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## Prüfbericht Nr. 5214012042

<b>Prüfauftrag:</b>	<b>Beurteilung eines Eco-Bogie Drehgestells aus GFK</b>
Auftraggeber:	BAFU, Bern
Prüfobjekt:	Diverse Unterlagen von Sciotech
Kundenreferenz:	Dr. Christoph Wenger
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Eidg. Materialprüfungs- und Forschungsanstalt  
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## 1. Einleitung

Im Auftrag des Bundesamtes für Umwelt (BAFU) erarbeitete die Abteilung Ingenieur-Strukturen der Empa eine Beurteilung der Eignung eines Drehgestells aus Glasfaser-Verbundwerkstoffen (Glasfaser verstärkter Kunststoff, GFK) für Eisenbahngüterwagen. Die Idee und das Projekt eines GFK Drehgestells wurde von der Firma Sciotech Projects Limited, Yateley Hants, England, (nachfolgend als Sciotech bezeichnet) dem BAFU vorgelegt. Das GFK Drehgestells wird von Sciotech als Eco-Bogie bezeichnet. Im Kapitel 2 werden die Dokumente die als Grundlage für die Untersuchung verwendet wurden, aufgelistet. Die Materialien die für das Drehgestell verwendet werden sollen sind im Kapitel 3 beschrieben und beurteilt. Im Kapitel 4 wird eine FE-Modellierung des Eco-Bogie Drehgestells beschrieben und Schlussfolgerungen und Beurteilungen vorgenommen. Schliesslich wird im Kapitel 5 noch ein Vergleich des neuen Eco-Bogie Drehgestells mit einem konventionellen Y25-Bogie vorgenommen.

Die Firma PROSE aus Winterthur erhielt ebenfalls vom Bundesamt für Umwelt (BAFU) den Auftrag das gleiche Drehgestell aus Sicht der Eisenbahntechnik zu validieren. PROSE führte eine lauftechnische Validierung mittels eines Mehrkörpersimulationsmodells durch. Die Resultate sind in den Berichten [1, 2] beschrieben und kurz zusammengefasst im Kapitel 6.

Die Empfehlungen an das BAFU betreffend dem weiteren Vorgehen wurden von der Empa und PROSE an der gemeinsamen Sitzung vom 18. Juli 2016 diskutiert und sind im Kapitel 7 beschrieben.

Zur zusätzlichen Information findet sich im Kapitel 9 eine Einführung in das Thema der Faserverstärkten Kunststoffe.

## 2. Grundlagen

Als Grundlage für die Untersuchung dienten die folgenden Unterlagen die der Empa vom BAFU digital zur Verfügung gestellt wurden (emails vom 4.3.2016):

- Documentation in response to Frageliste concerning Ecobogie.pdf
- a317\_120dpi\_ZEV\_rail.pdf (Zeitschriftenartikel "Reducing Maintenance of Tracks by a New Design of Environmentally Friendly Bogie", ZEVrail 140 (2016), 4. April)
- ECCM15\_fibre optic strain monitor.pdf (Konferenzbeitrag)
- Damping Measurements two types rubber material IPM report 2008.pdf
- Test\_Report\_Damp.pdf
- RM ppt 8 december vex3.pptx (Powerpoint Präsentation)
- Sechs CAD Zeichnungen als dwg-Files (EB2009R22.5T03.dwg, EB2010R22.5T01.dwg, EB2010R22.5T02.dwg, EB2010R22.5TA13.dwg, EB2010R22.5TA14.dwg, EB2010R22.5TA15.dwg)

### 3. Material GFK und Eco-Bogie

Nachfolgend wird das Material, das für das Eco-Bogie Drehgestell verwendet werden soll, kurz beschrieben, die Besonderheiten kurz beleuchtet und eine Beurteilung gegeben.

#### a. Glasfasern

Gemäss den Unterlagen von Sciotech werden Glasfasern verwendet, wobei nicht angegeben wird um welchen Glastyp (E, S, ...) es sich handelt. In Abbildung 1 sind die verschiedenen Glastypen kurz beschrieben. Mehr Informationen zu verschiedenen Glastypen können ausserdem dem Anhang entnommen werden.

Types of glass fibre	
Various glass compositions are available in fibre form and these are listed in Table 5.2	
fibre type	principle use
E	standard reinforcement, low alkali content (<1%)
A	high alkali content (10 – 15%), inferior properties to E and not widely used
C	improved corrosion resistance to E, normally used in form of surface tissue
E-CR	boron-free, good acid corrosion resistance, other properties similar to E
D	high silica and boron content, dielectric applications, radio frequency transparent
R, S	better mechanical properties than E but higher cost, so specialized applications
AR	alkali-resistant, for reinforcement of cement

Table 5.2  
Different types of glass fibre

Abbildung 1: Typen von Glasfasern, Kopie aus [3].

Mit grosser Wahrscheinlichkeit ist anzunehmen, dass es sich um gewöhnliches E-Glas handelt.

Anscheinend sollen die Glasfasern von der Firma OCV (Owens Corning, [www.ocvreinforcements.com](http://www.ocvreinforcements.com)) beschafft werden. Die Firma stellt scheinbar spezielle E-Glasfaser her. Zitat aus dem Flyer dieser Firma: *Advantex® glass fiber reinforcements from Owens Corning are both an E-glass and a true E-CR glass according to ASTM D 578, ISO 2078, and DIN1259-1. The product provides improved corrosion resistance compared to standard E-glass.*

Die Glasfasern werden in der Form von vier verschiedenen gestrickten (knitted) Geweben verwendet (Zitat aus Unterlagen von Siotech):

- Udimatt 1137/100 – this is essentially an unidirectional glass fabric with a small quantity in the transverse direction (50 g/m<sup>2</sup>) and random orientation (100 g/m<sup>2</sup>) – primary reinforcement for side arms of bogie frame, axle tie and brake sub-frames
- EBX 936 – a bidirectional stitch bonded fabric with fibers located at ± 45 degrees – primary reinforcement for bogie transom
- ELTM 900 – a bidirectional glass fabric with fibers orientated at 0° (600 g/m<sup>2</sup>) and 90° (300 g/m<sup>2</sup>) – secondary reinforcement on outside of bogie transom
- Multimatt spacer fabric - a 3D knitted fabric used as a spacer reinforcement for the interior of the spacer pads of the bogie sub-frame

Die von Sciotech angegebenen elastischen Materialeigenschaften dieser Gewebe sind im Kapitel 4 angegeben und wurden für die FE-Modellierung verwendet.

Beim Konstruieren mit Glasfasern muss auf folgende Besonderheiten von Glasfasern geachtet werden:

- Zeitstandsfestigkeit von Glasfasern (Langzeitfestigkeit kann 30% der Kurzzeitfestigkeit sein)
- Steifigkeiten können mit zunehmender Ermüdung abnehmen, ausserdem können Ermüdungsbrüche auftreten.
- Umgebungsbedingungen sind sehr wichtig und beeinflussen den Widerstand signifikant, Feuchtigkeit, Temperatur, pH-Wert (Säure/Basen), etc.
- Kriechen: UD-Lamine zeigen keine grosse Kriechdeformation, wenn sie in Faserrichtung belastet werden. Hingegen können grosse Kriechdeformationen entstehen, wenn diese Lamine senkrecht zur Faserrichtung oder unter Schub und Torsion belastet werden (Festigkeit und Steifigkeit der Matrix massgebend).
- Der Widerstand gegen Schotterschlag muss untersucht werden.

Beurteilung: Es spricht grundsätzlich nichts dagegen, dass die gewählten Glasfasern für ein Drehgestell eingesetzt werden können. Jedoch müssen bei der Entwicklung eines Eco-Bogie die oben aufgelisteten Besonderheiten vorgängig verifiziert und berücksichtigt werden.

## b. Matrix

In Tabelle 1 sind die Kunststoffe, die für das Eco-Bogie Drehgestell verwendet werden sollen, dargestellt.

resin type	product code	Manufacturer	component
iso-polyester	Crystic 199	Scott Bader	bogie frame
phenolic	J2027 L	Momentiv	outer bearing housing

Tabelle 1: Duromer Kunststoffe die für das Eco-Bogie verwendet werden sollen.

Demnach wird für den Eco-Bogie Rahmen eine Polyester mit der Bezeichnung Crystic 199 verwendet. Mit der Bezeichnung *Crystic 199* findet man im Internet ein Datenblatt mit folgenden Informationen zum Temperaturverhalten dieses Kunststoffes:

*Crystic199 is an isophthalic polyester resin. It is recommended for use in high performance applications, such as the aircraft industry, where superior thermal and electrical properties are required. Fully cured laminates made with Crystic 199 have excellent chemical and heat resistance. They can withstand long periods (1 year) at temperatures up to 150°C, and shorter periods at temperatures up to 200°C, with no serious loss of properties.*

Somit kann man also davon ausgehen, dass die Polyestermatrix kurzfristig eine Temperatur von bis zu 200°C ohne grössere Verformungen ertragen kann. Gemäss Angaben von PROSE können die Bremscheiben bei besonderen Fahrbedingungen wie z.B. bei längeren Talfahrten aber bis zu 400°C heiss

werden. Bei der Entwicklung des Eco-Bogies muss deshalb geklärt werden, wie hoch die lokale Temperatur der GFK-Tragstruktur durch die Abstrahlung der Bremsscheiben werden kann.

Ausserdem muss beim Entwickeln des GFK mit Polyestermatrix auf folgende Besonderheiten geachtet werden:

- Die Sprödigkeit von Polyester ist höher als Epoxidharze, dafür sind sie kostengünstiger.
- Generell ist darauf zu achten, dass Polyester gegenüber Feuchtigkeit sensibler ist als z.B. Epoxidharze. Polyesterharze haben geringen UV-Strahlungswiderstand und müssen unbedingt geschützt werden (Anstrich oder Einmischung von Pigmenten).
- Der Widerstand gegen Schotterschlag muss untersucht werden.

Beurteilung: Es spricht grundsätzlich nichts dagegen, dass die gewählte Polyestermatrix für ein Drehgestell eingesetzt werden können. Jedoch müssen bei der Entwicklung eines Eco-Bogie die oben aufgelisteten Besonderheiten vorgängig verifiziert und berücksichtigt werden.

### c. Herstellmethode

Der Eco-Bogie Rahmen, der in Abbildung 2 dargestellt ist, soll mit der RTM (resin transfer molding) Methode hergestellt werden. Eine ausführlichere Beschreibung dieser und anderer Methoden können dem Anhang entnommen werden. Die Idee ist, die ganze Struktur mit den verschiedenen Lagen und Faserrichtungen in einem Teil herzustellen. Mit dieser Herstellungsmethode können Bauteile mit hoher Qualität hergestellt werden.



Abbildung 2: Eco-Bogie Konzept. Der Eco-Bogie Rahmen in Grün.

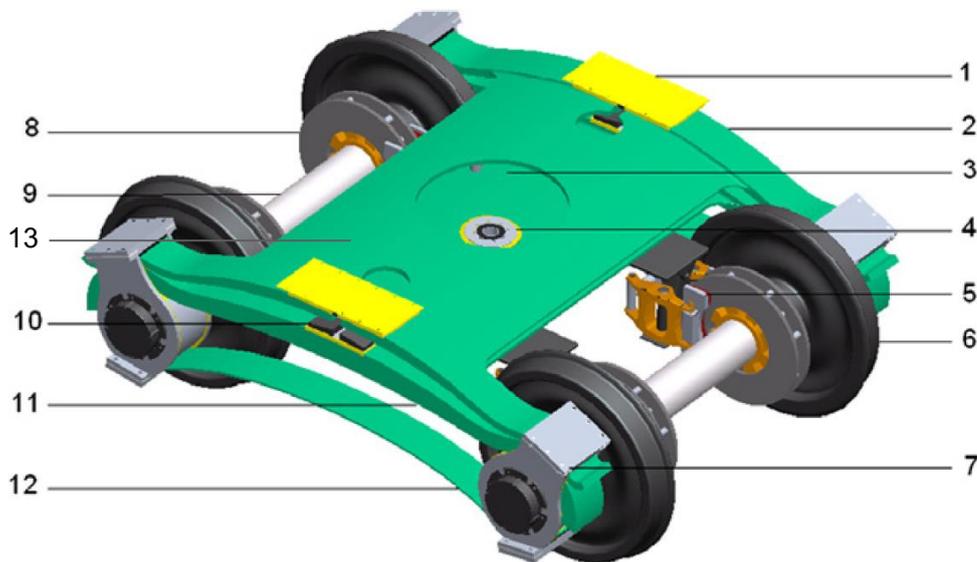
Beurteilung: Die Methode ist geeignet für die serienmässige Fertigung. Im Rahmen eines Entwicklungsprojektes müsste aber sicher überprüft werden, ob die Fertigungsqualität genügend ist (Matrix überall vorhanden, keine Luftblasen, etc.).

## 4. FE-Modelle des Eco-Bogie Drehgestells

### a. Einleitung

Zur Abschätzung des strukturellen Verhaltens des GFK Eco-Bogie Drehgestells (Abbildung 3) unter vertikaler Belastung wurden drei Finite Elemente (FE)-Modelle erstellt. Die Annahmen für die Modelle sind nachfolgend beschrieben. Es wurde die FE-Software Abaqus verwendet.

Mit diesen Modellen konnten die Vertikal- und Längs-Verschiebungen der beiden Achsen, die sich aus vertikalen Lasten ergeben, abgeschätzt werden. Anschliessend wurden diese Verschiebungskurven mit denjenigen die aus den Unterlagen von Sciotech hervorgehen, verglichen. Die vertikale Verschiebungskurve die von Sciotech angegeben wurde, wurde bereits in [4] publiziert.



Number	Name	Material
1	Side bearer	Polyurethane, nylon and rubber
2	Upper bogie frame	Glass fibre reinforced epoxy
3	Lower bogie transom	Glass fibre reinforced epoxy
4	Central pivot point	Steel, rubber and polyurethane
5	Calliper	Steel, rubber and brake pads
6	Wheel	Steel
7	Axle box	Steel, rubber and polyurethane
8	Brake disc	Steel
9	Axle	Steel
10	Bogie frame bearer	Rubber, polyurethane
11	Lower bogie frame	Glass fibre reinforced epoxy
12	Axle tie	Glass fibre reinforced epoxy
13	Upper bogie transom	Glass fibre reinforced epoxy

Abbildung 3: Übersicht über die verschiedenen Teile des Eco-Bogie, deren Bezeichnungen und die verwendeten Materialien. Gemäss Hou and Jeronimidis 2012, [4].

## b. Material

Gemäss den Angaben von Sciotech, wurden für das FE-Modell des Eco-Bogie drei verschiedene GFK Lamine verwendet:

- UDimatt 1137/100 ist ein unidirektionales Glass Gewebe und wurde für die "side arms" und "axle tie" verwendet.
- EBX 936 ist ein bidirektionales Glass Gewebe mit Fasern in  $\pm 45^\circ$  Richtung. Es ist die Hauptbewehrung des Eco-Bogie „transom“, wird aber auch in den "side arms" zur Verbindung mit dem „transom“ verwendet.
- Das GFK Gewebe ELTM 900 mit Fasern in  $0^\circ$  und  $90^\circ$  Richtung wird als Schutzschicht des "transom" benutzt.

Die Lamine werden ausserdem in zwei verschiedene Typen eingeteilt: „UD material“ und „Woven material“. Das UDimatt Laminat ist ein „UD material“ und die Lamine EBX 936 und ELTM 900 laufen unter der Kategorie „Woven material“. Die elastischen Eigenschaften der beiden Materialien und die Schichtdicken sind in Tabelle 2 aufgelistet.

	UD material	Woven material
E11 [GPa]	38	20
E22 [GPa]	9.75	20
E33 [GPa]	9.75	10
$\nu_{12}$	0.298	0.3
$\nu_{23}$	0.298	0.3
$\nu_{31}$	0.05	0.17
G12 [GPa]	3.38	5
G23 [GPa]	3.38	5
G31 [GPa]	3.38	5
Dicke [mm]	1.1	0.9

Tabelle 2: Elastische Eigenschaften und Schichtdicken der Materialien gemäss Sciotech.

## c. Geometrie

Die einzelnen Teile des Eco-Bogies haben verschiedene Schichtenaufbauten (Lay-up's). Auch die Bauteildicken können entlang der Bauteillänge variieren. Der Schichtenaufbau der Lamine von einigen Bauteilen sind in Tabelle 3 bis Tabelle 6 dargestellt.

Für die "axle ties", "upper transom" und "lower transom" wurde im FE-Modell vereinfachend eine konstante Dicke angenommen. Die Bauteildicken der „upper frames“ und „lower frames“ der „side arms“

wurden hingegen stufenweise reduziert. Die Bauteildickenreduktion wurde direkt nach der Verbindung der „transoms“ mit den „side arms“ vorgenommen. Die verwendeten Bauteildicken sind in Tabelle 7 angegeben.

layer #	UD	EBX	UD and EBX
L1-L6	6		
L7-L48			21
L49-L54	6		

Tabelle 3: Schichtenaufbau des „upper frame“ in der Mitte der Spannweite.

layer #	ELTM 900	EBX
L1-L2	2	
L3-L22		20
L23-L24	2	

Tabelle 4: Schichtenaufbau des „upper transom“.

layer #	UD	EBX	UD and EBX
L1-L12	12		
L13-L32			10
L33-L52			10
L53		1	
L54-L73			10
L74-L93			10
L94-L105	12		

Tabelle 5: Schichtenaufbau des „lower frame“ in der Mitte der Spannweite.

layer #	ELTM 900	EBX
L1-L2	2	
L3-L43		41
L44-L55	2	

Tabelle 6: Schichtenaufbau des „upper transom“.

Bauteil		Dicke [mm]
Upper frame	Mitte der Spannweite	54.3
	Enden	36.3
Upper transom		21.6
Lower frame	Mitte der Spannweite	107.3
	Enden	70.4
Lower transom		40.5
Axle tie		11.0

Tabelle 7: Dicken der verschiedenen Bauteile des Eco-Bogie, das für das FE-Modell verwendet wurde.

#### d. Modellierung

Wie bereits erwähnt, wurden drei FE-Modelle erstellt, um das Tragverhalten des Eco-Bogie zu modellieren und die Angaben von Sciotech zu überprüfen. Die Geometrie einzelner Bauteile wurde direkt aus den CAD Zeichnungen von Sciotech in die FE-Software Abaqus importiert. Es handelte sich um den „upper and lower frame“, den „upper and lower transom“ und die „axle ties“. Die Geometrie und die angenommenen Randbedingungen der drei Modelle sind in Abbildung 4 dargestellt.

