

Saimaa University of Applied Sciences  
Faculty of Technology, Lappeenranta  
Double Degree Programme in Civil and Construction Engineering

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# **APPLYING CARBON FIBER IN BUILDING STRUCTURES.**

Bachelor's Thesis 2010

## ABSTRACT

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Applying carbon fiber in building structures. 46 pages, 4 appendices

Saimaa University of Applied Sciences, Lappeenranta

Technology, Degree Programme in Civil and Construction Engineering

Bachelor's Thesis 2010

Tutors: Tero Liutu, Petri Himmi, Juri Kvach.

The purpose of the research was to study production technologies, properties of carbon fibers, methods of construction, using this material, compare carbon fiber and structures, using carbon fiber with traditional materials and structures and find out reasons for application in construction. In addition, my task was to create calculating tool in Excel to estimate effect of carbon fiber strengthening to the structure.

The study was commissioned by Juri Kvach, FM Stroiprojekt.

The calculating tool in Excel represents a program that calculates the existing cross-section of the beam, finds its ultimate bending moment, and compares this moment with existing or projecting moment. If moment is not enough, it is possible to choose strengthening material, its size and number of layers, and calculate bending moment of improved structure.

Calculations of the strengthened with carbon fiber beams shows increasing of ultimate bending moment up to 90% from initial moment of unstrengthened low-reinforced beams. Strengthening of high-reinforced beams does not give such effect because of changing the failure model to fragile, which is not allowed for concrete structures.

Keywords: calculation, carbon fiber, strengthening.

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# 1 INTRODUCTION

My bachelor's thesis is devoted to applying carbon fiber for construction, renovation and structure reinforcing purposes. Carbon fiber is not an absolutely new material, it is successfully applied in such fields as: aviation and aerospace industry, car industry, production of sport equipment, production of working clothes and military accoutrements, electronic industry, etc. Rather new is the idea of using carbon fiber in building structures. At the present time methods of strengthening of the structures with fibers are applying for different structures. Also very prospective directions of using carbon fiber is fiber-concrete and fiber-cement, reinforced with carbon fibers, using carbon fiber as post-tension or pretension reinforcing bars in new reinforced concrete structures, applying polymeric and metal composites for structures. The main reason that carbon fiber is considered as construction material so rarely, is its high price, but the general trend of increasing production of carbon fiber and reducing its cost can said might change this situation in the construction industry.

In my thesis I will try to study all uses of carbon fiber, find calculating methods, make a comparison of materials and make conclusions about reasonability of applying carbon fiber in terms of operating conditions and economics.

## 2 HISTORY

Initially production and application of carbon fibers was suggested and patented by Thomas Edison in 1880 for use as filaments in electrical lamps. These fibers were made of cotton or rayon fibers by pyrolysis. This fiber was very fragile and porous and has been replaced by tungsten. During the next 20 years he suggested to obtain carbon and graphitic fibers from different natural fibers.

The second time interest to carbon fibers appeared in the middle of the XX century, when suitable material for reactive engine parts was needed. Carbon fiber with its properties turned out to be one of the most suitable reinforcing materials for this purpose, because it was quite heat-resistant, has good heat insulation, has corrosion resistance against gas and fluid agents, high strength and stiffness. In 1958, Dr. Roger Bacon created high-performance carbon fibers at the Union Carbide Parma Technical Center, located outside of Cleveland(United States), Ohio. Those fibers were manufactured by heating strands of rayon until they carbonized. This process proved to be inefficient, as the resulting fibers contained only about 20% carbon and had low strength and stiffness properties. High temperature treatment allowed new material to reach tensile strength of about 330-1030 N/mm<sup>2</sup> and elastic modulus up to 40 kN/mm<sup>2</sup>.

In the early 1960s was proposed short mono-crystal graphitic fiber production technology, which enables to approach tensile strength about 20 kN/mm<sup>2</sup> and Young's modulus up to 690 kN/mm<sup>2</sup>. These fibers were grown within voltaic arc under the temperature of 3600 °C and pressure of 0,27 N/mm<sup>2</sup>. Nowadays this technology is very uncommon because of its expense.

In the same time period a process was developed using polyacrylonitrile (PAN) as a raw material. This had produced a carbon fiber that contained about 55% carbon and had much better properties than rayon based fibers. The polyacrylonitrile (PAN) conversion process quickly became the primary method for producing carbon fibers. Characteristics of first PAN-based fibers wasn't outstanding, but technology has been improved and after 10 years (to 1970s) were obtained carbon fibers with tensile strength of 2070 N/mm<sup>2</sup> and modulus of 480 kN/mm<sup>2</sup>. At this time has been shown the possibility to

produce fibers with elastic modulus up to  $800 \text{ kN/mm}^2$  and strength up to  $3 \text{ kN/mm}^2$ , using PAN technology.

During the 1970s, experimental work to find alternative raw materials led to the introduction of carbon fibers made from a petroleum pitch derived from oil processing. The first fibers based on petroleum pitch were made in the 1970s in Japan. These fibers contained about 85% carbon and had excellent flexural strength.

### 3 PRODUCTION OF FIBERS

There are existing 4 types of carbon fiber: cellulose based carbon fibers, PAN-based fibers, pitch based fibers, and vapor grown carbon fibers. The first three types use different raw materials, and the last one is different from the others by production technology. In this thesis I will consider the production of the two most common and most the suitable for our purposes types of carbon fibers, PAN-based fibers and pitch based fibers. Cellulose based fibers are worse than PAN-based and pitch based fibers in its properties. Vapor grown fibers show outstanding properties, but they are very expensive for construction.

#### 3.1 Production of pan-based fibers

All production technologies, excepting vapor grown fibers, are rather the same and consist of 3 stages: oxidation, carbonization and graphitization (Figure 3.1). After every stage carbon fibers with different structures and properties appear.

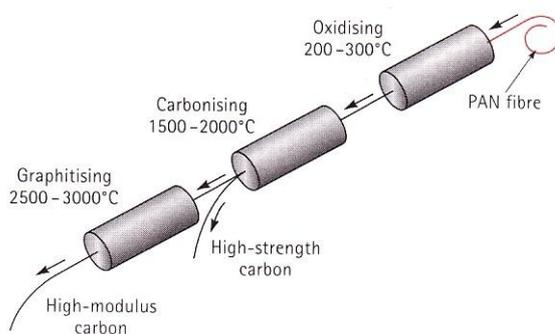


Figure 3.1 Basic scheme of production stages of PAN-based fibers (Askeland, 1998)

### 3.1.1 Preliminary stage

In the first stage it is necessary to choose suitable raw material for carbon fiber production. In this production method, manufacturers used polyacrylonitrile (PAN) continuous fibers. This fiber has a tensile strength of 60 N/mm<sup>2</sup> and elastic modulus of 3,8 kN/mm<sup>2</sup>. Properties of PAN fibers can be different for every manufacturer. PAN fibers can cost up to 50% from the future carbon fiber price. That is why some manufacturers use their own PAN fibers. A repeat unit of PAN fibers is given on figure 3.2.

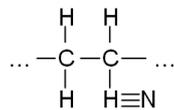


Figure 3.2 PAN fiber monomer.

To achieve continuous fibers, heavy reels of precursor fibers is required, and improved box handling facilities designed to suit the large packages. Introduction of robotics for continuous splicing can reduce downtime. The golden rule with precursor handling is to have the least number of contact points in order to minimize filament damage.

### 3.1.2 Oxidation

The acrylic precursor is stabilized by controlled low temperature heating (200-300 °C) in air to convert the precursor to a form that can be further heat treated without the occurrence of melting or fusion of the fibers. To achieve this end, a slow heating rate must be used to avoid run-away exotherms occurring during the stabilization process, exacerbated by the PAN precursor which is a poor conductor of heat. (Morgan 2005)

Stabilization can be achieved isothermally by heating at a constant temperature, but this is time consuming. A more practical method is a stepwise increase in temperature. A third method is a one-step stabilization, with temperature increasing along a tubular furnace. (Morgan 2005)

In the oxidation stage, the PAN fiber will increase in density from 1180 kg/m<sup>3</sup> to about 1360-1380 kg/m<sup>3</sup> for the oxidized PAN fiber (OPF). The density of OPF must be at least 1360 kg/m<sup>3</sup>, as otherwise, the fiber will tend to pull apart and break on entering the LT furnace. The upper OPF density limit for the production of carbon fiber varies with the manufacturer and some manufacturers will use a value as high as 1400 kg/m<sup>3</sup>. (Morgan 2005)

Gases such as HCN, H<sub>2</sub>O, CO<sub>2</sub>, CO, NH<sub>3</sub>, nitriles and miscellaneous tars are evolved during the oxidation of PAN and it has been the usual practice to pass these hot gases at about 300 °C over a heated platinum group metal deposited directly onto a high surface area material coated on a porous ceramic monolith block. (Morgan 2005)

Oxidized PAN is treated with a water based antistatic finish, dried and collected after plaiting into boxes positioned on a plaiter table with longitudinal and transverse movements to plait the OPF neatly into the boxes without entanglement. (Morgan 2005)

### **3.1.3 Low temperature carbonization**

Some workers have found that the presence of moisture in the OPF can reduce the strength of the carbon fiber produced and dry the OPF prior to entry into an LT furnace. The LT furnace can best be described as a tar removal furnace and normally comprises a multizone electrically heated slot furnace, purged with N<sub>2</sub> to prevent ingress of air and providing sufficient N<sub>2</sub> flow to remove evolved tars and gases. The temperature in the furnace is gradually increased in the zones to a final temperature of about 950 °C, a temperature above which the tars are decomposed leading to the deposition of a sooty product on the fiber, which causes the filaments to stick together and the carbon fiber properties to plummet. The gases evolved during carbonization at temperatures up to 1000 °C are listed in Table 1, with a brief interpretation of the reactions that occur. (Morgan 2005)

Temperature °C	Observation	Interpretation
220	HCN evolved and O <sub>2</sub> chemically bonded	Ladder polymer formation and oxidation of polymer
260	Little change. No modulus increase	No chain scission
300	Large CO <sub>2</sub> and H <sub>2</sub> O evolution, also CO, HCN and some nitriles. No modulus increase	CO <sub>2</sub> from -COOH groups in oxidized polymer. No cross-linking
400	CO <sub>2</sub> , H <sub>2</sub> O, CO, HCN and NH <sub>3</sub> evolved. Small evolution of C3 hydrocarbons and nitriles. Modulus increase	Cross-linking by intramolecular H <sub>2</sub> O elimination
500	Increased H <sub>2</sub> evolution. Some NH <sub>3</sub> and HCN evolved. Modulus increase	Cross-linking by dehydrogenation
600	Reduced H <sub>2</sub> evolution. HCN and trace N <sub>2</sub>	Cross-linking by dehydrogenation
700	N <sub>2</sub> , HCN and H <sub>2</sub> evolution. Modulus increase	Cross-linking by dehydrogenation and evolution of N <sub>2</sub>
800	Large increase in N <sub>2</sub> . H <sub>2</sub> and HCN still evolved. Modulus increase	Cross-linking by evolution of N <sub>2</sub>
900	Maximum evolution of N <sub>2</sub> , some H <sub>2</sub> , traces HCN. Modulus increase.	Cross-linking by N <sub>2</sub> elimination
1000	N <sub>2</sub> evolution decreases to about the same as at 800°C. Trace H <sub>2</sub> evolved. Modulus increase.	Cross-linking by N <sub>2</sub> elimination

Notes: Fiber yield 53.6%, 5.0% nitrogen content.

