Literature study
Development of a FRP-floor with integrated installations

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J. van Stormbroek

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Preface

This literature study is the start of the graduation project to the development of a FRP floor with integrated installations. FRP composites have a long been used in area's as boatbuilding, private planes and sporting goods, but only now these materials are beginning an upraise in the construction industry. Facade elements and bridges are examples of parts and structures made from FRP and are performing well.

With carbon and glass fibre reinforced polyester pedestrian bridges are possible with spans of 25 m and only a thickness of 1 m. Floors for buildings available now only span up to 18 m (hollowcore slabs) and with a plenum for building services the height comes close to a meter. Therefore it might be a good idea to create a floor with a large span 25 m. FRP is the material suitable for these long spans due to their high strength-to-stiffness ratio and good stiffness-to-weight ratio. If a plenum is needed for placement of the building services the floor will become too thick, the building services therefore will need to be integrated in the height of the floor.

This literature study is made to increase knowledge on FRP, which is still not a common material in construction. Therefore the study is started with a chapter on FRP history and existing applications. The second chapter is on FRP material parts, resins, fibres and core materials but also on production methods and developments on natural composites. The third chapter is on size limitations of floorplates and to see if a large span floor is a practical idea for the structure of a building. In the fourth chapter a short study is done on vibrations of floor and to which strength of vibrations can be tolerated, on this topic much academic discussion has been done. A short look is given to building services in chapter 5. In the sixth chapter an insight is given on the environmental impact of the use of FRP. The final chapter seven is used to discover the fire behaviour of FRP and to see if this is a problem for a building and how it can be improved.

This literature study is used as a base for the further development of a FRP floor. The development of an integrated FRP floor is described in another report, "Development of a FRP-floor with integrated installations".

Contents

Abstract

FRP composites have a long history, in shipbuilding since the early 1950-ties. In civil- and building engineering FRP is only used for specific purposes, FRP is not a mainstream material in construction.

Fibres are strong and stiff and most important in the determination of the material properties. The fibres are held together in a matrix made from resin. FRP is often made as a sandwich due to increased strength and stiffness. Many production techniques are available, (va-) RTM and vacuum injection are the two most likely to be used due to the possibility to make large parts with a high quality and good working circumstances.

Floor plates should not be wider than 3 m, the long span of 25 m can be well used in buildings.

Much discussion exists on vibrations and comfort, no consensus has been reached. Use will be made of a recent publication of the SBR [4.6] on this topic.

The internal climate should be comfortable for the users, building services should be accessible for maintenance and replacement. The services should be flexible.

The environment can be benefitted by the use of GRP, the largest benefit of GRP is the low need for maintenance and low energy use for production.

FRP is easily affected by fire. In tension half of the strength and stiffness is quickly lost at temperatures around 100° C, but the half of strength and stiffness remain are available till much higher temperatures. Measures can be taken to improve the fire safety of FRP.

1. Use of Fiber Reinforced Polymers in civil Engineering

Fiber Reinforced Polymers (FRP) are composite materials, a composite is a material made from two base materials which combination has improved properties compared to the base materials. A composite is often made from a basic matrix material used for compression and basic shape and an addition of a stronger material used for tension. The oldest example is clay bricks with added straw, a common used composite is steel reinforced concrete. In this chapter the focus will be on fiber reinforced polymers tough, first the development of FRP will be discussed. This is followed by applications of FRP in civil engineering, finally regulations and norms will be discussed.

FRP History

The first synthetic polymer developed was Bakelite in 1909, Bakelite is a combination of phenol and formaldehyde and often with a wood flour filler. Bakelite made solid curved pieces possible that were electrical insulating, as a result it was often used for early household electrics such a telephones and radio's. Phenol has a high resistance to fire, it burns poorly and chars heavily, as a result Bakelite can be used for handles of pans and equal applications. Phenol is still used as the resin for fire critical applications such as interior parts of aircraft.

An improvement was made with the development of glass fibers in 1938 and polyester- and epoxy resins in the 1940's, these resins are easier to work with and glass fibers an available reinforcing material. Glass fiber Reinforced Polymers (GRP) structures were made possible. The first applications of GRP were in radomes due to the ease of making curved shapes and being transparent to microwaves. The main civil application was the building of boats, boats have many curved shapes which can be easily made with GRP, the high strength on a density base compared to steel meant the hulls could be made lighter. GRP structures are also low maintenance and have a high durability, a GRP structure exposed to weather will need little cleaning not repainting and its mechanical properties will not be affected. GRP is corrosion free. An advantage in the production is a low initial investment in equipment, with simple tools a structure can be made. The application of GRP can also lead to reduction in the number of parts, reducing complexity and labour for the combining of parts.

A step forward in the mechanical properties of FRP was made with the development of carbon fibers in the 1960's, carbon fibers made laminates with higher E-modulus possible resulting in weight reductions. In the 1970's aramid fibers were developed, these fibers result in a small improvement of the stiffness of glass fibers but have a good resistance to impacts. Aramid fibers therefore are often used in tires and bulletproof vests. Due to different thermal expansion coefficients between epoxy, carbon- and aramid fibers laminates can be made which have stable dimensions. Such laminates are often applied for satellites due to large differences in temperature (in sun, in shade) and high demands by the equipment on board.

Civil engineering

An overview of FRP in civil engineering is given by Bank in "Composites for construction" [1.1]. In civil engineering multiple applications have been developed, these applications are often related to the possible production methods. Large curved architectural elements can be easily made with the building techniques used in boatbuilding, the same applies for façade elements. Reasons to use FRP in these applications are freedom of form and weather resistance.

With pultrusion (see chapter 2 FRP materials, production) longitudinal elements can be made on an industrial level with high consistent properties. One application of this production method is FRP reinforcement, FRP is corrosion resistant and can be applied with less concrete cover then steel rebar. Concrete with FRP rebar isn't effected by carbonation as steel rebar is. FRP rebar can also be applied at places were drilling will be done later, for steel rebar more expensive drills are needed, drilling trough FRP reinforcement can be done with normal concrete drills. FRP reinforcement (with glass or aramid fibers) can also be used in concrete if electro-magnetical equipment is used, steel rebar can interfere with the equipment, FRP doesn't.

With pultrusion it is also possible to produce profiles which can be used in construction, H, L, O shaped profiles are possible, planks can be made too. An overview is given in fig 1, taken from Fiberline [1.2]. With pultrusion profiles whole buildings can be made, for instance for electro-magnetical research. A common application of pultruded FRP profiles is in cooling towers due to their high durability.

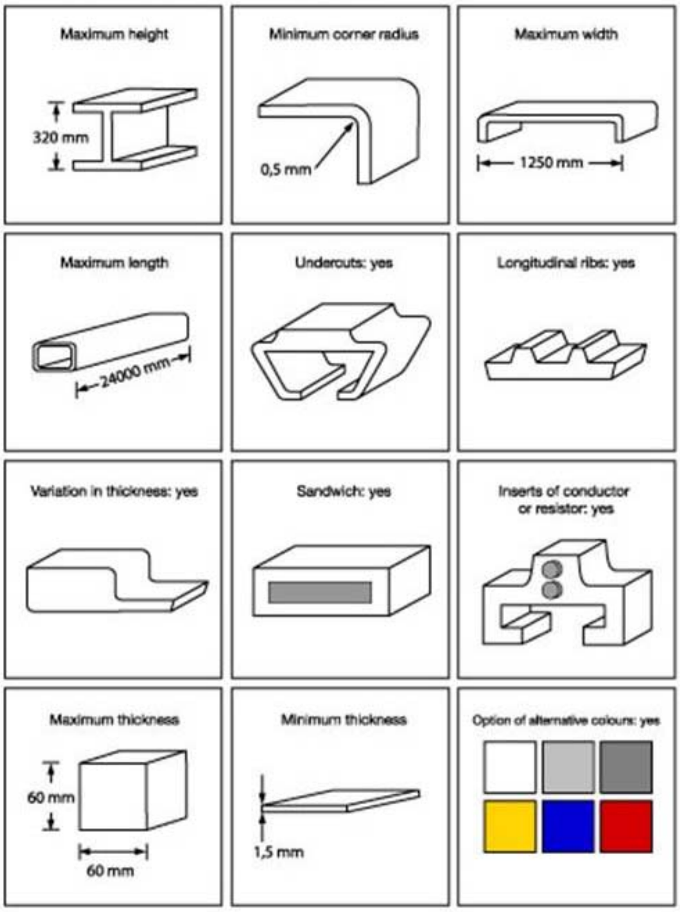


Figure 1: Design possibilities Pultrusion

Bridges, both for pedestrians and vehicles, can be made for FRP. The bridges can be made from pultruded FRP profiles [1.3] but FRP sandwich plates [1.4], [1.5] are also possible. Combinations between FRP and concrete are possible too, the FRP is used as a permanent mould and reinforcement [1.6]. Reasons to use FRP in bridges are low own weight, thus prefabrication possible, and low lifecycle costs due to low maintenance. In some situations it is possible to replace a concrete bridge deck with a FRP deck, the weight reduction can then be used to allow a higher variable load.

Tendons of bridges can be from carbon or aramid fibers, replacing steel, higher strength and stiffness can be reasons to replace steel. A lower need for protection of the tendons against weather is another reason.

External FRP reinforcement can be post applied to structures which don't meet regulations anymore, for instance due to damage caused by earthquakes. Carbon fibers can be externally bonded to concrete columns, walls and slabs by epoxy.

A drawback of FRP is the usual higher start off costs, the material cost are often higher then alternative materials and it might be hard to prove lower lifecycle costs. Clients are often hard to convince to use FRP, being conservative traditional materials are preferred. Due to often part for part production consistency of quality is low and very dependent on precession of the labourers. Polymers (and aramid fibers) suffer from creep, leading to increased deflections over time. When loaded in compression the fibers can buckle easily, a laminate therefore has lower properties in compression then in tension.

Regulations

The use of FRP in construction is not well regulated in Europe, one Euro code exists for pultruded profiles EN 13706-1/2/3 [1.7]. Some guides exist too, in the Netherlands the CUR 96 [1.8] can be used, the CRU 96 covers GRP structures. On a European level the Eurocomp design handbook [1.9] can be used. In Japan, Canada and USA codes have been written for the use of FRP in concrete, bridges and buildings. An overview can be found in the reader from the civil engineering course 'Fibre reinforced polymer structures'[1.10] at the TuDelft. The lack of codes is a reason for clients to have a lower trust in FRP.

2. FRP Materials

In this chapter the properties of FRP materials are described. A FRP laminate is made from 4 constituents, fibers are in a polymer matrix, the surface of the fibers are treated with a coupling agent and additives can be used. For a sandwich construction a core is used. In this chapter the fibers, matrix and cores are discussed. The production methods available for FRP are discussed as well as composites based on natural materials. The first part of the chapter is on general properties of FRP materials.

General properties

Due to the high cost of FRP often 'smart' shapes are used to reduce the amount of material needed, this concept is not new, steel beams are made as a H-profile to but as much material on the outside to increase strength and stiffness. A way to do this for FRP is with a sandwich structure, two strong and stiff plates are placed on each side of a lightweight core. The plates give strength and stiffness for bending, the core is used to transfer shear forces. The result is shown in Figure 2, taken from Mallick [2.1].