Modell 1 besteht nur aus dem „upper frame“. Damit soll die vertikale Steifigkeit unter „tare“ Belastung abgeschätzt werden. Die „tare“ Belastung ist das Eigengewicht des leeren Güterwagens. Das Drehgestell wurde so bemessen, dass der „upper frame“ die „tare“ Belastung aufnehmen kann, ohne dass sich der „upper frame“ und „lower frame“ berühren. Der „upper frame“ wurde auf der linken Seite als fixiert in alle drei Richtungen gelagert, auf der rechten Seite war die vertikale und Querrichtung blockiert aber die Längsrichtung frei gelagert (Abbildung 4). Diese Randbedingungen erlauben somit eine Längsverschiebung der einen Achse. Die vertikale Verschiebung bei beiden Achsen ist null weil das Bauteil

dort an den Achsen befestigt ist. Die Belastung wurde in Form einer vertikalen Verschiebung von 50mm des „side bearers“ aufgebracht.

Im zweiten Modell wurde zusätzlich zum „upper frame“ auch der „lower frame“ berücksichtigt. Mit diesem Modell wird die Belastung „laden load“, also Vollbelastung, untersucht. Die beiden Bauteile kommen in Kontakt und tragen die Last gemeinsam. Die gleichen Randbedingungen wie beim Modell 1 wurden verwendet, d.h. auf der linken Seite wurden alle drei Verschiebungen null gesetzt und auf der rechten Seite wurde die vertikale und Querrichtung als fix betrachtet und die Längsverschiebung frei verformbar gesetzt (Abbildung 4). Der sogenannte „bogie frame bearer“ wurde auch ins Modell eingebaut, da dies die Distanz zwischen den beiden Rahmen reduziert. Als Belastung wurde eine vertikale Verschiebung von 150mm auf den „side bearer“ aufgebracht. Als Ergebnis der Berechnung wurde die vertikale Verschiebung des „side bearer“ und die horizontale Verschiebung des „lower frame“ (d.h. Zunahme des Achsabstandes durch vertikale Last) registriert.

Im Modell 3 wurden die „transoms“, „axle ties“ und die „axles“ zum Modell 2 zugefügt. Die „axles“ wurden als starre Elemente modelliert. Die Randbedingungen wurden so gewählt, dass ein ähnliches Tragverhalten wie bei den Modellen 1 und 2 resultierte. Die „upper frames“, „lower frames“ und „axle ties“ wurden an die linke Achse starr verbunden und die drei Verschiebungen der linken Achse wurde zu null gesetzt. Die Längsverschiebung der rechten Achse wurde dagegen als frei verformbar gesetzt, wobei natürlich auch hier die vertikalen und Querverschiebung fixiert waren (Abbildung 4). Die „upper frames“ und „lower frames“ konnten sich horizontal gegeneinander und gegen die Achse verschieben, wobei die Normal-Richtung als unverschieblich und die tangentielle Richtung mit einem Reibungskoeffizienten von 0.2 angenommen wurde. Diese Randbedingungen sind natürlich eine grobe Vereinfachung der komplizierten „axle box“. Wie beim Modell 2 wurde die Belastung als vertikale Verschiebung von 150mm auf den „side bearer“ aufgebracht. Wieder wurden als Berechnungsergebnis die vertikale Verschiebung des „side bearer“ und die horizontale Verschiebung des „lower frame“ registriert.

Alle Bauteile wurden mit sogenannten S4R shell Elementen simuliert. Ausserdem wurde die nicht-lineare Geometrie für grosse Verformungen in der Software Abaqus aktiviert.

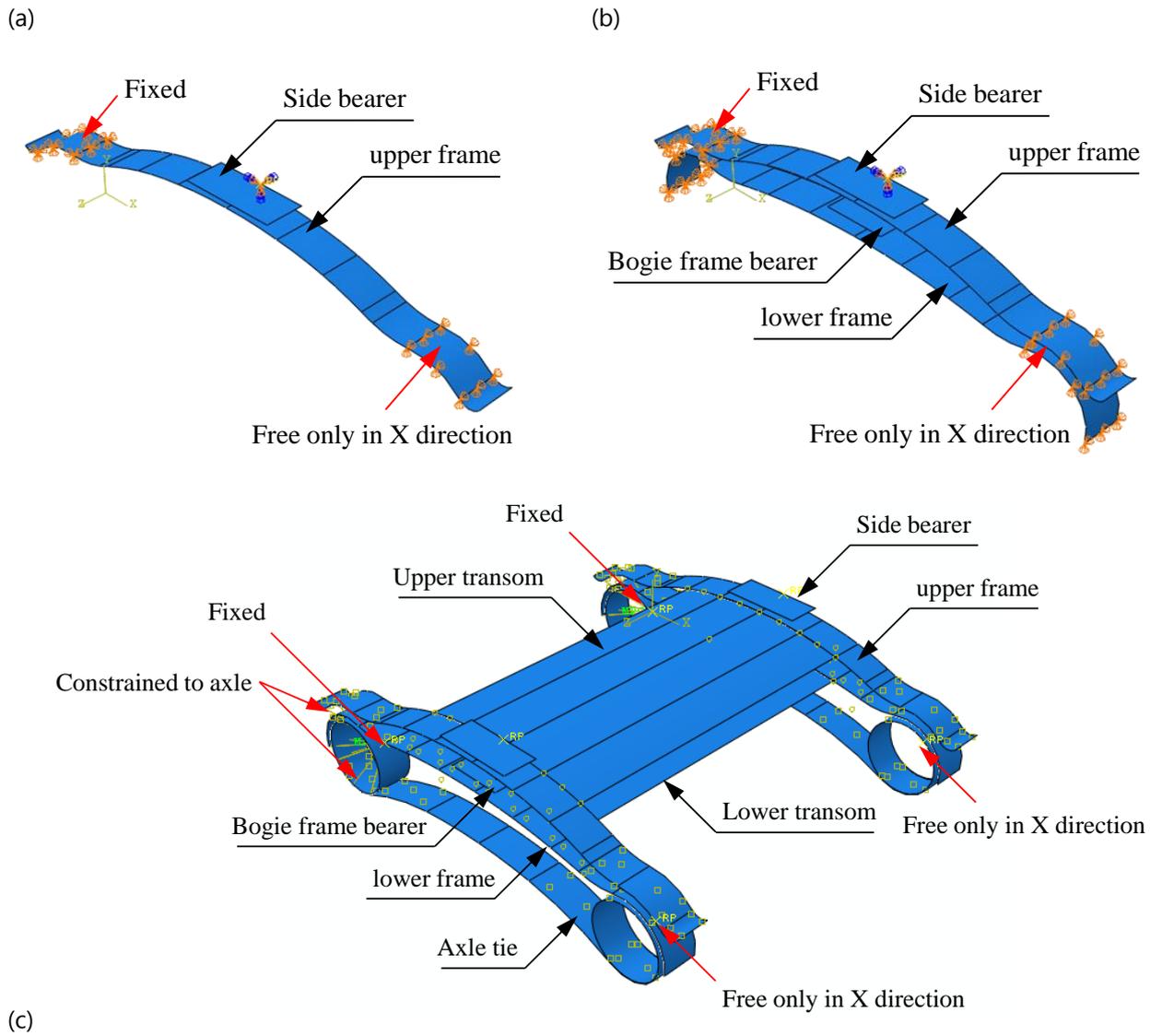


Abbildung 4: Geometrie und Randbedingungen des (a) Modell 1, (b) Modell 2 und (c) Modell 3.

## e. Resultate und Diskussion

Die berechneten Längsspannungen im verformten Eco-Bogie Modell sind in Abbildung 5 und Abbildung 6 für die FE-Modelle 1 und 2 für verschiedene Laststufen dargestellt.

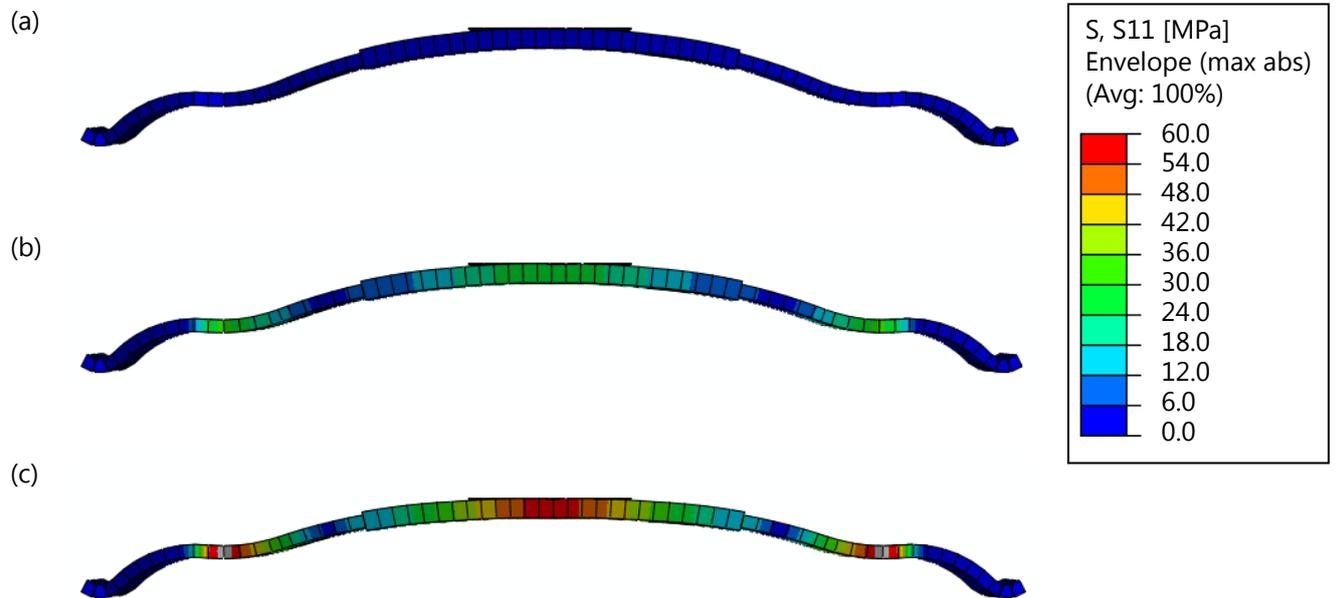


Abbildung 5: Absolute Werte der Längsspannungen (S11) im "upper frame" in Modell 1 bei (a)-(c) Faktoren 0 : 0.5 : 1 der aufgebrachten Verschiebung (50 mm) in Mega-Pascal (MPa), d.h. Newton pro Quadrat Millimeter.

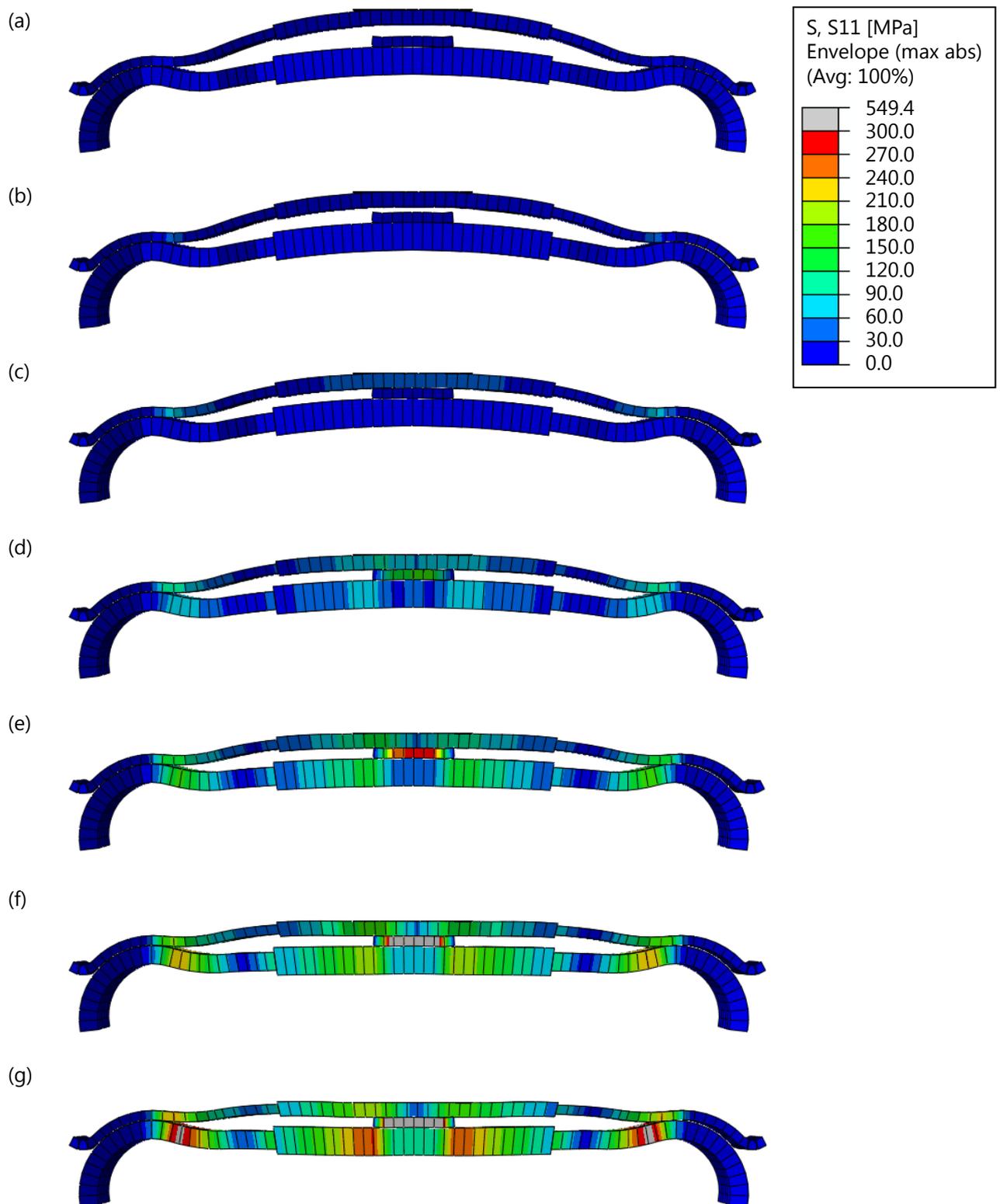
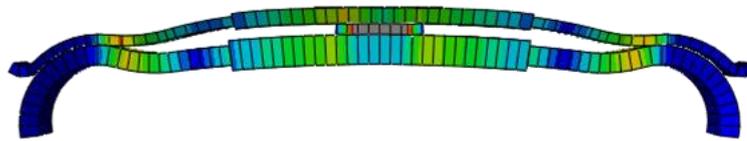
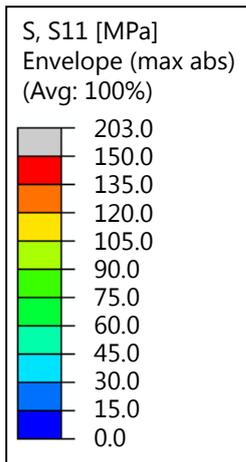


Abbildung 6: Absolute Werte der Längsspannungen (S11) in den "upper and lower frames" im Modell 2 bei (a)-(g) Faktoren 0 : 1/6 : 1 der aufgetragenen Verschiebung (150 mm) in Mega-Pascal (MPa).

Die berechneten Längsspannungen des Eco-Bogie unter „laden load“ (400 kN vertikale Last) ist in Abbildung 7a) and Abbildung 8a) for Model 2 and Model 3 dargestellt. Es ist ersichtlich, dass die absolute maximale Längsspannung etwa 120 MPa im Model 2 und etwa 150 MPa im Model 3 betragen. Ausserdem sind die horizontalen Verschiebungen des Eco-Bogie (d.h. die Zunahme des Achsabstandes) in Abbildung 7b) and Abbildung 8b) for Model 2 and Model 3 abgebildet.

(a)



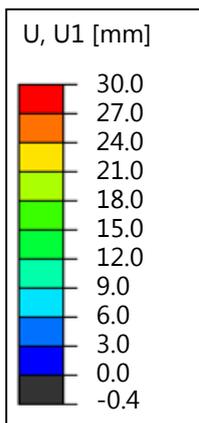
Step: Step-1

Increment 30: Step Time= 0.5600

Primary Var: S, S11

Deformed Var: U Deformation Scale Factor: +1.0e+00

(b)



Step: Step-1

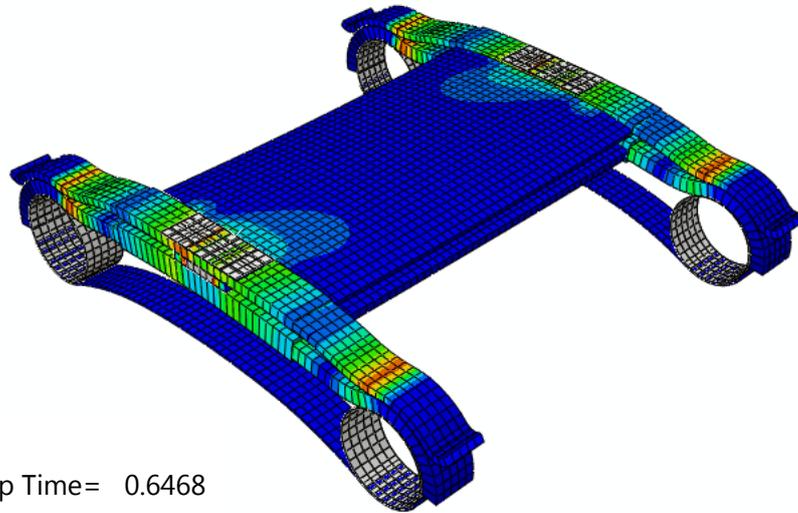
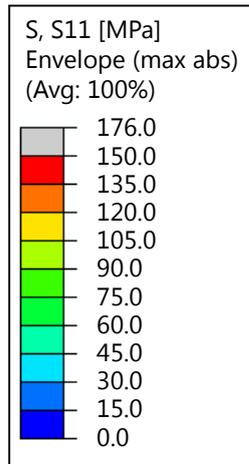
Increment 30: Step Time= 0.5600

Primary Var: U, U1

Deformed Var: U Deformation Scale Factor: +1.0e+00

Abbildung 7: (a) Absolute Werte der Längsspannungen (S11) und (b) Verschiebung (U1) in horizontaler Richtung im Modell 2 bei 400 kN vertikaler Last.