Table 3.1 Carbonization products of oxidized PAN fibers (Morgan 2005)

### 3.1.4 High temperature carbonization

Basically, the high temperature furnace elevates the temperature in a uniform manner to increase the fiber modulus, and a smaller fiber will give a higher modulus for a given residence time, but lesser yield. The product formed during carbonization is a good conductor and imposes no limitation on the heating rate by heat transfer. Heating rates above 20 °C per minute and temperatures above 1500 °C will impair the strength of the resulting carbon fibers. (Morgan 2005)

The presence of Na in the precursor does, however, pose problems in the HT furnace, either by forming elemental Na, or combining with the HCN released in the carbonization process to form NaCN. Consequently, a precursor with little or no Na is preferred. (Morgan 2005)

To prevent ingress of air, a flow of inert gas is introduced at either end of the furnace to produce a gas seal. A body flow of inert gas should be applied at the inlet end to remove any liberated Na via an outlet branch pipe, but the flow should be controlled to maintain an optimum concentration of HCN within the muffle, since the HCN has been found to have the beneficial effect of healing surface flaws on the fiber by cracking to carbon. Sufficient body flow at the outlet end is applied to ensure that waste products exit via the outlet branch pipe. (Morgan 2005)

Generally, N<sub>2</sub> is the preferred gas but Ar can be used, although it is some eight times more expensive, but it does give a carbon fiber with an improved strength, presumably due to the higher density and viscosity of argon. (Morgan 2005)

### **3.1.5 High modulus fiber production**

The high modulus furnace operates at about 2500 °C and employs a graphite muffle operating in a carefully controlled inert atmosphere. The conditions must be quiescent, since even low volume gas flow over the hot graphite element is sufficient to continually remove a molecular layer of graphite and cause severe erosion leading to premature failure. The added heat treatment provides an improvement in the orientation of the graphite crystallites, giving carbon fibers with a high Young's modulus. (Morgan 2005)

Line shrinkage in the carbonization stage is nominally of the order 5-8%. A low shrinkage value signifies a high fiber tension. If the tension is too high, then the fiber will break, and if it is too low, then the increased fiber catenary will permit the fiber to drag along the furnace floors, degrading the fiber cosmetics. The best carbon fiber properties were attained with shrinkage of about 7%. (Morgan 2005)

### **3.1.6 Surface treatment**

It is convenient to use an electrolytic surface treatment process, which permits a good measure of control to be exercised. A suitable water soluble electrolyte is chosen, giving a solution that is readily conductive. The carbon fiber is made the anode and passed close and parallel to graphite cathodes without touching. (Morgan 2005)

### **3.1.7 Collection**

Small tows are best collected using online winders. Winding machines are available that will doff automatically. Large tows are generally plaited into cardboard boxes with the boxes positioned on a plaiter table, smaller tows can be collected in tubs. (Morgan 2005)

## **3.2 Production of pitch based carbon fiber**

There are many types of melt spun precursors used for fiber production. An isotropic pitch precursor is used to make a GP (general purposes) grade carbon fiber, a mesophase pitch is used for HP (high performance) carbon fiber. Mesophase pitches can be divided into classes on the basis of their method of manufacture—preparation by means of pyrolysis, solvent extraction, hydrogenation, or catalyst modification. A variant of the hydrogenation process, termed the Dormant Process, will produce a carbon fiber which is intermediate between GP and HP. (Morgan 2005)

### **3.2.1 Stabilization (thermosetting) of spun fiber**

The pitch precursor fibers, as spun, are very weak and almost without exception, thermoplastic in nature, making it imperative that they are chemically treated to render them suitable for subsequent carbonization. This is best accomplished by some form of oxidation treatment in the gas phase using air, O<sub>2</sub> or an O<sub>2</sub>/N<sub>2</sub> mixture, ozone, NO, Cl<sub>2</sub>, SO<sub>2</sub> or SO<sub>3</sub> although it is possible to use alternative treatments in the liquid phase with HNO<sub>3</sub>, H<sub>2</sub>SO<sub>4</sub>, H<sub>2</sub>O<sub>2</sub> or KMnO<sub>4</sub>. The simplest, cheapest and most convenient process is air oxidation, which is an exothermic reaction. Air enriched with ozone does permit lower temperatures (60-70 °C) to be used initially and could promote crosslinking similar to the ozonation of phenanthrene in solution. (Morgan 2005)

There are basically two methods of air oxidation that can be employed, both of which are batch processes:

- 1) After the fiber has been spun it is wound directly onto a heat resistant spool (Figure 3.3) using a specially designed winder which treats the fiber with special care to prevent damage. The spools are then placed in an oxidation furnace and the fiber oxidized in situ on the spools. The spools must be carefully designed so that the oxidizing atmosphere reaches the center of the package to ensure uniform oxidation and the flow rates must be adequate to prevent any build-up of heat from the resulting exothermic reaction. (Morgan 2005)

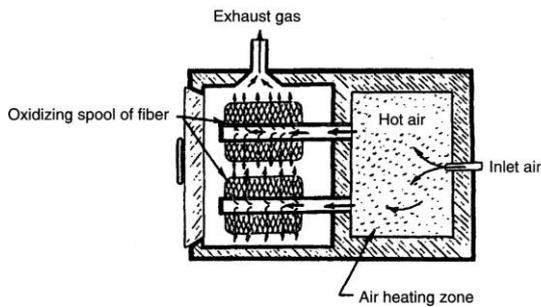


Figure 3.3 On the spool oxidation of mesophase fibers (Morgan 2005)

2) Collect the spun fiber by piddling into a suitable container to facilitate subsequent removal, with the container preferably on a plating table and with the fragile fiber being drawn from the container, spread on a conveyor belt and carried through the oxidation furnace. Large lengths can be processed by using a number of containers strung together by passing the fiber from one container to the next in a continuous manner and processing accordingly. The thickness of the fiber on the belt must be limited to prevent build-up of exothermic heat. (Morgan 2005)

The control of this oxidation process is critical, since under-oxidized fiber will remain partly thermoplastic and when processing in subsequent carbonization at higher temperatures, will permit filaments to fuse together, producing a carbon fiber with poor tensile strength. Over-oxidation will produce a brittle product, namely a carbon fiber with very poor tensile strength and will reduce the graphitizability of the pitch, which is believed to occur due to the formation of quinines that produce CO when pyrolyzed. Typical mesophase fiber required an increase of some 6% in mass for adequate stabilization and achieved this in 40 min at 260 °C with a mesophase fiber made from a solvent extracted fraction of Ashland 240 pitch, whilst an additional 1 hour of oxidation treatment only added a further 2% mass. (Morgan 2005)

The time required to effect thermosetting of the fibers depend on many factors such as the chosen oxidizing atmosphere, the temperature employed, the diameter of the fibers, the type of precursor pitch, its mesophase content, and the molecular weight distribution. The temperature used to effect thermosetting must not exceed the temperature at which the fibers soften or distort. The maximum temperature is dependent on the pitch precursor, its mesophase content and the molecular weight

distribution. The higher the mesophase content and molecular weight distribution of the pitch, the higher will be its softening temperature, and the higher the temperature at which to effect thermosetting, making it possible to effect thermosetting in less time. It is considered that a minimum temperature of 250 °C is required, whilst temperatures in excess of 400 °C can cause melting or excessive loss of carbon by burn-off, and treatment should preferably be in the range 275-350 °C. At such treatment temperatures, thermosetting can generally be achieved in 5-60 minutes, but 60 minutes should not be exceeded, since it is undesirable to render the fibers totally infusible. An isotropic pitch will generally require about 3 hours of treatment in a 20% oxygen atmosphere. As the oxidation proceeds, the temperature can be increased to speed up the reaction and typical final temperatures would be around 325-340 °C for an isotropic fiber and 300-310 °C for an anisotropic fiber. (Morgan 2005)

It is observed that a fiber with larger diameter filaments, spun from a mesophase pitch tended to elongate, whilst smaller diameter filaments shrank, presumably because they were more highly oriented. The elastic modulus of spun fibers increased with the draw ratio, but decreased with increasing thermosetting temperature and is attributed to a relaxation effect. (Morgan 2005)

To avoid filaments sticking together in the subsequent carbonization step, a two-step stabilization, a variant of the oxidation process, can be undertaken where the fiber is deliberately under-oxidized, followed by a solvent extraction with benzene or tetrahydrofuran to remove soluble fractions present in the surface layer of the fiber. (Morgan 2005)

Other techniques can be used to prevent fibers sticking during stabilization and are generally based on a form of a carbon graphite lubricant, such as colloidal graphite, or carbon black in aqueous or silicone oil suspension and applied to the fiber prior to stabilization. Although it is reported that suspensions of silica and calcium carbonate can also be used, it is unlikely since they would be sources for possible sites of internal flaws which may be formed during carbonization. (Morgan 2005)

### 3.2.2 Carbonization

The greatest weight loss occurs in the early stages of carbonization. Therefore, it is advantageous to apply an initial low temperature carbonization stage to avoid disruption of the fiber structure. Normally, about 30 seconds to 5 minutes is sufficient time, while suitable treatment would be about 0.5 minutes at 700 °C followed by 0.5 min at 900 °C in an inert N<sub>2</sub> atmosphere. A typical carbonizing furnace using a graphite hairpin element and capable of achieving 2000 °C is shown in Figure 3.4. (Morgan, 2005)