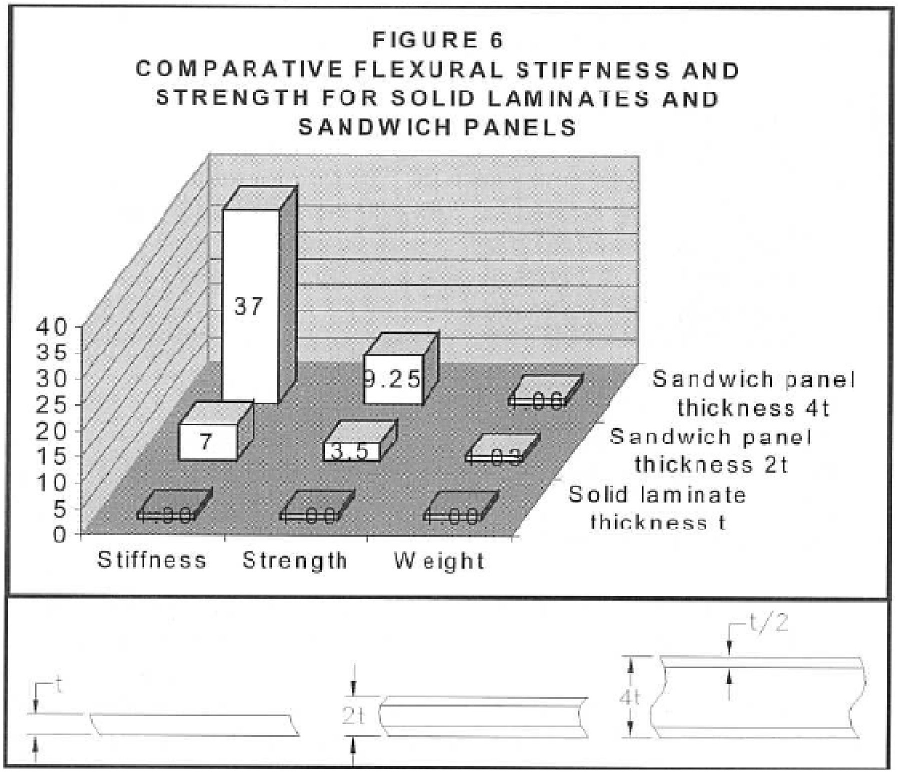


Figure 2: Comparative flexural stiffness and strength for solid laminates and sandwich panels

The fibers are made in a continuous tow, this tow is usually made into a fabric to make surfaces. As a result, during production fibers are placed layer for layer. These layers are called lamina or ply. The fabrics are available in many different forms, all fibers in the same direction (held together by only a few perpendicular threats) is called Uni-Directional (UD), fibers can be placed in the main direction and perpendicular (plain weave, twill, satin, etc). The woven fabrics differ in ease to handle and ease to apply to a curved surface. Glass fiber can be delivered in a mat also, in a mat the fibers are without direction. An overview is given in Figure 3.

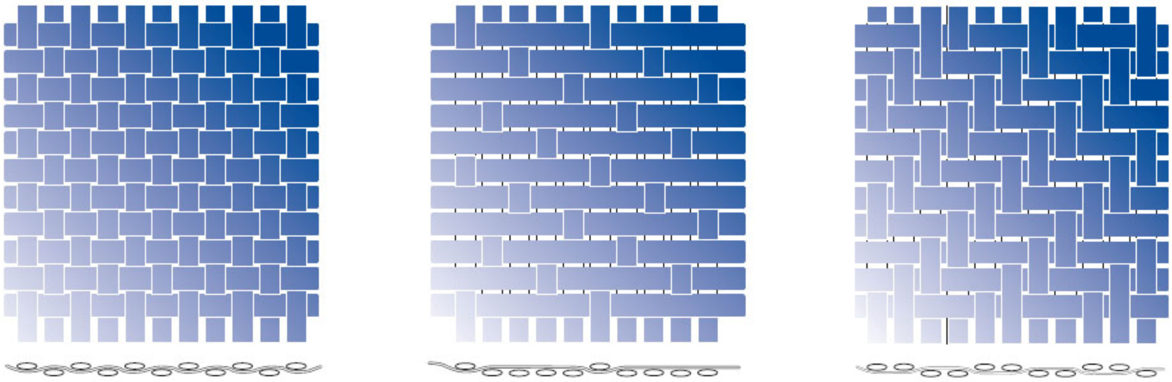


Figure 3: Fabrics, from left to right: Plain weave, satin weave, twill weave

The laminate is strongest and stiffest in the direction of the fibers, as a result a laminate is anisotropic (though quasi-isotropic is possible). The anisotropy causes the response of the laminate to stresses to be different to an isotropic material, the response is dependant to the fiber direction. Two examples are given in Figure 4, taken from Powell [2.2], this effect most important for a thin laminate.

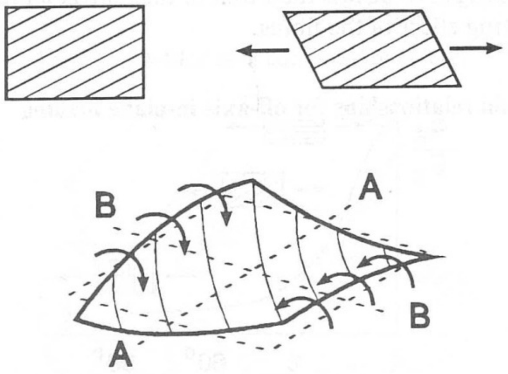


Figure 4: Showing distortion due to fiber alignment, anisotropical behaviour

The anisotropy is visible in the strength and stiffness to, as is shown in Figure 5. In Figure 5 it is also shown that it is most economical to place the fibers in the direction most needed, the difference in stiffness between UD (1) and quasi-isotropic (3) is very large, the same is valid for the strength.

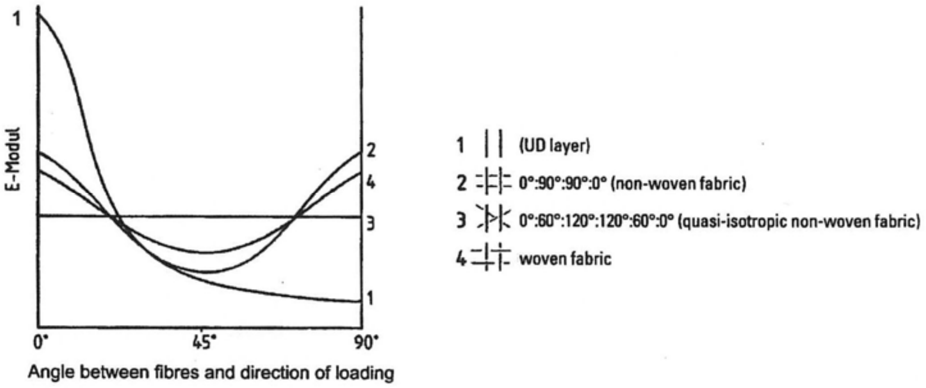


Figure 5: Effect of build up of laminate on stiffness (and strength)

Fibers

Many different types of fibers are available to create a FRP laminate, many very exotic and unlikely to be used in this project. Therefore only the most common and likely fibers to be used are discussed. Common fibers are: glass fibers, carbon fibers and aramid fibers. Within every type of fiber differences can be found, carbon fibers for instance can be made with higher strength (IM, intermediate modulus) or high modulus (HM), many more varieties are available.

Two main types of glass fiber are E-glass and S-glass, of which E-glass is the most common and S-glass the strongest and stiffest. S-glass is mostly used in aviation due to the higher costs. A reason to use glass fibers is the electric isolating properties of the material and its transparency for many forms of radiation. Glass fibers can be affected by moisture and can show creep. If glass fibers are prolonged loaded with a high stress the ultimate strength can be reduced (to about 60% of the initial ultimate strength), but generally this is no problem because the occurring stresses are generally a lot lower than the maximum stresses. The material properties of some glass fibers are given in Table 1, taken from Mathweb [2.3]. Cost are about € 3/kg for E-glass and double or higher for S-glass.

Table 1: Mechanical properties glass fibers

Glass fibers	Strength (MPa)	Stiffness (GPa)	Specific weight (kN/m^3)
E-glass	1500	70	25
S-glass	4500	85	25

Precursors of carbon fiber are PAN (Polyacrylonitrile) or rayon, but can be made from pitch to. Carbon fibers guide heat and electric energy well and have a good resistance against moisture. Material properties are given in Table 2, taken from [2.4] (Japan carbon fiber manufactures association, www.carbonfiber.gr.jp). Cost are about € 50/kg, but can be a lot higher depending on type of fiber.

Table 2: Mechanical properties carbon fibers

Carbon Fibers	Strength (MPa)	Stiffness (GPa)	Specific weight (kN/m^3)
Low elastic modulus (LM)	<3500	<200	19

Standard elastic modulus (HT)	>2500	200-280	19
Intermediate elastic modulus (IM)	>3500	280-350	19
High elastic modulus (HM)	>2500	350-600	19
Ultra high elastic modulus (UHM)	>2500	>600	22
Super high-tensile (SHT)	>4500		19

Aramid (short for: aromatic polyamide) fibers are mostly known under their trade names, Kevlar, Technora and Twaron. Aramids can be used as a replacement for asbestos in brake pads but also as reinforcement in composites. Different versions of the fibers have been developed for the different uses. UV light can affect Aramid fibers. Aramid fibers have a low density and can absorb a lot of energy, one use of aramids is in bulletproof vests. When used in laminates a problem of aramids is easy buckling under compression. In Table 3 properties of aramids are given, taken from [2.3] (mathweb/DuPont/Teijin). Cost are about € 35/kg.

Table 3: Mechanical properties Aramid fibers

Aramids	Strength (MPa)	Stiffness (GPa)	Specific weight (kN/m^3)
Kevlar 29	3000	70	14.4
Kevlar 49	3000	112	14.4
Kevlar 149	3500	179	14.7
Technora	3000	70	13.9
Twaron (high modulus)	3000	115	14.5

Matrix

The fibers are held in a polymer matrix, this matrix is made from a resin that hardens and becomes solid. The polymer matrix can be classified in two groups, thermoplastic and thermosetting.

Thermoplastics melt at higher temperatures and can be recycled, a drawback of thermoplastics is fatigue and creep, reasons not use thermoplastics. Yet developments are made to improve these drawbacks and carbon fiber reinforced thermoplastics can be used to make stringers in wings for aircraft [2.5], these reinforced thermoplastics are made by Ticona [2.6] and Ten Cate [2.7]. PPS (Polyphenylene Sulfide) and PEI (Polyetherimide) are two thermoplastics used as matrix material, PPS has a low glass transistion temperature of 100˚C, PEI can be used at higher temperatures of up to 300 ˚C. To form parts preimpregnated sheets are heated and then shaped in a mould with a high-pressure press. Due to the high force needed (800 kN for a 2000 cm^2 part) parts are limited to 50 by 50 cm, this technique is therefore unsuitable for large parts such as a floor.

Thermosetting polymers are most used to make structures, creep and fatigue are limited and production can be done without expensive equipment, large parts (whole bridges and boat hulls at once) can be made. Four types of resin are commonly used to make FRP structures, these will be discussed. To a thermosetting resin hardener is added which causes a reaction leading to the setting of the polymer, the geltime of the resin with the added hardener is usually some hours at room temperature but can be increased with additives. Sometimes curing is done at an elevated temperature, this increases the mechanical properties of the laminate and raises the glass transition temperature. Descriptions based on [2.1].

