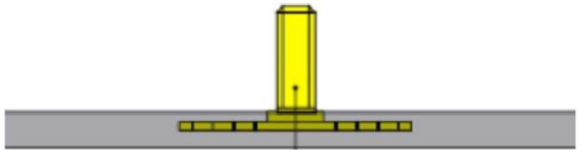


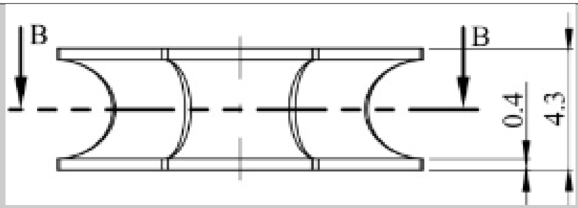
Figure 31: Bonded insert for bolt in composite laminate (Camanho and Matthews, 2000)

3.8.1 Location

Inserts can be located on the top, in the middle and through composites. Table 9 summarises the advantages and disadvantages of different insert locations. As the primary loading on the suspension arm is in-plane, through inserts are considered.

Table 9: Locations of Inserts inside Composites

Location	Advantages	Disadvantages	Application
 Figure 32: Top Insert (BigHead, 2017)	• Can be added during or post moulding • No holes • Easy inspection • High bonding area	• Low Load transfer • Susceptible to peeling and over torquing • Poor pull out strength	• Joining of non-structural composite parts
 Figure 33: Middle/Embedded Insert	• Good pull out and bending strength • Good twisting strength	• Poor bearing strength. • Increased likelihood of delamination at	• Joining to structural and non-structural parts in medium load

(Gebhardt and Fleischer, 2014)		insert base • Hard to inspect	applications. • Parts where through access is not possible.
 Figure 34: Through Insert (Troschitz, Kupfer and Gude, 2019)	• Good in plane bearing strength • Good pull-out strength with the use of washers • High load transfer	• Component needs to have through access. • Relatively heavy	• High load transfer applications with in-plane loads.

3.8.2 Modes of Failure

Composites with inserts can fail because of failure of the composite, failure of the insert or a combined failure of both. Figure 35 shows the critical macro failure modes due to in-plane loading. The subcritical micro damage modes in composites include matrix cracking, delamination, fibre/matrix shearing (Ataş and Soutis, 2013). While the failure modes of metals and composites are similar for in plane bearing load, metals tend to outperform composites because their ductility eases the stress concentrations(Duthinh and others, 2000).

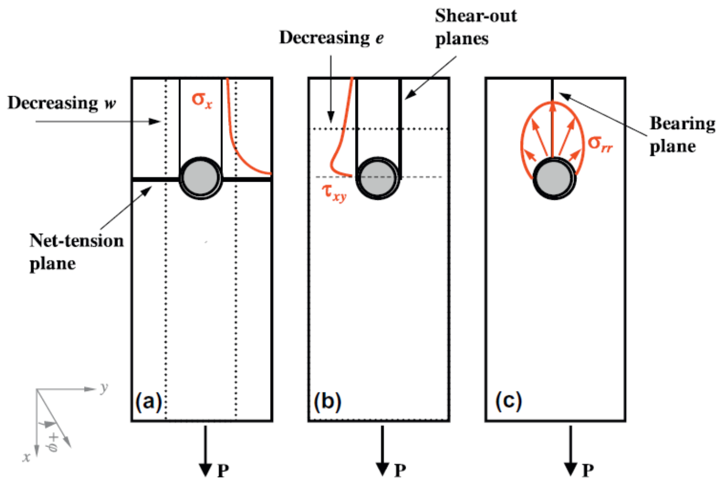


Figure 35: Modes of Failure in Composite plates (Ataş and Soutis, 2013)

3.8.2.1 Net Tension Failure

Lower width increases the chances of a net tension failure as the area that can carry the load is significantly reduced by the hole. The net tension strength of a composite is expressed by Equation 3-3.

Equation 3-3: Net-Tensile Strength of a Specimen

$$\sigma_{net\ tension} = (W - D) * \sigma_{tensile}$$

Where:

W is the width of the specimen

D is the diameter of the hole

$\sigma_{tensile}$ is the tensile strength of the material

However, in the case of pin bearing, there is also shear stress on the material. For SMC composites, this shear stress further reduces the net tension load capacity by ~15%. (Caprino et al., 2002)

3.8.2.2 Shear Out Failure

Shear strength of the composite is dependent on the edge distance of the hole from the edge. The shear stress of a composite can be expressed by Equation 3-4. The specimen will fail in shear out failure when the shear stress exceeds the shear strength of the material.

Equation 3-4: Shear Stress on a Specimen

$$\sigma_{shear\ stress} = \frac{P}{2 * e * t}$$

Where:

P is the applied Load

e is the distance of the hole from the edge

t is the thickness of the material

3.8.2.3 Bearing Failure

Bearing failure is caused by compressive stress on the material. Bearing stress is proportional to the projected area of the insert as shown in Equation 3-5.

Equation 3-5: Bearing Stress on a Material

$$\sigma_{bearing\ stress} = \frac{P}{A_{projected}}$$

Bearing failure is progressive in nature as shown in Figure 36. It results in matrix cracking, fibre buckling and delamination. It is gradual and observable and therefore the ideal failure mode. Bearing strength of materials is proportional to their compressive strength. Compressive strength of SMCs is hard to predict, however empirical data suggests that bearing strength can be up to 1.7 times the tensile strength.

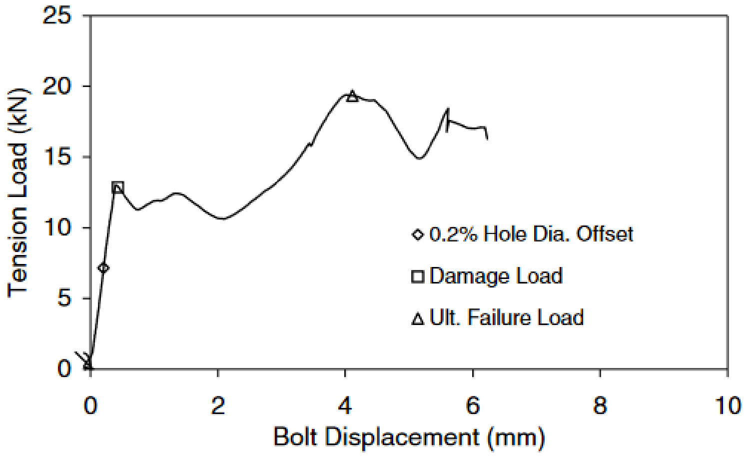


Figure 36: Typical Bearing failure load curve (Turvey and Wang, 2007)

3.8.2.4 Geometric Design Parameters

To achieve bearing failure, there are different geometric design recommendations for continuous composites and SMCs to avoid net tension and shear out failure as shown in Table 10.

Table 10: Recommended Part Width/Diameter and Edge Distance/Diameter Ratios for Bearing Failure in Single Pin Joints

Material	Type	W/D Ratio	E/D Ratio
Metals	-	~2	~1
SMC (Caprino et al., 2002)	-	5	2
UD (ASTM International, 2021)	Quasi-Isotropic	6	3
UD (Collings, 1977)	[0°/90°]	>4	>5
UD (Collings, 1977)	[± 45°]	≥8	>4
UD (Collings, 1977)	[0°/± 45°]	≥4	≥4
UD (Collings, 1977)	[0°/60°]	≥4	≥4

3.8.3 Shapes & Texture Inserts

Inserts can have different shapes and textures to improve their performance. While circular shape is the easiest to manufacture, a hexagonal shape can design to provide high torque resistance.

Different types of textures such as threads, knurls, screw arms, etc can be added to the insert surface to improve their adhesion and load transfer. Figure 37 shows a few commercially available texture options and Figure 38 displays their SMC panels and continuous fibre composites.

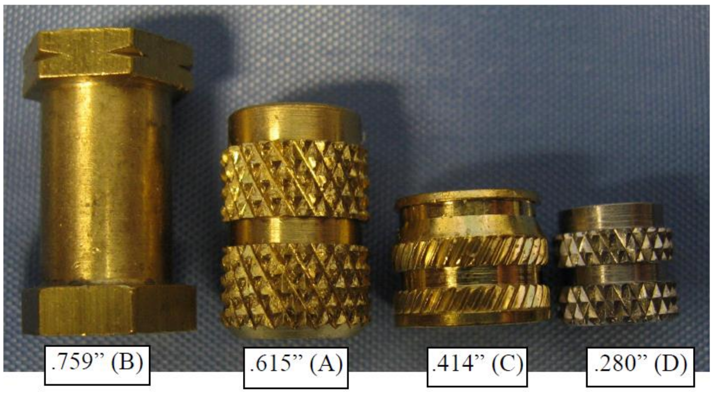


Figure 37: Different insert options (Reller, 2008)

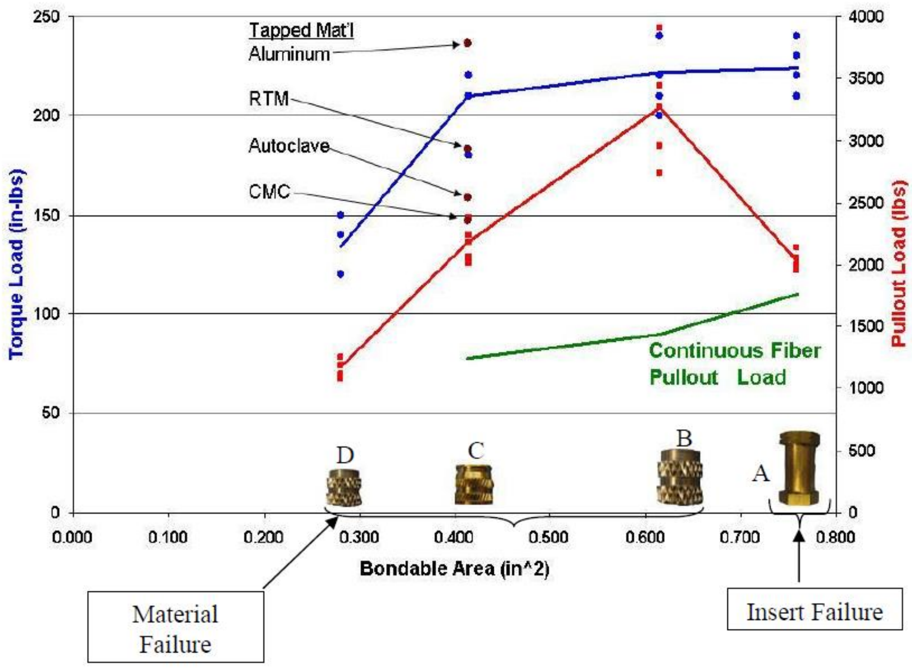


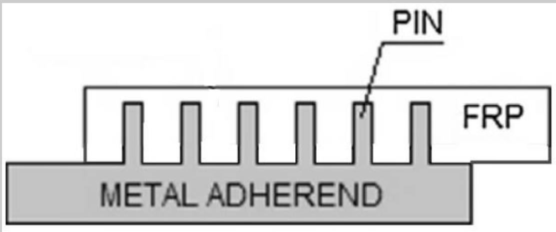
Figure 38: Load capacity of inserts (Reller, 2008)

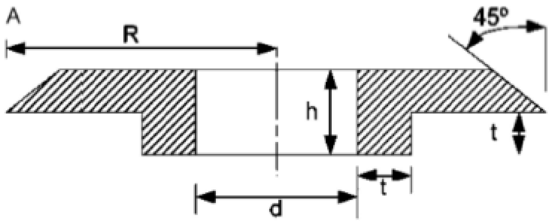
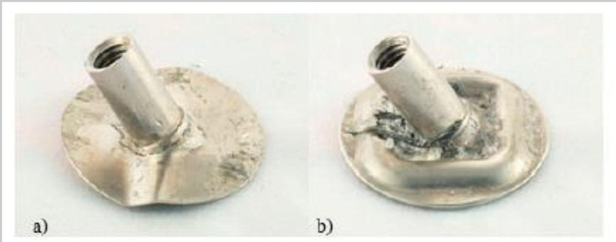
Figure 38 shows that high bondable area and diamond knurls lead to high pull-out strength. They also show that textured inserts perform better in discontinuous fibre composites as opposed to continuous laminates.

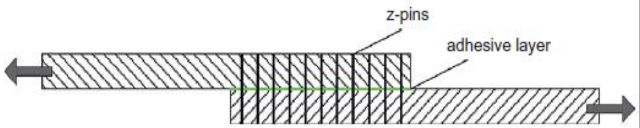
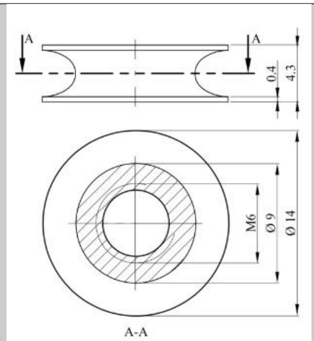
3.8.3.1 Additional Reinforcement options

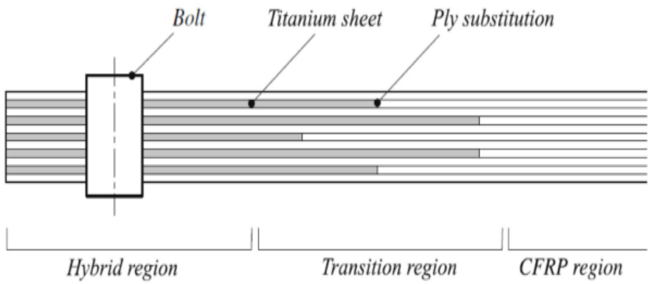
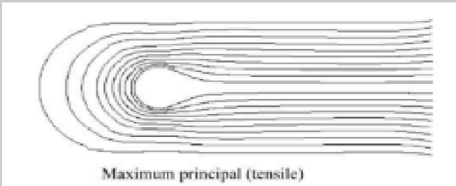
The principles, advantages and disadvantages of additional insert/joint reinforcement options is presented in Table 11.

Table 11: Reinforcement Options for Composite Joining

Name	Picture	Principle	Advantages	Disadvantages
Pin Joining	 **Figure 39 : Pin Joining of metal inserts in composites** (Graham et al., 2014)	Can be manufactured using cold metal transfer or additive manufacturing	Increases joint mechanical strength. Leads to progressive failure	Expensive, time consuming

Name	Picture	Principle	Advantages	Disadvantages
Tapered End	 **Figure 40: Optimised tapered ends for inserts** (Camanho et al., 2005)	Provide additional load path and tapering prevents sharp changes in stress.	Increases Joint strength by 21%. (Mirabella and Galea, 1997)	Added Mass. Needs to be co-moulded
Bead Pattern	 **Figure 41: Deformation of an insert with and without a bead pattern** (Gebhardt and Fleischer, 2014)	Higher moment of inertial leads to higher stiffness which in result leads to higher bending strength	It had no impact on tensile/pull out strength and led to a 38% increase in bending strength as opposed to a standard embedded insert	Added mass. Adding manufacturing cost from welding.