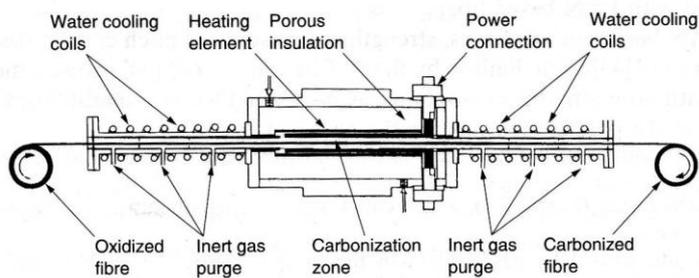


Figure 3.4 Diagram of a hairpin element furnace used to carbonize mesophase pitch fibers (Morgan 2005)

Carbonization is required to remove hetero-atoms like H, N, O and S in the form of H<sub>2</sub>O, CO<sub>2</sub>, CO, N<sub>2</sub>, SO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub> and tars. Above 1000 °C, the principal gas evolved is H<sub>2</sub>. Carbonization can be achieved in a string of separate furnaces with individual temperature settings, or one or more furnaces with zoned temperature control. After the initial carbonization stage, the temperature is increased to about 2000 °C. It was founded that at temperatures up to 1000 °C, some degradation of the structure occurred with attendant reduction of modulus, but as the temperature increased there was a marked increase in preferred orientation as the hetero-atoms were continuously released, forming a graphite-like structure. Strength and the modulus of carbon fiber made from a mesophase pitch increased with temperature. At 1500 °C, mesophase fibers could develop tensile modulus of the order of one third of the theoretical value for graphite( about 1000 kN/mm<sup>2</sup>). (Morgan 2005)

As with PAN based carbon fibers, strengths of mesophase pitch carbon fibers is limited by flaws. Possible reasons for the origin of flaws:

- Interfilament fusing, which could occur during spinning, insufficient oxidation, or thermal processing.
- Internal voids, caused by gas bubbles in the spun fiber, termed bloating, or due to the volatilization of foreign matter during the carbonization process. (In practice, gas bubbles should be released by venting the spinneret).
- Inclusion of foreign particles, due to inefficient cleaning of the precursor pitch.
- Surface defects, due to mechanical damage or surface contamination.

### **3.2.3 Graphitization**

A mesophase pitch based fiber can be further heat treated in a similar type of furnace, using a highly controlled inert atmosphere, at temperatures in the range 2500-3300 °C, preferably 2800-3000 °C, producing fibers with a high degree of orientation, where the carbon crystallites are parallel to the fiber axis. These fibers are truly graphitic and have a structure characteristic of polycrystalline graphite with a three-dimensional order. A residence time of about 10 s - 5 min may be employed. At these high temperatures, furnace lives will be relatively short due to the evaporation of graphite from the surface of the graphite electrodes, which will be aggravated by an excessive flow of inert gas across the hot element surface causing severe element and guard tube erosion. Therefore, these furnaces must be operated under quiescent conditions. A furnace with a hairpin element design cannot use argon since the gas ionizes across the element slot at about 2000 °C and so, N<sub>2</sub> is generally the preferred inert gas. (Morgan, 2005.)

### **3.2.4 Surface treatment of pitch based carbon fibers**

If the pitch fibers are to be introduced into a resin matrix, then it would be expected that some form of oxidative treatment would be applied to improve resin wetting and bonding. Surface treating a fiber which is graphitic in nature is difficult and great care would have to be taken to ensure that the fiber is not embrittled by the treatment process. When using pitch based carbon fibers in carbon-carbon composites, both the fiber and matrix are brittle materials and a weak interface would be preferred, which,

with the application of an applied load, would deflect cracks in the matrix, thus producing debonding at the fiber-matrix interface. Increased treatment did promote surface roughness, enabling more available surface for mechanical and physical interlocking. (Morgan, 2005)

## **4 PROPERTIES OF CARBON FIBERS AND COMPOSITES**

To choose suitable materials for building purposes we should mention its properties, which properties can help us to reach our goals and which proved to be useless or adverse. Each material is not ideal and has its own fields of application. That is why we should consider the advantages and disadvantages of carbon fibers.

### **The advantages are:**

- Availability in many grades and forms with wide ranging properties
- High elastic modulus, especially pitch based fiber
- High strength, especially PAN based fiber
- Low density, giving good specific properties
- Good thermal stability in the absence of O<sub>2</sub>
- High thermal conductivity, assisting good fatigue properties
- Low thermal expansion coefficient
- Excellent creep resistance
- Good chemical resistance
- Low electrical resistivity
- No significant inhalation problem with filament diameters down to 5 μm

### **The disadvantages are:**

- Relatively high cost, but prices have been falling and more emphasis is now placed on using large tows
- Low strain to failure with attendant handling problems
- Compressive strength is lower than tensile strength and larger diameter fiber does not give improved compression properties
- Poor impact strength of composites

- Care required during handling carbon fiber, since it is electrically conductive and can cause havoc with electrical systems
- Oxidizes in air at temperatures above 450 °C
- Exhibits anisotropy in the axial and transverse directions

#### 4.1 Types of carbon fibers and their main properties.

1) **Fibers based on viscose rayon (cellulose based):** Historically the first commercial carbon fibers, are difficult to produce with low yield, and main use is in existing space programs.

*Density: 1350-1450 kg/m<sup>3</sup>*

*Tensile strength: 0,66-0,82 kN/mm<sup>2</sup>*

*Young's modulus: 34-41 kN/mm<sup>2</sup>*

2) **PAN based Fibers:** Probably the most common carbon fibers, these fibers are not graphitic. This will limit the elastic modulus attainable, but strengths are greater than pitch based fibers.

*Density: 1750-1870 kg/m<sup>3</sup>*

*Tensile strength: 0,9-6,37 kN/mm<sup>2</sup> (usually more than 2,2 kN/mm<sup>2</sup>)*

*Young's modulus: 40-588 kN/mm<sup>2</sup> (usually more than 230 kN/mm<sup>2</sup>)*

*Elongation: 0,7% - 2,2%*

*Filament diameter: 4,4 – 7,2 μm*

3) **Pitch based carbon fibers:** These fibers are graphitic and can attain higher modulus than PAN based fibers, approaching the value for the graphite crystal (~1000KN/mm<sup>2</sup>).

*Density: 1900-2200 kg/m<sup>3</sup>*

*Tensile strength: 1,38-4,05 kN/mm<sup>2</sup>*

*Young's modulus: 159-966 kN/mm<sup>2</sup>*

*Elongation: 0,27% - 1,21%*

*Filament diameter: 6 – 11 μm*

More properties of different types of fibers from different manufacturers are presented in Appendix 1, tables 1-3.

### 4.1.1 Facts acting on strength and elastic modulus of carbon fibers.

Early work with SAF PAN based carbon fiber quickly established a relationship between Young's modulus of the carbon fiber and the production temperature. An early plot of attainable YM for a measured process temperature is given in the chart 4.1. Comparison of tensile properties of a mesophase pitch fiber with a PAN based carbon fiber produced at different process temperatures are presented in Chart 4.2. The modulus increases steadily with temperature, but the strength peaks at about 1575°C.

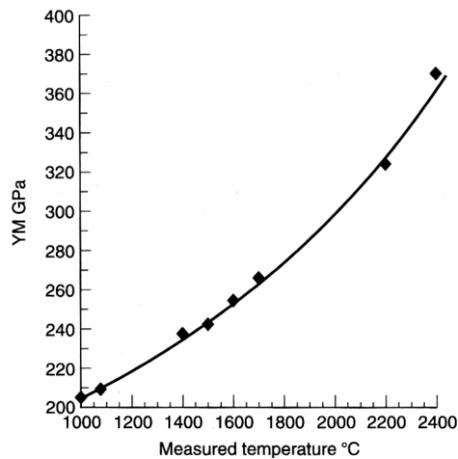


Chart 4.1 Young's modulus of a PAN based carbon fiber at given measured temperatures (Morgan 2005)

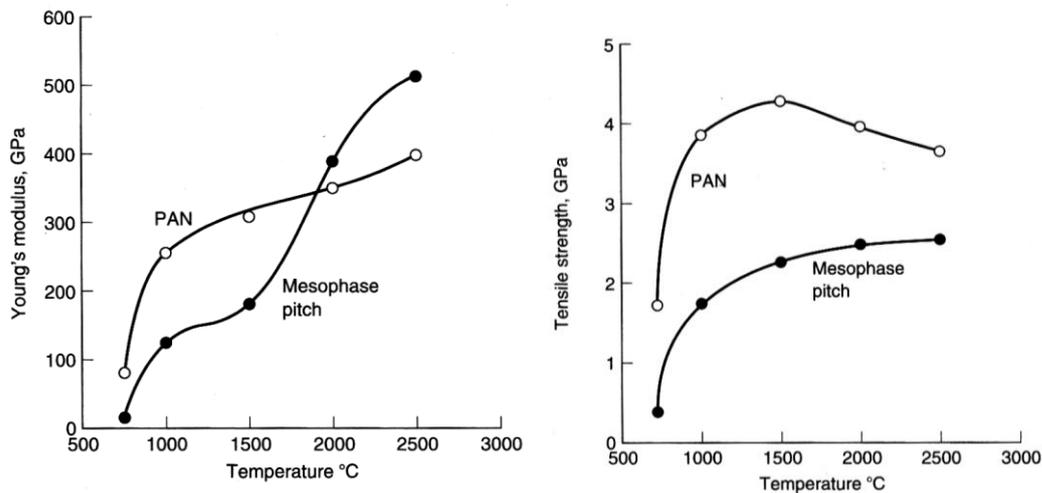


Chart 4.2. Tensile strength and Young's modulus for PAN based and mesophase pitch based carbon fibers vs. final heat treatment temperature (Morgan 2005)

As the quality of the PAN precursor has been improved and its diameter reduced, this has enabled carbon fibers to be produced with higher strengths, with a diameter of about 5  $\mu\text{m}$ . The smaller the carbon fiber diameter, greater is the strength (Chart 4.3). This fact explains the introduction of grades of carbon fiber with improved tensile properties having filament diameters of about 5  $\mu\text{m}$ , whereas other earlier grades have diameters of about 7  $\mu\text{m}$ . (Morgan 2005)