The most common and one of the cheapest resins is unsaturated polyester. Unsaturated polyester resin is made by the reaction of maleic anhydride and ethylene or propylene glycol, to this mixture saturated acid are added to increase cross linking between the molecules. Styrene is used as a diluent which make the polymeric more viscose easier to handle. Trace amounts of inhibitor are used to prevent premature polymerization during storage. The curing reaction is initiated by adding small amounts of a catalyst (such as organic peroxide or an aliphatic azo compound). The catalyst decomposes into free radicals which react (mostly) with the styrene molecules, the styrene molecules react with the polyester molecules to from a solid polyester. During curing styrene is released, which is a health hazard, some production methods prevent this release (see the production part of this chapter). Polyester can cure at room temperatures and resin preparation is simple, combined with the cost these are the reasons polyester is often used. A drawback of polyester is the large shrinkage (5 to 12 %) during curing.

The most expensive type of resin is epoxy, but these resins give the highest mechanical properties. Epoxy resins can be made from many starting materials and curing agents but most common is bisphenol A (DGEBA) as a base material and diethhylenetriamine (DETA) as a curing agent. Epoxies have a long cure time, but can be speeded up by an increased curing temperature. An advantage of epoxies is low shrinkage and the absence of volatile matters during curing. Epoxies have excellent adhesion to many materials and is therefore also often used as a glue, but also adhere very well to fibers and filler resulting in a higher quality of the laminate.

A combination between epoxies and polyesters is vinyl ester, this resin is made from a epoxy resin which reacts to an unsaturated carbonic acid. The vinyl ester resin is dissolved in styrene as is polyester and curing is also similar to polyester. The resulting polymer matrix has increased mechanical properties over polyester such as higher tensile strength and higher fracture resistance, while still being fast curing and having a low viscosity. Vinyl ester also shrinks during curing, 5 to 10 %. Vinyl ester resins have a price between polyester and epoxy resins.

Phenolic resins are the oldest synthetic resins but are still being used because of their high fire safety. A laminate made from phenolic resin has a low firespread and low smoke emission, this is the result of heavy charring of the matrix which also insulates the virgin material. Phenolic resins are made by the reaction of phenol with an aldehyde, for Bakelite phenol reacts with formaldehyde. The curing of Phenolic resins is done at elevated temperatures (in excess of 100˚C) or at room temperature with the addition of corrosive acids, making this resin more difficult to work with.

Core materials

To make a sandwich a lightweight core material is put between two plates, the plates are used for moment resisting and normal force. The core material transfers shear force. Three basic types of material can be used.

End-grain balsa is an old solution to be used as sandwich material, balsa is the lightest wood available and has good mechanical properties. It is also cheap and easy to work with, it can be bought in large sheets of individual blocks to make round (and double curved surfaces) possible. When a whole structure is impregnated with resin at once the balsa will not fill with resin. End grain balsa has a limited thickness.

Foams can be used as a sandwich material too, many foams are available and are made by expanding a polymer. Examples are EPS (expanded polystyrene), PU (polyurethane) and PIR (polyisocyanurate). Closed cell foams can be used to impregnate a whole structure at once because the cells won't fill with resin. Most foams will burn in case of fire, PIR is a foam which doesn't . During long uses foam cores can show strength loss and creep, for a long lifespan a foam core is unsuitable.

A third option is a honeycomb core, a honeycomb core has many webs placed under an angle to each other to form small cells, an example is shown in Figure 6. The webs are efficient in transferring shear and together the webs support each other to prevent plate buckling. Because only thin plates are used the used material can be of a higher density, materials with less or no creep can be used. Cores can be made from Nomex (aramid paper), aluminium or FRP. If the cells of the core are open a structure can't be impregnated because the cells will fill with resin, aluminium and nomex cores are open celled and an aluminium core sandwich is often made in two steps, first the top and bottom faces, which are then glued to the core. An alternative is to use pre-impregnated plies and production in an autoclave, but this is an expensive production method. The thickness of an aluminium and nomex core is limited. FRP cores can be custom made, thus a thick core is possible. For a long span floor the use of a FRP core is likely.

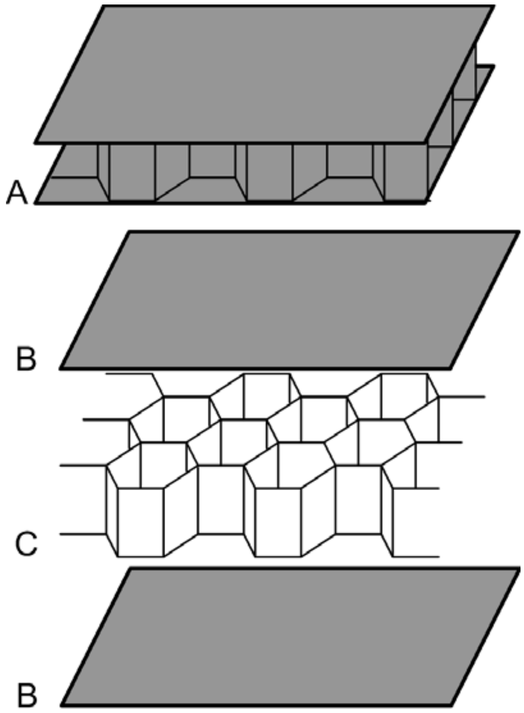


Figure 6: Honeycomb sandwich

Production techniques

A FRP part can be made with many different techniques, each has their advantages and disadvantages. Differences are on quality, release of volatiles, surface finish, shape limitations, equipment needed and speed of production. The figures are taken from Gurit [2.8].

The most simple technique is hand lay-up in which layers of fibers are wetted out by rollers or brushes. When enough layers have been placed the laminate is left to cure in atmospheric conditions. For this production technique very low viscosity resin is needed to have a good wet-out of the fibers. A disadvantage of this technique is the high release of styrene during production and its high dependence on the skills (and effort) of the labour, the process is labour intensive. The needed materials are very basic. One side of the laminate will have a good surface finish. Large parts can be made. Hand lay-up is shown in Figure 7.

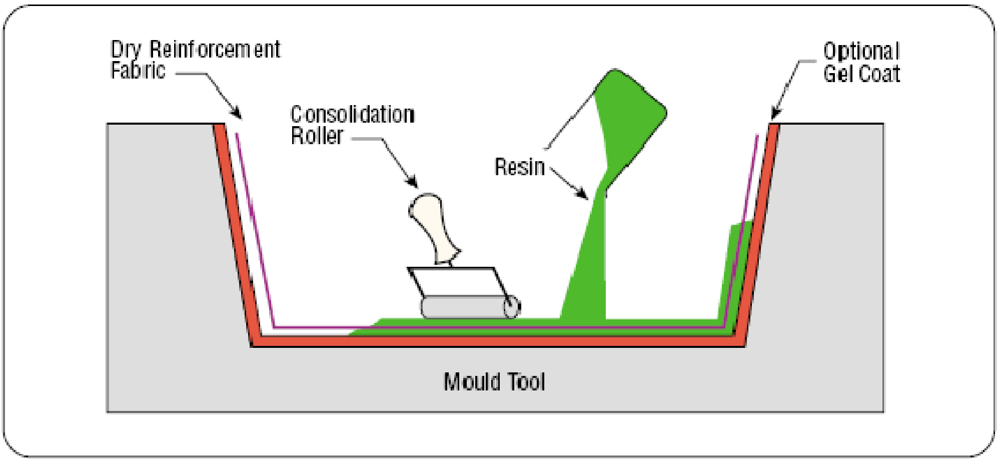


Figure 7: Hand lay-up

Spray lay-up is a more industrious process in which air pressurized resin is continuous shot out of a gun together with chopped glass fiber roving. The quality of laminates made with spray lay-up is low due to the use of short fibers and large resin fraction, making the laminates heavy. This method is a little less dependent on the labour, but still has influence. Due to the use of an open mould styrene is still released to the atmosphere. Large parts can be made, one side has a good surface finish. This production process is less time consuming as hand lay-up. Spray lay-up is shown in Figure 8.

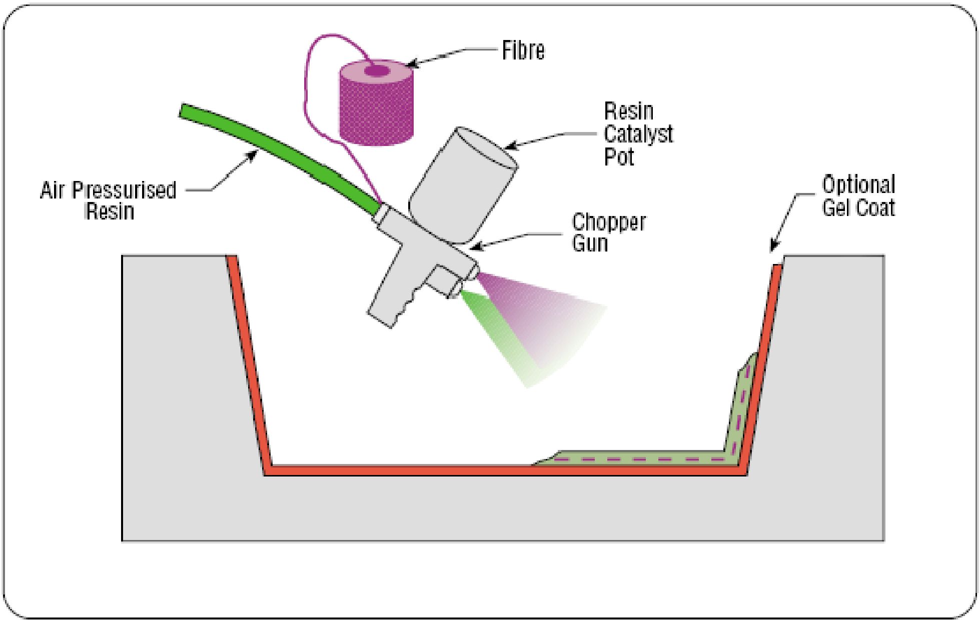


Figure 8: Spray lay-up

Higher quality can be made by vacuum injection. In this process the fibers are placed in a mould, the mould is then airtight closed with a foil. A vacuum is applied to the fibers and via one or more entrance points resin the fibers are wetted out. With this production method high fiber fractions are possible and the process can be controlled well, resulting in a high quality. To prevent voids in the laminate all air in the resin needs to be removed by placing the resin in a vacuum, a bleeder layer is applied between the fiber layers and the foil to have a good wet-out. Because of the vacuum the emissions of styrene and other volatiles can be caught and work circumstances improved. One side has a good surface finish. Large parts can be made. Vacuum injection is shown in Figure 9.