Name	Picture	Principle	Advantages	Disadvantages
Z-pins/ Stitching	 **Figure 42: Z-pins reinforcement in bonded joints** (Löbel et al., 2013)	Using rods made of titanium or composites to reinforce joints to increase toughness and ultimate strength.	Act as crack arrestors. Change failure mode from delamination to fibre fracture. Increase strength and stiffness. Increase in bearing strength by 7.4-9.8%.	Z-pins can cause local damage in laminates and lead to fibre rich regions. Complex manufacturing. Low Technology Readiness Level
Undercut	 **Figure 43: Through Insert design with an undercut** (Troschitz, Kupfer and Gude, 2019)	Material inside the undercut acts a barrier during pull-out test.	Increases the pull-out strength proportionally to the undercut volume.	Added mass. Non-uniform orientation of fibres can lead to variable pull in and push out strength.

Name	Picture	Principle	Advantages	Disadvantages
Titanium Foil	 **Figure 44: Hybrid Titanium sheet reinforcement** (Camanho et al., 2009)	Hybrid composite utilising isotropic properties of titanium in thin sheets to reduce stress concentrations around the joint.	Tensile Strength increase up 158%. (Camanho et al., 2009)	Added mass. manufacturing complexity. High material cost
Fibre Steering	 **Figure 45: Fibre Steering around a hole** (Li, Kelly and Crosky, 2002)	Continuous fibres matching load direction around holes with no discontinuity	Bearing strength increase by up to 36%. (Li, Kelly and Crosky, 2002)	High Manufacturing Complexity. Added weight of roving bundles

Name	Picture	Principle	Advantages	Disadvantages
Holes	 **Figure 46: Bighead Insert with holes** (BigHead, 2017)	Higher Interlocking with fibres and resin going through the holes. Increased in-plane surface area of the insert	Better load transfer. Lower Bearing stress due to high projected area	Fibre bridging may prevent effective interlocking
Quasi Linear Inserts	 **Figure 47: Quasi-Linear Insert** (Muth et al., 2018)	Spread the load uniformly using three bolts instead of one.	Fibre friendly load introduction and lower stress concentrations.	Added mass, complexity, and manufacturing/assembly cost

3.8.4 Adhesion

One of the primary modes of failure observed in embedded inserts is the separation between the metal insert and the composite. Therefore, the strength of the final component can be increased by increasing the adhesion strength between the metal insert and the composite. The adhesive strength is a function of a variety of factors including the type of adhesive, surface area, surface energy of substrate and adhesive, etc.

3.8.4.1 Adhesive

The resin of the SMC also acts as the adhesive in hybrid systems. The goal of the adhesive to not only provide strength but provide fibre friendly load transfer between the metal and fibres.

3.8.4.2 Surface Treatment

Surface energy of a metal substrate can be increased using surface treatments. Surface treatments also ensure reproducibility of the product and minimise the variability of the mechanical properties. A detailed overview of surface treatments for inserts and their impact is provided in Appendix C.

3.8.5 Material

Material choice of the insert can have a significant impact on load transfer and failure mode. Numerical analysis has suggested that more compliant materials (Brass, Aluminium) and thinner inserts are ideal as stiff inserts may cause premature damage to composite (Camanho and Matthews, 2000). However, this analysis was based on embedded inserts.

Experimental data for through inserts showed marginal increase in joint strength from aluminium to steel insert (Nilsson, 1989). As composites have low thermal expansion, a metal with a low thermal expansion coefficient is desirable.

3.8.6 Corrosion

There is a risk of galvanic corrosion when using carbon fibre and metals. Titanium and stainless steels have low galvanic potential and therefore low risk for galvanic corrosion. There are multiple options for coatings on aluminium inserts to prevent corrosion, however they add a process and increase cost.

3.8.7 Pre-Load

Pre-load is the initial compressive load applied on a joint. While bolt torque is measured when defining pre-load, the true variable at play is contact pressure. Higher torque and lower washer size increases contact pressure (Khashaba et al., 2006).

A lot of studies using all fibres and practically all matrices have shown benefits of preload. All observed increasing torque increasing bearing strength until a limit load and then the bearing strength plateaued. The increase has ranged anywhere from 14%-100% depending on material, geometry, stacking sequence, etc (Park, 2001)(Choi et al., 2018) (Galińska, 2020).

The bearing strength increases because of the friction between the laminate and the washer. Pre-load also causes a reduction in stress concentration around hole-edge (Choi et al., 2018). Lastly pre-load can also reduce impact of aging on degradation of mechanical properties.

On the other hand, a high pre-load can damage the composite in through thickness direction (Thoppul, Finegan and Gibson, 2009). Lastly, pre-load on composites reduces over time and this results in reduction of bearing strength. Therefore, to get reliable strengths, the creep profile of a material should be thoroughly investigated, or a minimum strength with no pre-load should be used.

3.8.8 Viscoelastic effects /Creep

Polymers exhibit creep and relaxation over time under load. These effects are increased at higher temperatures and moisture (Thoppul, Finegan and Gibson, 2009). As preload increases mechanical properties, through thickness creep can reduce preload over time and reduce the benefits gained by pre-loading. The relaxation is dependent upon materials, fibre orientation, initial pre-load, time, temperature, humidity, etc.

Examples:

- 1.25-4.25% relaxation over 30 hours in CF-Epoxy laminates. Higher pre-load lead to lower relaxation (Thoppul, Gibson and Ibrahim, 2008)
- CF-SMC 50% loss of pre-load in first 100 hours and then gradient significantly reduced. (Finck et al., 2019)

3.8.9 Aging

Aging is like creep; however, it can also occur when the part is not under load. It can be caused by moisture absorption, fibre degradation, matrix hydrolysis, etc (Galińska, 2020).

There are three key drivers of aging, i.e., temperature, humidity, and salt.

Example: In Glass fibre-polyester pultruded samples, single bolt joint strength was reduced by more than 50% when aged at 60 ºC for 6.5 weeks and reduced by 60% when immersed in 60 ºC water for 6.5 weeks. The effects of temperature were more significant than water. (Turvey and Wang, 2007).

Similar reduction has also been observed in Carbon Fibre/ Epoxy composites, so the effect is not limited to a particular resin or fibre.

Salt water exposure can result in reduction in joint strength up to 90% within 24 hours in GF/Epoxy composites. However, preloaded samples showed no reduction in strength (Ozen and Sayman, 2011).

3.9 Knowledge Gap

SMC joints need to be wider than metal joints to avoid net-tension failure. While, SMC is poor in tensile loading, it is excellent in bearing. On the other hand, UD is poor in bearing and excellent in tension. Therefore, this unique combination allows the opportunity to strategically utilise their best properties in bolted connections and it hasn't been investigated yet. No one has attempted to change the failure mode of a SMC specimens using UD tapes.

Metal inserts allow for dispersion of stress concentration and easy attachment for bushes. Novel insert shape designs provide the opportunity to introduce stress in favorable conditions in hybrid composites.

3.10 Goals of a Hybrid Composite

The goals of a hybrid composite are:

- UD fibres in the right location with right orientation and minimum waviness
- Low void content
- Good adhesion between UD and SMC
- Low residual stresses from shrinkage and thermal cycling
- Low and uniform shrinkage
- Predictable mechanical properties

3.11 Goals of an Insert

An insert should be:

- Able to transfer loads from the bolt to the composite structure
- Lightweight
- Corrosion resistant
- Cost effective
- Able to reduce the stress concentration on the composite

4 METHOD

The Method section is documented in the three stages of Design, Manufacturing and Testing.

4.1 Design

The Design section outlines the steps that lead to the predicted mechanical properties of the specimens. While the I-beam was chosen to replicate the complex moulding of a suspension arm, the flanges were chopped off for mechanical testing as shown in Figure 48.

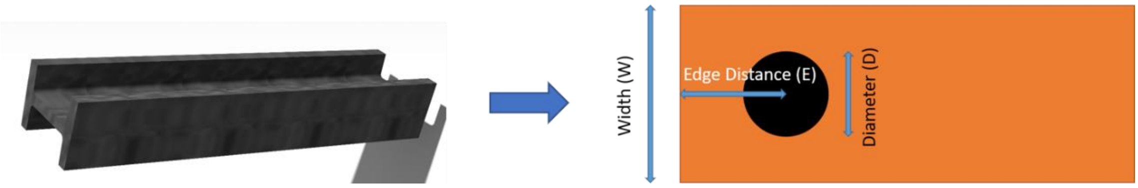


Figure 48: I-Beam to Test Specimen

Figure 49 shows the cross-section of the I-beam being moulded. After chopping off the flanges, the specimen length, width, and thickness were assumed to be 200 mm, 25 mm, and 5 mm respectively.

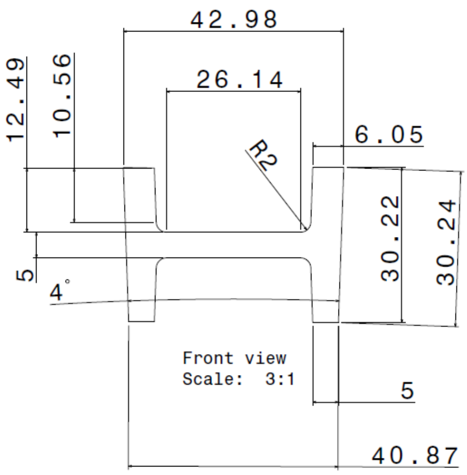


Figure 49: Tapered I-Beam Cross-section Drawing

4.1.1 Material Properties

The material properties of the SMC and UD being moulded are shown in Table 12. The datasheets of both the materials can be found in Appendix B.

Table 12: Material Properties of the Composites

Property	Carbon Fibre SMC	Carbon Fibre UD (Hexply M77)
Resin	Vinyl Ester	Epoxy
Tow	12K	-
Fibre Weight (%)	50	62
Fibre Volume (%)	37	49.4
Tensile Modulus (GPa)	25.3	127
Tensile Strength (MPa)	108	1980
Density (g/cm^3)	1.4	1.2
Elongation (%)	0.4	1.6
Curing time at Temp (°C)	35 s/mm at 135-145	7 min at 120 5 min at 130 3 min at 140
Cost (£/kg)	19	60

4.1.2 Design Loads

As the volume and the placement of UD is a design variable, the maximum failure loads of a pure SMC specimen are initially considered. The failure loads in Table 13 are calculated using the equations in section 3.8.2.

Table 13: Predicted Pin-Bearing Failure Loads of SMC Specimen

Net Tension Failure Load (N)	Bearing Failure Load (N)	Shear Out Failure Load (N)
6885	9180	29160

The specimen is predicted to fail in Net Tension, as it is the lowest failure mode. Therefore, the Net Tensile strength of the specimen is increased using hybridization and the bearing strength of the specimen is increased using inserts.

4.1.3 Hybrid Structural Design

A UD-SMC-UD sandwich design was chosen based on literature as shown in section 3.5.2. Additionally, placing UD strips on top and bottom allows partial curing of the UD which prevents UD flow.[5] Lastly, UD on top and bottom would also increase the bending stiffness of the beam.

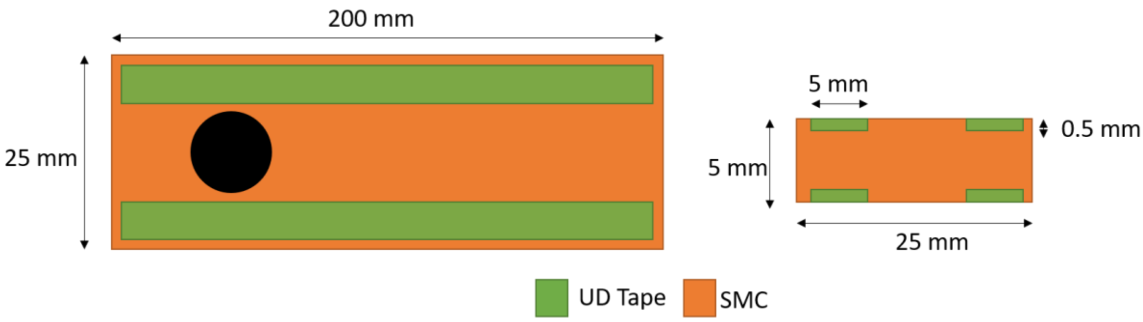


Figure 50: Hybrid Specimen Layout

The layout of the UD tapes and the SMC results in 8% volume of UD as displayed in Figure 50. UDs have a high tensile strength and stiffness, whereas SMC is notch insensitive and has a high bearing strength. Therefore, the SMC translates the bearing load from the pin to the UD using the adhesion. Table 14 outlines the failure loads of hybrid specimens.

[5] Cranfield holds a patent on partially curing UD in a hybrid composite structure.

Table 14: Predicted Failure Pin-Bearing Failure Loads of UD-SMC Hybrid Specimens

RoHM Net-Tension Failure Load (N)	Bearing Failure Load (N)	Iso-strain Failure Load (N)	Shear Out Failure Load (N)
22797	9180	10217	29160

The bearing failure loads and the shear out loads are the same as those stresses are still applied on the same cross-section of SMC. The RoHM Net-Tension assumes that SMC and UD will fail at the same time and adds the max load capacity of both the SMC and UD. The Iso-strain failure assumes equal strain in UD and SMC. As the elongation at failure of SMC is 0.4%, it is predicted that the SMC will fail before the UD which has an elongation to failure of 1.6% as shown in Figure 51.

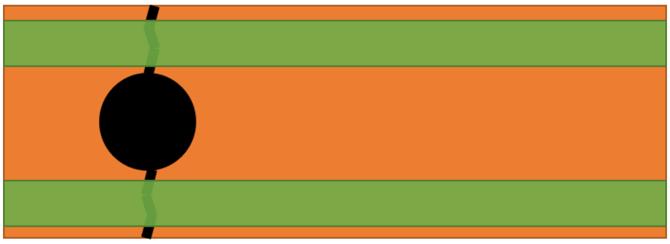


Figure 51: Net Tension Failure of Hybrid Specimen

4.1.4 Insert Design

The insert design is divided into insert material and insert shape.

4.1.4.1 Insert Material

Table 15 displays the mechanical, thermal, electrochemical, and cost properties of different potential materials for the inserts.

Table 15: Mechanical, thermal, electrochemical, and cost properties of material options (Granta design, 2020)

Material	Ultimate Tensile Strength (MPa)	Young's Modulus (GPa)	Density (kg/m^3)	Thermal Expansion Coefficient (μ/ °C)	Galvanic Potential (V)	Cost (£/kg)
Aluminium 6082	344	74	2700	23	-0.7	2
Aluminium 7075	580	76	2800	23.5	-0.7	4
Stainless Steel 304	500	205	8000	17	-0.1	2.5
Stainless Steel 316	600	205	8000	15	-0.14	3.2
High Carbon Steel 1095	720	215	7850	12.8	-0.47	0.67
Titanium (Ti-6Al-4V)	980	119	4430	8.9	-0.08	19.1
Brass	200	99	8400	18.5	-0.21	5.3

A simplified trade off table for material selection is showed in Table 16. As the primary composite material is Carbon Fibre SMC, it is critical that the insert shouldn't be prone to galvanic corrosion.[6] Secondly, cost is always a key factor for parts designed for mass-production. Lastly, the ultimate tensile strength of the material is important it determines the thickness of the insert.