(a)



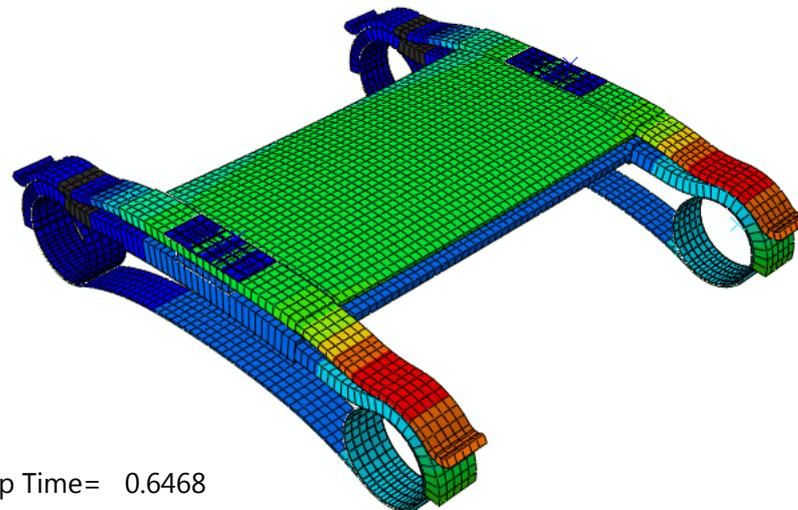
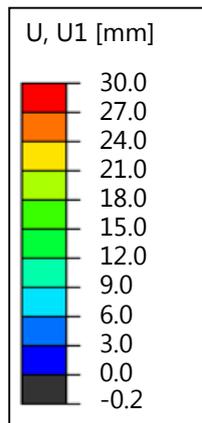
Step: Step-3

Increment 48: Step Time= 0.6468

Primary Var: S, S11

Deformed Var: U Deformation Scale Factor: +1.0e+00

(b)



Step: Step-3

Increment 48: Step Time= 0.6468

Primary Var: S, S11

Deformed Var: U Deformation Scale Factor: +1.0e+00

Abbildung 8: (a) Absolute Werte der Längsspannungen (S11) und (b) Verschiebung (U1) in horizontaler Richtung im Modell 3 bei 400 kN vertikaler Last.

In Abbildung 9 sind die mit dem FE-Modell berechneten Last-Verschiebungskurven denjenigen von Sciotech gegenübergestellt. Es ist ersichtlich, dass die vertikalen Verschiebungen (Abbildung 9, links) der drei Modelle mitdenjenigen von Sciotech einigermaßen gut übereinstimmen. Die Modelle 1 und 2 konnten die Steifigkeit des Eco-Bogie unter „tare load“ und „laden load“ gut abbilden. Das Modell 3

welches auch noch die „axle tie“ berücksichtigt, weist eine leicht grössere Steifigkeit auf als das Modell 2. Ein Vergleich der verschiedenen berechneten Steifigkeiten mit den von Sciotech angegebenen Steifigkeiten kann Tabelle 8 entnommen werden. Zusätzlich in Abbildung 9 (links) sind die berechneten Längsspannungen unter der Last von 400 kN angegeben.

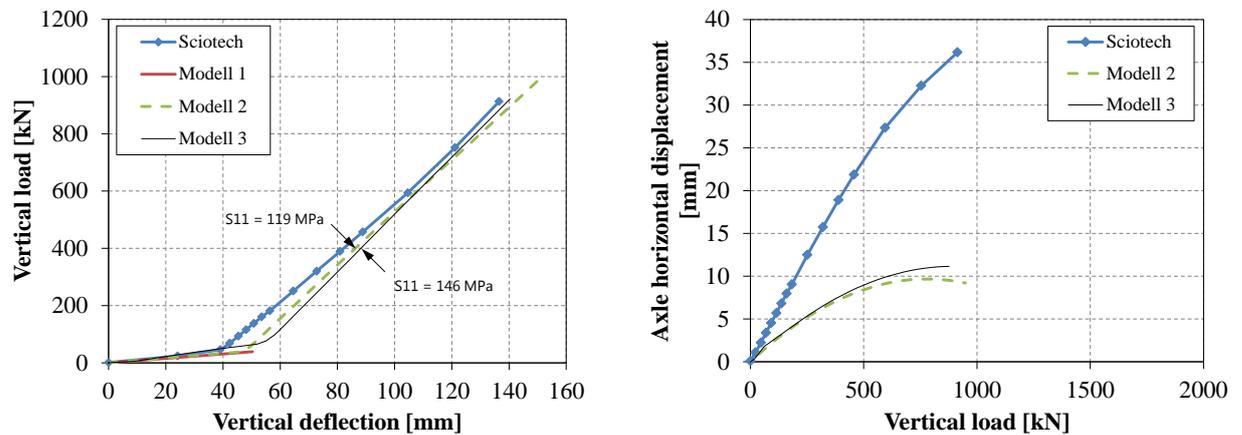


Abbildung 9: Kraft-Verschiebungskurven von Sciotech und berechnet mit FE-Modellen 1 bis 3.

Die mit den FE-Modellen berechneten horizontalen Verschiebungen (Abbildung 9, rechts) waren deutlich kleiner als von Sciotech angegeben. Die Vereinfachungen in den FE-Modellen waren wohl zu gross und das Verhalten der „axle boxes“ wurde nur sehr grob modelliert. Mehr Informationen zur Modellierung dieser „axle boxes“ wären nötig (Querdruck, Reibungsverhalten). In Abbildung 7b) und Abbildung 8b) ist ersichtlich, dass die horizontale Verschiebung des „lower frame“ 7.4 mm und diejenige des „upper frame“ 30.9 mm betragen. Dies zeigt, dass das FE-Modell nicht optimal ist, zum generellen Verständnis aber durchaus hilfreich ist.

Zustand	Steifigkeit [kN/mm]				Angepasste Steifigkeit*
	Sciotech	Modell 1	Modell 2	Modell 3	
unter "tare load" (Initial stiffness)	1.1	0.8	0.8	1.3	1.7
unter "laden load"	8.3	---	9.4	10.0	18.5

Tabelle 8: Übersicht der vertikalen Steifigkeiten der verschiedenen Modelle (\*: siehe Kapitel f).

## f. Änderung der Steifigkeit

Mit Hilfe des Modells 2 wurde eine kleine Parameterstudie erstellt, um den Einfluss der Rahmendicken auf die Steifigkeiten des Eco-Bogie zu untersuchen. Zu diesem Zweck wurde die Anzahl der äusseren UD-Schichten verdoppelt (siehe Tabelle 3 und Tabelle 5). Die ursprünglichen und neuen Rahmendicken sind in Tabelle 9 zusammengestellt.

Bauteil		Rahmendicke [mm]	
		Original (Modell 2)	Angepasste Steifigkeit
Lower frame	Mitte	107.3	133.7
	Ende	70.4	96.8
Upper frame	Mitte	54.3	67.5
	Ende	36.3	49.5

Tabelle 9: Ursprüngliche und angepasste Rahmendicken des „lower“ und „upper frame“.

In Abbildung 10 sind die Last-Verschiebungskurven die aus den ursprünglichen und den neuen Dimensionen berechnet wurden, dargestellt. Zusätzlich sind in Tabelle 8 die daraus resultierenden Steifigkeiten dargestellt. Es ist ersichtlich, dass die Steifigkeiten sich etwa verdoppeln. Die vertikalen Verschiebungen reduzieren sich etwa um 25%, die horizontalen Verschiebungen reduzieren sich etwa um 42% (Tabelle 10).

<b>Vertikale Verschiebung bei „laden load“</b>		
ursprüngliche Dimension:	86.2 mm	100%
angepasste Dimension	64.5 mm	75%
<b>Horizontale Verschiebung bei „laden load“</b>		
ursprüngliche Dimension	7.4 mm	100%
angepasste Dimension	4.3 mm	58%

Tabelle 10: Berechnete Verschiebungen (Modell 2) des Eco-Bogie bei „laden load“.

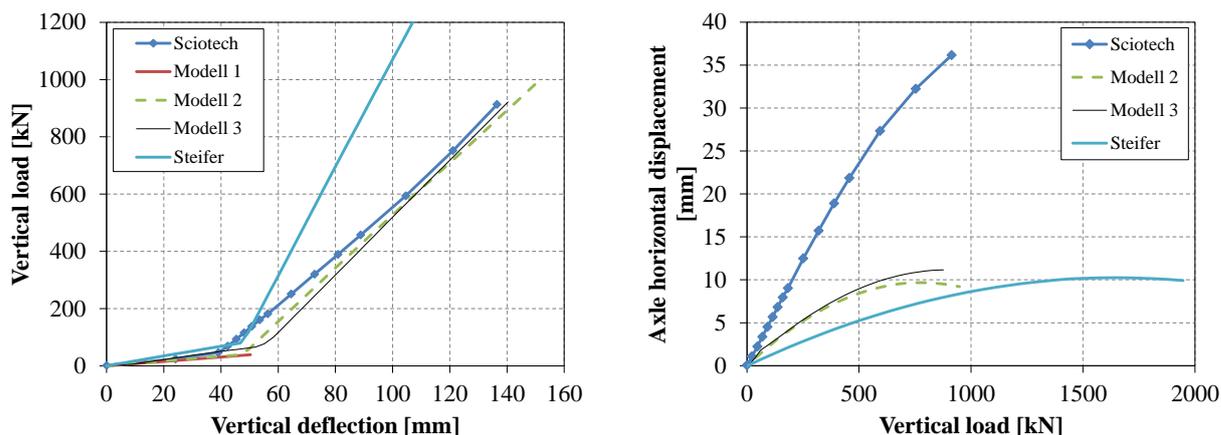


Abbildung 10: Vergleich der Kraft-Verschiebungskurven mit den ursprünglichen und angepassten Dimensionen.

### g. Schlussfolgerung aus der FE-Modellierung und Beurteilung

Aufgrund der Berechnungen mit den drei FE-Modellen können folgende Beurteilungen vorgenommen werden:

- Die vertikale bilineare Verschiebungskurve („tare“ und „laden load“) aus der statischen Belastung des Drehgestells von Sciotech angegeben, würde in etwa wie gewünscht funktionieren. Allerdings können die speziellen Randbedingungen der „axle box“ erst mit Hilfe eines 1:1 Prototyps geklärt werden.
- Eine Erhöhung der Anzahl Schichten ergibt eine Vergrößerung der Steifigkeiten und Verkleinerung der Verschiebungen in vertikaler UND horizontaler Richtung, d.h. das Verformungsverhalten des Systems kann durch Erhöhung und Reduktion der Anzahl Schichten variiert werden. Allerdings hat dies jeweils einen Einfluss auf das Verschiebungs bzw. Steifigkeitsverhaltens in alle Richtungen.
- Bei Voll-Last sind statische Längsspannungen in der Größenordnung von maximal etwa 120-150 MPa zu erwarten. Statisch sollten solche Längsspannungen vom gewählten GFK aufgenommen werden können, es erscheint aber eher fraglich, ob die Ermüdungsfestigkeit von GFK genügend ist. Ebenfalls scheint die Zeitstandsfestigkeit eher kritisch zu sein. Einige Erklärungen zu diesen beiden Themen (Ermüdung und Zeitstand) sind nachfolgend dargestellt.

#### Ermüdungsfestigkeit

Das Ermüdungsverhalten des speziellen Laminats, das für den Drehgestell zu verwenden ist muss experimentell bestimmt werden. Aus bereits vorhandenen Experimenten an ähnlichen Laminaten kann die Ermüdungsfestigkeit nur grob geschätzt werden.

Abbildung 11 zeigt beispielhaft die Ermüdungsfestigkeit von Glasfaser verstärktem Kunststoff (E-Glass mit Polyester) das der Untersuchung [5] von Professor Thomas Keller der EPFL entnommen wurde. Bei Lastzyklen in der Größenordnung von mehreren Millionen reduziert sich die maximale Ermüdungs-

zugspannung im Vergleich zur Kurzzeitfestigkeit deutlich. In diesem Beispiel liegt die Ermüdungszugspannung nach mehreren Millionen Lastwechseln etwa bei 100 MPa.

Durch eine Ermüdungsbeanspruchung kann sich ausserdem die Steifigkeit des GFK's reduzieren, siehe Anhang. Dies muss natürlich unter allen Umständen verhindert werden, da die Steifigkeit des Drehgestells die Fahrstabilität beeinflusst, siehe die Diskussion unten.

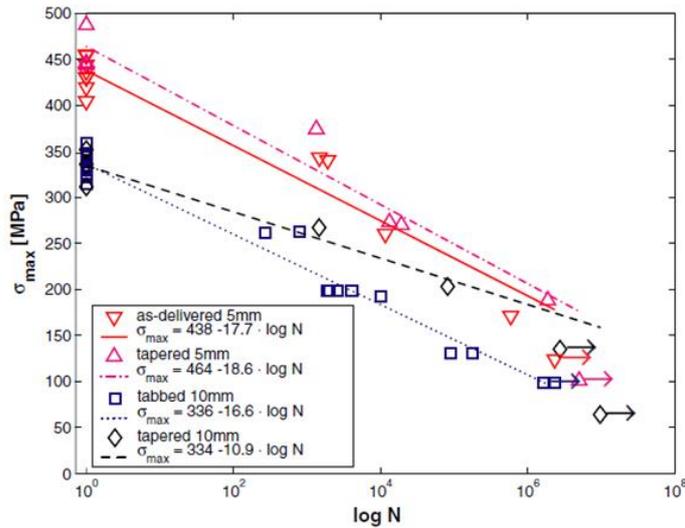
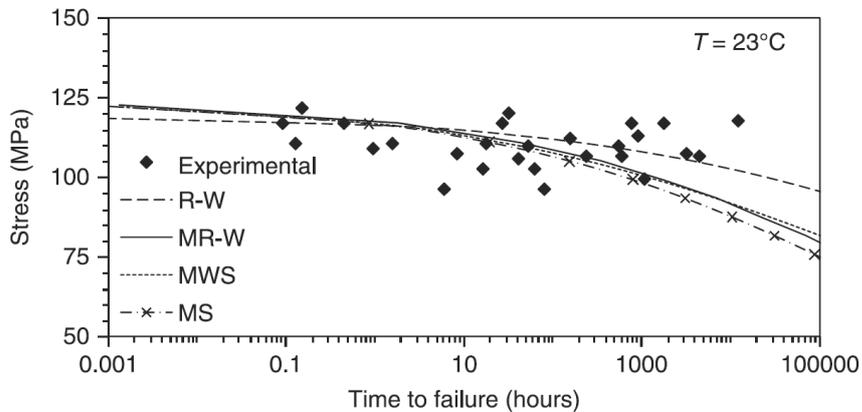


Fig. 9. S-N fatigue life curves in semi-logarithmic representation.

Abbildung 11: Zugspannung-Anzahl Zyklen-Diagramm aus [5] von GFK.

### Zeitstandsfestigkeit

Wie bereits in Kapitel 3 erwähnt, haben Glasfasern eine ausgeprägte Reduktion der Festigkeit durch Langzeitlasten. Abbildung 12 zeigt beispielhaft den Abfall der Festigkeiten bei Dauerlasten, die [6] entnommen wurde.



12.10 Experimental and calculated creep lifetime for glass-fibre/urethane composite at 23°C.

Abbildung 12: Dauer-Zugspannung Zeit Verhalten von GFK, aus [6].

## Umweltbedingungen

Natürlich beeinflussen die Temperatur, Feuchtigkeit und sonstige Umgebungsbedingungen die Ermüdungs- und Dauerstandsfestigkeit und es ist sehr wichtig, dass diese in den durchzuführenden Experimenten entsprechend untersucht werden.

Eindrücklich zeigt den Einfluss der Temperatur auf die Dauerstandsfestigkeit beispielweise die Untersuchung [7] in der ein Dauerhaftigkeitsbasiertes Bemessungskriterium für einen Kurzglasfaser Verbundwerkstoff für die Autoindustrie entwickelt wurde. Das Kriterium war eine zulässige Spannung in Prozent der mittleren Zugfestigkeit bei Raumtemperatur. Zitat : *These allowables vary from 56% of the UTS for short-time loadings at room temperature in air to 12% for  $10^8$  cycles at room temperature in air and just 3% in the case of a sustained load at 120°C with both environmental and prior load effects taken into account [7].*

## 5. Vergleich Y25-Bogie mit Eco-Bogie und Beurteilung

In Tabelle 11 ist ein vereinfachter Vergleich des konventionellen Y25-Bogies mit dem neuartigen Eco-Bogie dargestellt. Man kann davon ausgehen, dass das Eco-Bogie Drehgestell weniger Lärm verursacht und ein tieferes Gewicht hat, was für den Energiebedarf von Vorteil ist. Betreffend Dauerhaftigkeit und Unterhalt (ohne Verschleissteile) haben beide Konzepte ihre Vor- und Nachteile, werden hier aber in etwa als gleichwertig bewertet. Die Bearbeitbarkeit wird hingegen beim Y25-Drehgestell als besser beurteilt, da wenn z.B. neue Befestigungen nötig sind, bei GFK nicht einfach neue Löcher gebohrt werden können. Es wird angenommen, dass die Herstellkosten beim Eco-Bogie deutlich grösser sind. In Tabelle 12 sind ausserdem die verschiedenen Steifigkeiten angegeben. Wichtig dabei sind folgende Grundsätze:

- je kleiner die vertikale Steifigkeit desto besser die Entgleisungssicherheit
- je kleiner die Längs-Steifigkeit desto
  - besser die Radialeinstellung (weniger Lärm und Verschleiss, bringt aber beim Ecobogie nur etwas bei höheren Geschwindigkeiten, siehe [1, 2])
  - schlechter die Fahrstabilität (aufschaukeln bei gerader Strecke)

Beurteilung: Das Dimensionierungskonzept des Y25-Bogies ist fertig entwickelt und bewährt. Da die verschiedenen Bauteile (Rahmen, Dämpfer, Federn etc.) verschiedene Aufgaben übernehmen, ist dieses Konzept deutlich einfacher als beim Eco-Bogie in dem der GFK-Rahmen alle Aufgaben übernehmen muss. Dieses Dimensionierungskonzept ist sehr komplex. Da die Fahrstabilität ungenügend ist, müsste ein Weg gefunden werden, wie die Längssteifigkeit erhöht werden kann, ohne die vertikale Steifigkeit zu erhöhen. Ob dies möglich ist, scheint beim momentanen Kenntnisstand eher als unwahrscheinlich.