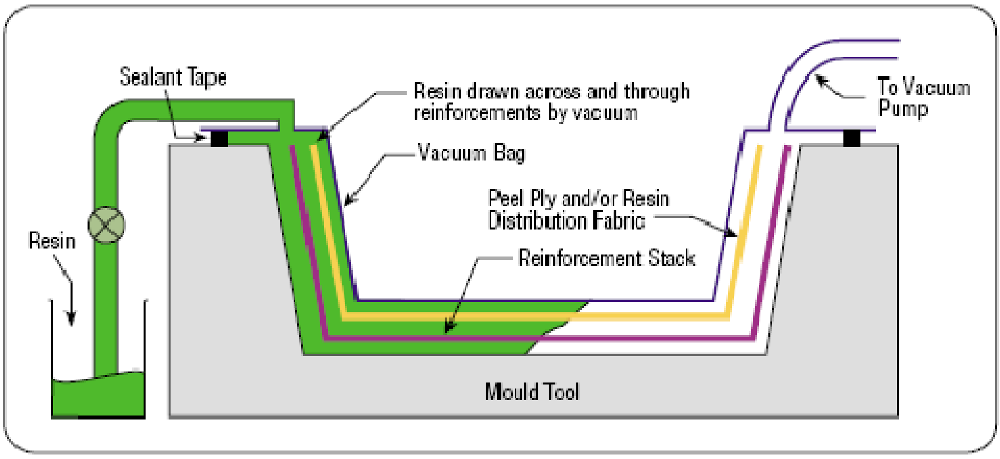


Figure 9: Resin injection

Another process to get a high quality is resin transfer moulding (RTM), two moulds are used in which the dry fibers are placed. The fibers are wetted out by forcing the resin into the space between the moulds by pressure, this process can be done with the assistance of vacuum (vacuum-assisted resin transfer moulding, VA-RTM) to prevent the release of styrene. With this process two good surfaces can be made. Large parts can be made, but will increase the costs of tooling. The speed of production is potentially higher then with vacuum injection. As with vacuum injection the resin needs to be treated and provisions need to be made to ensure a good wet-out of the fibers. RTM is shown in Figure 10.

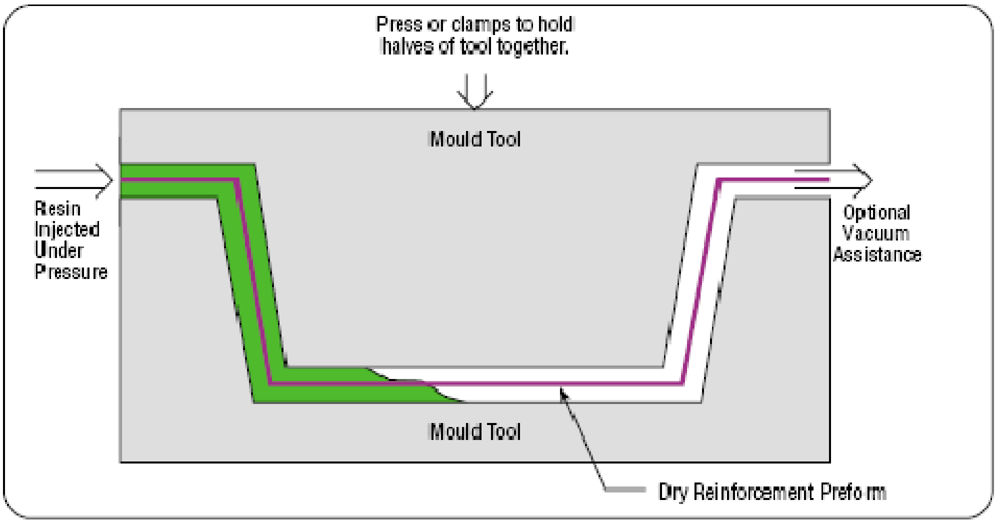


Figure 10: Resin transfer moulding

The highest quality is made with pre-pregs (preimpregnated fibers) which are placed in a mould covered in foil and kept in a vacuum. This part is then cured in an autoclave. With this method fibers can be placed very precise and no voids will occur, leading to a very high quality. The method is expensive due to the higher costs of the pre-pregs compared to the fibers and resin and the use of an autoclave. The size of the structure is limited to the size of the autoclave. This method is shown in Figure 11.

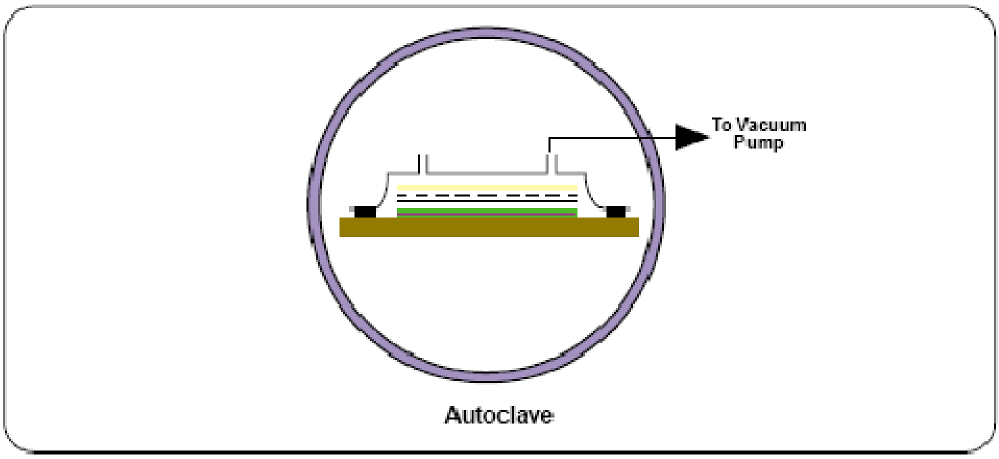


Figure 11: Use of autoclave

The most industrious method to produce FRP parts is pultrusion in which continuous parts can be made. Continuous fibers are taken from spools and let trough guides to be impregnated and shaped. Fabrics can be incorporated to increase transverse strength and stiffness. Volatiles emissions can be prevented. The process is shown in Figure 12. This production method is suited for large series due to highly automated production process and high cost for the guides.

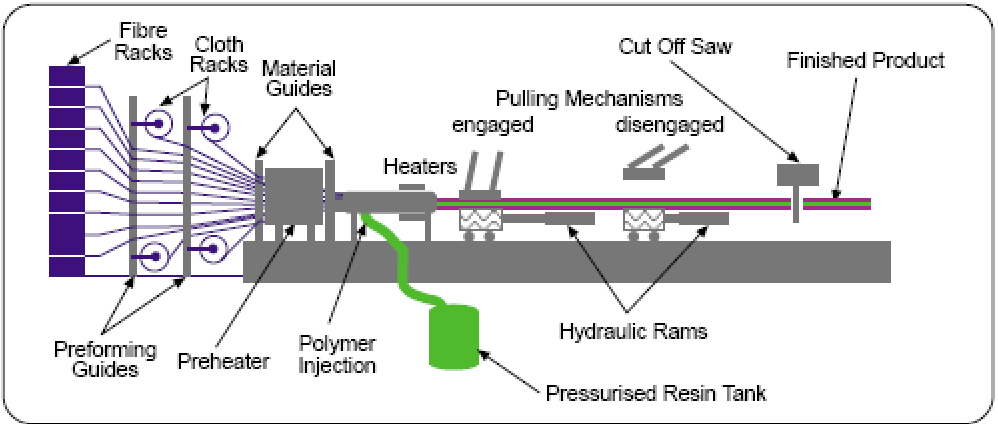


Figure 12: Pultrusion

Green composites

In line with the spirit of the time, efforts are made to reduce the environmental impact of FRP materials.

One direction is the use of natural fibers such as flax [2.9], jute and sisal. At the agricultural university of Wageningen a bulk moulding compound (BMC) has been developed of a thermoplastic polymer (polypropylene, PP) and short flax fibers [2.10], from the research of Bos [2.9] it was shown that flax fibers are unsuitable to be used in demanding FRP parts. Part of the research was focused on the application of flax fibers as reinforcement in windmill blades (in a thermoset matrix), one of the problems was the low adhesion between the flax fibers and polyester, good adherence was found with epoxy but this will lead to a large cost increase. Another problem was the low resistance to moisture, though the fibers can be treated by the plato process leading to a higher resistance to moisture [2.11]. If the fibers are washed in an alkaline solution the adherence with the resin can be improved [2.12]. The price of flax fibers is at the level of E-glass fibers, but the main use of flax is for the production of linen. As a result the demand is influenced by fashion and the price can vary from season to season. The length of flax fibers is limited due to the length of the plants, therefore only short fibers can be used, leading to lower mechanical properties, because flax is a natural product the quality can vary from year to year. A company in Delft, NDSP [2.13], makes composites based on flax fibers, but still use oil-based resins.

A more commercial natural fiber has been developed by Boerstoel [2.14], with a similar production method as used for aramid a continuous tow can be made from cellulose molecules. The produced quality can be controlled. Because a continuous tow is made, also fabrics can be made resulting in a higher quality laminate. The mechanical properties of this fiber are in the range of E-glass fiber. Netravalli used this fiber to create a laminate combined with soy-based resin [2.14]. With these base materials a fully recyclable laminate was possible, within a few weeks exposed to the elements the laminate was completely decomposed. The ‘garbage’ can be used as food for new plants, to create a new laminate (Cradle-to-Cradle, see chapter 7). These FRP laminates are still experimental and long term behavior is unknown, but this is an interesting development worth following.

Conclusion

The floor plates are likely large plates that need a high stiffness, a sandwich structure is likely to be used. E-glass fibers are the cheapest fibers and should be used as a base material, if added stiffness is needed use can be made of carbon fibers, aramid fibers are not likely to be used due to the limited compressive strength and relative high price. Due to the low price and ease to work with, polyester is matrix to be used. But phenol can be an option if fire is critical, phenol can be applied to the most critical part of the floor. Due to the lifespan of the floor a honeycomb core will be used, good mechanical properties are needed over a long period. The thickness of the floor will be large, therefore a FRP core will be used.

Floors are likely produced in large quantities, buildings have floor area’s over thousands of square meters. A fitting production process will need to be chosen, high quality is important, large parts need to be made and good labour circumstances are needed. Because large series are made more expensive moulds can be used, VA-RTM can be a good method due to high quality, no emission of volatiles and a little less labour than vacuum injection.

Green composites are a promise for the future, but at the present time not usuable.

3. Floorplate division and construction

Internal divisions

Multiple influences determine the sizes of an office floor, laws on labour circumstances and fire safety give maximal dimensions, see Figure 13 for an example. But culture has a strong influence too. Van Meel [3.1, van Meel 200] did research on this topic, a typical Dutch office has a depth of 12.6 m, in the centre a corridor 1.8 m wide and on each side offices 5.4 m deep. Alternatives have additional rooms in the centre of the buildings for archives, technical spaces or meetings. Instead of cell offices is an office garden possible to.

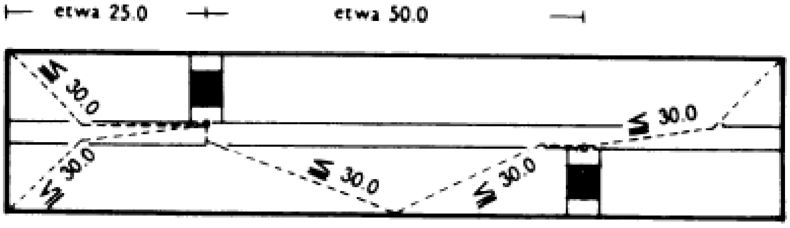


Figure 13: according to building codes, there must be eescape stairs no more than 30m from any point in a non-wotk room. It is best to calculate the distance of the staircases as 25m from the site boundary and distance between staircases as 50 m

Requirements on escape routes are given by the "Bouwbesluit"[3.2], in an office from each place in a compartment two escape routes should exist, the routes can coincide for a length of 30 m. Neufert [3.3] shows the consequence in figur14. From basic blocks of 14 by 25 m many layouts of buildings can be made with facades on the long sides, as is shown in Figure 14.