Table 16: Material Selection Trade-off Table

Material	Galvanic Corrosion	Cost	Ultimate Tensile Strength
Aluminium 6082	x	✓	✓
Aluminium 7075	x	✓	✓
Stainless Steel 304	✓	✓	✓
Stainless Steel 316	✓	✓	✓
High Carbon Steel 1095	x	✓	✓
Titanium (Ti-6Al-4V)	✓	x	✓
Brass	✓	✓	x

Therefore, the material chosen for the insert is SS316. Not only does it fulfil the selection criteria in Table 16, but it also has low thermal expansion, is easy to machine and has low lead times. SS316 was chosen over SS304 because of its superior mechanical properties and relatively minor cost difference.

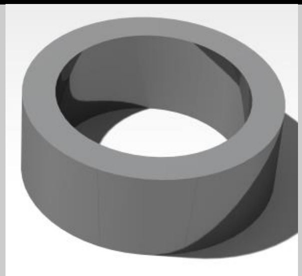
4.1.4.2 Insert Shape

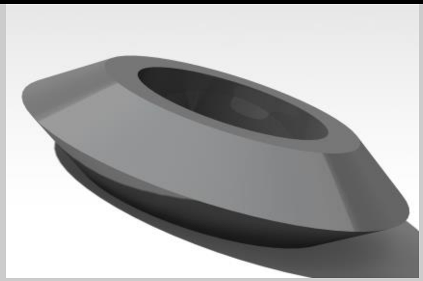
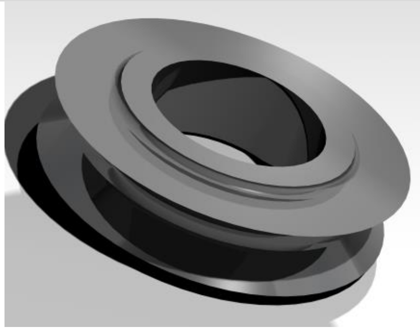
Inserts reduce stress concentrations and increase the projected area of load introduction and therefore reduce the bearing stress on the composite material. On the other hand, larger inserts decrease the W/D ratio of the specimen and in turn reduce the net tensile strength of the specimen as elaborated in section

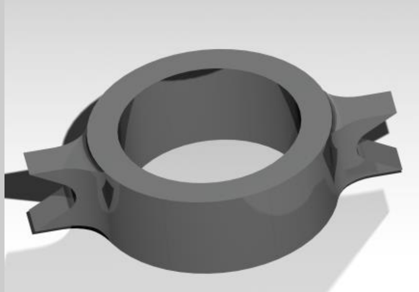
[6] While protective coatings can be applied to prevent it, their additional cost, processing, and complexity was not suitable for this project.

3.8.2.4. Therefore, depending on the composite material and expected failure mode, the thickness of the inserts can be varied. To ensure that the insert was not the weak point in the specimens, an insert thickness of 1.75 mm was chosen. This thickness ensured the insert was manufacturable, light, would not buckle during moulding and would still significantly ease the stress concentration. All variations of the insert have a base cylindrical thickness of 1.75 mm and are presented in Table 17. All inserts were sanded with a rough 80 grit sandpaper and cleaned with solvents before moulding.

Table 17: Insert Properties

Insert	Motivation	Projected Area (mm^2)	Bearing stress at 10 kN load (MPa)	Mass (g)	Cost (£)
 Figure 52: Cylinder	A cylinder is the simplest insert shape in use. It increases the projected area and in turn decreases the bearing stress on the material. It is easy to manufacture and can be cut from a tube.	67.5	148	2.42	2.68
 Figure 53: Knurled Cylinder	Knurling is a popular gripping technique used in the plastics industry. A diamond knurl with a pitch of 1.6 mm is chose because it is the deepest standard sized knurl on the market. The diamond grooves allow fibre-interlocking and efficient load transfer	67.5	148	2.01	7.93

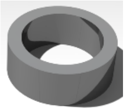
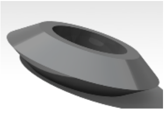
Insert	Motivation	Projected Area (mm^2)	Bearing stress at 10 kN load (MPa)	Mass (g)	Cost (£)
 Figure 54: Flying Saucer	The Flying Saucer increases the bearing strength of the specimen by increasing the projected area in the middle of the specimen.	84	119	5.94	3.4
 Figure 55: Yoyo	The Yoyo increases the bearing strength of the specimen by increasing the projected area near the location of the UDs at the top and bottom of the specimen.	84	119	5.57	5.33

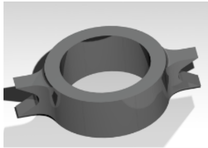
Insert	Motivation	Projected Area (mm^2)	Bearing stress at 10 kN load (MPa)	Mass (g)	Cost (£)
 Figure 56: 2d Yoyo	As bearing stress is dependent on the projected area, a 2d Yoyo is 2d projection of Yoyo insert with lower weight.	84	119	2.8	20.85
 Figure 57: Butterfly	The butterfly insert increases the projected area of the insert in line with the cylinder. It does not further reduce the W/D ratio of the specimen.	91.5	109	3.2	21.82

4.1.5 Design of Experiments

Table 18 outlines the nine experiments that are conducted with their specific composite material and insert. Three repetitions of each specimen were moulded totalling 27 test specimens.

Table 18: Design of Experiments

Specimen Type	Composite	Insert
1	SMC	None
2	SMC	 Cylinder
3	SMC-UD Hybrid	None
4	SMC-UD Hybrid	 Cylinder
5	SMC-UD Hybrid	 Knurled Cylinder
6	SMC-UD Hybrid	 Flying Saucer
7	SMC-UD Hybrid	 Yoyo

8	SMC-UD Hybrid	 2d Yoyo
9	SMC-UD Hybrid	 Butterfly

4.1.6 Predicted Strength and Modulus

Figure 58 displays the predicted strength of the composite structure using different methods. The bearing load prediction is derived from an empirical ratio of bearing strength to tensile strength of 1.7. The RoHM load assumes that all UDs and SMC will fail at the same point. The Iso-strain load assumes that the specimen is under equal strain throughout its cross-section and will fail when the strain reaches 0.4% (max elongation of SMC).

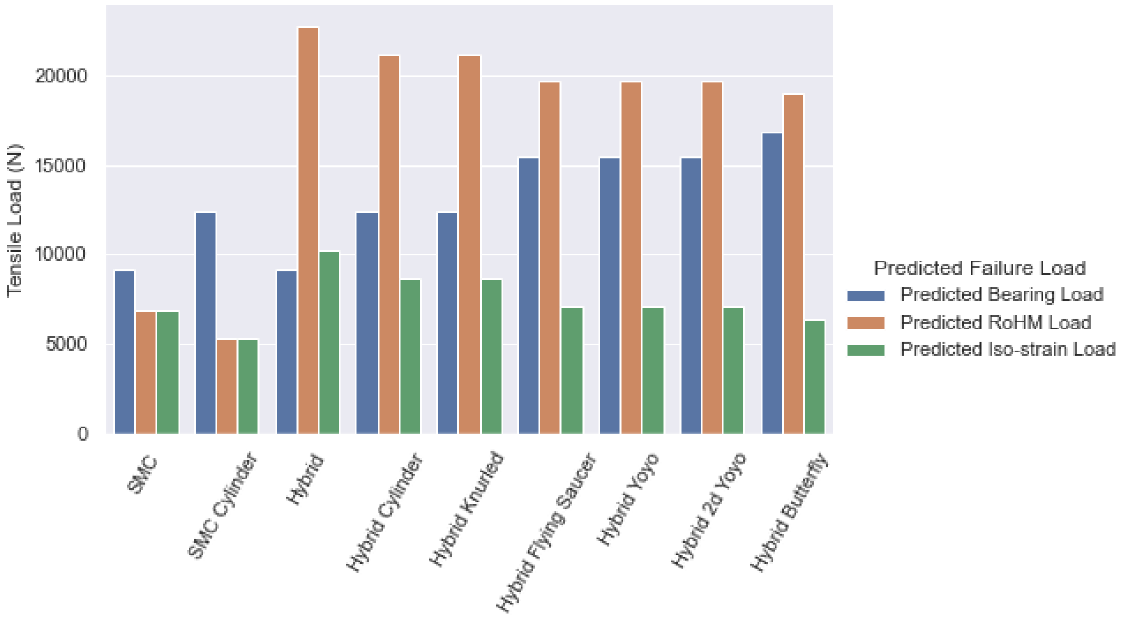


Figure 58: Predicted Failure Loads of all Configurations

Figure 59 displays the predicted modulus of all experiments calculated using RoHM as described in section 3.6.1.

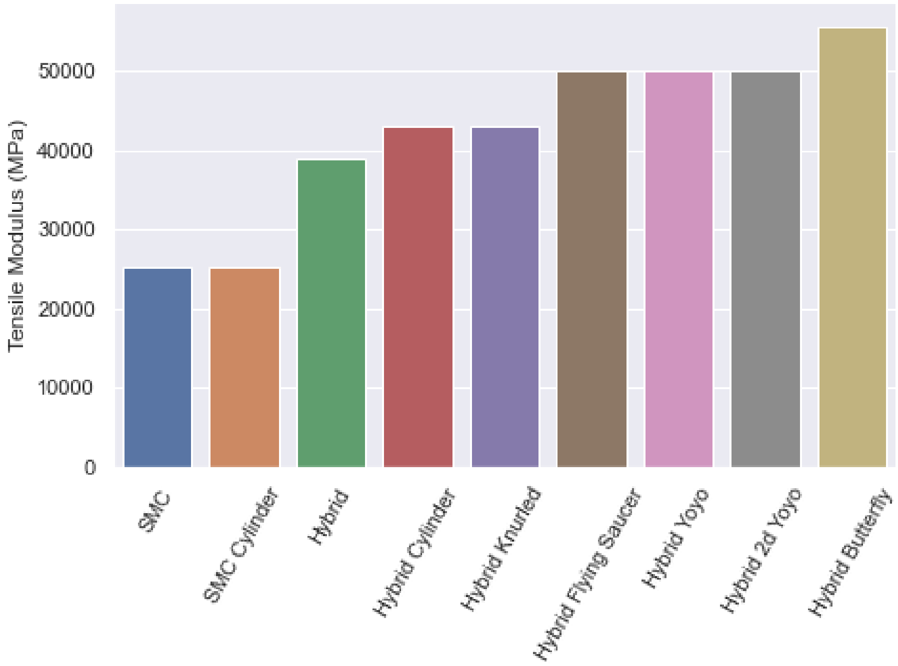


Figure 59: Predicted Modulus based on Rule of Hybrid Mixtures

4.1.7 Summary of Hypothesis's being tested

- Adding UD tapes around the hole increase the failure strength of a SMC composite.
- Adding UD tapes to a pin loaded SMC specimen changes its failure mode.
- A cylindrical insert increases the strength of a hybrid specimen.
- Increasing the projected area of an insert increase the failure strength of a hybrid specimen.
- Location of load introduction has an impact on failure load of hybrid composite specimen.
- A 2d insert with the same projected shape and area as a 3d symmetric insert have same performance in hybrid composites.
- Increasing the projected area in plane with the cylinder increase the bearing strength of the composite.

4.2 Manufacturing

The manufacturing of the specimens was done using a compression moulding machine that can both heat up the mould and apply high pressure as shown in Figure 60.

Figure 60: Compression Moulding Press

The male and female moulding tools used to make the I-Beams are shown in Figure 61.

Figure 61: Male and Female Moulding Tool

4.2.1 Charge Design

The charge design was based on few rules adopted from industrial best practices:

- Charge weight is final weight +5%
- Pyramid stacking sequence
- No complex charge shapes
- No small cuts of SMC

There is a variation in the SMC density, which meant that the charge weights varied by a small amount in different mouldings. Due to the high volume of the flanges compared to the web-section in the I-beam, only low flow charge design was manufacturable.

4.2.1.1 Low Flow Charge Design

A hole was punched in the SMC charge and placed in the mould as shown in Figure 62. Using a punched hole avoided the formation of any knit lines or weld lines.

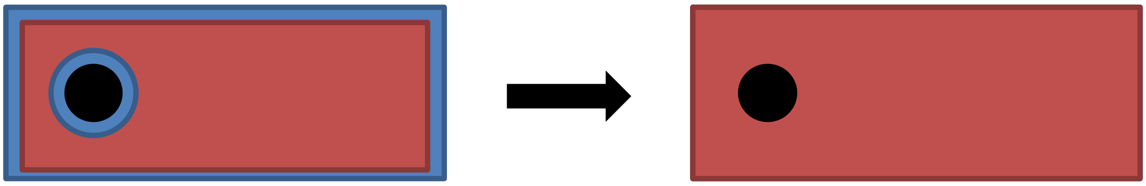


Figure 62: Charge Design with a Punched Hole

4.2.2 SMC Moulding

Figure 63 shows an illustration of the SMC moulding process. The charge was loaded into the mould at 80ºC, compressed at 100 bars and then heated all the way to 140. It was held at 140 for 5 mins before cooling down. This cycle ensured complete curing of the SMC.

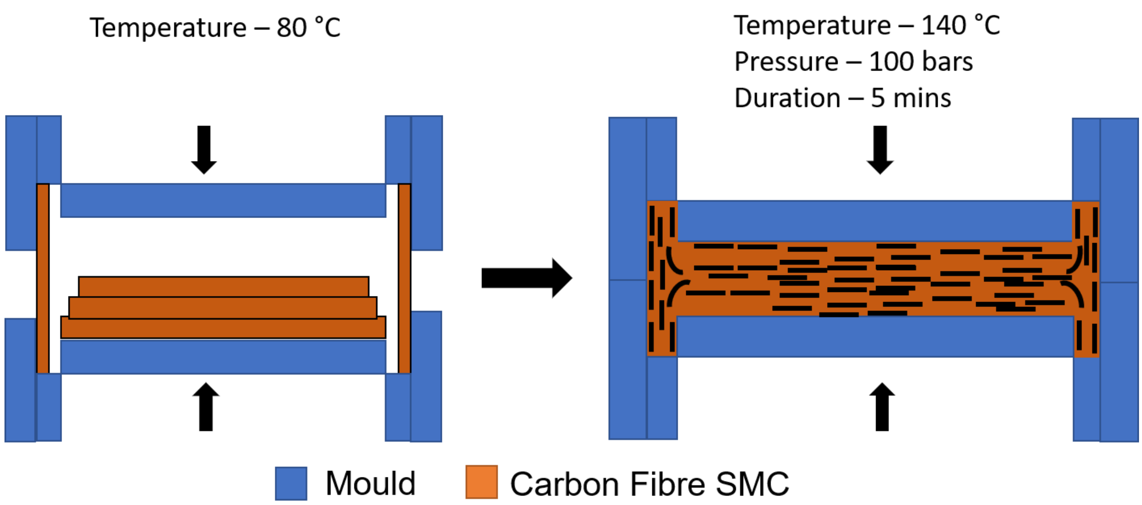


Figure 63: SMC I-Beam Moulding Process

Figure 64 shows one of the moulded SMC specimens. Some cosmetic marks from the moulding process are visible on the specimen.