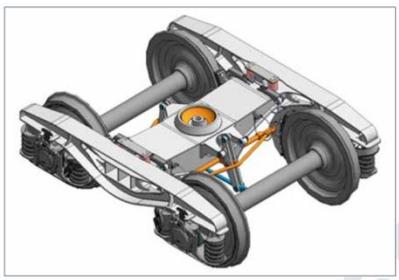
	 <small>Fig. 1: Y25 bogie with a steel bogie frame and pusher brake blocks for 22.5 tonne axle load</small>	 <small>Fig. 2: Eco-bogie with GFRP bogie frames and GRP axle ties to limit axle length and disc brakes for a 22.5 tonne axle load [2]</small>
Bezeichnung	Y25-Bogie	Eco-Bogie
Material	Stahl	GFK
Lärm	grösser	
Gewicht	grösser	
Dauerhaftigkeit	ähnlich	ähnlich
Unterhalt	ähnlich	ähnlich
Kosten		grösser
Bearbeitbarkeit	besser	
Dimensionierung	Einzelne Teile wie Rahmen, Dämpfer, Federn etc. werden einzeln für bestimmte Aufgaben dimensioniert.	Ein Bauteil wird für alle Aufgaben dimensioniert. → sehr komplex

Tabelle 11: Vergleich konventionelles Drehgestell Y25 mit Eco-Bogie.

Zustand	Steifigkeit [kN/mm]	
	Y25-Bogie	Sciotech: Eco-Bogie
Vertikal unter "tare load"	4	1.1
Vertikal bis "laden load"	10	8.3
Horizontal	$\infty$ *	20.7

Tabelle 12: Übersicht der vertikalen Steifigkeiten der verschiedenen Modelle (\*: abgesehen von einem nominellen Längsspiel je Radsatzlager von 4 mm).

## 6. Kurzzusammenfassung lauftechnische Validierung des Drehgestells durch die Firma PROSE

Die Firma PROSE führte fahrdynamische Simulationen zur Ermittlung der

- Fahrstabilität (aufschaukeln bei gerader Strecke)
- Kurven- und Wankverhalten (wackeln des Güterwagens, Ausnützung Lichtraumprofil)
- Entgleisungssicherheit

des Eco-Bogie Drehgestells durch. Als Grundlage für die Berechnungen dienten die Steifigkeiten wie von Sciotech angegeben. Siehe auch Kapitel 4 zum FE Modell zur Bestätigung dieser Steifigkeiten.

Die wichtigste Erkenntnis dieser Berechnungen ist, dass die Fahrstabilität des vorliegenden Eco-Bogie Drehgestells Konzeptes ungenügend ist. Der Grund dafür ist, dass die Längssteifigkeit (Änderung Achsabstand durch vertikale Last) zu klein ist. Bei konventionellen Drehgestellen wie z.B. der Y25-Bogie ist der Achsabstand praktisch unveränderlich und somit konstant (abgesehen von etwas Spiel).

## 7. Empfehlung an BAFU betreffend weiteres Vorgehen

Als erstes muss das BAFU entscheiden ob das Thema weiterverfolgt oder abgeschlossen wird. Falls das Projekt weitergeführt werden soll, wird folgendes Vorgehen empfohlen:

- Sciotech liefert ein neues Design um die angesprochenen Probleme zu lösen (grössere Längssteifigkeit ohne vertikale Steifigkeit zu erhöhen).
- Empa/PROSE überprüfen dieses nochmals Mithilfe Ihrer numerischen Modelle
- Wenn positiv, könnte der Bau eines Prototyps ins Auge gefasst werden. Anschliessend sind eine ganze Reihe von Versuchen nötig:
  - Materialcharakterisierung (Steifigkeiten, Statische und Ermüdungsfestigkeit des GFK)
  - Dauerhaftigkeit bezüglich Temperatur, Feuchtigkeit etc. des GFK
  - Dynamische Versuche am gesamten Bauteil: Laufversuche etc.

## 8. ANHANG

### 1. Introduction to fiber reinforced polymers (FRP)

A composite material is a material made from two or more constituent materials with different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components. The new material may be preferred for many reasons: common examples include materials which are stronger, lighter, or less expensive when compared to traditional materials [8].

Typical engineered composite materials include:

- Mortars, concrete
- Reinforced plastics, such as fiber-reinforced polymer
- Metal composites
- Ceramic composites (composite ceramic and metal matrices)

Composite materials are generally widely used in aerospace, automotive, sporting good, chemical industry, general engineering, missiles, nuclear energy and structures such as boats, swimming pool panels, race car bodies, bathtubs, storage tanks, imitation granite and cultured marble sinks and countertops. The most advanced examples are employed routinely on spacecraft and aircrafts [8].

The earliest man-made composite materials were bricks for building construction. Concrete is also a composite material, and is used more than any other man-made material in the world. Woody plants, both true wood from trees and such plants as palms and bamboo, yield natural composites that were used prehistorically by mankind and are still used widely in construction and scaffolding. Plywood gluing wood at different angles gives better properties than natural wood. The first artificial fiber reinforced plastic was Bakelite which dates to 1907, although natural polymers such as shellac predate it. One of the most common and familiar composite is fiber reinforced polymer (FRP) made of a polymer matrix reinforced with fibers. FRPs are a category of composites that specifically use fiber materials to mechanically enhance the strength and stiffness of plastics. The original plastic material without fiber reinforcement is known as the matrix/resin. The matrix is a tough but relatively weak material that is reinforced by stronger stiffer reinforcing filaments or fibers. The extent that strength and stiffness are enhanced in a fiber reinforced polymer depends on the mechanical properties of the fiber and matrix, their volume relative to one another, and the fiber length and orientation within the matrix.

### 2. Resin matrix

The resin system holds everything together, and transfers mechanical loads through the fibers to the rest of the structure. In addition to binding the composite structure together, it protects from impact, abrasion, corrosion, other environmental factors and rough handling [9]. Resin systems come in a variety of chemical families, each designed and designated to serve industries providing certain advantages like economic, structural performance, resistance to various factors, legislation compliance, etc.

Preferred resin characteristics include the following [10]:

- Low cost
- High elastic modulus
- Resin viscosity ranging from 100 to 500 cps
- High T<sub>g</sub> (70 °C or higher)
- Low moisture absorption
- Gel time of at least 20 min (workability time)
- Preferably curable at room temperature
- High toughness
- High chemical/corrosion resistance properties

In past, high cost of polymers was a limiting factor in their use for commercial applications. Currently, use of fillers in matrixes improved the properties of composites and ultimately reduced the cost of the product.

In following, some of the most common resins of the thermoplastic and thermoset families and the ones mostly used in FRP composite materials are described.

### ***Thermoplastic and thermosetting polymers***

**Thermoplastic polymers** are long chain molecules held together by relatively weak Van der Waals forces but the chemical valency bond along the chains is extremely strong, therefore, they derive their strength and stiffness from the inherent properties of the monomer units and the very high molecular weight [11]. These polymers will be either amorphous which implies a random structure with a high concentration of molecular entanglement or they will be crystalline with a high degree of molecular order or alignment. In the amorphous polymer, the random structure will become disentangled during heating and will change the material from a solid to a viscous liquid, whereas heating the crystalline polymer will change it to an amorphous viscous liquid. However, it is difficult to make a polymer which has a pure crystalline structure because of the complex physical nature of the molecular chains, consequently, the so-called 'crystalline' polymer should more correctly be described as semi-crystalline.

The main thermoplastic polymers used in FRP composite materials are polypropylene, polyethylene and polyester.

**Thermosetting polymers** are usually made from liquid or semi-solid precursors which harden irreversibly; this chemical reaction is known as polycondensation, polymerization or curing and on completion, the liquid resin is converted to a hard solid by chemical cross-linking which produces a tightly bound three-dimensional network of polymer chains. The molecular units forming the network and the length and density of the cross-links of the structure will influence the mechanical properties of the material; the network and length of the units are a function of the chemicals used and the cross-linking is a function of the degree of cure.

The main thermoset polymers used in FRP composite materials are the **epoxies**, the **vinylesters**, unsaturated **polyesters** and the **phenolics**.

In Table 1 the maximum continuous-use temperature for various thermosets and thermoplastics are presented.

Table 1 Maximum continuous-use temperature for various thermosets and thermoplastics [12]

Materials	Maximum continuous-use temperatures (°C)
<b>Thermosets</b>	
Vinylester	60–150
Polyester	60–150
Phenolics	70–150
Epoxy	80–215
Cyanateesters	150–250
<b>Thermoplastics</b>	
Polyethylene	50–80
Polypropylene	50–75
Acetal	70–95
Nylon	75–100
Polyester	70–120
Poly(phenylene sulfide)	120–220
Poly(ether ether ketone)	120–250
Teflon	200–260

### ***Polyesters resins***

Unsaturated polyester resins are the simplest, most economical resin systems that are easiest to prepare and show good performance. They are the most common systems used in composites by the wind turbine industry for the manufacture of blades. They are the most affordable, are easily processed, and possess adequate mechanical properties. However, most polyesters are brittle resins and have low-temperature resistance and significant moisture sensitivity. Generally, polyesters exhibit somewhat limited thermal stability, chemical resistance, and processability characteristics. Applications include transportation markets (large body parts for automobiles, trucks, trailers, buses), marine (small and large boat hulls and other marine equipment), building (panels, bathtub and shower shells), appliances etc.

### ***Epoxy resins***

Epoxy resins are a broad family of materials. The most common ones are prepared from the reaction of bis-phenol A and epichlorohydrin and contain a reactive functional group in their molecular structure. Epoxy resin systems show extremely high three dimensional crosslink density which results to the best mechanical performance characteristics of all the resins. Epoxy resins are widely used for high-performance composites, especially in aerospace, military, and sports industries. Epoxy resins generally offer an increase in mechanical properties compared to polyesters and vinylesters, but at a higher cost. Another disadvantage of epoxies is their relatively high water absorption rate in comparison with vinylesters. Epoxy resins are usually obtained in a two- or three-part system, which reacts when mixed together at the proper temperature. The toughness of the epoxies depends on the length of the polymer chain between the epoxy groups. Longer chains (higher molecular weight) result in tougher polymers.

Epoxyes are usually more expensive than unsaturated polyesters, but show important advantages. Epoxyes are stronger, stiffer, tougher, more durable, and more solvent resistant and have a higher maximum operating temperature than polyester thermosets. Epoxyes have high temperature resistance and good resistance to solvents and alkalis but generally have weak resistance to acids. The toughness of the epoxyes is superior to that of the polyester resins and therefore they will operate at higher temperatures. They have good adhesion to many substrates and low shrinkage during polymerization. This allows moldings of high quality, with good dimensional tolerance to be manufactured. Epoxyes generally have a high temperature resistance and can be used at temperatures up to 180°C with some epoxyes having a maximum temperature range up to 300°C (in the case of hot curing epoxyes).

### ***Vinylester resins***

Vinylesters are unsaturated esters of epoxy resins. They therefore have similar mechanical and in-service properties to those of the epoxy resins and equivalent processing techniques to those of the polyesters. Indeed, they are often identified as a class of unsaturated polyester, because of the cure and processing similarity. Generally the vinylesters have good wetting characteristics and bond well to glass fibers. They possess resistance to strong acids and strong alkalis and they can be processed at both room and elevated temperatures. Compared to polyesters, vinylesters offer reduced water absorption and shrinkage as well as enhanced chemical resistance.

Vinylesters are a chemical mixture of unsaturated polyesters and epoxy resins. The result is a resin with mechanical, thermal, and chemical properties similar to epoxyes, Table 2, with the ease of processing and high rate of cross-linking of unsaturated polyesters. Vinylester resins are also stiff and brittle, but are tougher than polyesters because of the presence of the epoxy backbone. Even further improved polyester, it is bisphenol chlorinated, or a combination of polyester and epoxy. Its curing, handling and processing characteristics are those of polyester, and it exhibits higher test results in corrosion temperature resistance and strength and has higher cost. Modifications of the molecule have produced even higher properties.

Vinylesters are well known for the resistance to environmental conditions because their high reactivity achieves complete curing more easily and rapidly than for polyesters. Vinylesters show higher elongation at break than polyesters, which also makes them tougher. The chemical resistance of vinylesters is generally greater than that of polyesters because of the influence of the methyl group.

### ***Polyurethane resins***

Polyurethane resins can be either thermoset or thermoplastic. Polyurethanes are formed by reacting two monomers, each with at least two reactive groups. Polyurethanes are very versatile polymers. Polyurethanes show superior toughness and elongation to failure; therefore, they are used in the automotive industry, for example, to manufacture car bumpers. Mechanical properties of polyurethanes will depend on the type of the monomer used. Ether-based polyurethanes show the highest mechanical properties and are also known for their short and fast solidification times, which makes them suitable for processing methods with faster injection times. There are semi-rigid and rigid polyurethanes. A low T<sub>g</sub> caused by the flexible polyol chains is a characteristic of semi-rigid polyurethanes, which results in good

flexibility. Rigid polyurethanes can be used at temperatures up to 150 °C because of the cross-link structure of the matrix material.

Table 2 Typical properties of three most used thermoset resins, adapted from [13]

	<b>Polyester</b>	<b>Epoxy</b>	<b>Vinylester</b>
Density (g/cm <sup>3</sup> )	1.1–1.4	1.2–1.4	1.04–1.1
Tensile modulus (GPa)	1.6–4.1	2.5–5.0	3.2–3.6
Tensile strength (MPa)	35–90	50–110	68–80
T <sub>g</sub> (°C)	70–120	100–270	100–150
Cost	Inexpensive	Very expensive	Expensive
Main application	<ul style="list-style-type: none"> <li>• Widely used for FRP components</li> </ul>	<ul style="list-style-type: none"> <li>• Used in wet lay-up applications and laminate fabrication</li> <li>• Outstanding adhesion and bonding characteristics</li> </ul>	<ul style="list-style-type: none"> <li>• Used commonly in FRP rebars (alkali resistance)</li> <li>• Reduced moisture absorption and shrinkage</li> </ul>
Viscosity (cps)	500	900	200

### ***Isophthalic resins***

Often referred to as Iso, it is improved polyester. It has a slightly higher cost, improved strength, thermal stability and mild resistance to corrosion conditions. Improved resistance to water permeation has prompted its use as a gel barrier coat in marine applications. Improved chemical resistance has led them to extensive use in underground petroleum tanks with satisfactory service life. They are also used in salts and mild acids.

### ***Phenolic resins***

Phenolics are a class of resins commonly formed by the reaction of phenol (carbolic acid) and formaldehyde, and catalyzed by an acid or a base. Their curing characteristics are different from other thermosetting resins such as epoxies because water is generated during the curing reaction. Phenolics are used for aircraft interiors, stowbins, and galley walls, as well as other commercial markets that require low-cost, flame-resistant, and low-smoke products. Phenolic composites have many desirable performance qualities, including high temperature resistance, creep resistance, excellent thermal insulation and sound damping properties, corrosion resistance, and excellent fire/smoke/smoke toxicity properties. Phenolics are used for various composite manufacturing processes such as filament winding, injection molding, and compression molding. Phenolics provide easy processability, tight tolerances, reduced machining, and high strength. Because of their high temperature resistance, phenolics are used in exhaust components, missile parts, manifold spacers, commutators, and disc brakes.

Phenolics have good dimensional stability and resistance to acids and have good flame retardant properties, low smoke generation and high heat resistance. In addition, they have high resistance to water vapor transmission and water uptake. They are not stable in ultraviolet radiation. The finished colors of phenolic resins will either be black or brown. Additives and fillers can customize resins to improve their suitability for specific applications. Additives are used to tailor processability (e.g. reduce viscosity, reduce

resin shrinkage) or to alter material properties (e.g. increase toughness). Depending upon the material selected, fillers can impart improved smoke and fire resistance, mechanical strength, water resistance and surface smoothness.

### 3. Fiber reinforcements

The fibers are usually glass, carbon, aramid, or basalt. Rarely, other fibers such as paper or wood have been used. The polymer is usually an epoxy, vinyl ester or polyester thermosetting plastic, and phenol formaldehyde resins are still in use. The development of fiber reinforced polymer for commercial use was being extensively researched in the 1930s. Today, each of these fibers is used widely in industry for any applications that require plastics with specific strength or elastic qualities. Glass fibers are the most common across all industries, although carbon-fiber and carbon-fiber-aramid composites are widely found in aerospace, automotive and sporting good applications. These three (glass, carbon, and aramid) continue to be the important categories of fiber used in FRP.

#### ***Glass fibers***

Mass production of glass strands was discovered in 1932 when Games Slayter, a researcher at Owens-Illinois, accidentally directed a jet of compressed air at a stream of molten glass and produced fibers. Glass fiber is by far the most predominant fiber used in the reinforced polymer industry as the most multipurpose fiber [14].

Fibers made from glass are manufactured in many varieties for specific uses. It typically has a silica content of greater than 50 percent, and the composition with different mineral oxides give the resulting product its distinct characteristics. Various glass types, classified by ASTM C 162 [15], are as below, Table 3 and Figure 1:

**A-glass** - Alkali glass made with soda lime silicate. Used where electrical resistivity of E-glass is not needed. A-glass or soda lime glass is the predominate glass used for containers and windowpanes.

**AR-glass** – Alkali Resistant glass made with zirconium silicates. It is used mainly in Portland cement substrates.

**C-glass** – Corrosive resistant glass made with calcium borosilicate. It is used mainly in acid corrosive environments.

**D-glass** – Low dielectric constant glass made with borosilicate. It is used mainly in electrical applications.

**E-glass** – Alkali free, highly electrically resistive glass made with alumina-calcium borosilicate. E-glass is known in the industry as a general-purpose fiber for its strength and electrical resistance. It is the most commonly used fiber in the fiber reinforced polymer composite industry.

**ECR-glass** – An E-glass with higher acid corrosion resistance made with calcium aluminosilicate. It is used where strength, electrical conductivity and acid corrosion resistance is needed.

**R-glass** – A reinforcement glass made with calcium aluminosilicate used where higher strength and acid corrosion resistance is needed.

**S-glass** – High strength glass made with magnesium aluminosilicate. It is used where high strength, high stiffness, extreme temperature resistance, and corrosive resistance is needed.

**S-2 glass** – Glass similar to S-glass, but with somewhat improved properties. S-2 fiber glass is the ultimate in high strength glass fiber that provides the highest level of performance available in all glass fibers. It is produced with a higher level of silica than standard glass fiber. It offers the ultimate physical properties including high tensile and compressive strength, high temperature resistance, and improved impact resistance.

Fibers used for structural reinforcement composites generally fall into the categories of E-glass, AR-glass and S-glass. Of all the fibers available for structural strengthening and reinforcement, E-glass is by far the most used and is the least expensive.