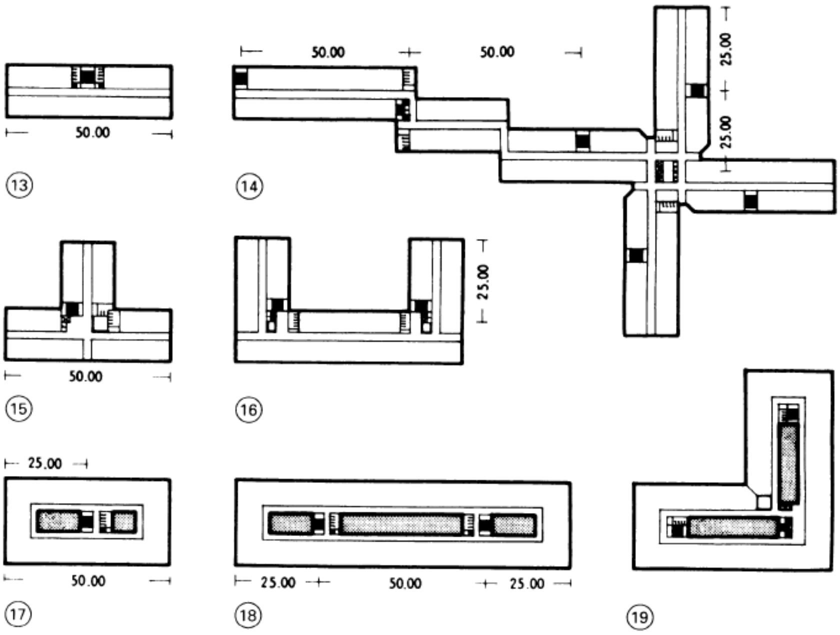


Figure 14: Buildings made from 25 x 14 m blocks

Construction

The span of a floor has a large influence on the shape of the vertical load bearing structure. If a block of 14 by 25 m of the previous paragraph is taken as start of point this can be shown. A floor with a short span of 7 m will need to span from facade to face with a support in the middle. A medium span floor of 14 m can span from facade to facade, or from end wall to end wall with a support in the middle. A floor with a long span of 25 m can span from end wall to end wall.

To give the clients a large freedom in the division of the internal space columns are often unwanted, these elements can’t be moved and can be an obstruction. The medium- and long span floors give an advantage on this area.

If all dead weight is brought to the end walls, it can give an advantage for the stability of the building and a reduction of structural elements. With a long span floor the bearing structure can be made by only using a vertical core, floors and an end wall. The core gives a fixed point, and the end wall prevents rotation and displacement in its direction. The facade can be made without load bearing function. Because all dead load is resting on the stabilizing elements the structure is efficient in using its dead weight for stability. Especially for high buildings this can be an advantage. The floor will need to function as a stiff plate to allow such a structural system.

Long span floor should not used in combination with portals, portals prevent horizontal translations by using moment resisting connections and stiff elements, if only a few portals are needed the portals will need to be very stiff.

Transportation

A vehicle on Dutch roads is limited by law to maximum dimensions [3.4]. The maximum width is 3.00 m, maximum height of 4.00 m, a length of 22.00 m and maximal mass of 50.000 kg. A vehicle with dimensions larger than these are qualified as an exceptional transport and need an additional permit. From a practical point of view it would be practical not to exceed the width and height requirements, to prevent large damages to the roads the load of a truck should be less than 50.000 kg. A truck with a larger length should be less of a problem.

Conclusion

Floor plates with a span length of 25 m can be well used in buildings, this span corresponds to fire regulations and therefore to many applied floor sizes. With long span floors a completely free internal space can be made. The floor can be used to simplify the main structure of the building, the floor should be used with a suitable structural system though. In the design of the floor the maximum dimensions for vehicles on the Dutch roads should be taken in account.

4. Vertical vibrations of the floor

Total absence of vibrations in a building is an unrealistic and impossible requirement. Comfort, or “a conscious wellbeing”, in a building merely demands the absence of “sensible” vibrations during the largest part of the time. The threshold for noticing vibrations therefore gives the lowest boundary value for acceptable vibrations in buildings [4.1, griffin 1996].

Vibration disturbance in a building can be caused by an external source such as traffic, but the source of the vibrations can also come from within the building, examples are household equipment, ventilation systems, closing doors and footfall. The experience of the users of a building not only depends on what they feel, but also on what they see and hear, what they expect and if they think the situation can be improved and if they except complaining can lead to a solution. A problem with vibrations of lightweight floors is low frequency vibrations which are caused by human activity, mostly walking, but also running and jumping, for instance from jumping children. Walking is done with a frequency from about 1.6 Hz to 2.4 Hz, harmonics can cause the floor to vibrate in its eigenfrequency and lead to strong excitations [4.2, Ljunggren 2006]. People play a double role in this system, they are both cause and sensor. In most situations the vertical direction is dominant.

Research has shown large variances between test subjects. McKay [4.3] did a study with 48 test subjects, at a vibration of 4 Hz the average threshold for perception was at 0.021 m/s^2 r.m.s., with the most and least sensitive test subjects at 0.057 m/s^2 r.m.s. and 0.011 m/s^2 r.m.s. The most important result from the research was the conclusion the criteria of the individual subjects is important and that the subjects guess whether they felt a vibration. The study from Parsons and Griffin [4.4] with 36 subjects has shown a similar result.

Reiher and Meister [4.5] where the first to do research to the perceptibility of vibrations. This research has influenced many codes, but the result does not seem to be in line with more recent studies of McKay [4.3] and Parsons and Griffin [4.4]. The quality of the study from Reiher and Meister can be doubted on many grounds, size of subject group, quality of vibration, the effect of sounds, design of the experiment and absence of statistical analysis. In this study the speed of the vibration is taken as the criterion.

The German DIN code DIN 4150 from 1939 and later the update in 1975 have been based on the research from Reiher and Meister. But a difference can been found in the region from 10 Hz to 100 Hz, the codes allow a higher value. A recent guide from the Dutch SBR [4.6] uses the German DIN code as a basis. The guide has been developed to be applicable for floors made from any material and predict the performance of a floor. The effects of mass of the walker and walking frequency have been taken in account. The eigenfrequency and modal mass need to be known, as is the damping, with these properties and graphs the performance can be determined. If a computer calculation is preferred the tools are given for this too.

In 1974 the ISO publishes norm 2631 with threshold values for vertical and horizontal vibrations, the acceleration is taken as a criterion in this code. This norm is replaced in 1989 by ISO 2613-2 (BS 6472 uses equal criteria). The study by Parsons and Griffin [4.4] shows the code to be incorrect (proposal for the code was published in 1985), the curves of these codes overestimate the effects of low frequency vibrations (2 to 11 Hz) and underestimate the effects of high frequency vibrations (higher than 11 Hz). The various codes are compared in Figure 15, the result of the research of Parsons [4.3] is given in Figure 16. In the latest version of the code, ISO 2631-2 (2003), the criteria of 1989 have been withdrawn: Values above which vibrations in buildings don't lead to negative remarks are not given because the possible bandwidth is to wide to be published in an international standard.

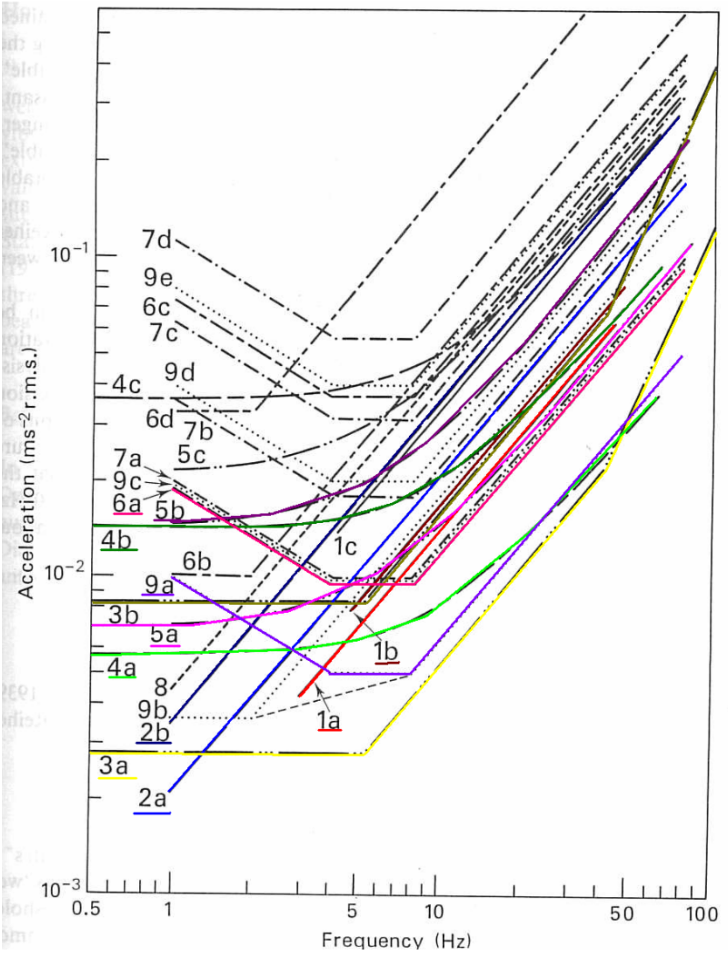


Figure 15: Comparison between codes

1a: Reiher and Meister (1931) - below weakly acceptable for vertical vibration
2a: DIN 4150 (1939) – PAL=0: threshold of perception
2b: DIN 4150 (1939) – PAL=5: just perceptible
3a: DIN 4025 (1958) – K=0.1: threshold of perception
3b: DIN 4025 (1958) – K=0.3: just perceptible
4a: VDI 2057 (1963) – K=0.1: threshold of perception
4b: VDI 2057 (1963) – K=0.25: just perceptible
5a: DIN 4150 (1975) – KB=0.2: residential areas
5b: DIN 4150 (1975) – KB=0.4: Business areas
6a: ISO 2631 (1974) – z-axis threshold of perception
9a: ISO 2631-2 (1989) – z-axis base curve

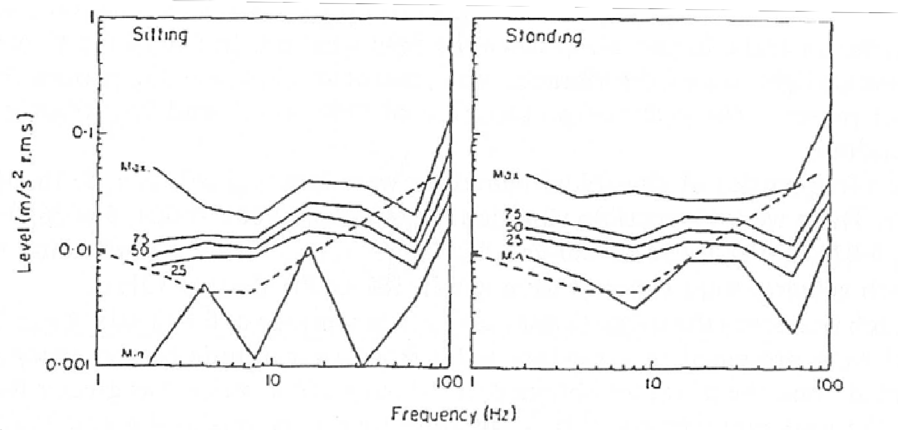


Figure 16: Percentiles and range of vibration thresholds for 36 sitting and standing subjects exposed to vertical vibration, compared with the base curve proposed in ISO 2631 [4.3]

The Dutch NEN 6702:2007 mentions vibrations, but only two crude criterions are used. The dead weight of the floor should be at least 5 kN/m^2, but if this criterion is not met the eigenfrequency should be at least 3 Hz. Floors for gymnastic halls and dance floors should have an eigenfrequency of at least 5 Hz.