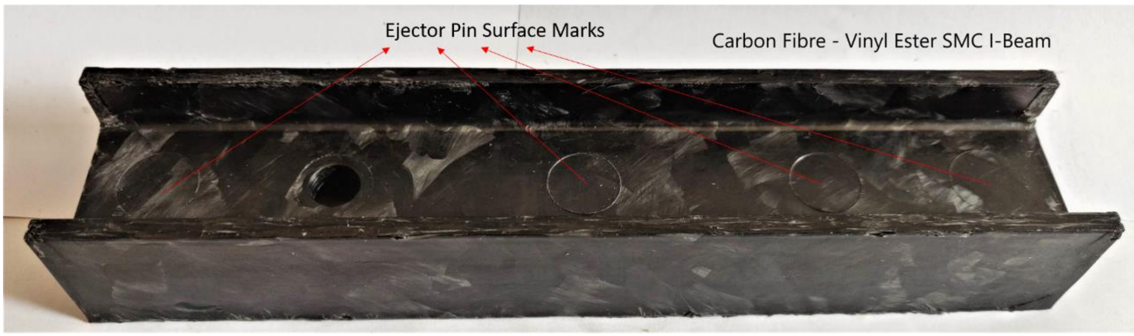


Figure 64: SMC Moulded Specimen

4.2.3 Hybrid I – Beam Moulding

The moulding process of the hybrid I-beam is illustrated in Figure 65. A silicon elastomeric tool was used for partial curing of the UD to prevent UD flow. It was observed that wiping the tool with a solvent prior to moulding increased the surface energy of the tool and ensured UD adhesion to the tool.

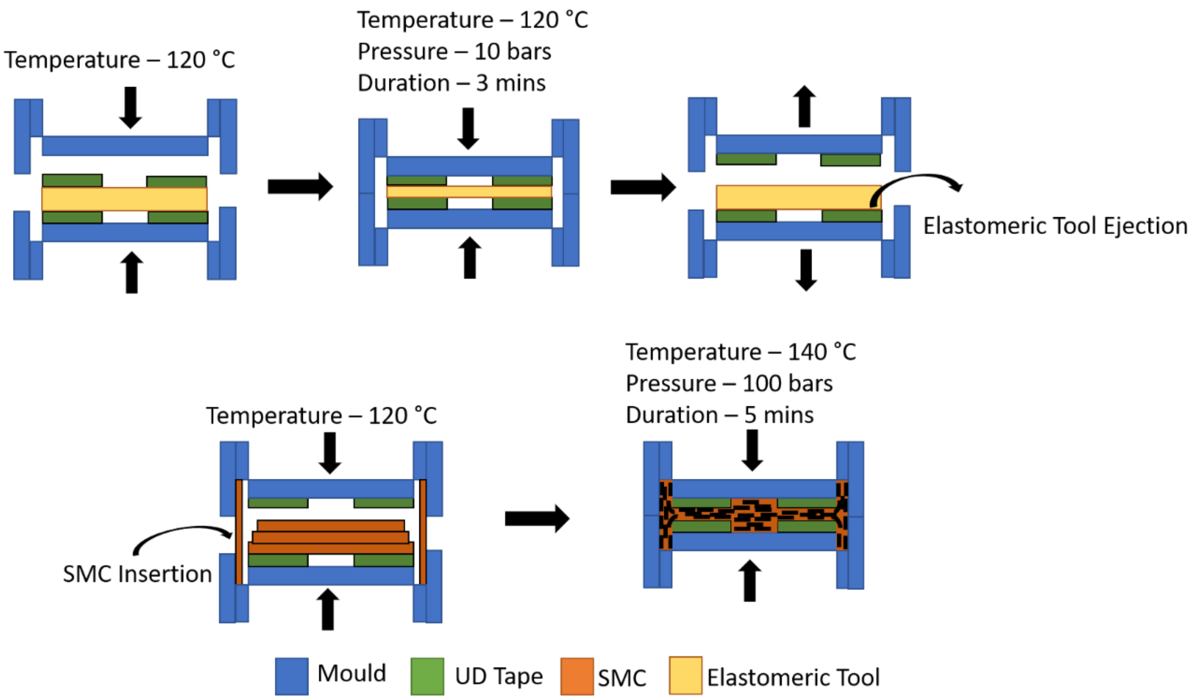


Figure 65: Hybrid I-Beam Moulding Process

4.2.3.1 Elastomer Designs

The Elastomeric tool went through a couple of iterations as shown in Figure 66. These advancements ensured higher confinement of the UD during partial curing and led to more consistent mouldings.

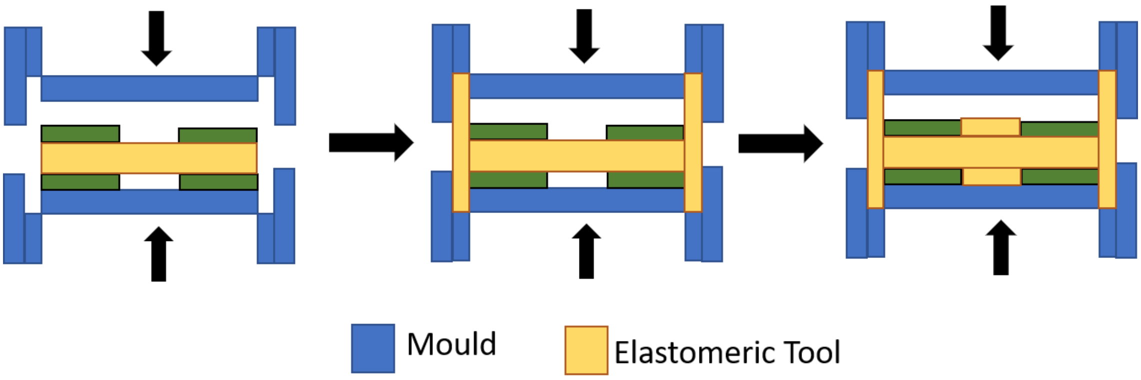


Figure 66: Elastomeric Tool Iterations

An example of the resultant hybrid moulding is presented in Figure 67.

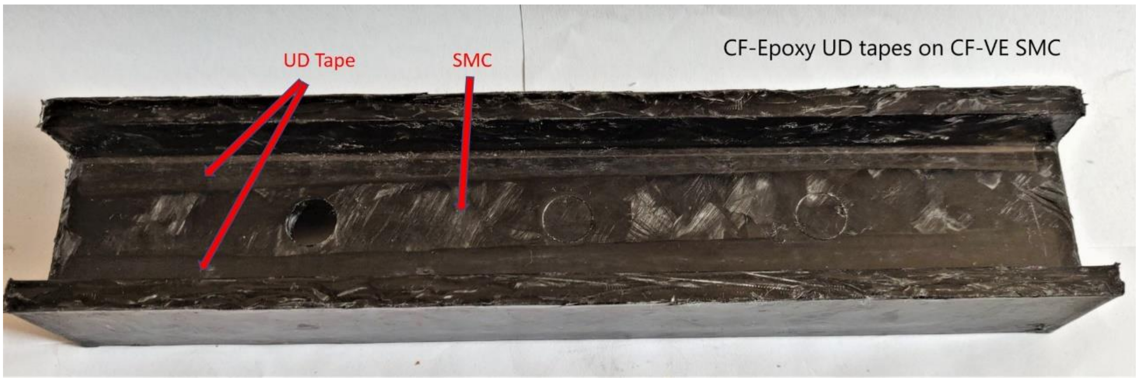


Figure 67: Hybrid I-Beam Moulding

4.3 Testing

4.3.1 Sample Preparation

To perform pin-bearing test based on the ASTM 5961 standard, the flanges of the I-beam were chopped off leading to a flat specimen. The bottom quarter of the specimen was sanded, and steel tabs were bonded using epoxy. The resulting test specimens along with their respecting inserts are displayed in Figure 68

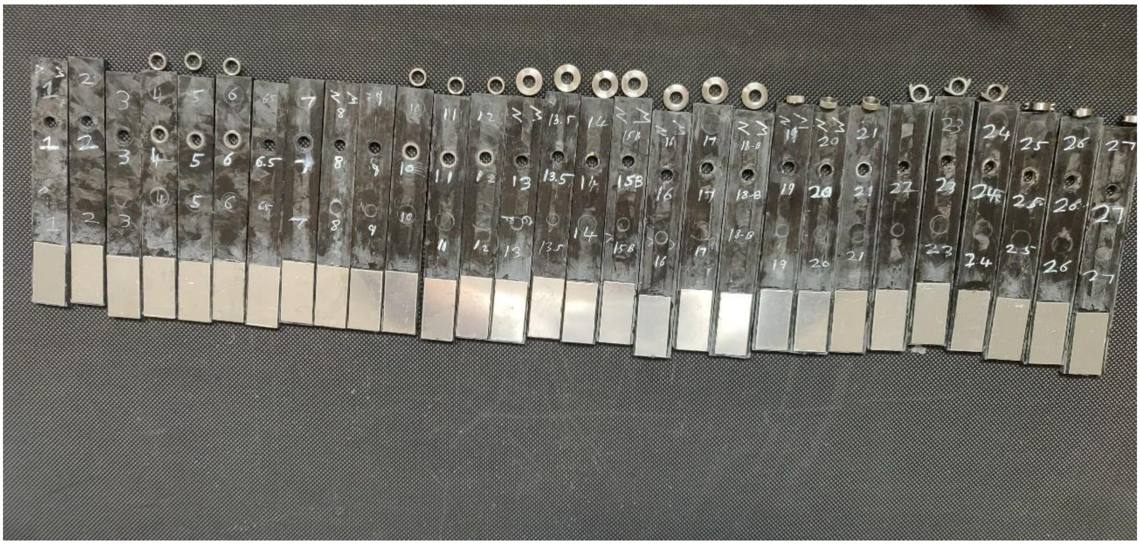


Figure 68: Specimens with their respective inserts

4.3.2 Machine Set up

The pin-bearing test set up of the machine is displayed in Figure 69. A laser extensometer was used to measure the displacement of the specimen under load. As per the ASTM 5961 standard, the specimen was torqued up to 5 Nm. A higher bearing strength and stiffness is expected with higher torques, but higher torques add an unpredictable variable.

Figure 69: Pin-Bearing Test Set Up

5 RESULTS

This section describes the results of the moulding and the testing of the specimens. The chapter is divided in qualitative and quantitative results.

5.1 Qualitative Results

5.1.1 Moulding Results

The moulding process was iterative, and the results generally got better with experience. Due to the mould release agent in the SMC, the cylindrical inserts did not stick inside the specimen and were held in place with friction. All the other inserts were mechanically locked in the material.

Figure 70 shows an example of gel tearing on the surface of SMC Specimens. This phenomenon occurred when the SMC could dwell in mould before compression moulding. Even at temperatures as low as 70ºC, the outer layers of the SMC started gelling. This was mitigated by eliminating dwell time.

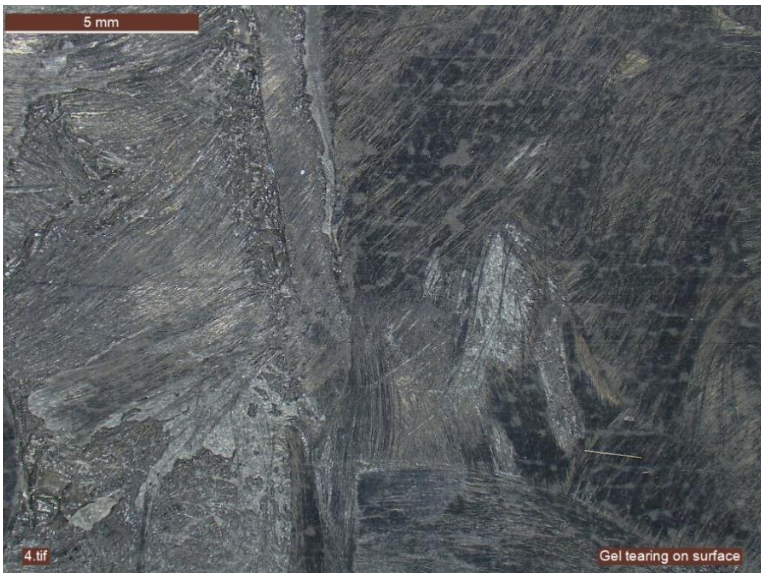


Figure 70: Gel Tearing on Surface

After chopping off the flanges, voids were observed in early specimens as shown in Figure 71. The number of visible voids decreased with higher charge mass and higher pressure.

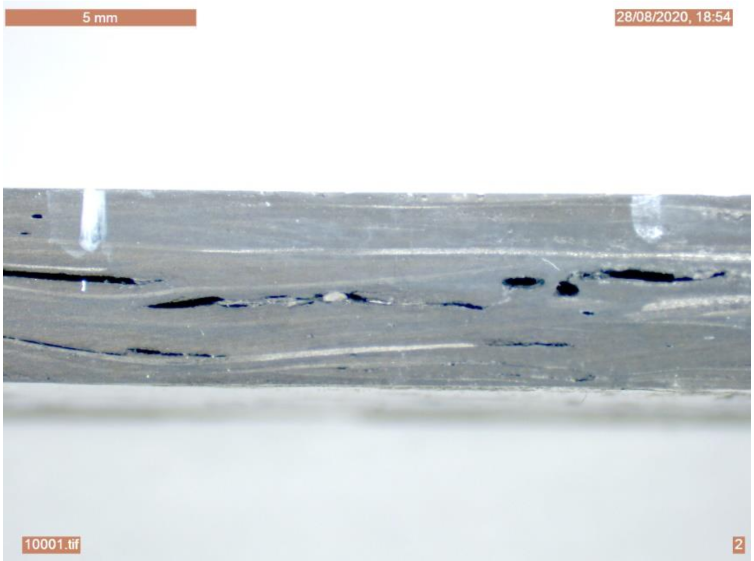


Figure 71: Voids in Specimens

In some specimens, UD-SMC delamination was observed as shown in Figure 72. These were a couple of mm long and may have occurred due to the use of silicon elastomeric tool.

Figure 72: UD-SMC Delamination

The minimum force that can applied consistently by the press is 10kN. This led to a pressure of 50 bars on the UD during the partial curing cycle and in turn led to resin bleed from the UD. This resin bleed caused dry spots on the surface of the UD as shown in Figure 73.

Figure 73: Dry Region from Resin Squeeze Out

A resin-rich region was observed at the interface of UD and SMC in a few specimens as shown in Figure 74. This occurred because the UD tape formed a step over the SMC.

Figure 74: Resin-rich Region at the UD-SMC Interface

High fibre waviness was observed at the cross-section near the insert in few specimens as shown in Figure 75. This was likely due to the high flow of SMC in the region. Waviness of fibres is detrimental to joint strength, as curved fibres cannot translate tensile loads efficiently.