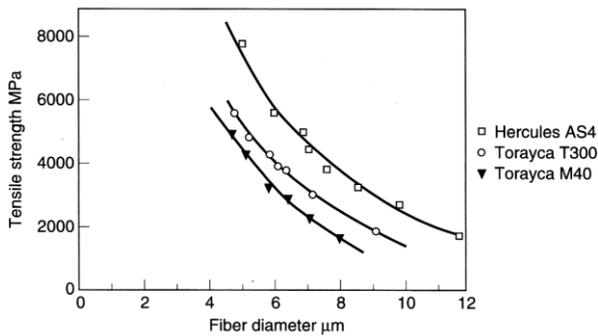


Chart 4.3 Tensile strength of carbon fiber monofilaments as function of fiber diameter (Morgan 2005)

It was found that significant increases in modulus (Chart 4.4) could be recorded with PAN based carbon fibers by hot stretching (loads of up to 0.5 g filament<sup>-1</sup> at temperatures of 2600 °C and 2800 °C for times up to 30 min), but there was a loss in strength following such heat treatment. The use of higher strains could restore the fiber strength, although in practical terms, the long treatment times to obtain this increased modulus could be a disadvantage. It is probable that this improvement in strength is due to a reduction in the filament diameter during hot stretching, hence there would be a reduced number of flaws in a smaller unit volume. (Morgan, 2005)

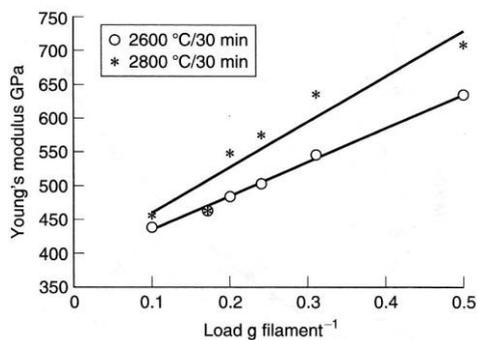


Chart 4.4. The effect of load on Young's modulus of fibers stretched for 30 min at 2600°C and 2800°C (Morgan 2005)

## 4.2 Thermal expansion of carbon fibers.

Thermal expansion is an important property for extraordinary cases, as it determines saving of shape and rigidity under high temperatures. Also this property is very important for long-span structures. The longitudinal coefficient of thermal expansion has values from  $-1,5 \cdot 10^{-6} \text{ 1/}^\circ\text{C}$  to 0, transverse CTE from  $2,2 \cdot 10^{-5} \text{ 1/}^\circ\text{C}$  to  $5 \cdot 10^{-5} \text{ 1/}^\circ\text{C}$ . It was established that CTE of carbon fiber depends on elastic modulus (Chart 4.5).

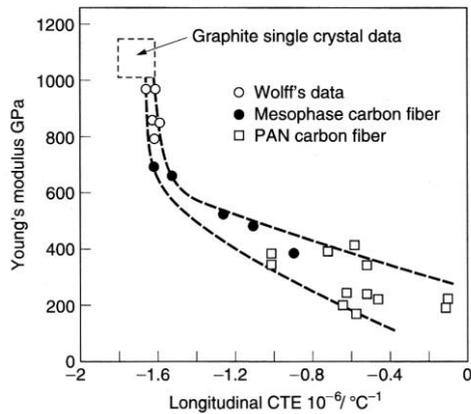


Chart 4.5 Correlation between Young's modulus and the coefficient of thermal expansion for a selection of carbon fibers (Morgan 2005)

## 4.3 Chemical resistance

One of the advantages of carbon fiber is good chemical resistance. Carbon fibers mostly consist of carbon. The carbon content of the modern fibers is usually more than 95%. Carbon is nonreactive in common conditions. Carbon fiber represents a long carbon polymer chain and does not have free bonds required for reactions. Most of the chemicals in low concentration had no effect on the fibers (Table 2). This makes it possible to use carbon fiber in concrete structures, which works in aggressive environment conditions.

Concentration	H <sub>2</sub> SO <sub>4</sub>	HCl	NaOH	NH <sub>4</sub> OH	HNO <sub>3</sub>	Acetic acid	H <sub>2</sub> O <sub>2</sub>	Chromic acid
1%	Fair	Good	Fair	Good	Good	Good	Good	Fair
10%	Fair	Good	Poor	Fair	Good	Good	Fair	Poor
Conc.	V. poor	Poor	(20%)Poor	Fair	V. poor	Good	Fair	V. poor

Table 4.1 Chemical resistance of carbon fiber

## **5 POSSIBLE USES OF CARBON FIBER IN BUILDING ENGINEERING.**

In this part I will try to make an overview of structures with carbon fibers which are already used in construction or just considered as alternative solutions. The idea of using fiber for buildings probably appeared with appearance of the first high performance carbon fibers. The main fields for use carbon fibers today are strengthening of the structures, use of carbon fiber composites in precast concrete, use in fiber-cement, and use carbon fiber composite plastic profiles. Possible cases for application are: tension elements, ropes, dismantable and permanent shuttering, and prestressing bars.

### **5.1 Reinforcing the structures.**

Nowadays strengthening is one of the most common cases for applying carbon fibers in building engineering. The main idea is to glue textiles or laminates onto outer surfaces of the structure to improve strength and rigidity. This type of external reinforcing is used to provide fail-safe usage of unique, expensive and historically important structures, when construction teardown or replacement of structures is much more expensive than repairing or not even possible. This concerns transportation, hydro technical facilities and architecture memorials. Applying this reinforcement for usual structures should be economically reasonable.

For wooden structures apply carbon fibers with elastic modulus of more than 300 kN/mm<sup>2</sup>. There are two methods of reinforcing the wooden structures: by gluing down on the surface and by pasting into the pre-made saw cuts. The second method is usually used, when it is required to save initial look of the structure. External reinforcing elements made of carbon fibers are used most often for sawn and laminated wooden beams in the places with big bending moments. Bidirectional canvas gluing onto the bottom surface of the beam is used where main tensile stresses can cause cracks along the element axis. Gluing of canvas to the plywood beam web in shear zones strongly increases its rigidity. The main advantages of this reinforcing for wooden structures in comparison with traditional methods are: fast and easy to install, possible to make it invisible.

The main field in reinforcing of brick and stone structures is eccentrically loaded structures, columns, pylons, and piers. In traditional methods of strengthening, specialists should solve the problem by including steel clamps in the work. To provide joint work of brick elements and steel clamps, they should try to create initial efforts in the clip by heating the clamps and using the extendable mortars. Technically it is possible, but it is labour-intensive and not manufacturable. Pipe shells made of carbon fiber is an effective alternative to steel clamps, because its inclusion in the work of structure is provided during installation of the wrap to the strengthening element through the gluing layer. Actual-size tests of brick columns, carried out in the stone laboratory of ЦНИИСК (CSRIBS - Central Science and Research Institute of Building Structures) in 2004 have shown improvement of bearing capacity of columns reinforced with carbon fibers in 1,5 – 2 times in comparison to unreinforced columns. Also, external strengthening using textiles applied for load bearing walls is affected by subsidence of soils and new openings. The traditional solution in this case is installation of steel brackets and profiles through the anchor fastenings on the wall followed by filling of gaps with extendable mortars. Applying carbon fiber external reinforcing elements for strengthening allowed the avoidance of installing the anchors, involved bigger volumes of material into the work, and avoid the damage to intact structures.

When reinforcing of steel tensile elements with carbon fibers, it is appropriate to do it symmetrically from the center of gravity of the element section. For this purpose, applied carbon fibers with similar to steel elastic modulus and with maximum possible strength, for instance  $E=200-230 \text{ kN/mm}^2$ ,  $TS=4800 \text{ N/mm}^2$ .

Installation of reinforcement for steel elements consists of following procedures:

- Cleaning of surface from pollutions (possible, with blast cleaning)
- Covering of element surface with adhesive (usually epoxy glue)
- Installation of external reinforcing elements: canvas and stripes
- Protective and fireproof painting
- Installation of additional fixing elements

For reinforcing of eccentrically-loaded steel structures, it is appropriate to use carbon fibers with maximum possible elastic modulus (up to 700 kN/mm<sup>2</sup>). Improvement of stability for steel plates, like a high beam web from the plane of flexure, can be done by gluing the external reinforcement elements symmetrically from the center of gravity of the cross-section.

The main field for applying the carbon fiber for strengthening is concrete structures. All information about strengthening is given in part 6 of this thesis.

## 5.2 Using of carbon fiber in precast concrete

This field is relatively young and rapidly developing. Carbon fibers in precast concrete started to appear in quantity-production from 2003. Now it is a very common material for precast elements in the USA.

A carbon fiber grid is used in the panel faces to replace steel mesh reinforcement, and as a mechanical link to the outer and inner sections of the concrete wall (Figure 5.1). Non-corrosive carbon fiber grid reinforcement in the wall panel face allows less use of concrete, which reduces weight and raw material usage. The wall panels with carbon fiber grid reinforcement can weigh about 40% less than conventional precast panels.

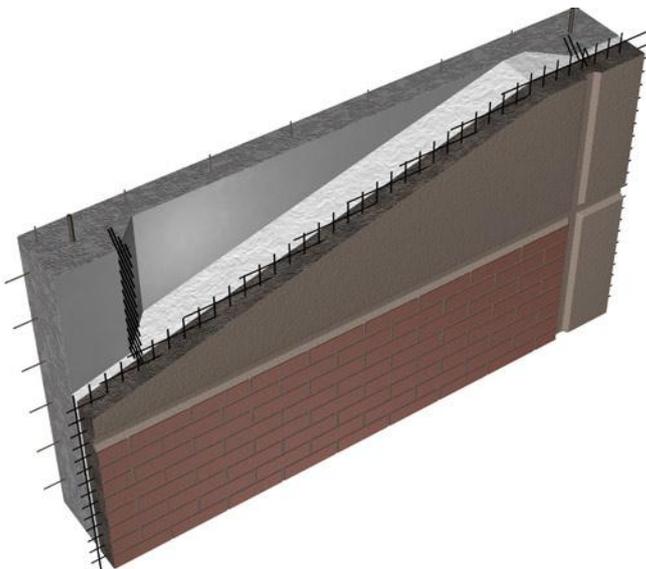


Figure 5.1 Wall panel with carbon fiber mesh reinforcement and carbon fiber shear gird between outer and inner faces of the panel (<http://altusprecast.com/>)

Carbon fiber is used as a shear grid or shear truss to connect the inner and outer concrete surface of sandwich wall panels, creating a fully structurally composite, thermally efficient unit. Carbon fiber grid is integrated as reinforcing in the double tee slab to replace conventional steel mesh (Figure 5.2). Replacing welded gird with carbon fiber grid in the slabs reduces weight and the need for chemical protection.