No census is reached on whether the acceleration or the speed of the vibration is the best criterion to judge a vibration. Because the vibration behaviour can be described by a sinus, the speed of the movement and the acceleration are strongly related, one being the derivative of the other [4.9].

It is important to make a difference between vibrations which can be felt, and vibrations which cannot be tolerated. Allen [4.7] sets the limit to about 0.5 % g, or 0.05 m/s^2. Problems with vibrations can be prevented by raising the eigenfrequency and by increasing the damping of the floor, for instance by the interior.

To the damping of vibrations by FRP structures research has been done by Aluri [4.8]. The dynamic behaviour of three FRP bridges has been studied, and from two the damping has been determined. The FRP bridges damp vibrations worse than concrete and steel bridges. The results are given in Table 4.

Table 4: Results research Aluri, damping of FRP bridges

Type of bridge	Number of bridges tested	Average damping value (%)	Lowest damping value (%)
Concrete	213	7.9	2
Steel-concrete composite	12	8.4	5.5
Prestressed concrete	4	2.2	0.8
Steel	14	1.3	0.4
FRP-current study	2	1.24	0.5

Conclusion

In the design of a lightweight FRP floor the vibration behaviour will be important. If the floor is to uncomfortable for the users it will be impossible to use. Due to the still existing discussion on the right criterion it is hard to chose one, but a boundary will need to be found. The guide by the SBR [4.6] will be used, this guide is both recent and comprehensive.

5. Internal climate control

The goal of HVAC (Heating Ventilation Air Conditioning) is the support of building functions [5.1]. The building functions like living, working and sporting determine too which comfort- and user requirements the internal climate should comply. The requirements determine, together with the shape and thermal properties of the building, which installations are needed.

HVAC comply with their goal if they have enough power and are properly placed in the building, making sure negative effects don't occur on other areas of the internal climate. For this enough room should be reserved at suitable locations. To keep complying with the requirements in the future the HVAC should be accessible for maintenance and replacement. For a building which needs to be flexible in its use, the HVAC should be flexible and adaptable too. For this good accessibility is needed too.

The effect of external- and internal heat loads can be limited by thermal buffering capacity, this capacity is dependent on the mass of the building and its accessibility. Especially floors and walls are important for this capacity. These surfaces are accessible if they are not covered by lowered ceilings, wall panelling or raised floors. The covers can have advantages though, for instance for the placement of HVAC provisions. Lowered ceiling for instance have the advantage lighting fixtures can be built-in and through these fixtures a large part of the lighting heat can be removed directly.

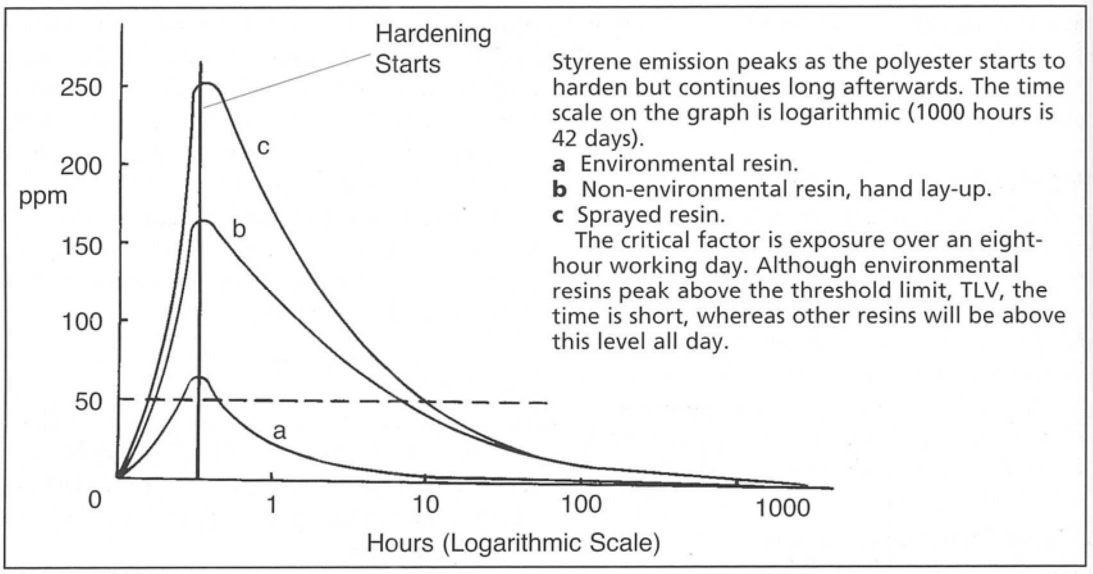
Air ducts are often insulated, the fresh air is often cooled and condensation can occur on the ducts. Often the insulation is done with mineral wool with an aluminium foil coating, but if the ducts are left in sight a more durable coating is used to prevent damage. Due to their large size (volume) the position is often determined by the resulting view if the ducts are left in sight. If this is done improper placing should be prevented.

Climate requirements for houses and schools are given by NEN codes in the Netherlands. NEN 5066 gives temperature demands for heating, NEN 1087 gives ventilation requirements. For offices the reference is often made to the guide from the Dutch Rijksgebouwendienst, the NEN 13779 can be used too.

Installations are vital for a building, with installations a comfortable internal climate is possible. The installation should be accessible for maintenance, change and replacement. Air ducts have the largest cross-section and are most critical for placement.

It is possible to combine the pipes for a cooling ceiling with a sprinkler installation [5.2]. Sprinklers can be an advantage during fire, and cooling ceilings are an efficient and comfortable method to cool a space.

If polyester or vinyl ester resin is used during production styrene will be emitted, the amount depends on the used resin and the process, an example is shown in Figure 17, taken from [5.3 de plesis]. European codes limit the emission of styrene at 50 ppm, from 20 ppm styrene will be noticed by smell. It can be seen in the figure that even with the least favourable method the styrene emission will be quickly beneath allowed limits, and even quickly beneath the smell threshold. It is unlikely the users of a building with FRP floors will have odour nuisance from styrene emitted from the floor.



Styrene emission peaks as the polyester starts to harden but continues long afterwards. The time scale on the graph is logarithmic (1000 hours is 42 days).

- **a** Environmental resin.
- **b** Non-environmental resin, hand lay-up.
- **c** Sprayed resin.

The critical factor is exposure over an eight-hour working day. Although environmental resins peak above the threshold limit, TLV, the time is short, whereas other resins will be above this level all day.

Figure 17: Styrene emission

Conclusion

In the design of the floor space should be reserved for HVAC needed to allow the building to function. A system should be developed for the placing of the front-end equipment and distribution to make a sensible whole. Installed overcapacity can be an advantage with future changing demands in mind. In relation to replacement and maintenance of the installations the front-end equipment and, by preference, also the ducts they should be accessible. It is not wise to hide these parts in the floor.

6. Environmental aspects of the usage of fibre reinforced polymers

Environmental aspects with respect to material choice are a subject that is gaining more and more importance in engineering. Yet a good comparison of available materials on environmental aspects is often not made at the beginning of a project. For a good comparison design are needed with a high amount of detail, but these are often not available, a reason not to make a comparison. Another reason not to make a comparison is the focus on initial costs, and not on life-cycle costs.

Footbridge

For the commission of a footbridge at the harbour of Noordland in the Oossterschelde (NL) by the Dutch Rijkswaterstaat a study was performed by Daniel [6.1] on the environmental impact of the choice for a material. Sketch design where made for each material and have been ecologically compared.

The pedestrian bridge is made in two parts, each spanning 13.6 m with a width of 1.6 m and a load of 4.0 kN/m^2, with a maximum deflection of l/250. The following material choices have been studied:

- Steel, coated, S235 or S335, with a wooden deck
- Stainless steel, wooden deck
- FRP, E-glass fibre reinforced polyester
- Aluminium
- Concrete, C35 including reinforcement

The performance of each option is quantified on the following criteria;

- Initial costs
- Maintenance costs for 50 years use
- Environmental impact

To quantify the environmental impact no use has been made from existing methods like lifecycle analysis because these were found to be poorly applicable. Existing methods are designed for simple products but a bridge was to complex and not yet designed into enough detail. Therefore a limited, but workable, alternative method was chosen. The criteria are:

- The energy use, stored energy in the material is taken in account trough the exergy method
- The pollution of air and water, caused by material sourcing, production and maintenance

The first criterion serves not only to determine the amount of energy use, but also shows the size of the contribution to processes as greenhouse effect, sea level rise and climate change. The result of the second criterion gives an impression of the pollution caused by the material choice.

An importance difference is in the maintenance of the materials, a steel bridge will need sandblasting and repainting twice during the lifespan where other materials only need periodical inspections. For the aluminium and FRP bridge the prediction is made to replace the deck once, though its probably not necessary to do so, to take unexpected mechanical damage in account.

In the comparison the following aspects have been take in consideration:

- Total amounts and costs of materials
- Available production techniques used, their costs, conditions, requirements, available warranties, risks for surrounding etc.
- Transport and placement conditions, needed timeframe, heavy equipment and other conditions
- Inspections and maintenance requirements during the lifetime of the bridge
- Environmental aspects during all involved processes

The result is given in Table 5:

Table 5: Cost (initial and maintenance), exergy use and pollution of materials

Material of the bridge	**Criterion**			
	Initial Costs	Maintenance Costs	Energy consumption	Volume of produced pollution
Structural steel	Painted: **€ 40 000** aluminium coated: **€ 50 000**	Painted: **€ 30 000** aluminium coated: **€ 6 000**	“exergy” method **294 000 MJ**	water: **697.4 m^3** air: **7.09 10^6 m^3**
Stainless steel	in AISI 316 L: **€ 110 000** in AISI 304 L: **€ 96 000**	in AISI 316 L: **€ 6 000** in AISI 304 L: more and shorter lifecycle	“exergy” method **329 600 MJ**	Not investigated, certainly more than structural steel
Composites	In pultruded GRP: **€ 70 000**	rough estimate: **€ 17 000**	“exergy” method **120 000 MJ**	water: **85.8 m^3** air: **7.92 10^6 m^3**
Aluminium	AIMgSi1: **€ 77 000**	rough estimate: **€ 19 000**	“exergy” method **268 700 MJ**	water: **565.3 m^3** air: **41.0 10^6 m^3**
Concrete	C35: **€ 30 000**	rough estimate: **€ 10 000**	“exergy” method **277 200 MJ**	water: **341.9 m^3** air: **31.04 10^6 m^3**

In the table it is shown the exergy use of the GRP alternative is much lower than from all the other alternatives, the pollution of water is also a lot lower and the pollution of air as close to the pollution of air by the steel alternative, but still much lower than from aluminium and concrete.

In the comparison of the alternatives some aspects have not been taken in account, for instance the demolition of the bridge at the end of the lifetime. Should the demoltion been taken in account this would have lead to a high increase in the energy consumption of the concrete alternative. The demolition and reuse of concrete demands a lot of energy use. The environmental friendly design was the GRP bridge, this design has been chosen on that criterion.