Table 3 Glass Filament Typical Mechanical Properties [14]

Fiber type	Density (g/cm <sup>3</sup> )	Tensile Strength MPa	Modulus GPa	Elongation %
A-glass	2.44	3300	72	4.8
AR-glass	2.7	1700	72	2.3
C-glass	2.56	3300	69	4.8
D-glass	2.11	2500	55	4.5
E-glass	2.54	3400	72	4.7
ECR-glass	2.72	3400	80	4.3
R-glass	2.52	4400	86	5.1
S-glass/S-2 glass	2.53	4600	89	5.2

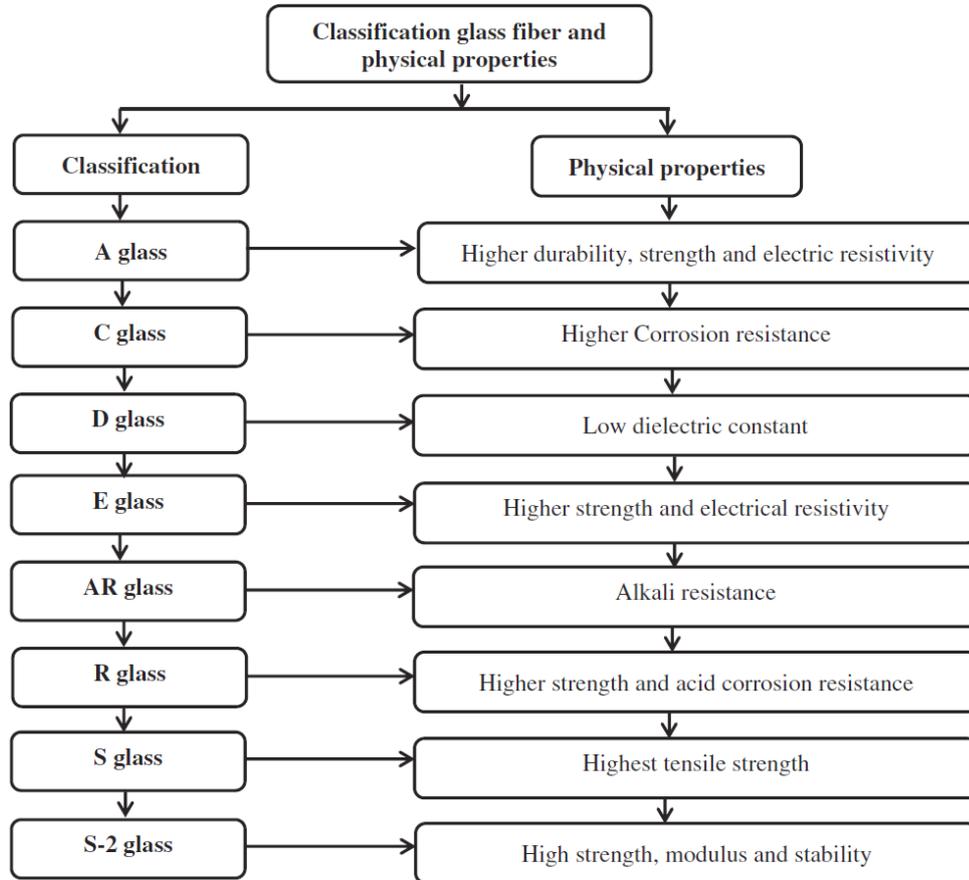


Figure 1 Classification and physical properties of various glass fibers [16]

### **Carbon fibers**

Carbon fiber production began in the late 1950s and was used in industry beginning in the early 1960s. The carbon fibers play a crucial role in a variety of specialized applications such as aerospace, automobiles, chemical industry, general engineering, missiles, nuclear energy, reinforcement in composite materials, and textiles, owing to their inherent properties, including high strength and stiffness, dimensional stability, low coefficient of thermal expansion, biological compatibility, and fatigue resistance. Carbon fibers have been classified on the basis of the fiber structure and degree of crystallite orientation: ultrahigh-modulus (UHM), high-modulus (HM), intermediate-modulus (IM), high-tensile-strength (HT), and isotropic carbon fibers.

Carbon fibers generally have excellent tensile properties, low densities, and high thermal and chemical stabilities in the absence of oxidizing agents, good thermal and electrical conductivities, and excellent creep resistance [10].

### **Aramid fibers**

Aramid fibers are high strength fibers that are better known for their use in bullet- and fire-resistant clothing. High strength, high elastic modulus, and high abrasion resistance make these fibers well suited for fiber reinforced polymer (FRP) reinforcement and strengthening applications, Table 4. Aramid is a synthetic fiber made from the polymer aromatic polyamide. It was first introduced in the 1960s as a meta-

aramid and later as para-aramid. The chemical bonds of a para-aramid are aligned in the long direction of the fiber. Meta-aramid bonds are not aligned but are rather in a zigzag pattern and therefore will not develop the higher tensile strength of para-aramid bonds [17].

- Meta-Aramid: Fibers made from meta-aramid have excellent thermal, chemical and radiation resistance and are to make flame retardant textiles such as outerwear for fire fighters and racing car drivers. Meta-aramid has a low compressive strength and absorb and dissipate energy perpendicular to the fiber direction making it the preferred fiber used in bullet-proof vests and other ballistic resistant, personnel armor.
- Para-Aramid: Higher strength para-aramid filaments are those more commonly used in fiber reinforced polymers for civil engineering structures, stress-skin panel, and other high tensile strength applications. An advantage of these fibers is that they are flexible and highly abrasion resistant making them an ideal choice for high strength braids and ropes. For anchoring FRPs to structures, these fibers are an excellent choice due to their ability to form around small radius.

Table 4 Properties of a few of the most popular para-aramid products [17].

Fiber type	Density, (g/cm <sup>3</sup> )	Tensile Strength, MPa	Modulus, GPa	% Elongation
Kevlar 29	1.44	2920	83	3.5
Kevlar 49	1.44	3600	124	2.9
Kevlar 149	1.47	3450	179	1.5
Technora T-200	1.39	3000	70	4.4
Twaron	1.44	3000	80	3.3
Twaron HM	1.45	3000	124	2.0

### **Comparison of different fibers**

In this section, the characteristic properties of three most used fibers in the industry are compared to each other and in some cases compared to normal steel, Table 5, Table 6, Figure 2, and Figure 3.

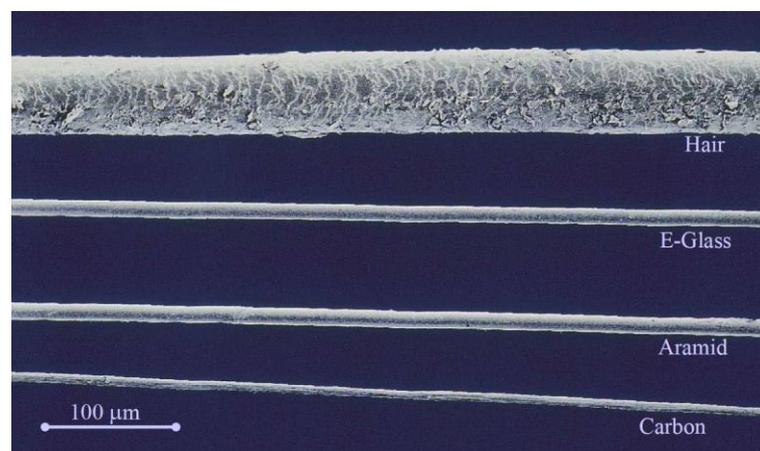


Figure 2 Comparison of the fiber diameter of three most common fibers to the human hair [13]

Table 5 Properties of fibers compare to normal steel

	Carbon fiber	Kevlar fiber	E-glass fiber	Steel
Single fiber tensile strength (GPa)	3.5	3.6	3.4	1.3
Specific strength, strength/weight ratio (kN.m/kg)	2000	2500	1300	170
Single fiber tensile modulus (GPa)	230	60	22	210
Density ( $10^3$ -kg/m <sup>3</sup> )	1.8	1.4	2.5	7.8

Table 6 Summary of characteristics of three most used fibers in the industry [13]

Glass Fibers	Carbon Fibers	Aramid Fibers
<ul style="list-style-type: none"> <li>• Inexpensive</li> <li>• Most commonly used</li> <li>• Several grades available:</li> <li>• E-Glass</li> <li>• R-Glass</li> <li>• AR-Glass (alkali resistant)</li> <li>• High strength, moderate modulus, medium density</li> <li>• Used in non weight/modulus critical applications</li> </ul>	<ul style="list-style-type: none"> <li>• Significantly higher cost than glass</li> <li>• Several grades available:</li> <li>• Standard modulus → 250-300 GPa</li> <li>• Intermediate → 300-350 GPa</li> <li>• High → 350-550 GPa</li> <li>• Ultra-high → 550-1000 GPa</li> <li>• High strength, high modulus, low density</li> <li>• Superior durability and fatigue characteristics</li> <li>• Used in weight/modulus critical applications</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate to high cost</li> <li>• Two grades available</li> <li>• 60 GPa elastic modulus</li> <li>• 120 GPa elastic modulus</li> <li>• High tensile strength, moderate modulus, low density</li> <li>• Low compressive and shear strength</li> <li>• Some durability concerns</li> <li>• Potential UV degradation</li> <li>• Potential moisture absorption and swelling</li> </ul>

As it can be seen in Table 6, glass fibers are the most used fibers in all domains, however carbon fibers are used in applications where high initial cost is justified, eg. Aerospace industry. The stiffness of carbon fibers are higher than steel, however their ductility is much less.

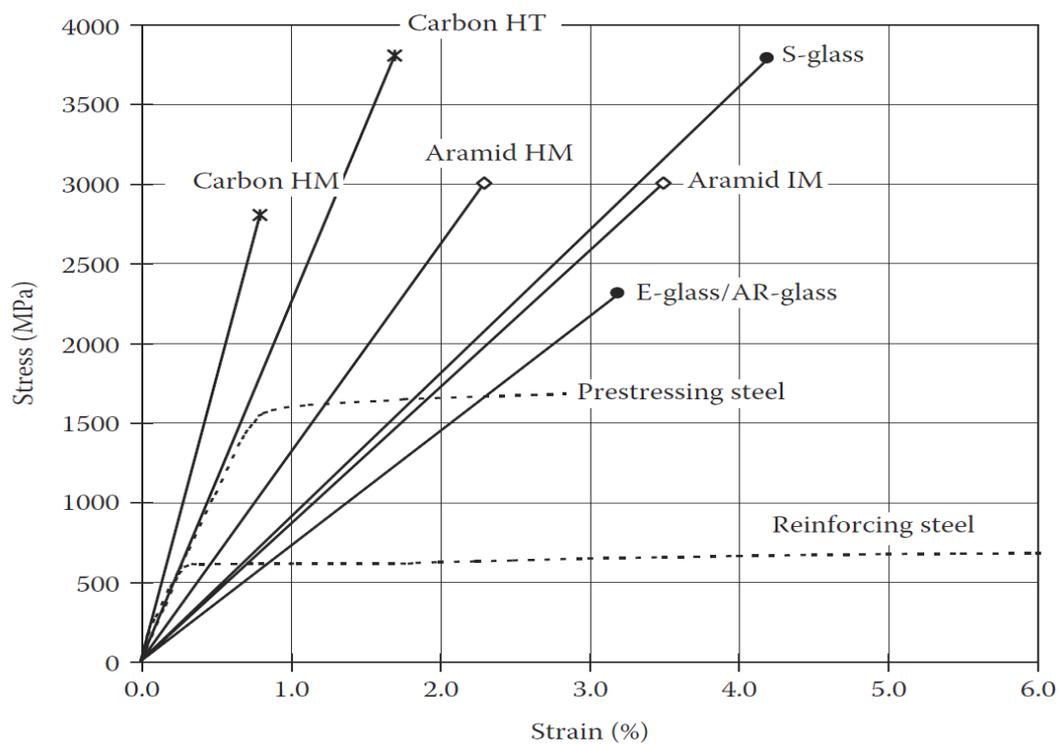


Figure 3 Stress-strain diagrams of single fibers [18]

#### 4. Fiber architecture and forms of fiber reinforcements

Regardless of the materials, reinforcements are available in different forms to serve a wide range of processes and end product requirements. Materials supplied as reinforcements include roving, milled fiber, chopped strands, and continuous, chopped, or thermoformable mats. Reinforcement materials can be designed with unique fiber architectures and can be pre-formed (shaped) depending on the product requirements and manufacturing process [10]. Fiber preforms are often manufactured in sheets, continuous mats, or as continuous filaments for spray applications. The four major ways to manufacture the fiber preform is through the textile processing techniques are: Weaving, Knitting, Braiding, and Stitching.

##### **Unidirectional**

Unidirectional reinforcements include tapes, tows, unidirectional tow sheets, and rovings (which are collections of fibers or strands). Fibers in this form are all aligned parallel in one direction and providing the highest mechanical properties. Composites using unidirectional tapes or sheets have high strength in the direction of the fiber. Unidirectional sheets are thin, and multiple layers are required for most structural applications.

### ***Rovings***

Roving consists of many individual filaments wound into a single strand. The product is generally used in processes that use a unidirectional reinforcement, such as filament winding and pultrusion. Rovings are used primarily in thermoset compounds, but can be used in thermoplastics as well.

### ***Mats***

Reinforcing mats consist of fibers laid across each other and held together by a binder. They are usually described by weight per unit area. The type and amount of binder used to hold the mat together dictate the differences between mat products. In some processes such as hand lay-up, it is necessary for the binder to dissolve. In other processes, particularly in compression molding, the binder is required to withstand the hydraulic forces and the dissolving action of the matrix resin during molding. Therefore, two categories of mats, i.e., soluble and insoluble, are produced.

### ***Woven, stitched, and braided fabrics***

Multidirectional reinforcements are produced by weaving, knitting, stitching, or braiding continuous fibers into a fabric from twisted and plied yarns. Fabrics refer to all flat-sheet, roll goods, irrespective of whether they are strictly fabrics.

**Woven fabrics** are fabricated on looms in a variety of weights, weaves, and widths. In a plain weave, each fill yarn or roving is alternately crossed over and under each warp fiber, allowing the fabric to be more drapeable and to conform to curve surfaces. Woven fabrics are manufactured, wherein half of the strands of fiber are laid at right angles to the other half ( $0^{\circ}$ – $90^{\circ}$ ).

**Stitched fabrics**, also known as nonwoven, stitched, or knitted fabrics, have optimized strength properties because of the fiber architecture. In the woven fabric, two sets of interlaced continuous fibers are oriented in a  $0^{\circ}$  and  $90^{\circ}$  pattern, where the fibers are crimped and are not straight. Stitched fabrics are produced by assembling successive layers of aligned fibers. Typically, the available fiber orientations include the  $0^{\circ}$  direction (warp),  $90^{\circ}$  direction (weft or fill), and  $\pm 45^{\circ}$  direction (bias). The assembly of each layer is then sewn together. This type of construction allows for load sharing between the fibers so that a higher modulus, both tensile and flexural, is typically observed.

**Braided fabrics** are engineered with a system of two or more yarns intertwined in such a way that all of the yarns are interlocked for optimum load distribution. Biaxial braids provide reinforcement in the bias direction only with fiber angles ranging from  $\pm 15^{\circ}$  to  $\pm 95^{\circ}$ .

### ***Chopped Strand Mat***

Multiend rovings consist of many individual strands or bundles of filaments, which are then chopped and randomly deposited into the matrix resin. Chopped strand mat is not a very strong material because of the short fiber length, Figure 4. However, it is isotropic. This means that it is equally strong in all directions. Processes such as sheet molding compound (SMC), preform, and spray-up use multiend roving. Multiend rovings can also be used in some filament winding and pultrusion applications.

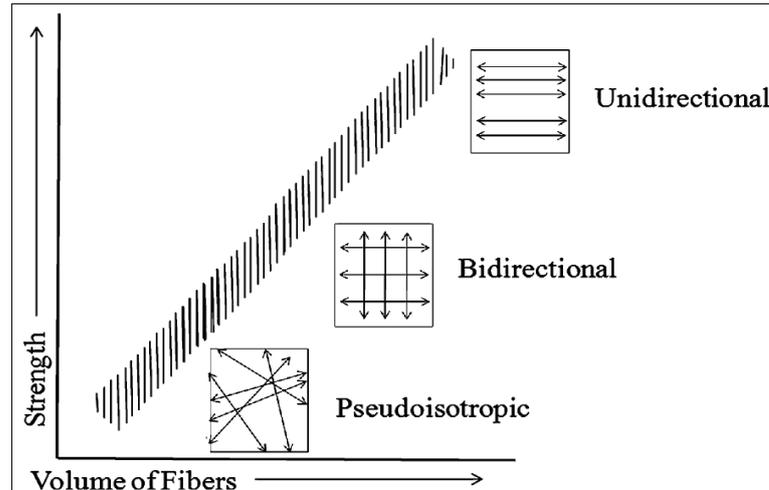


Figure 4 Relationship between strength and fiber orientation [10]

### **Prepregs**

Prepregs are a ready-made material made of a reinforcement form and polymer matrix. Thermoset or thermoplastic prepregs are available and can be either stored in a refrigerator or at room temperature depending on the constituent materials. Prepregs can be manually or mechanically applied at various directions based on the design requirements.

### **Sandwich construction**

A typical sandwich construction consists of two strong and relatively thin outer sheets or faces separated by but bounded to a layer of a less dense and low-cost core material, which has lower strength and lower stiffness, Figure 5. The faces bear most of the in-plane loading and transverse bending stresses. The core separates the faces and resists deformation perpendicular to the face, while providing a certain degree of shear rigidity along planes perpendicular to the faces. The face materials could be metals, plywood, or a FRP composite. The core could be made of materials such as foamed plastics, synthetic rubbers, balsa wood, honeycomb, and truss. The sandwich architecture provides exceptional flexural stiffness compared to monocoque structures, while reducing weight and cost.