Figure 5.2 Double T slab with carbon fiber mesh (<http://altusprecast.com/>)

Main reasons to use carbon fiber in precast concrete:

- 1) Non-corrosiveness: Because carbon fiber will not oxidize, it will not cause rusting, staining or spalling as can occur with steel reinforcing. Consequently, precasters can reduce the amount of concrete cover—three inches or more in the case of some wall panels—that would have been required to protect the reinforcement.
- 2) Weight: As noted previously, the opportunity to reduce the amount of concrete cover can lead to significant weight reductions: up to 50% in wall panels and up to 8% in double tees. For architects and engineers, reduced weight contributes to cost savings starting with foundations and building superstructure and extending to lower shipping costs and crane expenses.
- 3) Thermal efficiency: The use of carbon fiber grid enables improved thermal performance, because carbon fiber composites, which are used in precast production has low thermal conductivity and reduces the transfer of heat or cold from outside to inside. The insulation embedded in the walls can deliver 100 percent of its rated performance without hot spots or cold spots. As a result, building owners can benefit from long-term energy savings.

A carbon fiber grid costs more than twice as much as conventional steel reinforcing. But that is usually more than offset by reductions in concrete and chemical treatments that would have protected the steel, as well as lower HVAC demands and the possibility of reducing the building foundation and substructure.

### 5.3 Carbon fiber in bridge construction

A prospective field of applying carbon fiber is bridge construction. Since 1992 there have been built several footbridges made mostly from fiber reinforced composites. Examples are the 40m span Fiberline Bridge in Denmark, 38m span Lleida Footbridge in Spain and the 56 m span opening Fredrikstad Bridge in Norway. The last bridge represents an opening footbridge, made of carbon and glass fiber reinforced plastic and drawn by one hydrocylinder from each side (Figure 5.3). The main reason for application of carbon fiber reinforced plastic was to provide bridge weigh reduction and economy of lifting equipment.



Figure 5.3 Opening footbridge in Fredrikstad, Norway

<http://www.fireco.no/references/Gangbru%20Vesterelven.pdf>

Advantages of fiber reinforced composites in bridges:

- Easier, faster and more economic installation - smaller cranes required
- Ability to bring larger sections to site reducing assembly time and cost
- Resistant to atmospheric degradation, de-icing salts, chemicals from spillages, etc.
- Reduction in maintenance requirements, through-life costs and disruption
- Carbon fiber reinforced plastics are thermally stable which may remove need for expansion joints.

In bridge construction fibers can be used in the main load bearing structures, decking, cables and supports. Concrete bridges can contain carbon fibers as mesh reinforcing in the decking.

#### **5.4 Other uses of carbon fiber**

Carbon fibers can be used for making fiber reinforced plastic profiles. Some manufacturers offering their I-beams, rectangular and circle-section pipes. Strength of this profiles can be up to  $1800 \text{ N/mm}^2$ . Such high strength in aggregate with low weight and low deflection make this solution suitable for construction, but it still a very unique structure. Developing of the idea of composite profiles leading to usage of carbon fiber composites for permanent and dismantable formworks production.

Carbon fiber is a good replacement of steel filaments in fiber-concrete. The fibers, used for fiber concrete are usually cheap cellulose or PAN-based fibers that gave low thermal conductivity in comparison with steel and also provide good cohesion with concrete. This solution is good for high loaded floors and roads. In fiber-cement, carbon fibers replace asbestos, because carbon fiber does not provoke any inhalation problems.

Textiles made of carbon fiber can be used in the glue laminated timber or laminated veneer lumber. Usually textiles are gluing between the wood laminates. Weight reduction in this case can be up to 40%. Textiles also help to save load-bearing capacity of the timber structure when making the holes and cuts.

## **6 TECHNOLOGY OF REINFORCING OF CONCRETE STRUCTURES USING CARBON FIBERS.**

The main idea of this kind of strengthening is to use carbon fiber material in those places on the structure, where it works better. The best mechanical properties carbon fiber obtains under tension load. In every stress condition tensile stresses is attended. Carbon fiber strengthening is gluing tightly to the structure in direction of main tensile stresses. System of strengthening consists of: primers for concrete surface, puttying mixes, adhesives, unidirectional or bidirectional textiles and laminates, protective and fireproof covers. Primers thinned to the surface to achieve required cohesion between concrete and gluing material of canvas. Puttying mixes are used for filling of cracks and caverns and smoothing of surface. Adhesives are used for gluing of textiles and laminates to the structure surface. Very common gluing materials are: epoxy, polyether and vinyl-ether resins, they provide sufficient cohesion with concrete and reinforcing textiles.

Advantages of strengthening with carbon fiber:

- Carbon fibers can assume any shapes and provide close contact to the strengthened structure.
- Strengthening using carbon fibers allows to avoid interference to the initial structure.
- Carbon fiber straps is easy to install to the structure. Installation of this straps didn't require such high skill from worker, like in traditional methods. Therefore works with carbon fiber textiles cheaper, than with traditional materials.
- Using of easy technologies can make the works faster and save time.
- In many cases it is possible to save original shape of the structure and save space.
- Quality of strengthening with carbon fibers is relatively high especially in comparison with traditional methods for columns.
- For some structures it is possible to use pretension of outer straps made of carbon fibers.

Disadvantages of this strengthening method are:

- Low fire resistance of resins, used as adhesive for gluing of straps.
- Expensive materials.
- This method is not applicable for high reinforced beams and slabs, where fragile failure can occur in compressed zone of concrete.

## **6.1 Principal schemes of reinforcing of the main types of structures**

The strengthening solution depends on structure. The main structures, that are usually reinforced by carbon fiber are columns, beams and slabs. Also, carbon fibers can be used for strengthening holes and cuts in the slabs and beams. Each structure has its own method of reinforcing, but the main goal is the same – use carbon fiber in the direction of tensile stresses. Further, main cases of strengthening of concrete structures will be considered.

### **6.1.1 Compressive elements**

Reinforcement of axially-loaded and eccentrically-loaded elements is implemented by arrangement of pipe shells over the cross-section of elements with fibers in the pipe shell turned perpendicularly to the axis of structure, and the pipe shells arranging along the length of the whole structure (Figure 6.1). Columns with high bending moments also should be reinforced like bendable elements.

### **6.1.2 Bendable elements**

Reinforcement of beam structures is implemented by gluing of textiles onto the bottom edge of the beam with fibers, turned along the beam axis and gluing of vertical and inclined straps in the ends of the beam with fibers, turned perpendicular of the beam axis (Figure 6.2)

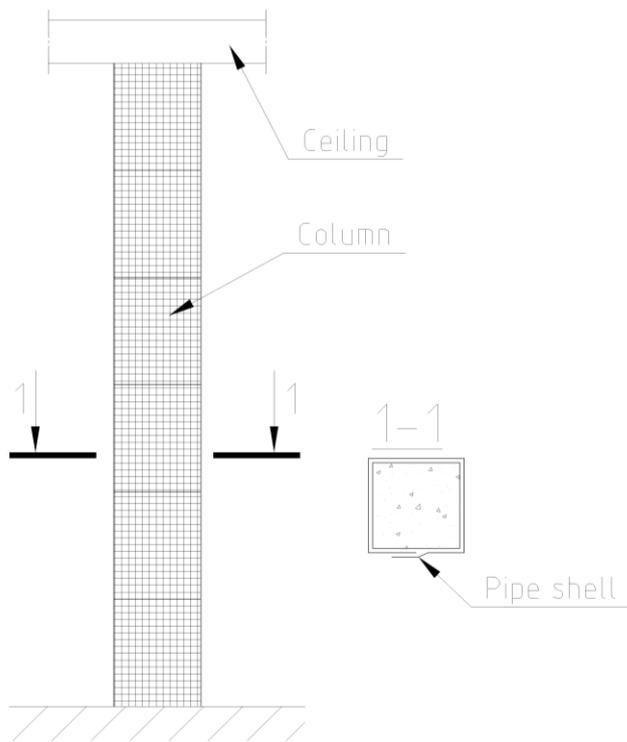


Figure 6.1 Principal scheme of reinforcing the column

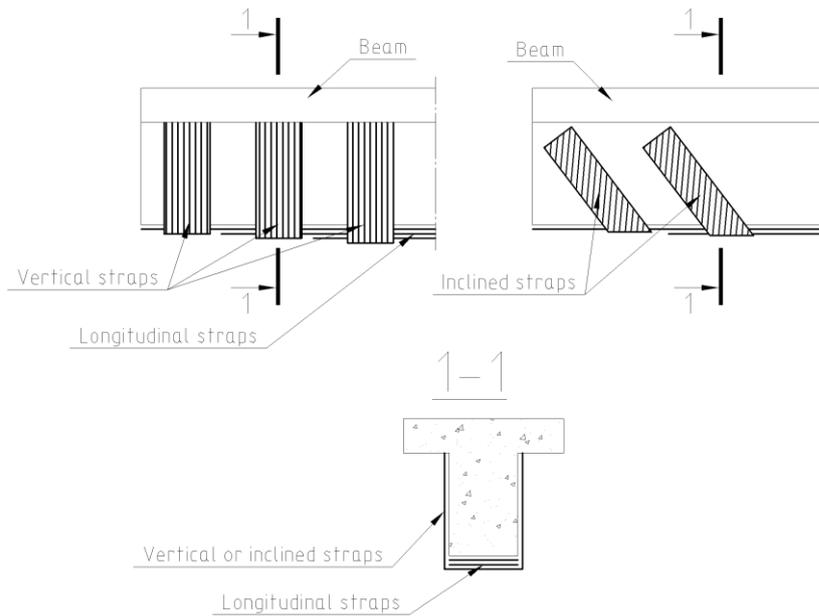


Figure 6.2 Principal scheme of reinforcing the beam

### 6.1.3 Slabs

Reinforcement of slabs is implemented by gluing the straps onto the bottom surface with fibers situated along the structure axis, and then perpendicular straps the over them (Figure 6.3). This scheme can be applied for holes and cuts in the slab.