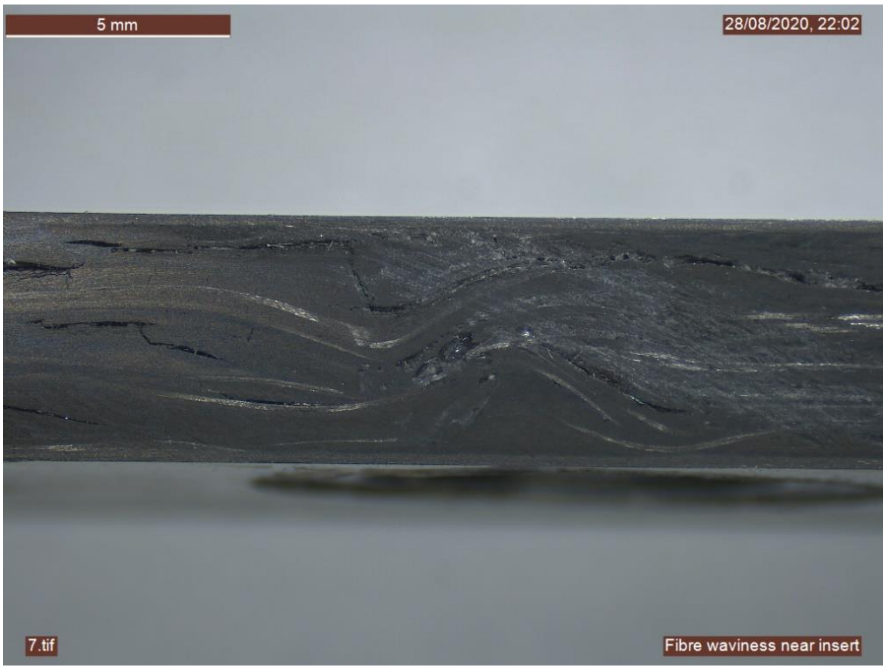


Figure 75: Fibre Waviness near Insert

Figure 76 and Figure 77 show the successful flow of fibres into the Flying Saucer and Yoyo inserts validating the charge pattern.

Figure 76: Fibre Flow around Flying Saucer Insert

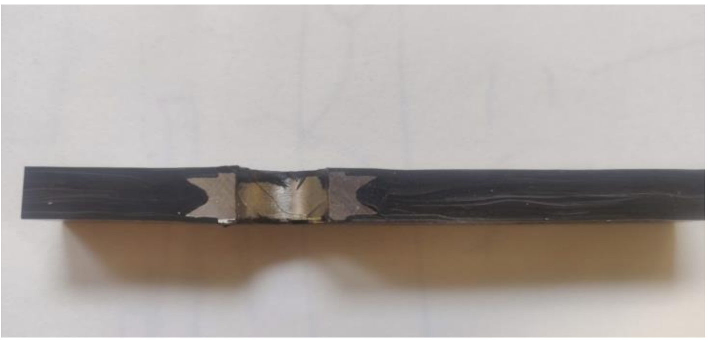


Figure 77: Fibre Flow around Yoyo Insert

5.1.2 Test Results

Almost all specimens displayed some degree of asymmetric failure on one side as shown in Figure 78. This was likely due to the local variability of modulus in SMC.

Figure 78: Asymmetric Failure of Specimens

5.2 Quantitative Results

5.2.1 Geometric Properties

The geometric properties of the specimens are detailed in Table 19. The mould closed with a gap of 5 mm, however the SMC sprung to higher thickness after moulding. This spring back was proportional to the amount of the charge placed in the mould.

The flat specimens were made by chopping off the flanges. This involved sawing the flanges and filing the edges which introduced a variation in the specimen width.

Table 19: Specimen Geometric Properties

	Thickness (mm)	Width (mm)
Mean	5.45	29.43
Standard Deviation	0.37	1.56
Min	4.88	26.32
Max	6.01	32

5.2.2 Mechanical Properties

The failure mode of all specimens was either net-tension failure or combination of bearing and net-tension failure. The failure load of all specimens was multiplied by a scaling factor to account for the differences in the cross-section area. Figure 79 displays the resultant bar graph. The hybrid specimen with the knurled insert performed the best followed by the Yoyo, 2d Yoyo and the Butterfly Inserts.

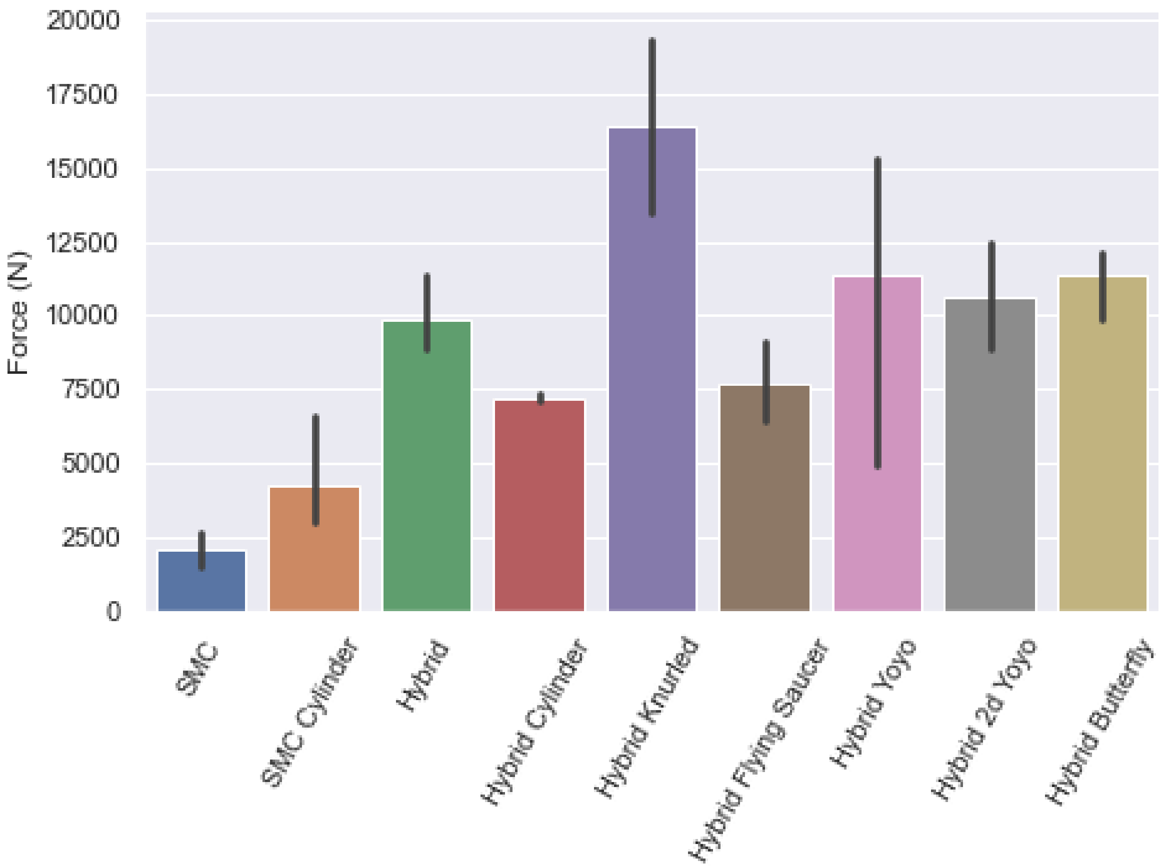


Figure 79: Failure Loads Proportional to the Cross-Section Area of the Specimens

Figure 80 shows the Load-Displacement graph of the hybrid specimens with knurled inserts. The second specimen had two partial failures instead of a single complete failure. This was observed in a lot of specimens and is attributed to modulus variability of the SMC leading to higher local loadings on the UD tapes on one side.

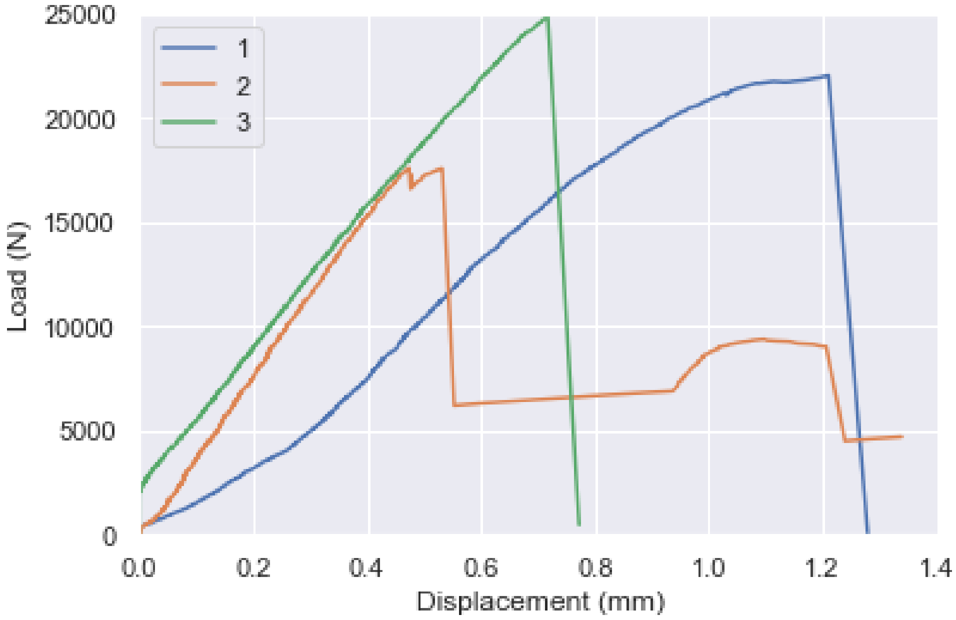


Figure 80: Hybrid Specimen with Knurled Insert

The butterfly inserts displayed a unique progressive bearing failure where the joint retained significant load capacity after max load as shown in Figure 81.

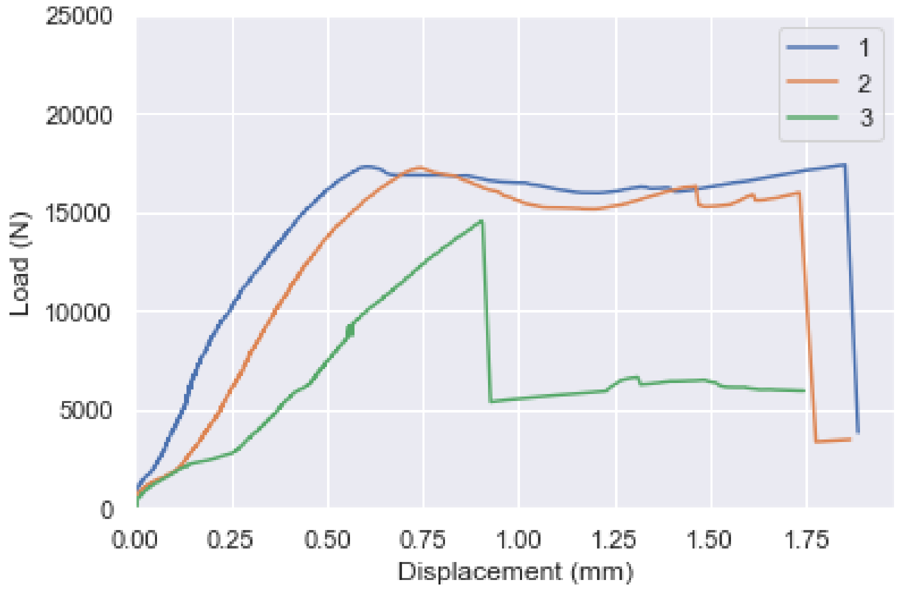


Figure 81: Hybrid Specimen with Butterfly Insert

The Load-Displacement graphs of all the other inserts can be found in Appendix A.

6 Discussion

6.1 Mechanical Performance

6.1.1 Strength

A comparison of the predicted and tested loads of the experiments is presented in Figure 82. The primary failure mode of all specimens was either net-tension or bearing followed by net-tension. The Knurled, Flying Saucer and Butterfly displayed explicit bearing failures in tested specimens.

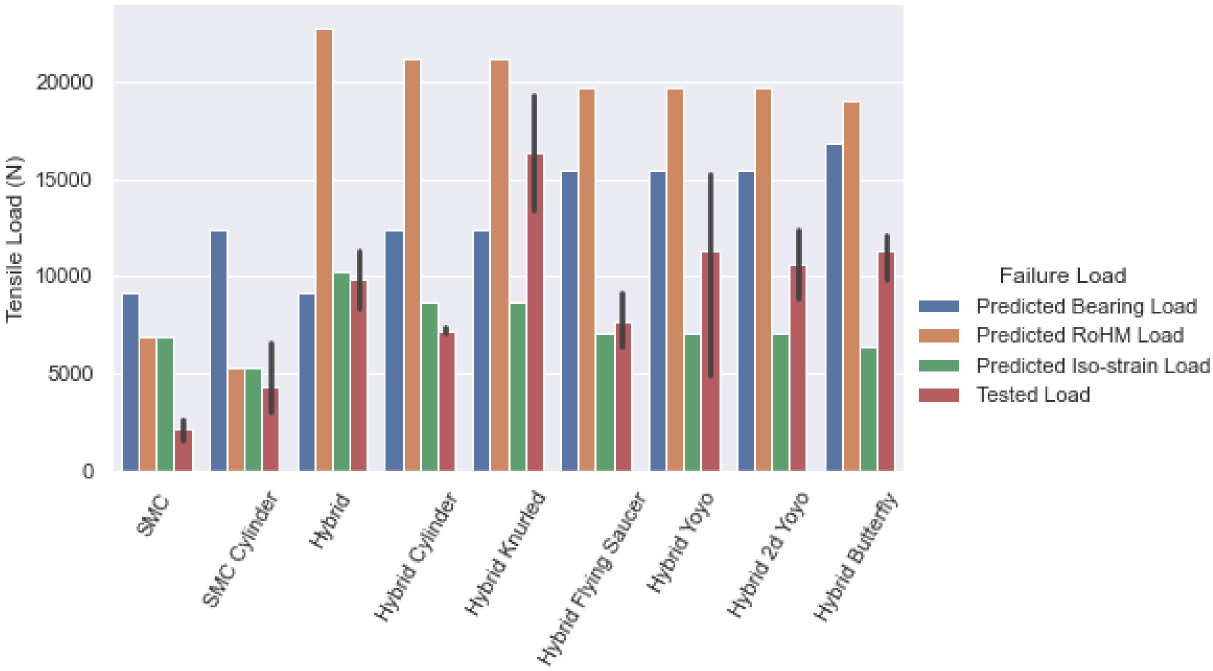


Figure 82: Comparison of Predicted and Tested Failure Loads

It can be observed that the SMC specimens didn't perform as predicted. The two likely reasons are the inherent variability of SMC moulding and the fact that these were the first few mouldings and the processing parameters got better with more mouldings.

The hybrid specimen increased the strength of SMC by about 200 % with < 7% UD placement in critical region. The tested strength of hybrid specimen was similar to the predicted bearing strength and iso-strain strength. This predictability is one of the key benefits of hybrid composites.

The cylindrical inserts in both the SMC and the Hybrid were held in the specimen with friction and therefore had no adhesion and poor mechanical interlocking. This led to the specimens behaving strangely as the inserts settled in during testing.