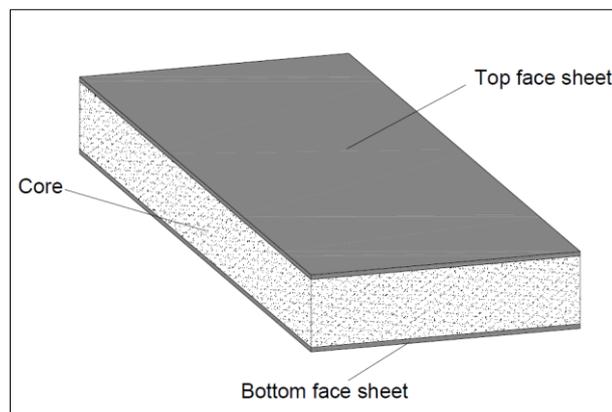


Figure 5 Typical sandwich construction

## 5. FRP Composites

Fiber reinforced polymer (FRP) composites are made by combining a plastic polymer resin together with strong reinforcing fibers. Composite materials produce a combination properties of two or more materials that cannot be achieved by either fiber or matrix when they are acting alone, Figure 6. The components retain their original form and contribute their own unique properties that result in a new composite material with enhanced overall performance. Reinforcing polymer material with fibers improves their strength and stiffness. High-strength, lightweight FRP composites (GFRP, CFRP, and AFRP) have been widely used in defense and aerospace systems for many years and have been used more recently in luxury automobiles, wind turbines, compressed gas storage tanks, and construction. Lightweight, strong and stiff materials make an attractive combination of properties for manufactured products. Lightweight materials deliver significant energy savings during transportation. Furthermore, the strength, durability, and structural properties of FRP composites are beginning to expand the service life of industrial equipment, buildings, and other infrastructure.

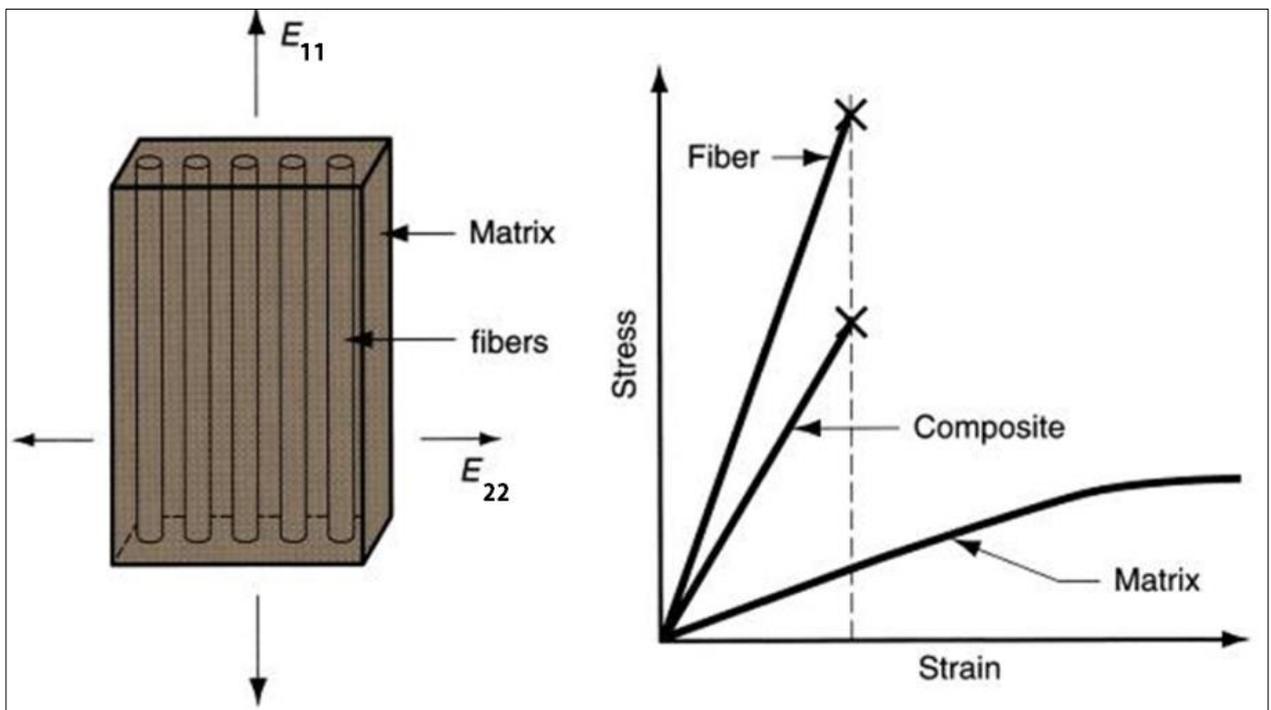


Figure 6 Comparison of the fiber/matrix stress-strain behavior to the composite

### ***Glass-fiber reinforced polymer (GFRP)***

The glass fibers are made of various types of glass depending upon the fiberglass use. These glasses all contain silica or silicate, with varying amounts of oxides of calcium, magnesium, and sometimes boron. To be used in fiberglass, glass fibers have to be made with very low levels of defects.

Fiberglass is a strong lightweight material and is used for many products. Although it is not as strong and stiff as composites based on carbon fiber, it is less brittle, and its raw materials are much cheaper. Its bulk strength and weight are also better than many metals, and it can be more readily molded into complex

shapes. Applications of fiberglass include aircraft, boats, automobiles, bath tubs and enclosures, swimming pools, hot tubs, septic tanks, water tanks, roofing, pipes, cladding, casts, surfboards, and external door skins.

### ***Carbon-fiber reinforced polymer (CFRP)***

They have been extensively used in composites in the form of woven textiles, prepregs, continuous fibers/rovings, and chopped fibers. The composite parts could be produced through filament winding, tape winding, pultrusion, compression molding, vacuum bagging, liquid molding, and injection molding.

### ***Comparison of different FRPs and some remarks***

Comparisons of different FRPs and steel are presented in Table 7, Figure 7, and Figure 8. Advantages of application of FRPs can be summarized as [13]:

- Aesthetic appeal
- Ability to mold complex shapes
- Various surface finishes available
- Lightweight
- Durability / Corrosion resistance
- Parts integration
- Cost effectiveness
- Electrical properties

Disadvantages and Limitations of FRPs are [13]:

- Properties of many important composites are anisotropic - the properties differ depending on the direction in which they are measured – this may be an advantage or a disadvantage
- Many of the polymer-based composites are subject to attack by chemicals or solvents, just as the polymers themselves are susceptible to attack
- Composite materials are generally expensive
- Manufacturing methods for shaping composite materials are often slow and costly

The reasons why FRPs are not used more are [13]:

- High cost of raw materials
- Lack of design standards
- Few 'mass production' processes available
- Properties of laminated composites:
  - Low through-thickness strength
  - Low interlaminar shear strength
- No 'off the shelf' properties - performance depends on quality of manufacture

Table 7 Typical Mechanical Properties [13]

Material	Ultimate Strength (MPa)	Elastic Modulus (GPa)	Failure Strain (%)
Glass FRP	517-1207	30-55	2-4.5
Carbon FRP	1200-2410	147-165	1-1.5
Aramid FRP	1200-2068	50-74	2-2.6
Steel	483-690	200	≥10

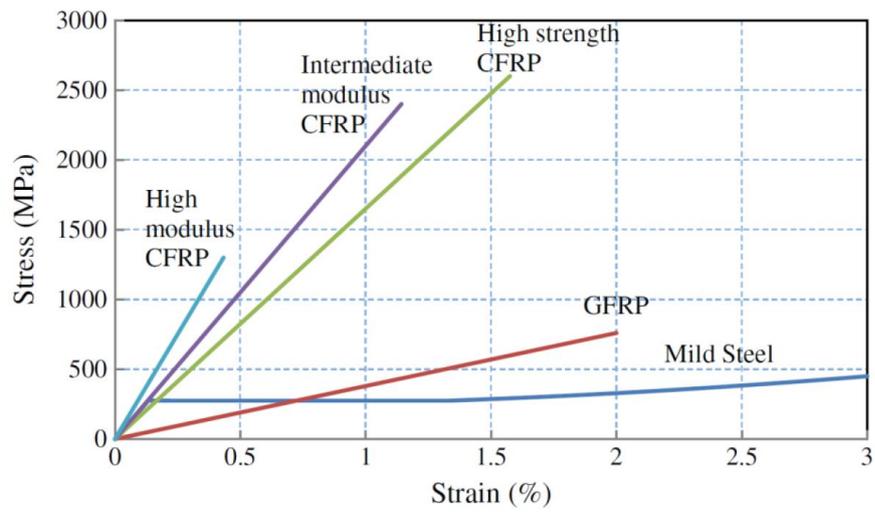


Figure 7 Stress-strain behavior of some FRP composites compared to steel [13]

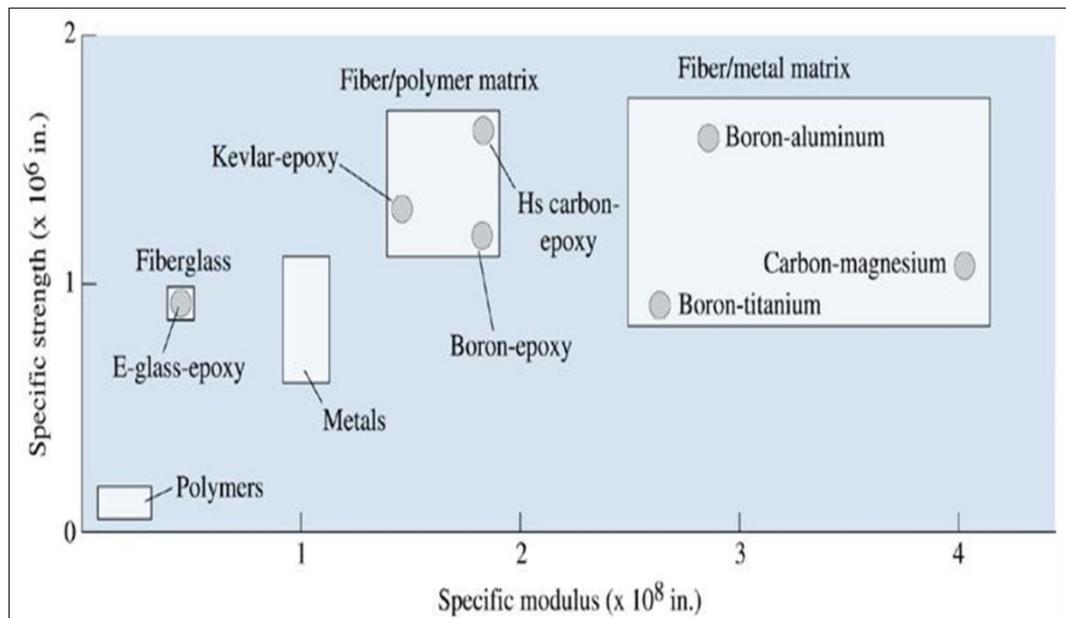


Figure 8 Comparison of the specific modulus and specific strength of several composite materials with those of metals and polymers [19].

## 6. Manufacturing methods of FRP composite materials

Researchers and industries have developed a great number of manufacturing techniques. The costs of production, as a considerable part of total costs, usually determine which will be followed for a product. Different processes usually take either low capital investment with high labor, or high capital investment with low labor. The molding processes of FRPs begin by placing the fiber preform on or in the mold [9]. The fiber preform can be dry fiber, or fiber that already contains a measured amount of resin called "prepreg". Dry fibers are "wetted" with resin either by hand or the resin is injected into a closed mold. The part is then cured, leaving the matrix and fibers in the shape created by the mold. Heat and/or pressure are sometimes used to cure the resin and improve the quality of the final part. The different methods of forming and manufacturing FRPs are briefly explained in following.

### ***Hand lay-up on open mold***

Hand lay-up is the most widely used manufacturing method. It is a simple but effective process which takes relatively low capital investment but high labor cost. "Open" molds are tools that reproduce (or duplicate) only one side of a product, or a component. For the other side another mold has to be used, and another component has to be fabricated. The two components are glued back to back and the outcome is a product with two finished "faces". Hand lay-up is performed in the following steps, see Figure 9: Pigmented gel coat is first applied by brush or spray. After gel coating, a thin coat of resin (usually polyester) and a thin layer of reinforcement are placed on, and worked by hand with brushes and rollers, so the resin fully impregnates the fabric. Other layers (usually chopped strand mat) follow, until the desired thickness and strength are achieved. After cure, the component is pulled out of the mold (or released) and trimmed. Post-curing at elevated temperatures in or out of the mold may also take place. The mold is cleaned, re-released (if no multiple release agent is used) and returned to use. Quality is relatively poor, mainly because high resin/reinforcement ratio is incorporated in the finished product (higher resin/reinforcement ratio implies lower strength/weight ratio).

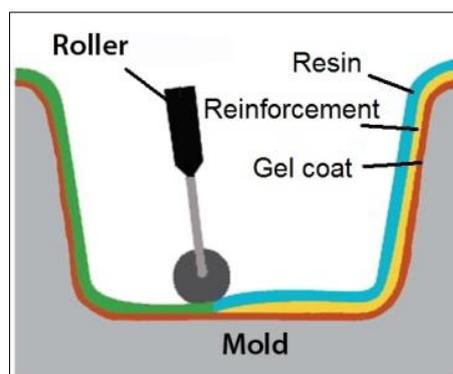


Figure 9 Schematic of the hand lay-up manufacturing process [10]

### ***Hand lay-up assisted by vacuum bagging***

The previous process can be greatly improved by vacuum bagging, with a small increase in capital investment. The gel coat and impregnating procedure is the same, but before cure, the component is

sealed on the mold under a vacuum bag. The air is drawn and the component is compressed by the atmospheric pressure against the mold surface by the vacuum bag (serving as the "upper tool".) This pressurization drives the excess resin and most of the entrapped air out of the component. The improvement in strength/weight ratio is so great, that the product can be classified even as "aerospace quality". The process is particularly useful for small production runs and prototyping.

### **Spray-up**

This relatively low capital investment process is developed for high volume production. Chopped fiber reinforcement together with resin (usually polyester) in the form of a spray are deposited simultaneously on to the released and gel-coated open-mold surface, see Figure 10. The resulting outcome closely resembles that of chopped strand mat. Quality is poor, mainly because the component incorporates a high resin ratio, but it is a very economical way of manufacturing low priced parts.

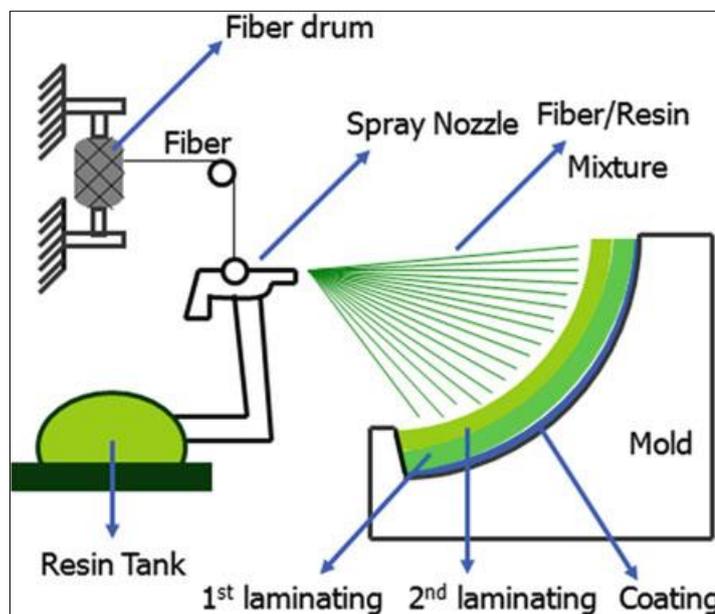


Figure 10 Schematic of the spray-up manufacturing process [10]

### **Resin infusion**

It is similar to vacuum bagging, with the difference that reinforcement is laid on the mold dry. The mold and the reinforcement are sealed and vacuum is drawn from one side. Once air-tightness is assured resin and hardener are mixed and introduced in the dry reinforcement by the sucking power of vacuum. A special "flow fabric" and network of "spiral tube" facilitate the procedure and make sure that resin travels fast everywhere in the mold cavity, and fully impregnates all the layers or dry reinforcement. The outcome is aerospace quality, repetitive, featuring very low resin content and high strength.

### **RTM and VARTM**

They are also called injection molding, this capital intensive process employs a coupling (male and a female) metal mold that is heated. The reinforcement is cut with precision and placed in the mold cavity.

Usually instead of laying the pieces of reinforcement fabric one by one, a preform is used (many different layers of reinforcement are pre-cut and held together in particular pattern, according to the shape of the mold, with the help of a "binder"). This way loading the reinforcement in the mold can be done with one move, see Figure 11. After loading the reinforcement, the two matching molds are closed tightly and catalyzed resin is pressed inside through the carefully positioned openings or injection "gates". The air is expelled through other carefully positioned openings, the "vents", and the reinforcement is saturated. The whole process can be assisted by vacuum (Vacuum Assisted RTM), see Figure 12. When full cure is reached, the component is ejected from the mold cavity. RTM is used for high production volumes. Quality is very good and highly repetitive.

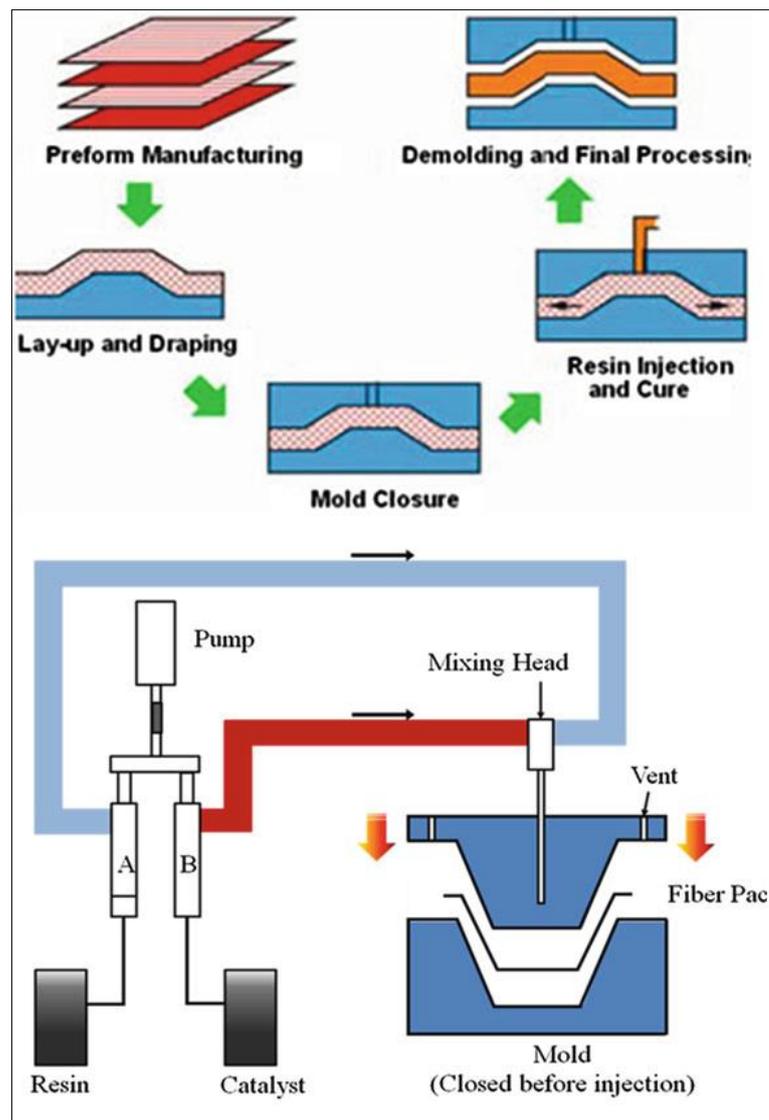


Figure 11 Components and representative configuration in the RTM process [10].