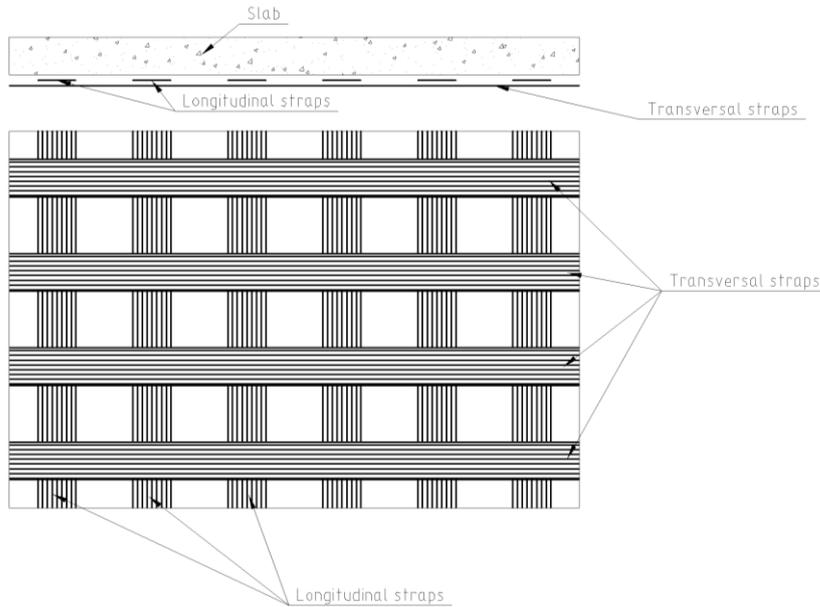


Figure 6.3 Principal scheme of reinforcing the slab

### 6.2 Preparing the surface for gluing.

Preparation starts with marking of lines on the structure according to the strengthening project. The surface is cleaned from paint, oil and coating of cement by blast cleaning or with metal brushes and following with high pressure water ablation (pressure usually more than 100 atm.) For good cohesion of adhesive with concrete, the surface should be rough-finished, and it can be reached by treatment of the concrete surface with chisel, and followed by dressing with metal brushes. Then follows covering with primer liquid for hardening of the outer layer of the structure and improvement of cohesion between adhesive and concrete surface.

Reinforcing with carbon fibers gives good results if rejection from flatness is less than 5 mm on a 2 m base and 1mm on a 0,3 m base. Small defects with a depth less than 5 mm and an area less than 25 cm<sup>2</sup> did not strongly affect reinforcing quality. These defects can be removed by polymer-cement slurries with fast hardening. Smoothing of the big areas of the concrete surface can be attained by polymer-cement repair mixes with sand or breakstone aggregate.

If the protective layer is broken because of corrosion of the reinforcing bars, the protective layer is removed, reinforcing bars cleaned from corrosion products, treated with corrosion converting liquid, and then the protective layer is restore with a special repair mixes.

To provide close contact of tape or textile to the structure it is important to make cants or fillets in the outward corners and fillets in the inward corners (Figure 6.4). Cracks with a size of more than 0,3 mm, should be repaired with epoxy or polyurethane compositions. Cracks less than 0,3 mm can be scoured with polymer-cement slurries. Tapes and laminates are cut according to the project, marked with number and size and packed up in the bags.

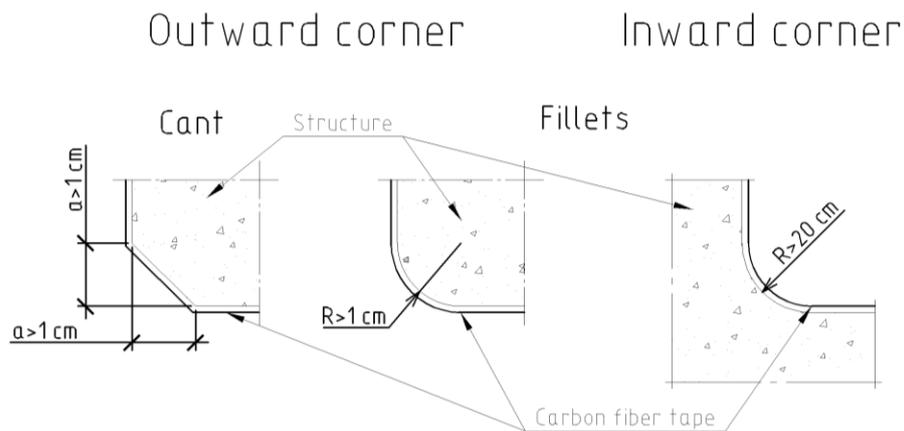


Figure 6.4 Sizes of cants and fillets of the strengthening structure

Preparation of the adhesive from several components should be done as provided by the manufacturer. Components should be mixed manually or by low-speed drill with special attachment to avoid mix aeration.

### 6.3 Gluing of tapes and textiles

Before covering the structure with adhesive its surface should be blown with compressed air. Tapes and textiles should be always putt down on the adhesive layer on the structure without folds and excessive extension. After placement, textiles should be pressed to the structure by rolling. During this rolling, textile is saturated with adhesive. Rolling should be carried out from the middle of the tape or textile to the ends in a longitudinal direction along the fibers. After rolling, the surface with textile should be sticky to touch, but without excess adhesive. Before the gluing of the next textile, the previous textile should be covered with adhesive. Rolling of the next tapes or textiles is the same as for first layer. After the gluing of the last tape or textile, the surface should be finished with a layer of the adhesive. When the strengthening structure is multilayered gluing of all the layers should be done during one working shift followed by the hardening of whole section.

Gluing of tapes and textiles to the horizontal surface should be done from above by two workers working from the middle of the structure to the ends. Placing of the next layers can be done just after the rolling of the previous. An example of strengthening made from above is shown in figure 6.5



Figure 6.5 Example of strengthening made above the structure (Teke brochure “Structure strengthening with composites”)

Gluing of tapes and textiles to the horizontal surface from below should start from the one end fixed on the structure and go to the other with rolling and fixing of the textile along the structure. Depending on viscosity of the adhesive, gluing of straps can be done just after covering the structure with adhesive or after a pause. Usually this procedure is done by two workers. Example of the structure, made from below, shown on the figure 6.6.



Figure 6.6 Strengthening the hole in the slab

(<http://www.buildings.com/ArticleDetails/tabid/3321/ArticleID/5837/Default.aspx>)

For facilitation of working procedure in structures with big spans, it is possible to glue textile in separate parts, which should be connected with overlapping along the structure. Overlapping should be more than 100 mm. Gluing with an overlap can be done on the wet or on the hardened adhesive.

When strengthening vertical structures, the coating of adhesive is performed downright (figure 6.7). Gluing of vertical straps is implemented by fixing of the textile on the upper part of the structure, placement and smoothing of the textile followed by rolling. Gluing of horizontal straps to the vertical surface is done by fixing of the textile in the extreme position (left or right) followed by placement, smoothing and rolling.



Figure 6.7 Strengthening of vertical structure (Teke brochure “Structure strengthening with composites”)

Gluing of straps to the structure can be done at environmental temperatures from  $+5^{\circ}\text{C}$  to  $+45^{\circ}\text{C}$ . The temperature of the surface under strengthening should be more than  $+5^{\circ}\text{C}$  and more than a dew-point of  $3^{\circ}\text{C}$ . For increasing the temperature, additional local heaters can be used. The strengthening structure should be dry and an acceptable humidity of the surface is less than 5%. The time of hardening usually takes more than 24 hours for  $+20^{\circ}\text{C}$  temperatures and more than 36 hours for  $+5\dots+20^{\circ}\text{C}$  temperatures. To provide fire resistance, durability, and with aesthetic in mind, the strengthening structure can be covered with different surfaces (polymer-cement, polyurethane and fire-retarding agents, compatible with adhesive). To provide good cohesion of the covers with the strengthening structure, the last coat should be done with small dry sand.

#### **6.4 Gluing the laminates**

Laminate can be glued to the outer surface of the structure and into the grooves in the structure (figure 6.8). The preparing procedures are the same like for textiles and tapes. Before gluing laminates, cover the surface with a thin layer of adhesive (about 1-1.5 mm), and the strengthening surface also should be covered with the same layer of adhesive. Then the laminate is placed on the structure, and rolling provides close contact between the laminate and the strengthening structure. Excess adhesive should be removed from the edge of the laminate. If the project of strengthening demands several layers of laminates, laminates should be glued to each other before gluing to the structure. The outer surface of reinforced structure can be painted or covered with polymer-cement slurry.



Figure 6.8 Laminates glued into the grooves (Teke brochure “Structure strengthening with composites”)

### 6.5 Construction features of making the reinforcing straps

The technology of strengthening using carbon fibers has its own requirements for determining the size and placement of the reinforcing straps, taking special protective measures, and recommended fastening of the reinforcing straps. Following these requirements helps to provide proper working conditions to the strengthened structure, improve its quality, and avoids flaws of the final structure.

- 1) Number and size of the straps is prescribed by the calculations.
- 2) Maximum number of strengthening straps in one section is limited by effective cohesion forces with structure surface.
- 3) Tapes and laminates should overlap reinforcing zone more than 100 mm for concretes with compressive strength more than  $25 \text{ N/mm}^2$  , for concretes with compressive strength less than  $25 \text{ N/mm}^2$  overlapping should be more than 150-200 mm.
- 4) For a multilayer structure of reinforcing element it is reasonable to make each subsequent layer shorter in length of overlapping to reduce normal and tangential stress in the end zones. The shortest layer should correspond with the requirements of item 3. For through beams with one layer, reinforcing straps should go over the zero moment point on 150 mm. If strengthening is multilayer, every subsequent strap should be 150 mm shorter than the previous.

- 5) In bendable structures strengthened with carbon fibers, cracks can occur. High concentrations of shear stresses between concrete and composite appears in the crack zone. Following partial delamination is possible. For limitation of delamination and improvement of anchorage of strengthening elements it is important to make lateral structural reinforcing straps at the end zones of structure. Gluing of lateral straps should be carried out after gluing of every longitudinal strap.
- 6) Incline straps are made of two parts, initially gluing the one part from one side, then rolling, then gluing the second part from the other side. These two parts should be overlapping on the bottom surface of the beam.
- 7) When reinforcing the beam floor it is recommended to continue the reinforcing straps from the slab and glue these straps to the side face of web to improve anchorage. To prevent exfoliation of the covering layer of concrete it is possible to wrap up the strap over the web.
- 8) The strengthening structure should provide moisture movement from the concrete.
- 9) In some cases gluing of straps did not provide the required load transfer. In these cases it is necessary to install additional anchorage into the structure. This anchorage is a carbon fiber stick with the strand on one side. Sticks are pasted to the structure outside the strengthening zone. The soft part of this stick is gluing to the tapes or textiles.