Knurled inserts had the best performance and further increased the strength of the hybrid specimens by 60%. There are two key reasons for the high performance:

- It gripped the SMC on front and the sides, significantly improving the stress distribution in the specimen as displayed in Figure 83.
- It occupied the lowest amount of critical space around the hole, which increased the composite material in the region increasing its net tensile strength.

Figure 83: Gripping Effect of the Knurled Insert

The specimens with the Yoyo insert had a significantly higher strength than the ones with the Flying Saucer insert. This showed that the load introduction close to UD is better than load introduction in the midddle. The also proves the assumption of iso-strain is not true in hybrid composites. An iso-strain material would be immune to changes in the location of load introduction.

The Yoyo insert performed marginally better than the 2d Yoyo with the same projected area. This aligns well with the theory that projected area is a good variable to predict bearing stress[7]. The 2d Yoyo is half the weight of the Yoyo insert and is four times the cost. Mass production of inserts using casting will bring down the cost, but the additional complexity may not be worth the weight savings.

The Butterfly inserts had a very progressive failure dominated by bearing. This was likely due to its high projected area and because it did not occupy the critical area around the insert. The progressive failure mode is valuable as it allows for detection and repair without catastrophic disassembly. Overall, the strength of all specimens was significantly dominated by the Width/Diameter ratio.

6.1.2 Stiffness

A comparison graph of the predicted tensile modulus and tested tensile modulus is displayed in Figure 84. A high degree of variability is observed in the tested modulus. The standard hybrid specimens and the hybrid specimens with the Knurled inserts had the best performance.

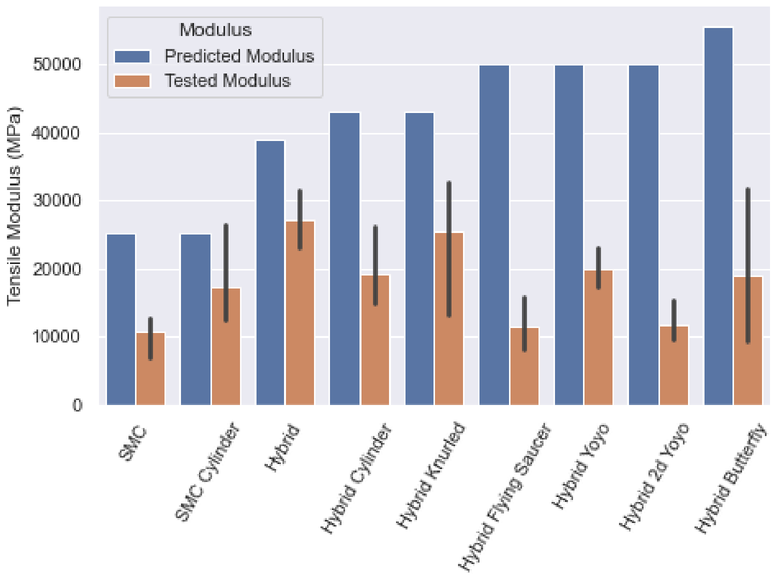


Figure 84: Comparison of Predicted and Tested Modulus

[7] The literature states that it's an approximation and works within 5% of actual bearing strength.

The hybrid specimens with the best tested performance had a modulus like the predicted modulus of the SMC. In hindsight, this is because the bearing load is directly applied only to the SMC in the current hybrid configurations.

The predicted modulus was calculated using the RoHM, which would have been valid in calculating the bending stiffness. However, as the loading was primarily applied via the SMC, the predicted modulus was wrong.

6.2 Manufacturing Process

During compression moulding, the mould always closed with a gap of 5 mm, however the resulting specimen's thicknesses ranged from 4.88 to 6.01 mm. The final thickness of the specimen was proportional to the amount of charge placed in the mould. There are two key phenomenon taking place here:

- The SMC shrinks as it cures. The SMC has additives that reduce the overall shrinkage, but local shrinkage is still observed.
- When more charge than the mould capacity is added, some of the resin will squeeze out as flash, however, the rest will be compressed and will spring back after the load is released.

High charge and high-pressure lead to lower void contents. However, they also make it difficult to obtain net-shape parts. Therefore, a spring back allowance must be designed in moulds to achieve consistent net shape parts with low voids.

Fibre Waviness was observed in the critical region near the insert due to high flow. The punched holes should be as small as possible to minimize flow in the region.

It was observed that wiping or spraying the mould with a solvent before partial curing of UD increased its surface energy and improved the adhesion of the UD to the mould.

The minimum force of the press (10 kN) was too high for the UD and led to resin bleed. The impact of this resin bleed is not conclusive. A thinner elastomeric tool can be used to ensure that the mould closes before significant force is applied to the UD.

Resin-rich regions were observed at the UD-SMC interface. UD tapering should be applied in both dimensions to avoid resin rich regions at the interface.

6.3 Comparison with aluminium

Table 20 shows the comparative performance of the hybrid composite with different Aluminium alloys under similar pin loading conditions.

Table 20: Comparison of Hybrid Composite and Aluminium under Pin Loading

Property	Hybrid Composite with Knurled Insert	Al 6060	Al 6082 T6
Tensile Load (N)	16000	5400	11250
Tensile Modulus (GPa)	26	69.5	69.5
Density (kg/m^3)	1522	2700	2700

The tensile strength of the hybrid composites is significantly higher than those of the Aluminium alloys even with a significantly lower density. However, in its current configuration, the stiffness of the hybrid composite is limited by the stiffness of the SMC

6.4 Proposed Design

To improve the consistency of hybrid specimens, the asymmetric failure needs to be addressed. The primary cause of asymmetric failure is variable modulus and low elongation at failure of the current SMC. Replacing the current Vinyl Ester based SMC with a higher elongation epoxy SMC should significantly improve reliability. Additionally, SMC with thinner tows should further reduce variability as they would have smaller stress concentrations at bundle ends.

To increase the stiffness of the hybrid specimen, additional UD tapes at angle of 45 ^{o} near the loading point are proposed as shown in Figure 85.

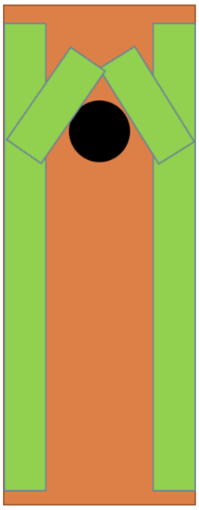


Figure 85: Angled UD Strips to Increase Stiffness

Given the progressive failure of the Butterfly Insert, an optimised insert with a similar design philosophy is proposed in Figure 86.

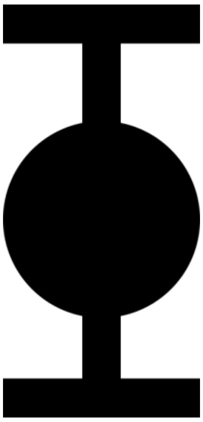


Figure 86: Tie Fighter Insert Design

7 Conclusion

This report investigates the variables affecting bearing load introduction in hybrid composites. The two key variables in this design were the UD placement and the insert design. Complex I-sections were compression moulded using SMC and UD-SMC hybrid composites with novel inserts. These specimens were then tested in a pin-bearing condition.

The conclusions of the moulding process are:

- SMC springs back after compression moulding and should be accounted for in mould design.
- Wiping the mould with solvents before partial curing allows the UD to stick to the mould.
- UD tapering should be used in all directions when possible.

The conclusions of the design process are:

- Placing the UD strips around the hole in hybrid composites synergistically utilises the high tensile strength of UDs and the high bearing strength of SMCs.
- Hybrid composites increased the tensile strength of the specimen by over 200% by using < 7% UD.
- Knurled inserts further increased the performance of hybrid composites by 60% because of their ability to grip the SMC.
- Location of load introduction via an insert is more important than the projected area of the insert.
- Increasing the projected area of the insert in-line with the loading direction leads to progressive failure.
- Width/Diameter ratio is one of the most critical factors in insert performance.
- Hybrid composites have a significantly higher strength when compared to Aluminium alloys, but smart solutions are needed to achieve high stiffness.

8 Recommendations and Future Work

The projected showed very promising results. It demonstrated that in narrow beams, knurled insert is the ideal choice because of it's low form factor and gripping capacity. Further work can be conducted to increase the strength, stiffnes, attractiveness and reliability of the hybrid composites.

- Hybrid design with 45º UD tapes should be investigated as a means to increase joint stiffness.
- Torque relaxation over time in hybrid composites should be studied.
- Process Cost Comparison between compression moulding and aluminum forging should be conducted.
- Alternate elastometric tool material should be investigated because of manufacturing concerns with silicon.
- The high aspect ratio SMCs made by Mitsubishi should be considered for higher predictability.
- Hybrid specimens should be manufactured using CF UD and Epoxy based SMC because of their higher elongation and stiffness.
- Hybrid Specimens with CF UD and Glass Fibre Epoxy should be investigated as a low cost alternative.