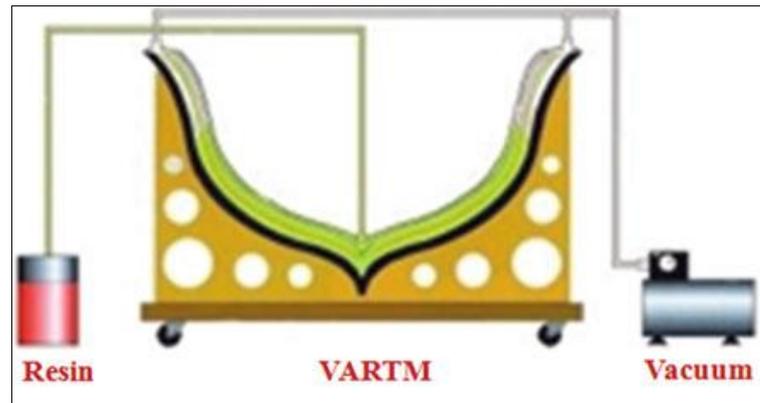


Figure 12 Vacuum-assisted resin transfer molding (VARTM) process [10]

### ***RTM light***

This process is a conjunction of RTM and resin infusion. Like RTM we have two matching molds, but here they are made out of composites. Usually upper one is thinner and more flexible than the lower. The two molds are closed (or sealed) air tightly by vacuum pressure alone or vacuum and other mechanical clamping. Catalyzed resin is pressed inside the mold. Injection pressure is much lower than in RTM, where metal molds are used. Heat may be applied, but usually, again, much lower than in RTM. However, much bigger components can be manufactured with RTM light, mainly because composite molds can be constructed much bigger. Also, it is less capital intensive than RTM.

### ***Hot press molding***

Like RTM, two matching metal molds are heated. Instead of dry reinforcement, prepregs or pre-impregnated preforms are used. Prepregs are fabrics that are pre-impregnated with resin (sometimes resin and fillers) and treated with temperature in such a way that are partially cured. When reheated in hot press molding, the resin becomes liquid again, and finally cures.

### ***Cold/warm press molding***

It is the same as hot press molding, with the difference that reinforcement is placed in the mold dry and impregnated by hand, with brush and rollers. The mold closes with lower pressure. After partial cure, pressure and temperature can be raised. Raising pressure or temperature too early will cause too much resin to escape from the cavity, leaving the reinforcement too dry or "resin starving". For lower production runs, it is a low capital intensive method, as in this process the mold can be made by composites.

### ***Filament-winding***

It is a capital-intensive process used mainly to manufacture small and large diameter tubing and pressure tanks in medium to high production volume. As the name implies, it involves the winding of continuous, pre-saturated reinforcing filaments around a rotating mandrel, until the whole surface is covered at the desired depth. The filaments are saturated as they pass through a resin bath just before they meet the mandrel, see Figure 13. The winding, depending on the complexity of the machine, can be performed in

two or more angles. Also, pre-impregnated filament can be used (prepreg winding). After cure, at the final stage of production the mandrel has to be removed, usually with the help of a hydraulic extractor. New, computer controlled machines and the use of new, innovative mandrels (like inflatable or sectional) and mandrel shapes have made possible the manufacture of surprisingly more complex components. Quality of the finished products is usually very good, as the filament reinforcement is continuous and price relatively low. However, most of the wound products are somewhat resin rich, and lack longitudinal reinforcement (mandrel rotation prohibits reinforcement to be placed along the longitudinal axis of the component).

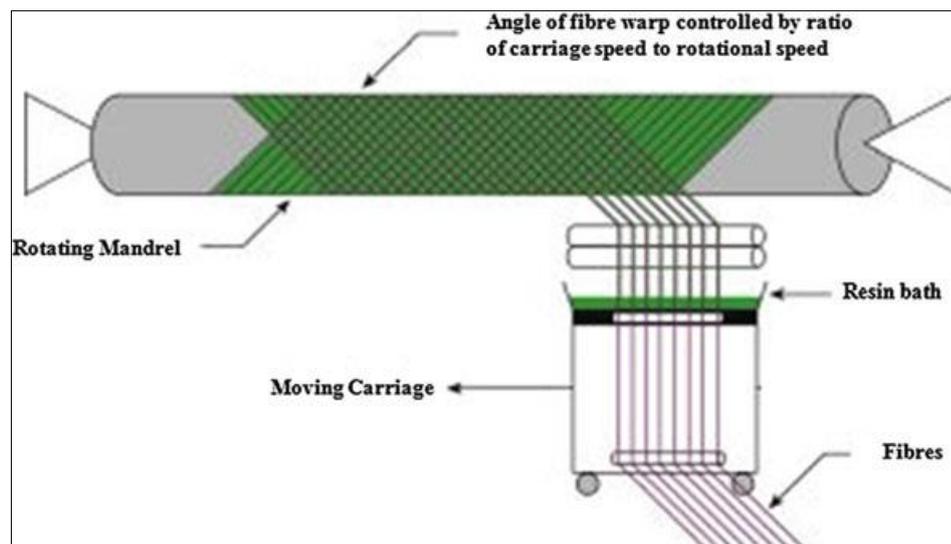


Figure 13 Schematic of the filament winding manufacturing process [10]

### **Pultrusion**

It is a sophisticated, continuous, high capital and material intensive process for the manufacture of composite profile. Unlike filament winding which mounts reinforcement in the transverse (or circumferential) direction of the mandrel, pultrusion places the primary reinforcement in the longitudinal direction. It is performed by pulling continuous filaments together with chopped strand mat tapes through a resin bath to a heated metal die cavity of the desired cross section and shape, Figure 14. This die serves as the mold and the curing oven at the same time. The higher the temperature of the die, the larger the speed of pulling. It is also possible, instead of using a resin bath for saturation, to inject the resin directly into the die cavity. As the profile is pulled out already cured, a saw at the end of the production line cuts it to the desired length. Of course, length of the product is unlimited. Quality of pultruded parts is very good and price very low. They are used mainly in the construction industry. Their main disadvantage is the lack of transverse reinforcement as the pulling mechanism makes its placement very difficult. Characteristic of pultrusion method are:

- Continuous fibers pulled through resin tank, then preforming die & oven to cure
- Production rates around 1 m/min.

- Applications are to sporting goods (golf club shafts), vehicle drive shafts (because of the high damping capacity), nonconductive ladder rails for electrical service, and structural members for vehicle and aerospace applications.

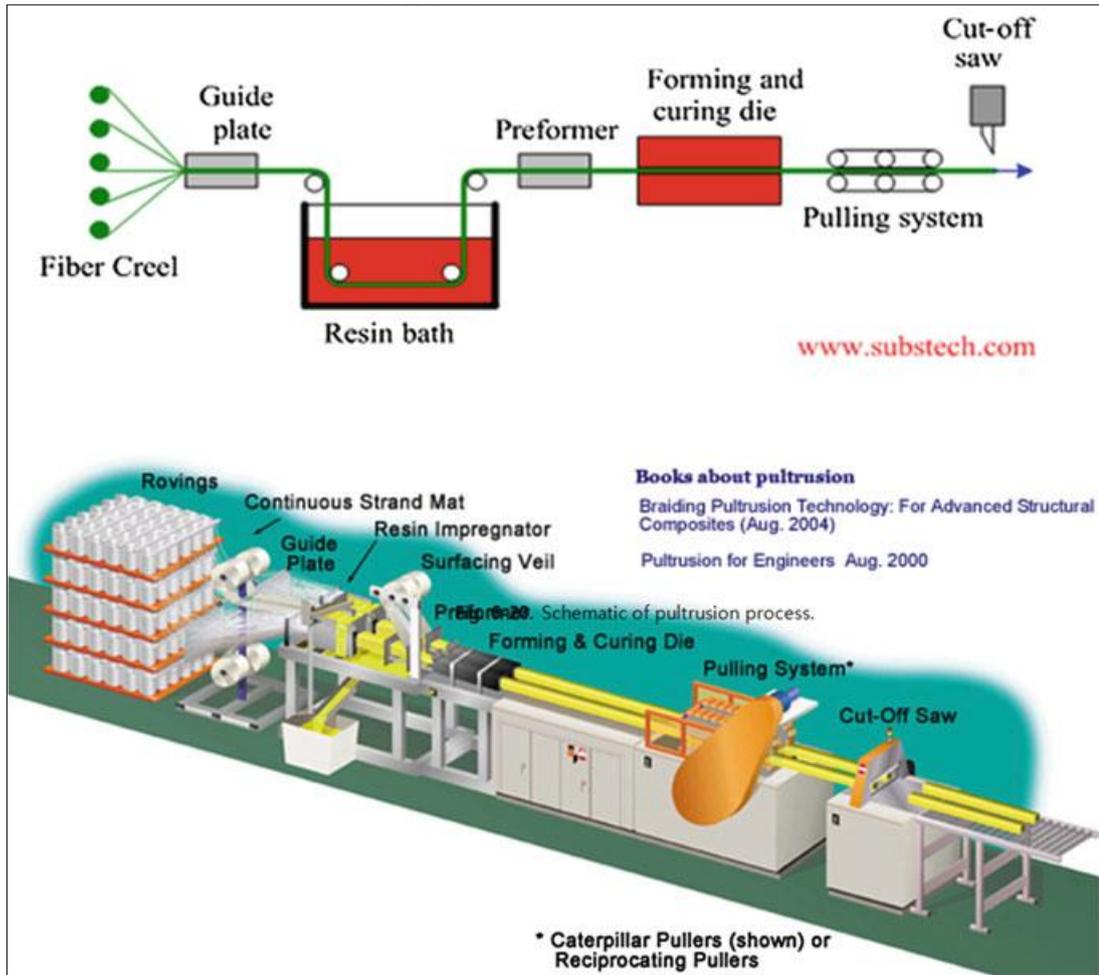


Figure 14 Schematic illustration of the pultrusion manufacturing process [10]

### **Prepreg**

Passing reinforcing fibers or fabrics through a resin bath is used to make a prepreg. The resin is saturated (impregnated) into the fiber and then heated to advance the curing reaction to different curing stages, Figure 15. Prepreg is the composite industry's term for continuous fiber reinforcement; pre-impregnated with a polymer resin that is only partially cured. Prepreg is delivered in tape form to the manufacturer who then molds and fully cures the product without having to add any resin. Prepreg is the composite form most widely used for structural applications.

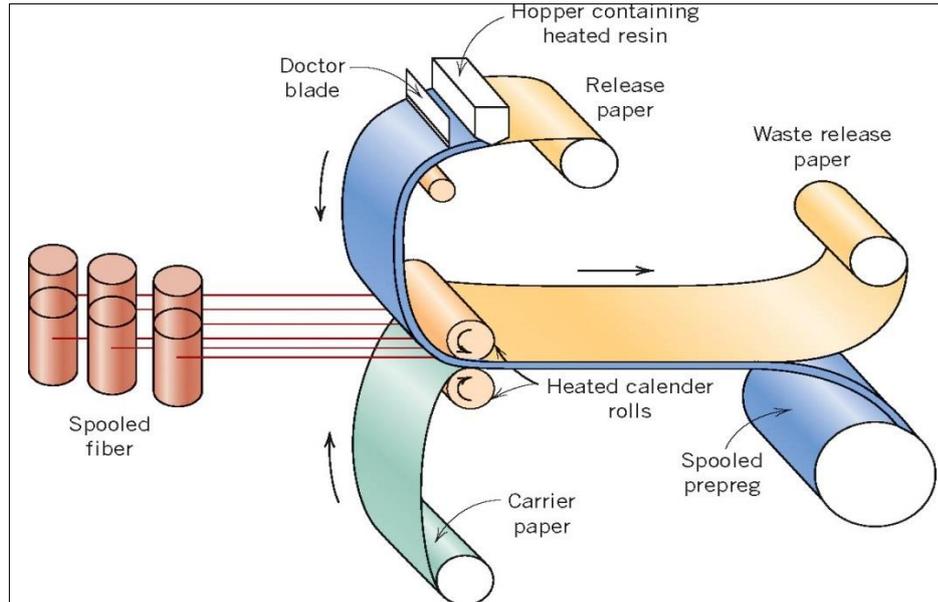


Figure 15 Schematic illustration of the prepreg manufacturing process [20]

### **Autoclave**

In this capital intensive process, metal or composite mold is treated with multiple release agent and loaded with layers of prepreg. The whole mold is sealed in a vacuum bag. The air is drawn out of the bag. The vacuum pressed mold and bag are placed in an airtight heating chamber (or an autoclave). The door of the autoclave closes and heat is applied (usually 120 -180° C). As a result of heating the resin starts to liquefy. This is when pressure is introduced (usually 3 – 8 atm.) This way, the air and excess resin are expelled out of the component. After a few minutes in these conditions the component is cured. Air is released from the machine and the cooling cycle starts. In a fraction of an hour the machine cools and the door can open. Autoclave unmatched quality manufacturing is an exotic production method that increases the spectrum of composite processing. Autoclave products are used in industries like aerospace, military and everywhere quality and performance are very important, Figure 16.



Figure 16 A large autoclave that is used to make the wings of Boeing 787 [21]

## 7. Durability and service life of FRP composites

Durability issues regarding application of FRP composites continue to cause doubt about the effectiveness and long-term performance of FRP components, Table 8 and Figure 17. For several decades, researchers have engaged in identifying degradation mechanisms and predicting the time-dependent response of FRP composite materials under multiple exposure conditions in order to characterize the effectiveness, or ineffectiveness, of the material in environments indicative of real applications [18].

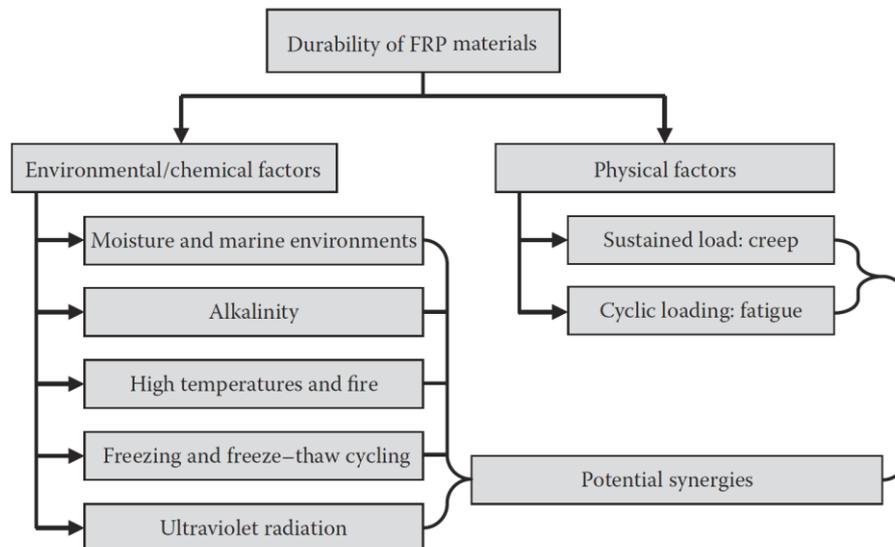


Figure 17 Potentially harmful long-term factors for FRP-reinforcing materials [18]

Table 8 Some remarks about durability of polymer composite materials.

Water Absorption	<ul style="list-style-type: none"> <li>• Polymers absorb water</li> <li>• Water acts as a plasticizing agent</li> <li>• Lubrication</li> <li>• Tg (Glass transition temperature), elastic modulus, and yield stress are all lowered when water is absorbed</li> <li>• Dimensional changes</li> </ul>
Creep/Stress Relaxation	<ul style="list-style-type: none"> <li>• Most thermoplastics are susceptible to Creeping and/or stress relaxation</li> <li>• This can even occur at room temperature!</li> </ul>
Effects of Temperature, Glass-Transition Temperature (Tg)	<ul style="list-style-type: none"> <li>• Above the Tg, the thermoplastic gradually softens and eventually turns into a viscous fluid.</li> <li>• Repeated heat-cycling causes thermal aging or degradation.</li> <li>• Effects of Temp. on thermoplastics is similar to that of metals, (for increased T, Increased toughness, strength/modulus of elasticity decreases)</li> </ul>
Recycling	<ul style="list-style-type: none"> <li>• Thermoplastics can be recycled by melting them down and reshaping them into new products</li> <li>• Thermoset matrix can be also thermally recycled, however it will be a difficult and expensive task.</li> </ul>
Fatigue	<ul style="list-style-type: none"> <li>• Fatigue: degradation or failure of a structural material or element after repeated cycles of loading and unloading</li> <li>• Carbon FRPs display outstanding fatigue behaviour</li> <li>• Glass FRPs display intermediate/satisfactory fatigue resistance</li> <li>• Aramid FRPs are sensitive to fatigue</li> </ul>

### ***Environmental attack protection***

In some composite designs, it may be necessary to provide a corrosion or weather barrier to the surface of the product. A surface veil is a fabric made from nylon or polyester that acts as a very thin sponge, which is capable of absorbing resin to 90 % of its volume. This helps to provide an extra layer of protective resin on the surface of the product. Surface veils are used to improve the surface appearance and ensure the presence of a corrosion resistance barrier for typical composite products such as pipes, tanks, and other chemical process equipment. Other benefits include increased resistance to abrasion, ultraviolet (UV), and other weathering forces. Veils may be used in conjunction with gel coats to provide reinforcement to the resin.

### ***Fatigue behavior of FRP Composites***

Composite materials exhibit very complex failure mechanisms under static and fatigue loading because of anisotropic characteristics in their strength and stiffness. Fatigue causes extensive damage throughout the specimen volume, leading to failure from general degradation of the material instead of a predominant single crack. A predominant single crack is the most common failure mechanism in static loading of isotropic, brittle materials such as metals. There are four basic failure mechanisms in composite materials as a result of fatigue: matrix cracking, delamination, fiber breakage and interfacial debonding. The different failure modes combined with the inherent anisotropies, complex stress fields, and overall non-linear behavior of composites severely limit our ability to understand the true nature of fatigue.