(Cherniavsky, 2006)

## **6.6 Quality control for strengthening (according to Russian norms)**

Quality control consists of an inspection test, operating control, and acceptance inspection.

The inspection test applies for all materials used for construction. Before starting the construction following things should be checked:

- accompanying documentation,
- condition of packing,
- external appearance of the materials and its weight.

Every batch of materials should be accompanied with quality control documents, which should consist of:

- name of manufacturer,
- date of documents,
- batch number,
- name of production,
- number of products,
- test results,
- acceptable retention cycle,
- stamps and signatures from the quality control department of the manufacturer.

Operating control consist of the following:

- Quality control of the surface, external appearance of the structure, and absence of pollutions assessed visually. Flatness of the surface assessed with straight rule and feeler.
- Compressive strength of concrete can be defined by one of the non-destructive testing methods.
- During preparation of the adhesive, controlling proportion of components, homogeneity of adhesive after mixing, and absence of impurities and clots.
- Visual and weight rate control of thickness and uniformity of adhesive layer during covering the structure.
- Checking of fiber orientation, placement, absence of folds and unimpregnated places after rolling.
- During the gluing and hardening of the strengthening elements it is necessary to record environmental temperature, humidity, and temperature on the concrete surface, and time of hardening.

Acceptance inspection.

- After the hardening visual control is carried out to diagnose external flaws.
- Control of internal defects like delamination and incomplete gluing are carried out by acoustic probing, light tapping of the strap with a hammer or using another non-destructive testing methods.

- Delamination of an area less than 10 cm<sup>2</sup> and overall delamination less than 3% from the strengthening surface is accepted. In other cases, flaws should be repaired by cutting and replacing with the same amount of material.

Results of the quality control should be recorded on the accompanying documentation for the work.

## 7 COMPARISON OF MATERIALS

In this part I will compare materials by cost and strength. The cost of carbon fiber material is very high. A comparison diagram of the costs of materials is seen on the chart 7.1. More detailed information is given in Appendix 2. Results show that the cheapest carbon fibers are still much more expensive than other materials. Carbon fiber is three times more expensive than structural steel, and usually this ratio is about 10-50. The cost of carbon fiber can be compared with titanium, some refractory metals, and some non-ferrous metals. The most expensive carbon fibers used for construction can cost as much as silver. But this drawback is compensated by carbon fiber properties. Carbon fiber is the one of the strongest materials in the world. On the chart 7.2 is given a diagram, which shows tensile strength and elastic modulus for different fiber materials.

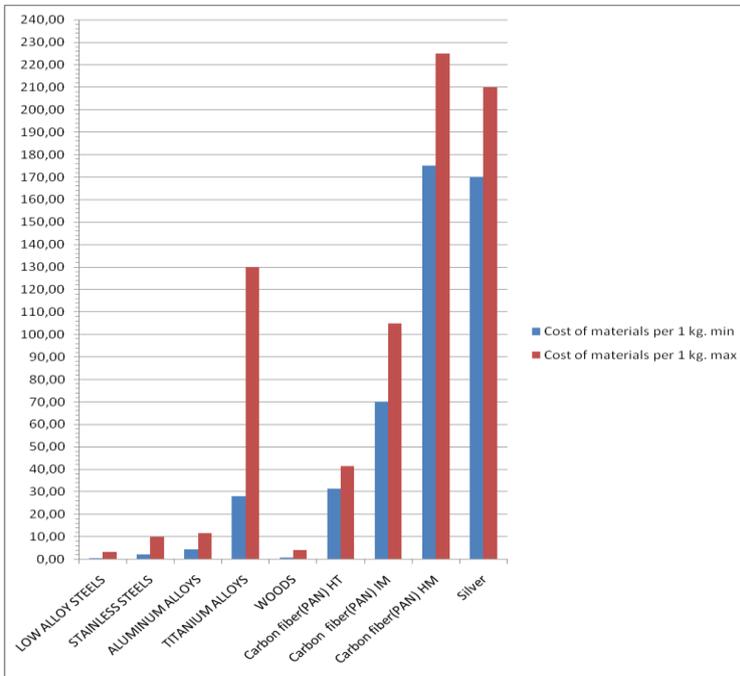
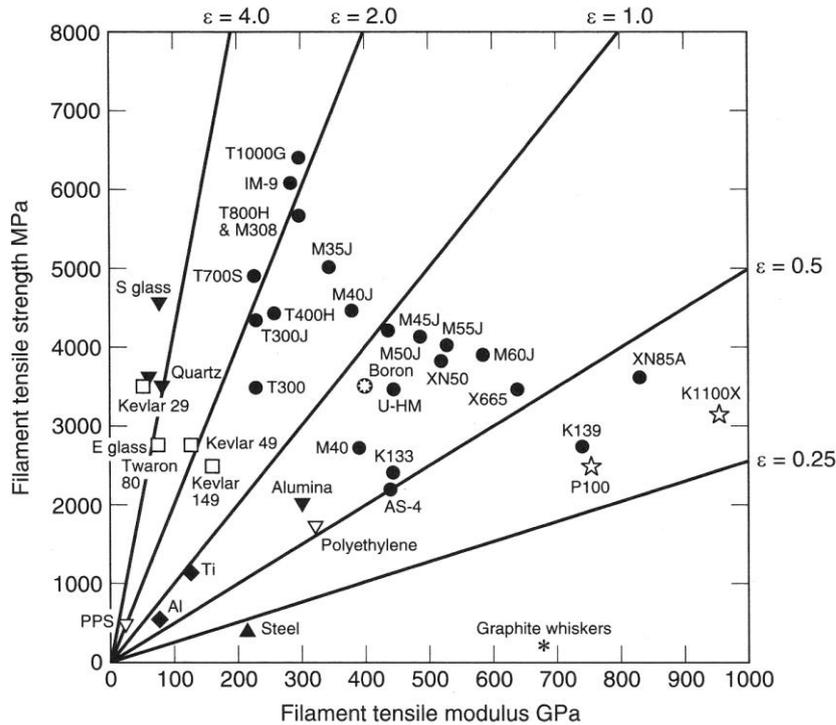


Chart 7.1 Comparison of the cost of main construction materials in USD for 2007



Fiber strength as a function of the modulus for carbon, ceramic, metal, polymer fibers and graphite whisker. • Carbon fiber, ☆ Cellulose based carbon fiber, □ Aramid fiber, ▼ Ceramic and glass fibers, ◆ Metal fiber, \* Graphite whiskers, ▽ Organic polymer fiber.

Chart 7.2 Tensile strength and Young's modulus of materials (Morgan 2005)

Wide-ranging carbon fiber has the best tensile strength and Young's modulus in comparison with other materials. If we divide mechanical properties to the cost of materials, we can say that "specific by cost" properties of carbon fiber material is able to meet the competition.

## 8 CALCULATIONS

I chose calculation of the beam on bending moment to determine effect of the carbon fiber strengthening, and to compare it with the traditional method of strengthening. For calculations, the method chosen was presented in the Guide for Strengthening of Concrete Structures by Composite Materials According to SP 52-101-2003, published in 2006 by the Interaqua company. This method is based on world experience in this field, and on many tests, performed by this company during 10 years. I have done my calculations according to Russian norms, because I write this thesis for the Russian branch of the FMC company. All calculations are done for the elastic stage.

For the example calculations I take two beams. The first beam is low reinforced and the second is high reinforced. The first one is made of concrete B25, according to Russian norms with main reinforcement of three 20mm diameter bars made of reinforcing steel A500, section is 300X600. The second beam is the same, but the main reinforcement is four 25mm diameter bars made of reinforcement steel A500. In my examples both beams are overloaded or planning to be overloaded. The first beam's ultimate moment is 214,4 kN\*m, the existing or planning moment is 250 kN\*m, and overload is 35,6 kN\*m. The second beam's ultimate moment is 400,9 kN\*m, the existing or planning moment is 430 kN\*m, and overload is 29,1 kN\*m.

The first target was to determine effect of strengthening of high and low reinforced beam by two different types of fibers. The first type was high-tension carbon fiber textile MapeWrap C UNIAX 300/10 with a tensile strength of 4800 N/mm<sup>2</sup> and Young's modulus of 230 kN/mm<sup>2</sup>. The second type was more like high-modulus carbon fiber textile. Its name is Wabo Mbrace 530 whose tensile strength is 3517 N/mm<sup>2</sup> and Young's modulus is 372 kN/mm<sup>2</sup>. The width of straps was 300mm for both types of fibers. The thickness of the first straps were 0,165mm, and of the second - 0,167mm.

An overview of the calculating tool and formulas is given in appendix 3. Results of calculations are shown in figure 16 and figure 17 as diagrams. In these figures are shown solid-line segments and dot-line segments. Dot line in the beginning of the diagrams means that the strengthening strap is overstrained or delamination can occur if the bending moment will increase to ultimate moment of strengthened beam. In this case it is important, that tension in the strap  $\sigma_f$  should be less than design resistance(ultimate strain) of the beam  $R_{fu}(\sigma_{fu})$ . The dot line in the end part of diagrams, where bending moment decreases with increasing the number of the straps means that increasing of strengthening area leading to decreasing of tension in the reinforcement and ultimate bending moment, depending on tension is decreasing. In real cases the diagram of the ultimate bending moment should not fall with increasing of strengthening layers. The end point of the diagrams on figures 16 and 17 is the point where failure mode becomes fragile, and that is not allowed in reinforced concrete structures. According to SP 52-101-2003, to avoid fragile failure it is important that a relative high of

compressed zone of the concrete  $\xi$  should be less than ultimate high of compressed zone of the concrete  $\xi_R$ .