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APPENDICES

Appendix A Force Displacement Graphs

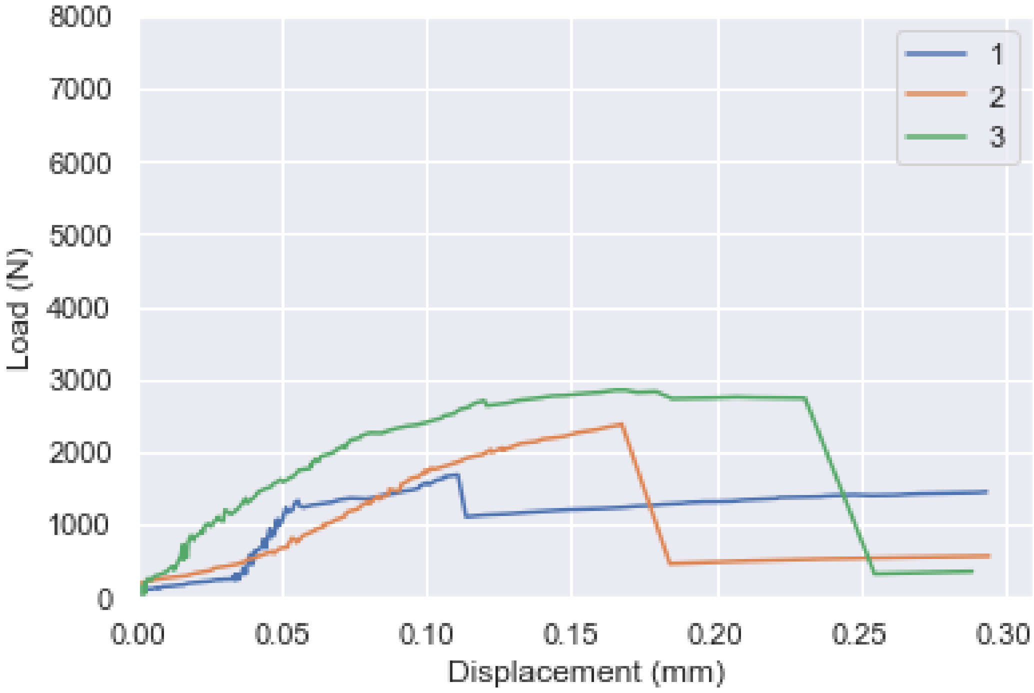


Figure 87: SMC Specimen

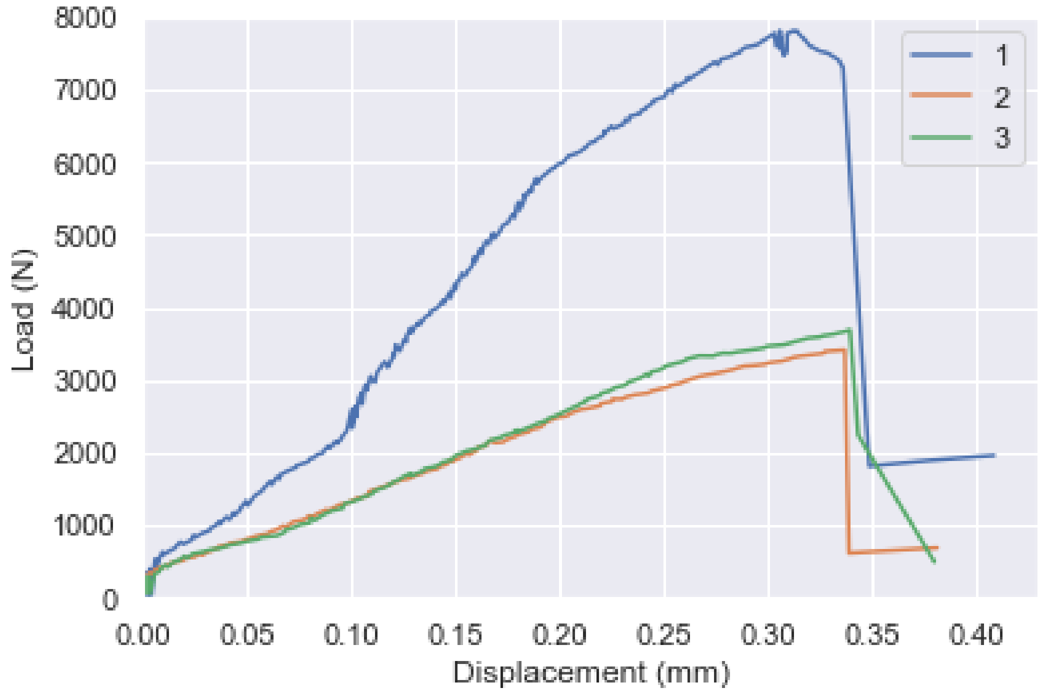


Figure 88: SMC Specimen with Cylindrical Insert

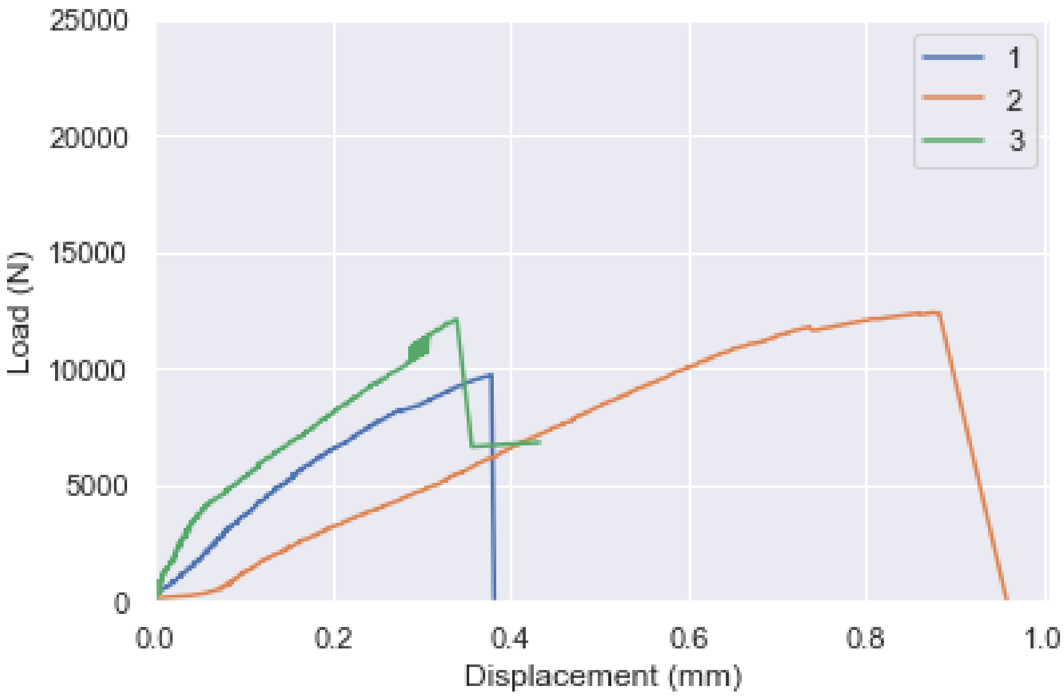


Figure 89: Hybrid Specimen

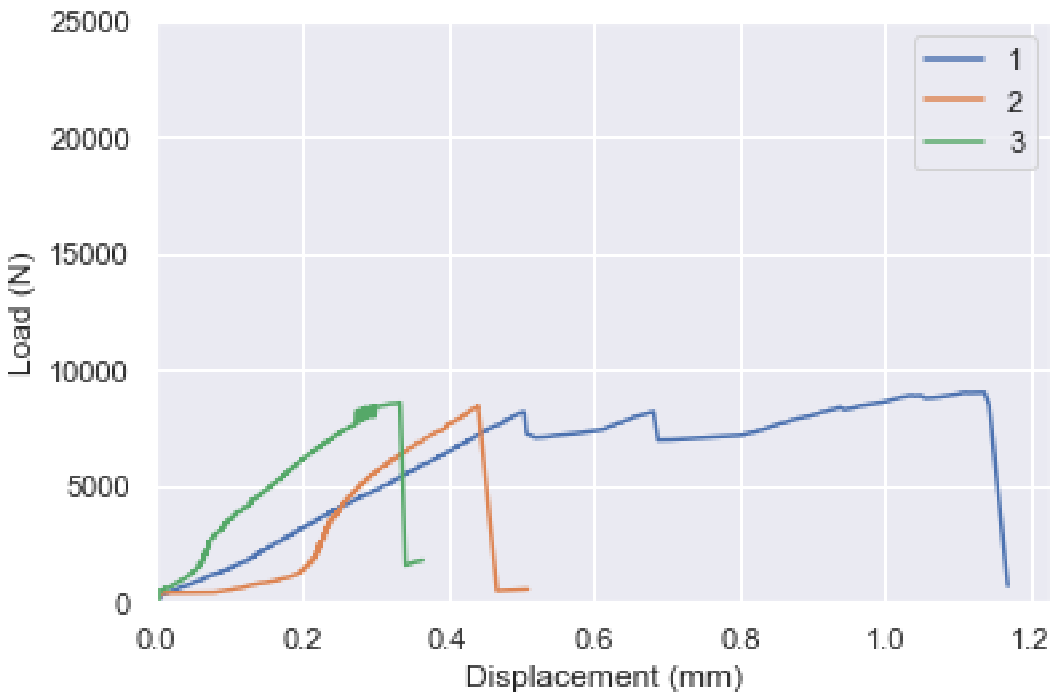


Figure 90: Hybrid Specimen with Cylindrical insert

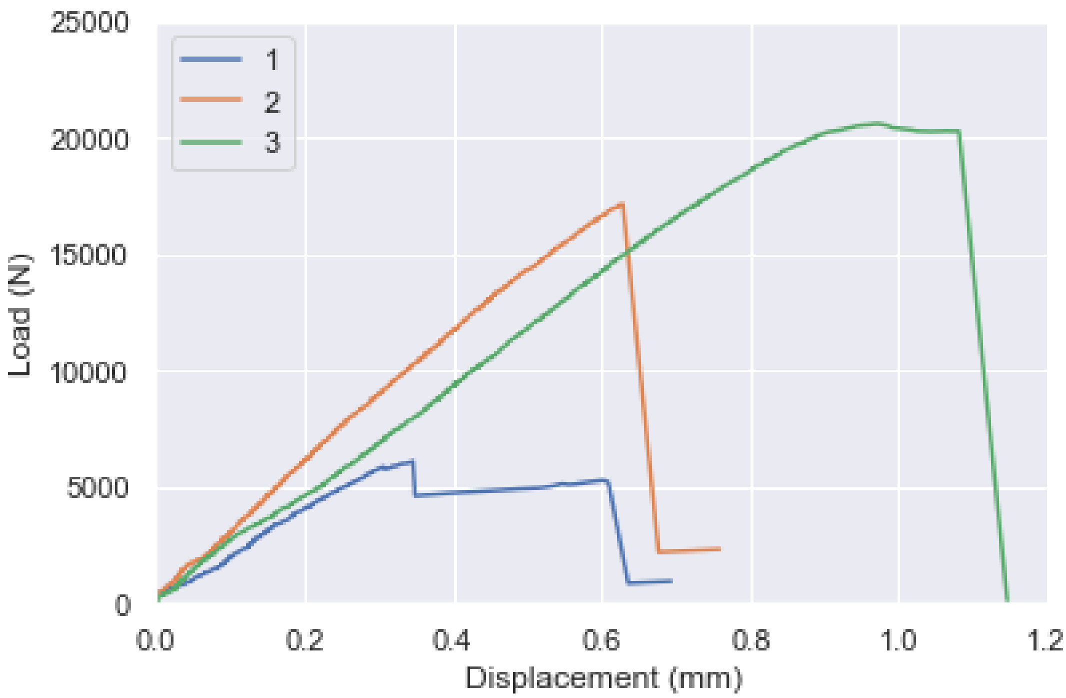


Figure 91: Hybrid Specimen with Yoyo Insert

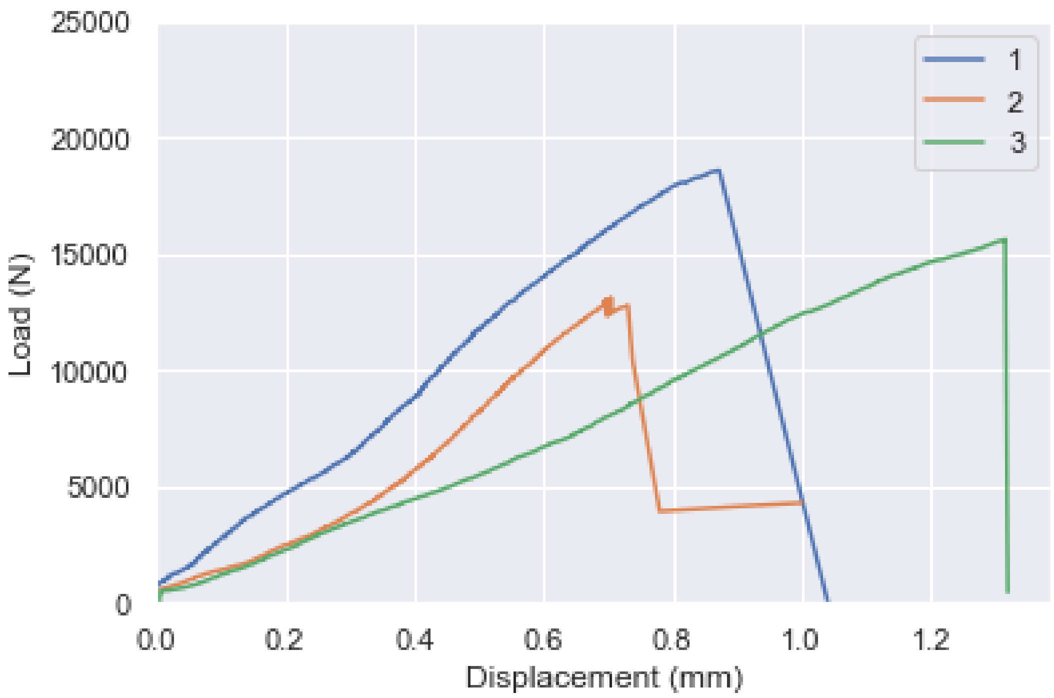


Figure 92: Hybrid Specimen with 2d Yoyo Insert

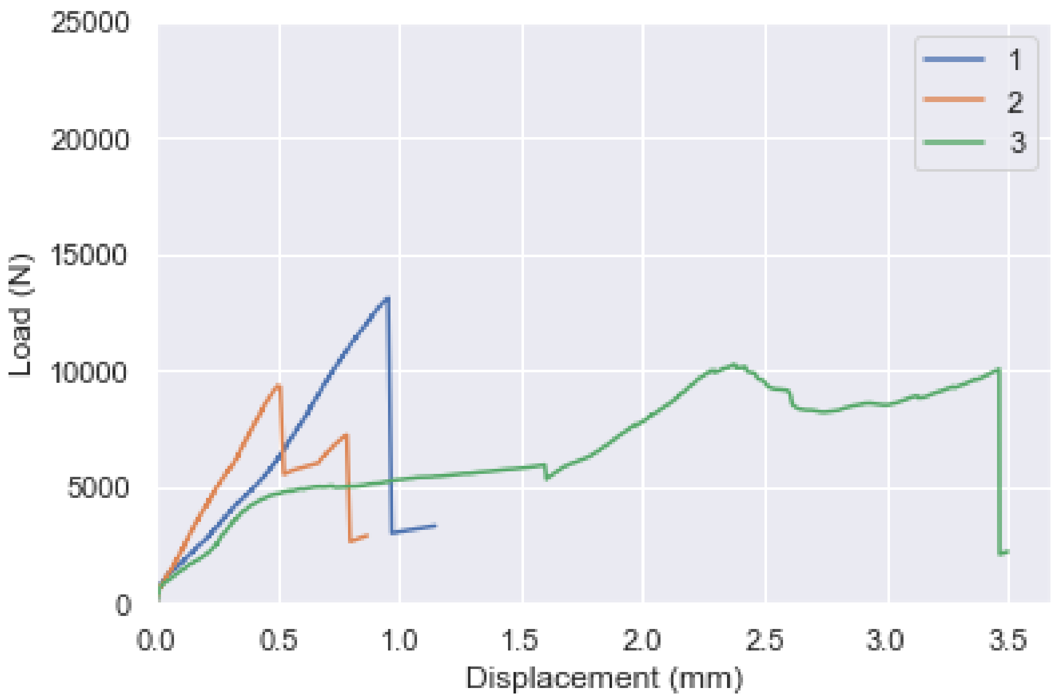


Figure 93: Hybrid Specimen with Flying Saucer

Appendix B Datasheets

B.1 Carbon Fibre UD

HexPly® M77
fast curing epoxy resin matrix for prepregs

HEXCEL®

Product Data Sheet

Description
HexPly® M77 is a fast curing hotmelt, thermosetting epoxy resin matrix, specifically designed for prepreg applications at which short cure cycles are required. M77 is recommended for curing at 120 – 150°C and is suitable for a range of pressures (5 – 35bar). M77 can be used for manufacture of large industrial components, suitable for cure of thin and thick sections.

Resin Matrix Properties
Dynamic Thermal Properties by DSC (ISO 11357-5)
(cure -40 to 270°C @10°C/min) [(1)]

Uncured T_g: 5 – 15°C
T_{Onset}: 118 – 132°C
T_{Peak}: 132 – 142°C
Enthalpy: 340J/g +/-20%

(1) Data obtained from neat resin upon delivery

Isothermal Cure Properties by DSC

Temperature	Cure Time (95%) [(2)]
120°C	≤9min
130°C	≤6min
140°C	≤3min
150°C	≤1.5min

(2) time to 95% conversion (ISO 11357-5), total scan time 15min @120 – 140°C, 2min @150°C

- Optimum cured T_g: 130°C +/-5°C (following a 15min cure @130°C) [(3)]
- Typical cured T_g: 130°C +/-5°C (following a 2min cure @150°C) [(3)]

(3) according to ISO 11357-2 using a 10°C/min ramp rate, -40 to 270°C; based on 95% conversion

- Density (ISO 1183-1): 1.15 – 1.25g/cm³
- Color: Off white - Yellowish
- Tack: Moderate

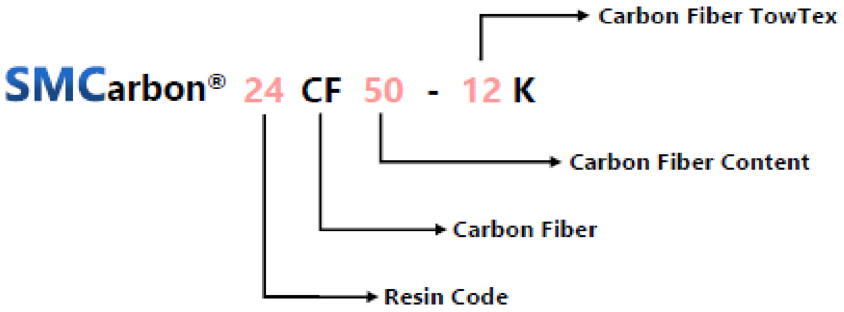
B.2 Carbon Fibre SMC

Polynt-SMCarbon® 24 CF50-12K

Generic Information

Sheet moulding compound based on vinyl ester resin and reinforced with carbon fibres for compression moulding. This material has great potential for weight reduction and allows a high degree of design freedom. The SMCarbon-Series is particularly suitable for structural applications where high mechanical properties are required.

Code Description



Material Description

Packaging:	roll	Fiber length:	25 mm
Material width:	500 mm – 1200 mm	Fiber tow tex :	12 K
Shelf life at -18°C:	6 months	Nominal fiber content $^{w}/_{w}$:	50 %
Shelf life at RT 23°C:	8 weeks	Areal weight:	1.200 g/m² – 1.800 g/m²
		Typical cure temperature:	135 – 145 °C
		Typical moulding pressure:	80 – 120 bar
		Typical cure time:	35 s/mm

Storage and Handling

Store the product in its original sealed packaging at 23°C. Leave product to reach room temperature before unrolling, to prevent condensation. The usual precautions when handling uncured synthetic resins and fine fibrous materials should be observed, and a Safety Data Sheet is available for this product. The use of clean disposable inert gloves provides protection for the operator and avoids contamination of material and components.

Mechanical Properties on cured material

Properties were determined on compression-moulded specimens according DIN EN 14598.

Properties	Method	Unit	Value
Density	ISO 1183 A	g/cm^3	1,40
Shrinkage	ISO 2577	%	-0,09
Tensile Modulus	ISO 527-4	N/mm^2	25.300
Tensile Strength	ISO 527-4	N/mm^2	108
Flexural Modulus	ISO 14125	N/mm^2	22.600
Flexural Strength	ISO 14125	N/mm^2	285
Impact Strength	ISO 179	KJ/m^2	45
Glass Transition Temperature	ISO 11357-2	°C	150
Heat distortion temperature	ISO 75-2	°C	> 200

Epovia® Optimum RF 5000

Resin Epoxy Vinylester Urethane

Version : October 2015

Appearance
Clear Ambercoloured liquid resin

Main resin characteristics
Epoxy Vinylester Urethane Resin
Thickening with magnesium oxide

Moulding information
SMC / BMC

Main applications
Industrial parts

Shelf life and storage
- Store in the shade out of direct sunlight below 30°C in sealed containers
- The shelf-life will be reduced if the resin is exposed to higher temperatures
- Use within shelf life specified on the container.