An important difference in the application of materials in a bridge or a floor is the climate, a bridge is always outside and exposed to the elements while a floor is inside a building, reducing the need for maintenance. This difference will result in a different result than given in Table 5, for steel a protective coating or painting is no longer needed, reducing the environmental impact.

Comparison on stiffness

A comparison can be made with the exergy data from the article of Daniel [6.1], for an equal stiffness the needed amount of material and energy can be determined. First assume a concrete plate of 0.1 m thick and one meter wide, the EA of this cross-section is 3.1 10^9 N m/m, the weight of 1 meter is 0.1 · 1 · 24 = 2.4 kN, the needed energy is 2.4 · 100 · 11 = 2640 MJ. For steel and FRP the same calculation can be made, the result is in Table 6.

Table 6: comparison exergy values of materials based on equal stiffness

Material	E-modulus (N/mm^2)	Density (kN/m^3)	Thickness (mm)	EA (N m/m)	Cost (€) (rough material)	Exergy (MJ)
Concrete	31 000	24	100	3.1 10^9	10	2640
Steel	210 000	76	15	3.1 10^9	140	5324
Glass fibre reinforced Polyester	40 000	19	78	3.1 10^9	410	4891

Important to note with this table is the CO_2 production of concrete during production, in the production of concrete chalk ($CaCO_3$) is transferred to calciumoxide (CaO). This transfer requires a lot of energy, but this process also produces CO_2 because this is the removed from the chalk, as a result the production of CO_2 is 2.5 times larger than only the use of energy. An advantage of FRP is the possibility to regain stored energy at the end of the lifetime, by burning the composite about 30% of the energy can be reclaimed.

7. Fire

In buildings a risk of fire is always present. Off course fire should always be prevented, but in case a fire does occur the users should be given enough time to evacuate the building. In this chapter an overview of the requirements for fire safety are given, followed by the behaviour in fire of the matrix and the fibres. The behaviour of a whole laminate can then be described and finally possibilities of protection.

Requirements

The fire safety is arranged on multiply aspects, the requirements are given by law in the Bouwbesluit [3.2] from which references are made to codes to determine the performance. To prevent rapid spread of fire a building is made up from fire compartments, if a fire occurs in one compartment it should take at least 60 minutes before the fire spreads to the next compartment. Fire can spread by burning trough the division or by going around it, for both the 60 minute limit is set. A floor is nearly always a division between two fire compartments and thus a floor should prevent fire from spreading trough it during 60 minutes.

Another aspect of fire safety is the integrity of the whole building. Progressive collapse of the building should, for a certain amount of time, be prevented. These demands vary based on use of the building and height and can be up to 120 minutes for buildings with floors higher than 13 meters above the ground level. Progressive collapse occurs when the main bearing structure fails. A part of the structure is a part of the main bearing structure when due to its failure the whole main bearing structure fails. A floor can be part of the main bearing structure, for instance if the floor serves as a support to reduce the buckling length of a column.

Behaviour of matrix during fire

In general thermosetting matrix materials goes through four stages during increasing temperature. During the first stage the temperature raises from room temperature till just less than the glass transition temperature of the laminate. The second stage is around the glass transition temperature, during which the matrix losses resistance and can be easily deformed. During the third stage the matrix remains weak and easily deformable. In the final stage the matrix starts to burn (when exposed to flames and oxygen) and vaporize. Part of the resin can also turn into char, the amount of charring depends on the resin. Mouritz and Gibson have written a good book on FRP composites in fire [7.1].

The development of the E-modulus of a polyester matrix and a vinyl ester matrix is shown in Figure 18. The glass transition temperature (often revered to as T_{glass}) is the temperature at which the matrix has lost half of its strength/stiffness, for the polyester matrix in Figure 18 the glass transition temperature is 90^o C, for vinyl ester T_{glass} is about 10^o C higher. The glass transition temperature of a resin can be influenced by its composition, the precise mixture has influence, so has additives, but for all thermosetting resins T_{glass} can be increased by curing at elevated temperatures. The maximum gain is limited though, gains of 40° C will not be reached.

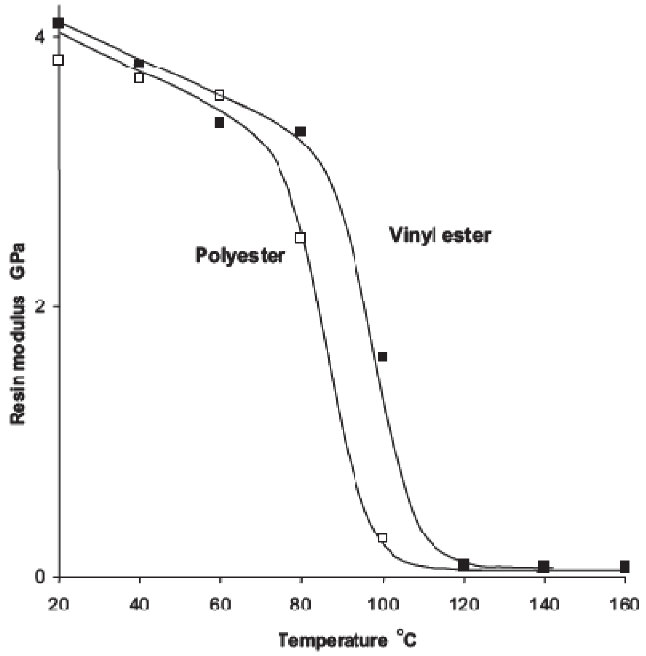


Figure 18: Decreasing E-modulus of matrix (polyester and vinyl ester) due to increasing temperature

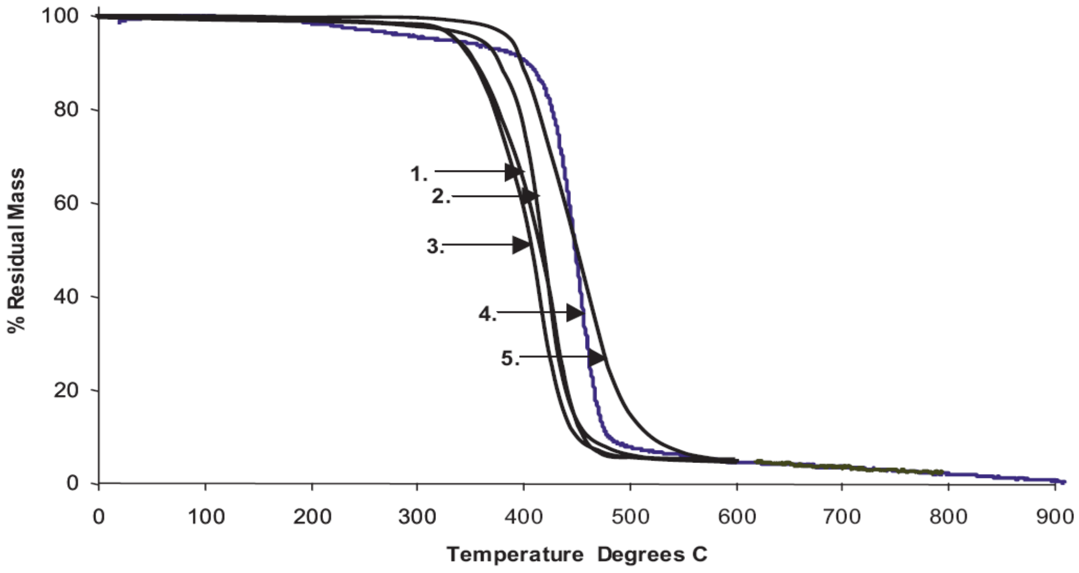
Polyester and vinyl ester matrices burn at about the same temperature, this is caused by styrene being released from the matrices. Both only produce a limited amount of char, only about 5 to 10 % of their mass turns into char.

Epoxy matrices differ a lot in their composition, their behaviour in fire therefore also differs a great deal. In general, epoxies burn rapidly and completely, little char is produced.

Phenolic resin is the best matrix for fire critical applications. The resistance of phenol to fire is large, during fire a large part of the matrix is turned into char, insulating the unaffected part of the laminate. This process can be compared to wood, which also chars and protect the unaffected part. During production small droplets of water are formed and enclosed into the laminate, by turning into vapour these enclosed droplets cool the laminate.

Figure 19 shows the thermogravimetric analyses (TGA) of matrices made with styrene (-like) solvents, it is shown all types vaporize at a similar temperature of around 450° C. It is also shown this process is quick, it takes about two to three minutes.

A fire proof matrix is Vubonite, an inorganic phosphate cement. Vubonite does not melt below 1000° C and a fireproof laminate can be made together with glass fibres.



Thermogravimetric analysis traces for solvent monomer resins at 25°C/min in nitrogen . 1. orthophthalic polyester; 2. isophthalic polyester; 3. halogenated (HET acid) polyester; 4. vinyl ester and 5. Bisphenol A polyester.

Figure 19: Transition into gasses of styrene based resins in a nitrogen atmosphere

Behaviour of fibres during fire

Between types of fibres large differences can be seen. E-glass fibre is not affected by fire till 830^{o} C, at this temperature the fibres start to weaken and at 1070^{o} C they start to melt. But carbon fibres start to oxidize at a lot lower temperature of about 400^{o} C, although between production process differences are found. But for the oxidation of carbon fibres a high heat flux is needed and a lot of oxygen. As a result the fibres on the outside are often affected, but fibres more to the inside are protected by the outer fibres due to reducing the heat flux and starving of oxygen.

Aramid fibres start to soften at 300^{o} C and disintegrate from 450^{o} C up. Aramid fibres can stand flames well though.

Manfredi [7.2] is one of the few who did research to the behaviour of natural fibres during fire. He performed a TGA on sisal, flax and jute fibres. The result of the TGA is given in Figure 20. In the range around 100^{o} C the mass loss is caused by vaporizing water from the fibres. All types of fibre start to lose mass quickly form 300^{o} C up. No studies have been done to the development of strength and stiffness of natural fibres in increasing temperatures.

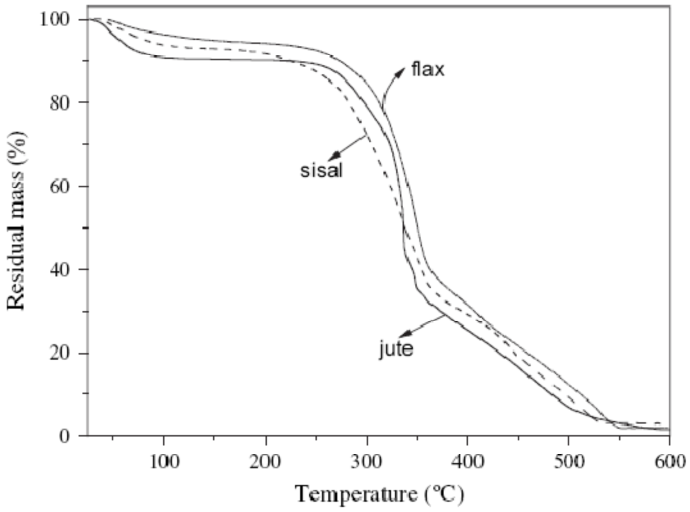


Figure 20: TGA curves of sisal, flax and jute fibres

Behaviour of a laminate during fire

The behaviour of a laminate in fire is mostly determined by the matrix. If the laminate is in compression failure will occur quickly after T_{glass} of the resin. When the resin has become weak it can't prevent the fibres from buckling and the laminate will fail. Laminates in compression should be very well insulated from fire. When loaded in tension a laminate will lose its strength and stiffness in stages. Till T_{glass} of the resin the strength and stiffness of the laminate remain constant, but from T_{glass} these properties decrease to about ½ of the original values. The weakening of the resin, which also prevents load distribution between the fibres, causes the reduction of the properties. The remaining strength and stiffness are further reduced when the fire affects the fibres.