Fatigue failure can be defined either as a loss of adequate stiffness, or as a loss of adequate strength. There are two approaches to determine fatigue life; constant stress cycling until loss of strength, and constant amplitude cycling until loss of stiffness. The approach to utilize depends on the design requirements for the laminate.

In general, stiffness reduction is an acceptable failure criterion for many components which incorporate composite materials. Figure 18 shows a typical curve of stiffness reduction for composites and metals. Stiffness change is a precise, easily measured and easily interpreted indicator of damage, which can be directly related to microscopic degradation of composite materials.

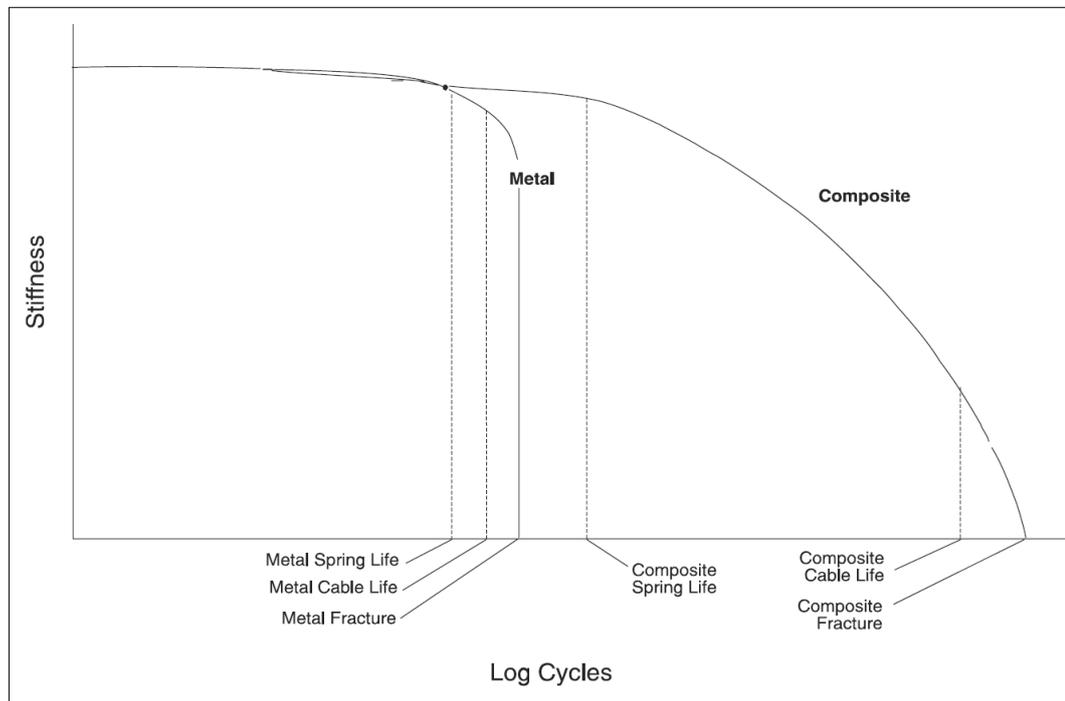


Figure 18 Comparison of Metal and Composite Stiffness Reduction [22]

In a constant amplitude deflection loading situation the degradation rate is related to the stress within the composite sample. Initially, a larger load is required to deflect the sample. This corresponds to a higher stress level. As fatiguing continues, less load is required to deflect the sample, hence a lower stress level can exist in the sample. As the stress within the sample is reduced, the amount of deterioration in the

sample decreases. The reduction in load required to deflect the sample corresponds to a reduction in the stiffness of that sample. Therefore, in constant amplitude fatigue, the stiffness reduction is dramatic at first, as substantial matrix degradation occurs, and then quickly tapers off until only small reductions occur.

In a unidirectional fiber composite, cracks may occur along the fiber axis, which usually involves matrix cracking. Cracks may also form transverse to the fiber direction, which usually indicates fiber breakage and matrix failure. The accumulation of cracks transverse to fiber direction leads to a reduction of load carrying capacity of the laminate and with further fatigue cycling may lead to a jagged, irregular failure of the composite material. This failure mode is drastically different from the metal fatigue failure mode, which consists of the initiation and propagation of a single crack.

Minor cracks in composite materials may occur suddenly without warning and then propagate at once through the specimen. It should be noted that even when many cracks have been formed in the resin, composite materials may still retain respectable strength properties. The retention of these strength properties is due to the fact that each fiber in the laminate is a load-carrying member and once a fiber fails the load is redistributed to another fiber.

There are many different theories used to describe fatigue life of composite materials. However, given the broad range of usage and diverse variety of composites used in the industry, theoretical calculations as to the fatigue life of a given composite should only be used as a first-order indicator. Fatigue testing of laminates in an experimental test program is probably the best method of determining the fatigue properties of a candidate laminate. Further testing and development of these theories must be accomplished to enhance their accuracy. Despite the lack of knowledge, empirical data suggest that composite materials perform better than some metals in fatigue situations. Figure 19 depicts fatigue strength characteristics for some metal and composite materials.

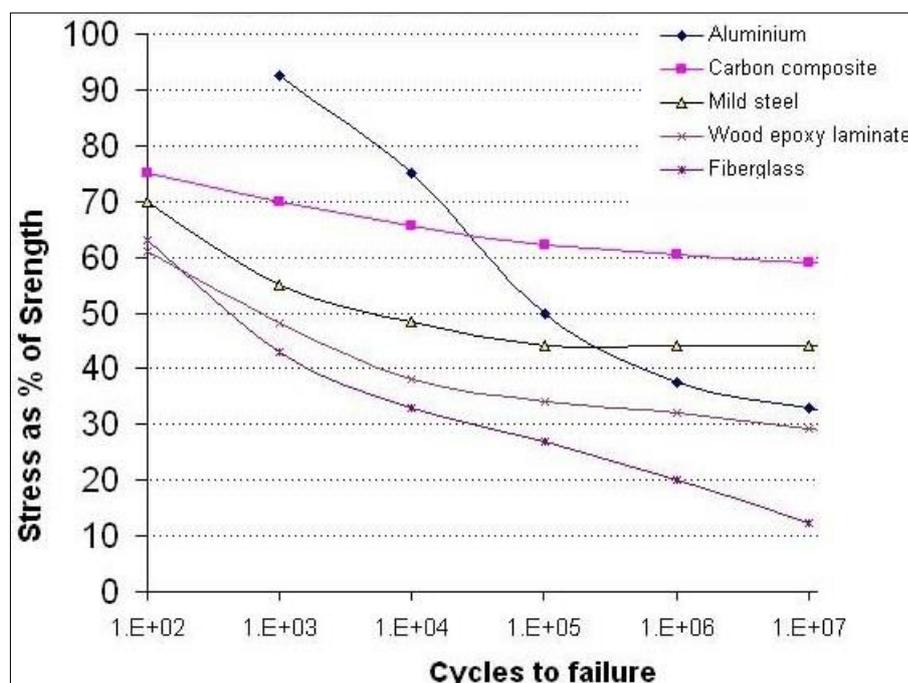


Figure 19 Comparison of fatigue strengths of aluminum, CFRP, steel, GFRP, and wood epoxy laminate [23]

## Creep behavior of FRP Composites

The application of a force to a material over a sustained period of time induces creep and if this force eventually leads to cracking, fracture, or rupture, the process is termed as stress cracking, static fatigue, or creep rupture. Further, if the environment speeds up the process, the rupture is termed as environmental stress cracking. The creep of a composite material will depend on the reinforcement and the matrix. Carbon fibers are not significantly affected by creep, although some loss of strength can be expected to occur under sustained loading. However, the matrix will exhibit creep, and a thermoplastic will exhibit creep to a higher extent than a thermosetting resin. However, if the fiber is well aligned in a unidirectional composite, it will have good resistance to creep along the fiber axis, although it would display creep during torsion and flexure. Plastics do tend to recover when the stress is removed, as long as no damage has occurred

## 8. Some applications of FRPs in the industry

In recent decades, FRPs have found wide applications in commercial and civilian aircraft, recreational, industrial, and transportation markets. In this section, some of the application will be presented as examples, however, more applications can be find in the literature.

One of the pionier industry to use modern FRPs is the aerospace industry where high strength and light materials is the best fit. Figure 20 shows the application of composite in Airbus A380 for example. Figure 21 shows a drawing of a cross section of a FRP wind blade. Figure 22 shows a photo of a carbon fiber-reinforced epoxy bicycle frame. Figure 23 illustrates a large variety of FRP structural and non-structural profiles made by pultrusion. Figure 24, Figure 25, and Figure 26 show some example of the application of FRPs in civil engineering where light materials help quick installation.

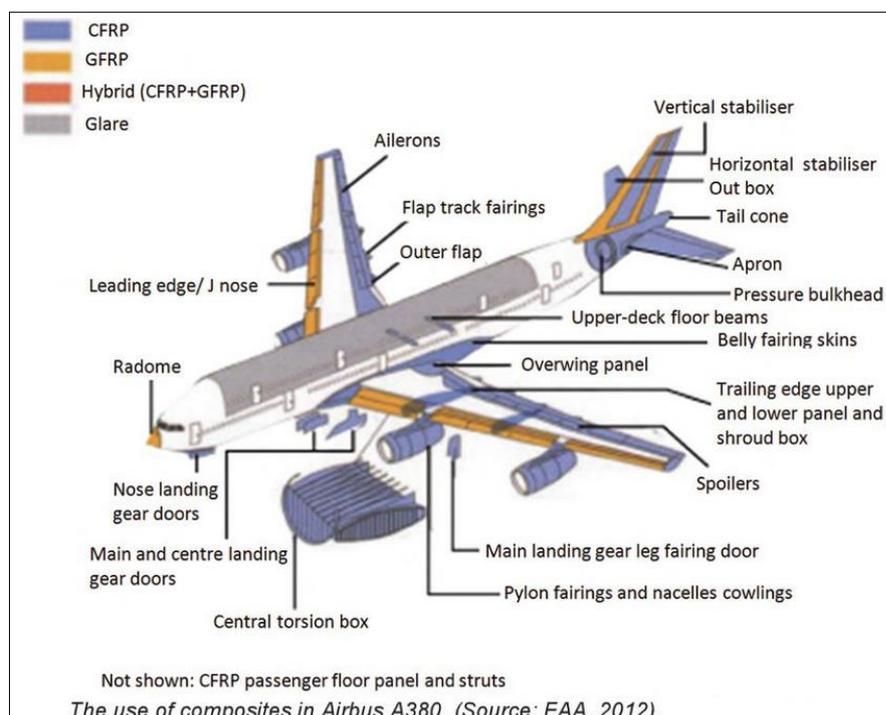


Figure 20 Use of fiber-reinforced polymer composites in Airbus 380 [24].

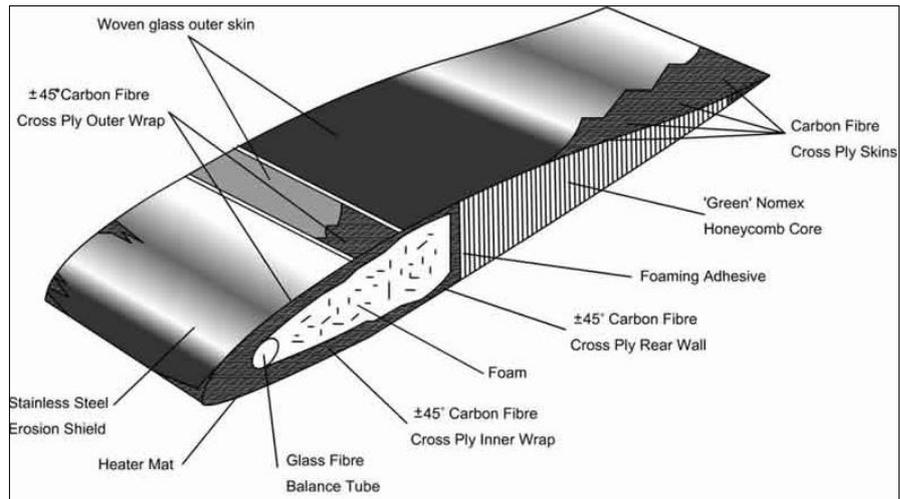


Figure 21 Cross section of a FRP wind blade [25].



Figure 22 Carbon fiber-reinforced epoxy bicycle frame [26].

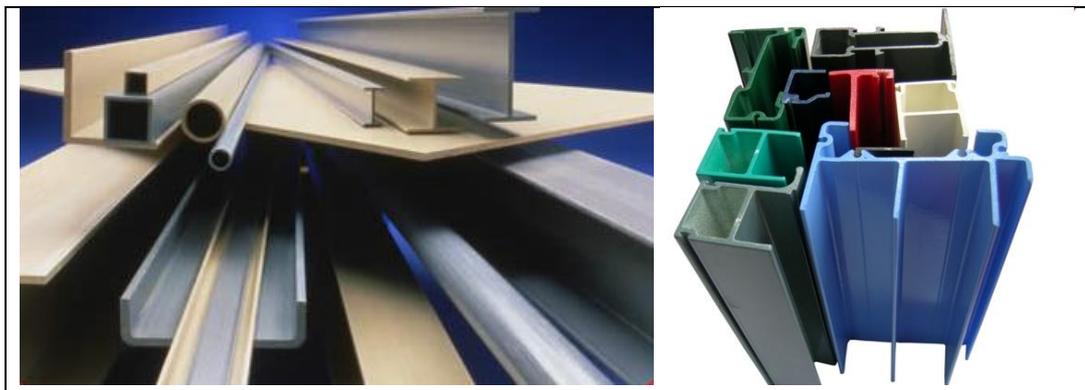


Figure 23 A large variety of FRP structural and non-structural profiles made by pultrusion are available [13].



Figure 24 An example of a footbridge made of FRP profiles, there are many similar bridges world wide [27].



Figure 25 Eyecatcher Building, Basel, Switzerland, Height: 15 m, Storeys: 5 [28].



Figure 26 An example of a sandwich structure, Novartis entrance roof, Basel Switzerland [28].

## 9. Literatur

1. Frank, F., Porges, O., and Schmidt, M., *Mehrkörpersimulationsmodell Eco-Bogie, Kurzbericht*. 01.06.2016. p. 17.
2. Frank, F., Porges, O., and Schmidt, M., *Lauftechnische Validierung Eco-Bogie*. 30.06.2016. p. 25.
3. Mayer, R.M., *Design with reinforced plastics*. Bourne Press Ltd, Bournemouth, United Kingdom. 1993. 212.
4. Hou, J. and Jeronimidis, G., *A novel bogie design made of glass fibre reinforced plastic*. *Materials and Design*, 2012. **37**: p. 1-7.
5. Keller, T., Tirelli, T., and Zhou, A., *Tensile fatigue performance of pultruded glass fiber reinforced polymer profiles*. *Composite Structures*, 2005. **68**(2): p. 235-245.
6. Guedes, R.M., *12 - Time-dependent failure criteria for lifetime prediction of polymer matrix composite structures*, in *Creep and Fatigue in Polymer Matrix Composites*. 2011, Woodhead Publishing. p. 366-405.
7. Corum, J.M., Battiste, R.L., Ruggles, M.B., and Ren, W., *Durability-based design criteria for a chopped-glass-fiber automotive structural composite*. *Composites Science and Technology*, 2001. **61**(8): p. 1083-1095.
8. Shahverdi, M., *Mixed-Mode Static and Fatigue Failure Criteria for Adhesively-Bonded FRP Joints*. 2013, EPFL.
9. FIBERMAX-COMPOSITES, *TYPES OF RESIN FAMILIES*  
[http://www.fibermaxcomposites.com/shop/index\\_files/resinsystems.html](http://www.fibermaxcomposites.com/shop/index_files/resinsystems.html), 2002 - 2014.
10. Park, S.-J., *Carbon fibers / Soo-Jin Park*. 2015.
11. Hollaway, L.C., Head, P.R., and Hollaway, L.C., *Advanced polymer composites and polymers in the civil infrastructure*. 2001.
12. Park, S.-J., Seo, M.-K., Park, S.-J., and Seo, M.-K., *Interface Science and Composites*. 2014.
13. Motavalli, M., Shahverdi, M., and al., e., *Course: Fibre Composite Materials in Structural Engineering* ETH Zurich, <http://www.empa.ch/web/s303/lectures>, 2014.
14. Prince Engineering, P. and Engineering, E.C., *Glass Fiber Differences and Properties*.  
<http://www.build-on-prince.com/glass-fiber.html>, 2016.
15. ASTM, *Standard Terminology of Glass and Glass Products, ASTM C162-05 (Reapproved 2015)*. ASTM, 2015.
16. Sathishkumar, T.P., Satheeshkumar, S., and Naveen, J., *Glass fiber-reinforced polymer composites - A review*. *Journal of Reinforced Plastics and Composites*, 2014. **33**(13): p. 1258-1275.
17. Prince Engineering, P. and Engineering, E.C., *Properties of Aramid Fibers*. <http://www.build-on-prince.com/aramid-fibers.html>, 2016.
18. Zoghi, M., *International Handbook of FRP Composites in Civil Engineering*. 2014.
19. Shakelford, *Composites and carbon fibers Topic 2. Reading assignment Askeland and Phule*, . *The Science and Engineering of Materials*, 4 th Edition, Ch. 16., 2014.
20. Godbee, G., *Quality Assurance and Nondestructive Evaluation of Composite Materials*. slideplayer, 2014.
21. Angus Batey, D., *Boeing's billion dollar gamble*. <http://www.dailymail.co.uk/home/moslive/article-1308128/Boeings-billion-dollar-gamble-Inside-worlds-biggest-building-new-787-Dreamliner-plane-built.html>, 2014.
22. Corten, H., *STP497-EB, Composite Materials: Testing and Design*. ASTM, 1972.

23. MikeJohns, *Material strength and fatigue* <http://www.boatdesign.net/forums/boat-design/material-strength-fatigue-13174.html>, 2006.
24. Wahab, M.A., *Joining composites with adhesives : theory and applications*. 2016.
25. Williams, E.L. and Turner, I., *Composite Materials and Helicopter Rotor Blades*. University of Bath., 2014.
26. Mallick, P.K. and Mallick, P.K., *Fiber-Reinforced Composites - Materials, Manufacturing, and Design (3rd Edition)*. 2014.
27. FiberlineDenmark, *Structural profiles*. <https://fiberline.com/structural-profiles>, 2016.
28. CCLab, *Projects*. <http://cclab.epfl.ch/>, 2016.