Other possible process
Pultrusion

Other possible applications

Precautions for handling
Please find the current SDS on internet www.ccpcomposites.com

Characteristics, Methods and Conditions	Values (Average values)
Liquid properties	
-Specific gravity at 23 °C :	1.05 – 1.10 g/cm³
-Viscosity (dPa.s): V23	Brookfield at 23°C
Spindle 2 Speed 50 rmp :	22
-Solid content (%) : PC53	60
-Reactivity :	
Méthod :	R 03 (100g)
Test temperature :	130 °C
Catalyst system :	1 % TBPB
	Tube Ø 18 ht 75 mm
Gel time :	180 s
Peak time :	230 s
Peak temperature :	260 °C
Mechanical properties (cured resin non reinforced)	
Post cure (4 hrs at 80°C) and (2 hrs at 120°C)	
-Tensile ISO 527 (1999)	
-Tensile strength (MPa) :	35
-Tensile modulus (MPa) :	3500
-Elongation at break (%) :	1.25
-Flexural ISO 178 (2003)	
-Flexural strength (MPa) :	80
-Flexural modulus (MPa) :	3000
Thermomechanical properties (cured resin non reinforced)	
-HDT ISO 75-2 A (1999) (°C):	130

B.3 Glass Fibre SMC

Technical data sheet

SMC 24/50 RN-1090

material properties

characteristics	method	unit	value
surface weight	ISO 10352	g/m²	1800
fibre content	ISO 1172	%	50
fibre length	PA 3.01	mm	25
curing time @ 145°C	ISO 12114/2	s/mm	14
specific density	ISO 1183 A	g/cm³	1,63
shrinkage	ISO 2577	%	0,08
flexural modulus	ISO 14125	N/mm²	13.200
flexural strength	ISO 14125	N/mm²	320
tensile strength	ISO 527-4	N/mm²	170
tensile modulus	ISO 527-4	N/mm²	12.000
impact strength	ISO 179	KJ/m²	130
heat distortion temperature	ISO 75-2 A	°C	>200

Properties were determined on compression-moulded specimens according DIN EN 14598

storage and processing recommendation

storage condition	store dry at max. 25 °C and out of direct sun light
moulding time	30 s/mm
moulding pressure	80-120 bar
moulding temperature	145 °C

This technical leaflet issued in the month of May 2021 replaces any other version printed before.

Appendix C Adhesion of Metals and Composites

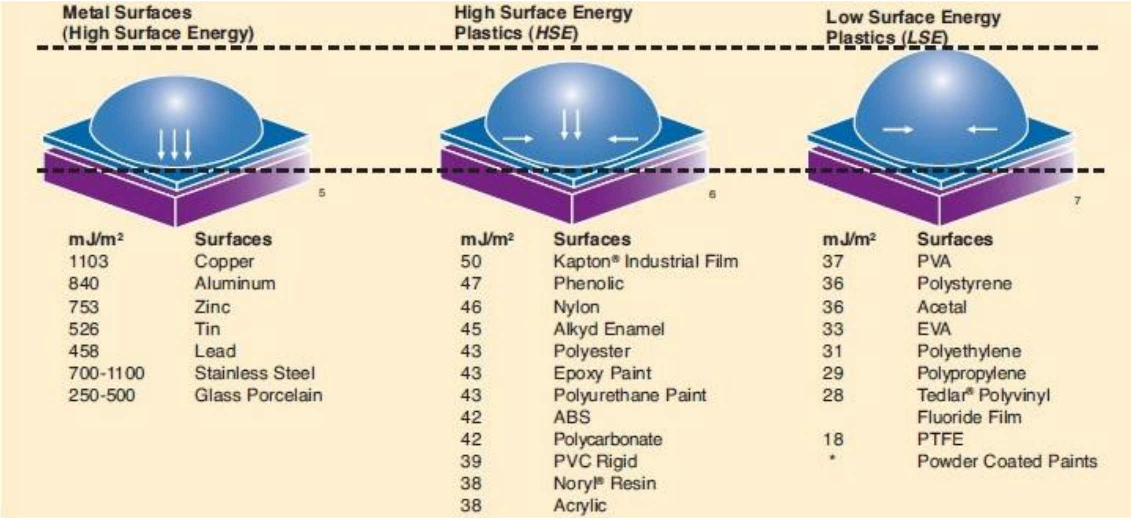


Figure 94: Surface Energy of different materials (Candotape, 2016)

The surface energy of a lot of materials is displayed in Figure 94. This surface energy can be increased with surface treatments.

The surface treatments can be broadly divided into coatings and mechanical treatments and their effectiveness can vary metal to metal.

The recommended surface treatment for aluminium inserts is Phosphoric acid Anodising. Figure 95 shows the surface structure of Aluminium after Phosphoric Acid Anodization which increases its surface energy and therefore enhances the adhesion between the metal and the substrate.

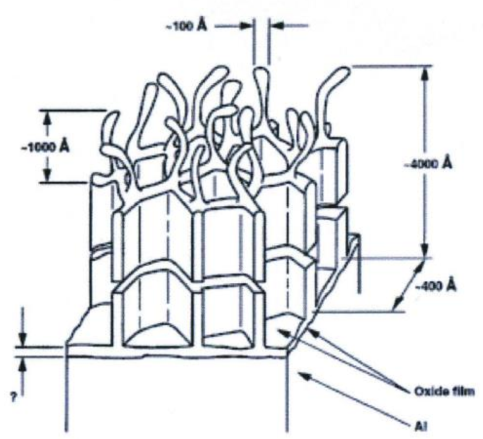


Figure 95: Aluminium surface microstructure after Phosphoric Acid Anodization (Vander Voort et al., 2004)

Figure 96 displays the strength of the lap joints of stainless-steel samples with carbon fibre coupons using different surface treatments. It can be observed that the surface treatments only increase the tensile strength of the joint, but also reduce the variability of the joint.

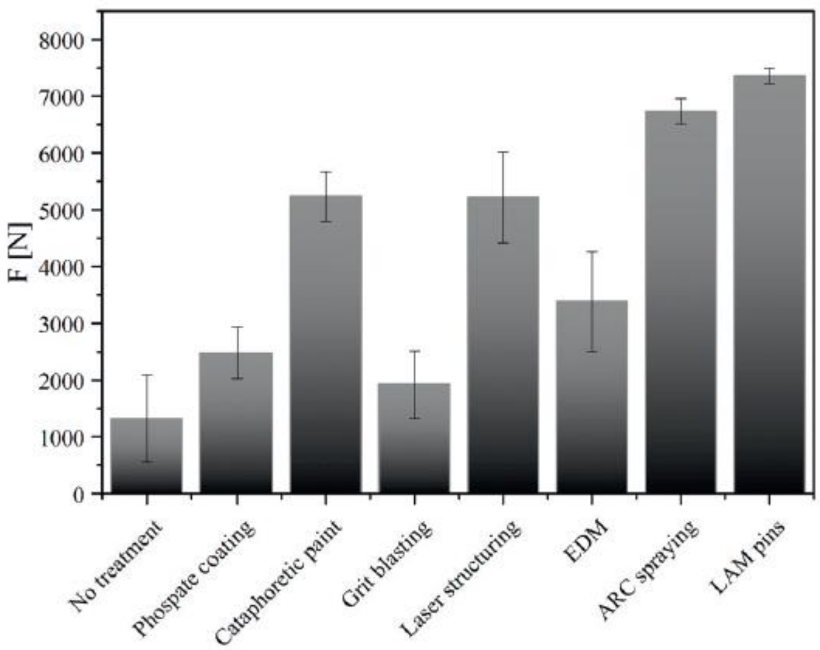


Figure 96: Tensile strength of stainless-steel carbon fibre lap joints with different surface treatments on metal (Gebhardt and Fleischer, 2014)

Figure 97 displays the impact of the surface treatments on the strength of the standard insert. It can be observed that impact of the surface treatments isn't nearly pronounced in inserts as opposed to lap joint tests. This is primarily because substrate adhesive failure is one of the failure modes of the insert. The added adhesive strength does not necessarily influence the delamination and insert deformation. Therefore, even though the impact of surface treatments on final strength is moderate, their impact on reduction of variability is valuable.

	Tensile tests	Bending tests
Untreated inserts	100%	100%
Cataphoretic painting	110%	131%
Laser structuring	119%	112%
Arc spraying	128%	141%
Laser additive manufacturing pins	142%	127%

Figure 97: Tensile and Bending strengths of embedded inserts with different surface treatments (Gebhardt and Fleischer, 2014)

Appendix D Risk Assessment & Mitigation Plan

Table 21: Risk Assessment and Mitigation Plan

Risk	Mitigation Plan
Risk of irritants in SMC resin	Wear gloves, lab coat
Itching/Irritation from Fibres	Always wear gloves when handling uncured fibres
Styrene from vinyl ester	Cross flow ventilation
Heavy Steel Moulds	Wearing gloves and always moving moulds in the presence of someone in the lab
Hot Moulds	Wait till mould have cooled before unloading them from the machine
High Compression Load	Closing the press door before applying load
Tensile Loading test	Using an acrylic shield and/or safe distance between specimen and humans
Plague	Had 2 shots, had the plague, wear mask indoors and social distancing (when possible)

Appendix E

E.1 Insert Tolerance and Manufacturing Load

During Manufacturing, the inserts will be under compression loads from the mould. The insert shouldn't yield or buckle under these loads. The compression pressure on the complete cross-section during moulding is 100 bars. Therefore, the compression load on the insert is proportional to the cross-sectional surface area of the insert.

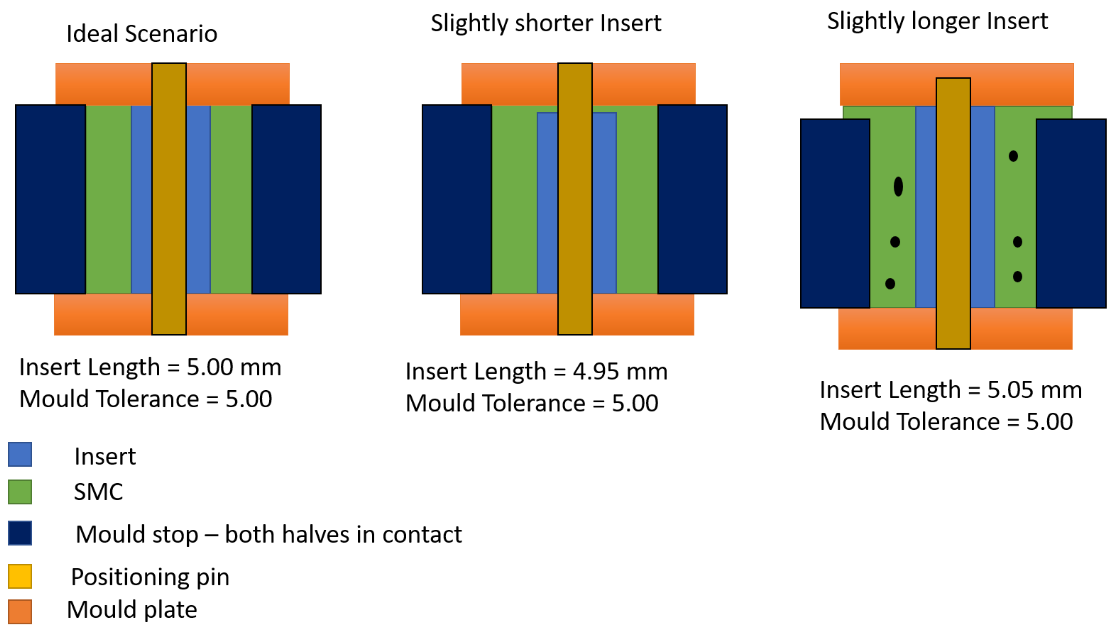


Figure 98: Impact of Insert Tolerance on Loading

Figure 98 shows the importance of the tolerance of the inserts. Therefore, to ensure mould closure and predictable compression loading on the insert, the length of the insert should be 5mm or less.

E.2 Medium Flow Trapezoidal

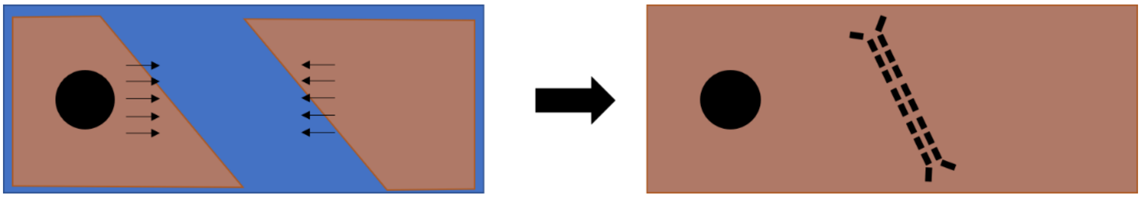


Figure 99: Medium Flow Trapezoidal Charge Design

E.3 Hybrid Flat Sample Moulding

About halfway through the project, it was realised that there was a shortage of SMC material and new material wouldn't arrive in time. Therefore, last few samples were moulded as flat samples as shown in Figure 100. This ensured that all the mouldings could be done with the existing material.

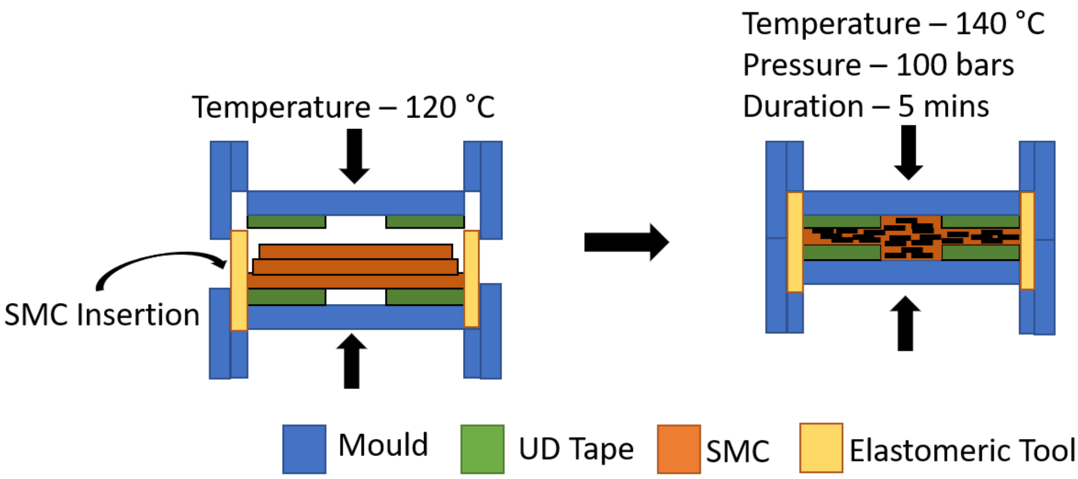


Figure 100: Hybrid Flat Sample Moulding