The processes occurring in a laminate (glass fibre polyester) during fire are shown in Figure 21.

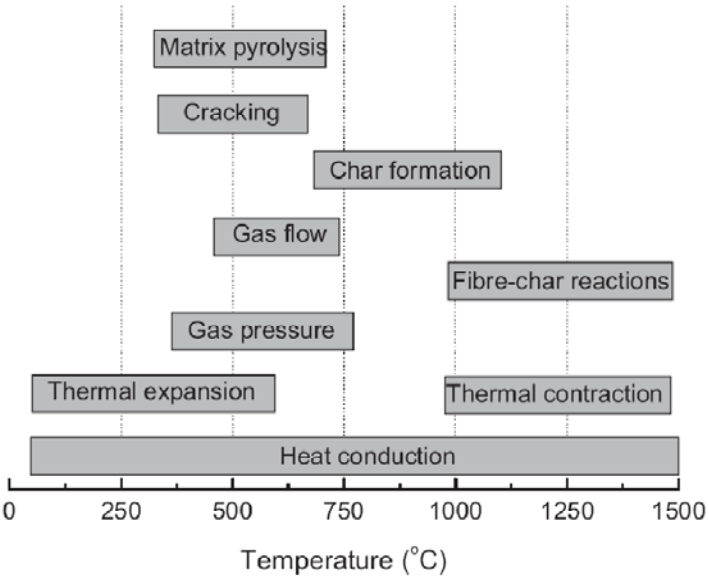


Figure 21: Processes in a laminate during fire (temperatures are approximate and depend on composition of material and fire conditions)

Figure 22 shows the strength of glass fiber reinforced matrices in elevated temperatures. The effect of the glass transition temperature of the strength of the laminate is clearly shown. The thermosetting laminates remain about ½ of their original strength in this test. The thermoplastic matrix (polypropylene) shows quick weakening (around 50^{o} C) and melting (at 180^{o} C). The behaviour of the thermosetting matrices is much saver in this experiment, the strength loss is lower and the remain strength is longer available.

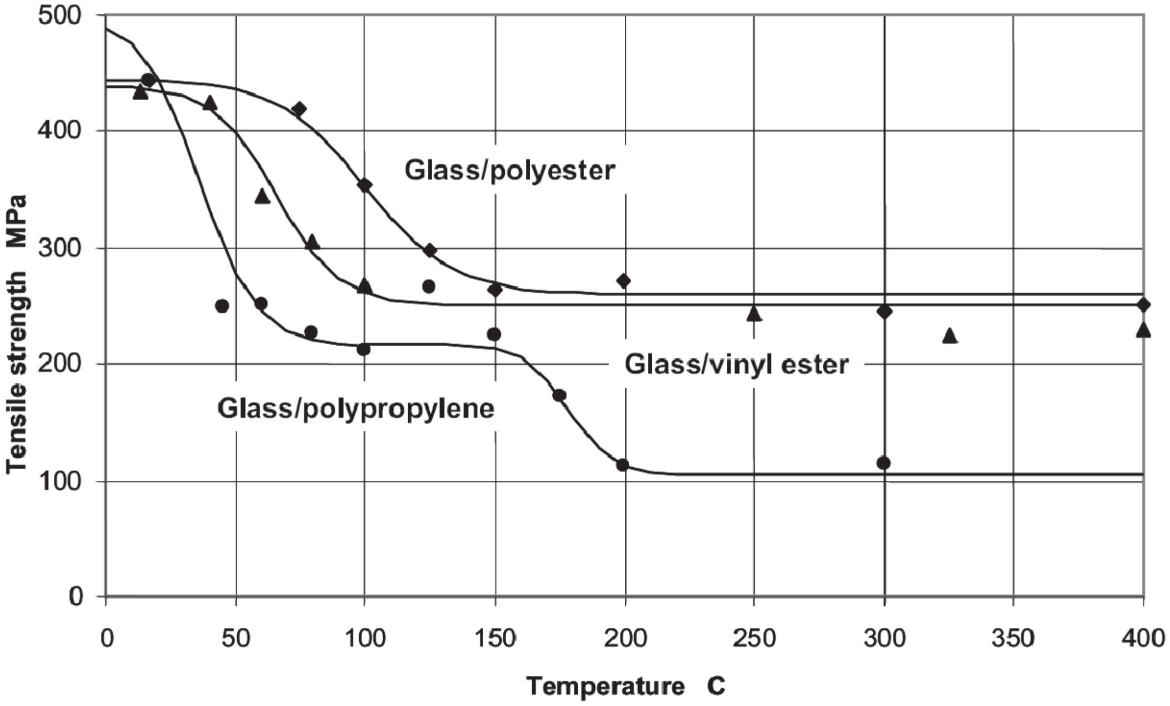


Figure 22: Strength of glass fiber reinforced matrices during elevated temperatures

Figure 23 shows a pultruded laminate during increasing temperatures. The development of the modulus is comparable to the strength as shown in Figure 22. Figure 23 also shows the effect of the weakening of the matrix clearly, the transverse stiffness of the UD core reduces to nil.

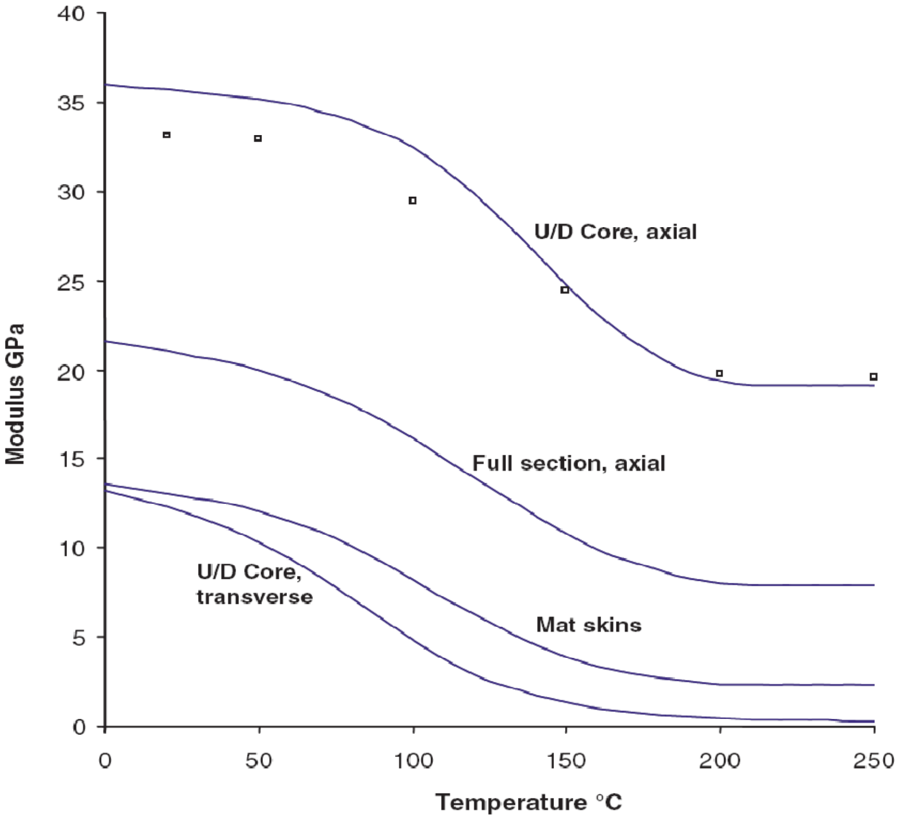


Figure 23: GRP pultrusion profile during fire, section is 60% of volume UD core, with skins of continuous swirl mat

Protection of a laminate during fire

Three basic solutions are available for the protection of a laminate during fire. A matrix can be chosen with good fire properties, for instance phenol or inorganic phosphate cement. The laminate is fire proof by itself. Increased cost or difficult workability can be problems with solution.

The second option is to add additives to the matrix, these additives can increase the fire safety of a laminate on multiple manners. Additives can reduce smoke production, increase charring or lower temperatures by adding thermal mass. Often large amounts of fillers are needed reducing mechanical properties of the laminate. Additives can be very chemical, for instance halogens, by adding these the smoke production will decrease, but the smoke is toxic. The use of additives is complex and one of the alternatives might be more practical.

The final solution is to add a layer to the laminate. A protective insulating layer can be applied on the surface of the laminate reducing the heat flux and thus keeping the laminate cooler. A cooler laminate has a higher strength and stiffness as is shown in this chapter. A voluminous insulation materials can be applied such as mineral wool. An added benefit of mineral wool is the possibility to use it to improve the acoustics of the room, a large added thickness to the laminate can be disadvantageous. The laminate can be coated with intumescent paint. This time of paint foams if heat is added, by the foaming an insulating layer is formed. Intumescent paint is a common fireproofing material for steel structures. A layer of an insulating and inflammable polymer such as an acrylic calcium sulphate (Acrylic One) can be applied too. By adding such a layer the laminate will be protected from flames and due to the insulating properties the heat flux will be lower as will the occurring temperatures.

Appendices

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ii. Index of tables

iii. References

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iv. Definition of terms used

An isotropic	Material properties differ per direction
Curing	Process in which the matrix sets by cross-linking of the molecules of the polymer, caused by heat or curing agents
Eigenfrequency	The frequency in which a structure will vibrate freely
E-modulus	Also Youngst-modulus, stiffness
Epoxy	Type of resin
Extrusion	Process of making a continuous shape by forcing a solid material trough a dye
FRP	Fiber Reinforced Polymer, sometimes Fiber Reinforced Plastic
Glass transition temperature	Temperature at which a thermosetting polymer has lost half of it's strength at room temperature
GRP	Glass fiber Reinforced Polymer, often also Glass fiber Reinforced Polyester
HVAC	Heating Ventilation Air Conditioning, abreviation for the climate controling Building Services
Isotropic	Material properties are equal in all directions
Laminate	FRP structure with multiple layers of reinforcement and matrix
Laminea	One layer of reinforcement and its matrix
Mould	The cavity onto which the a plastic material is placed and from which it take sit shape
Phenolic	Type of resin based on phenol
Ply	same as: Laminae
Pre-impregnated	Factory made fabric, already saturated with resin and additives, will need increased temperature to permanently set
Prepreg	see: Pre-impregnated
Pultrusion	Industrious production method for FRP, continuous sections can be quickly made
RTM	Resin transfer moulding, production method in which resin is forced between two solid moulds by pressure to wet-out the reinforcement placed between the moulds
TGA	Thermogravimetric analyses, method to measure the loss of solid mass due to increasing temperature in an inert atmosphere
Tglass	see: Glass Transition Temperature
Thermoplastic	A type of plastic which softens every time it is heated
Thermoset	A type of plastic which sets once permanently
Tooling	see: Mould
UD	see: Unidirectional
Unidirectional	a term to discribe the situaltion in which all fibres in a laminate/ply are aligned in the same direction
VA-RTM	Vacuum assisted resin transfer moulding, adaptation of RTM
Vinyl ester	A type of resin
Wet-out	Complete wetting/saturation of fibrous surface with a liquid resin