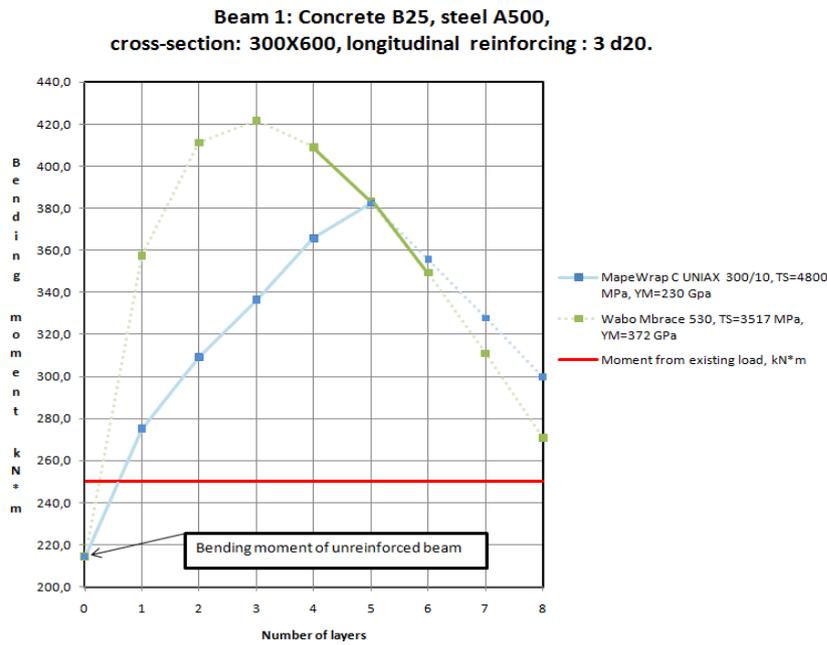


Chart 8.1 Correlation between bending moment of strengthened structure and number of strengthening layers for low-reinforced beam and two types of textile

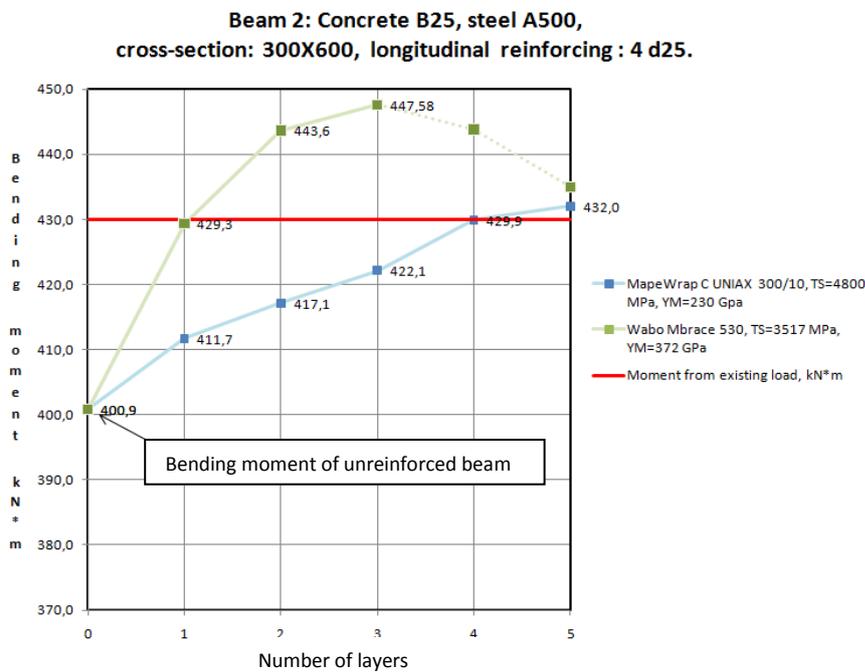


Chart 8.2. Correlation between bending moment of strengthened structure and number of strengthening layers for high-reinforced beam and two types of textile

Results of calculations shows high effect from strengthening made of carbon fiber for low-reinforced beam and low effect for high-reinforced beam. The maximum value for ultimate bending moment was about 90%. Textiles with high elastic modulus and low tensile strength give better results than those with low elastic modulus and high strength.

A second target was to compare different variations of the carbon fiber strengthening with some traditional method for the one section. For comparison with the carbon fiber strengthening method, I chose a very common and easy to calculate strengthening method. This method consists of removal of a safety layer of concrete, welding additional reinforcing bars to the bottom bars of the beam, and renewal of safety layer of concrete. The initial structure is a beam with cross-section of 300X600 mm, concrete is B25, reinforcing is steel A500 3 rebars, and diameter 20mm. For simplification of calculation I have taken for strengthening the same steel as was used in the beam for main reinforcing. Also I did not take into account any affects caused by welding and features of work of the new rebars. For the carbon fiber strengthening I did not take into account possible overstraining and delamination of the strengthening straps. The area of strengthening was the same for all types of strengthening and based on rebars diameters.

The results are presented in figure 18 as a diagram and in appendix 4 as a table. The end point of all diagrams is the appearance of fragile failure mode. We can see that carbon fiber strengthening increases the ultimate bending moment faster and leads to fragile failure mode faster, than reinforcement made of reinforcing steel, welded to the bottom rebars of the beam. For the same area, carbon fiber strengthening is more effective then steel. Theoretically, maximum value of the ultimate bending moment can be reached by high modulus carbon fiber straps. In my example this was done by S&P reinforcing straps with tensile strength of 2650 N/mm<sup>2</sup> and Young's modulus of 640 kN/mm<sup>2</sup>. However calculations show that such high values cannot be reached because of possible delamination and overstraining of the straps, or because of appearing of the fragile mode of failure. I marked successful results with green color in the table in appendix 4.

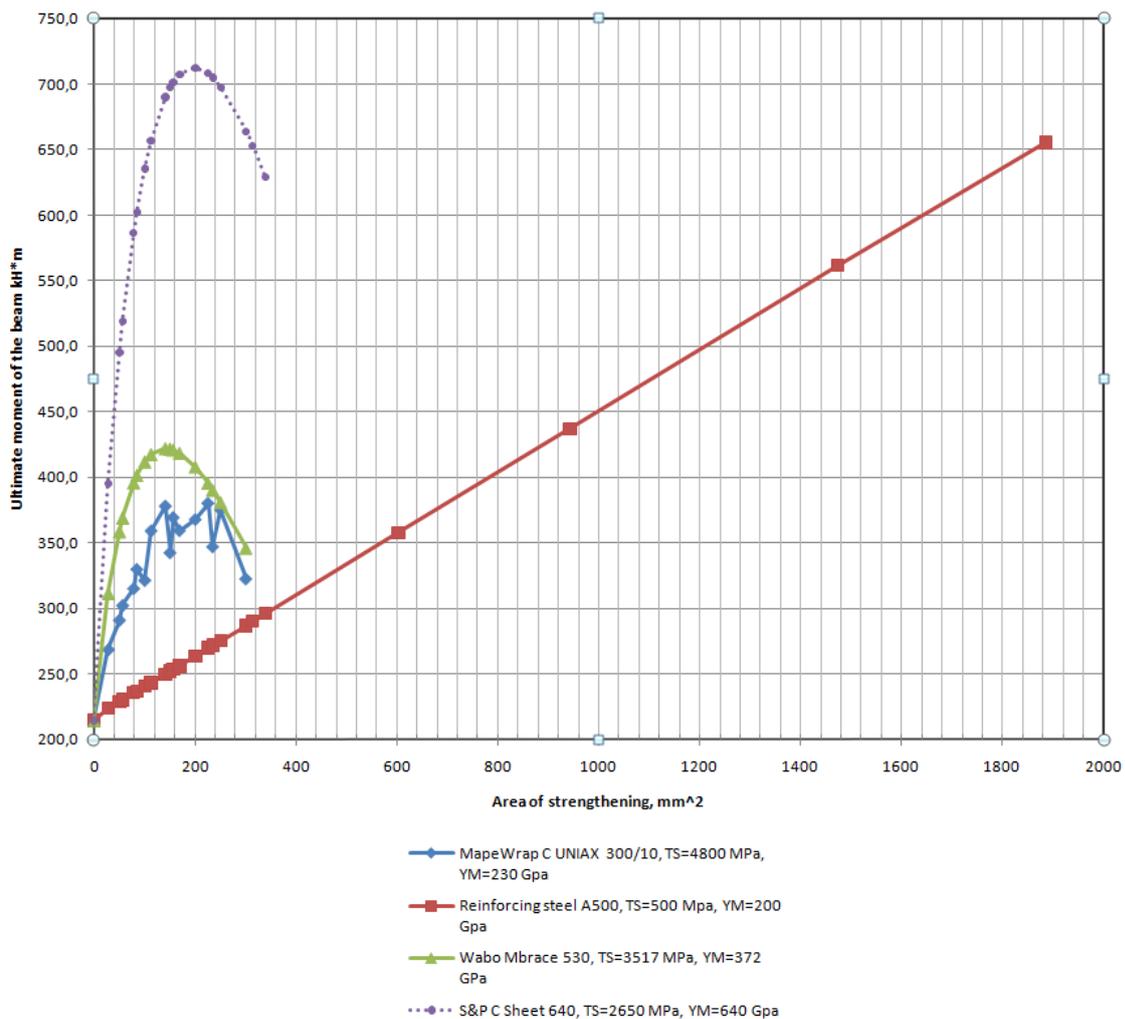


Chart 8.3 Diagram of calculated bending moments in dependence of strengthening material and its area

To reach the same result, for example, a bending moment of 290 kN\*m, we can use 50 mm<sup>2</sup> of carbon fiber material or 339,3 mm<sup>2</sup> of reinforcing steel A500; to reach bending moment of 420 kN\*m we can use 157mm<sup>2</sup> of carbon fiber material, or 942,5 mm<sup>2</sup> of reinforcing steel A500. The maximum difference of area of strengthening material is 6-7 times, but theoretically it can be more. In this case the cost of reinforcing, including costs of all materials and labor is about the same for both methods. Every method has its own limitations. The main limitation of carbon fiber reinforcing is fragile failure mode, which can be reached faster than for steel and possible delamination. The main limitation for steel strengthening is weldability of reinforcing steel and conditions of the beam.

## 9 CONCLUSIONS

Carbon fiber is a relatively new and expensive material, but it does not mean that we cannot use it for construction. In many cases, the cost of this material is reasonable by its properties, working expenses, life-time expenses, special cases, and when use of any other materials is impossible. For example, carbon fiber would be a good solution, if we change the purpose of the room from classroom to storage. The main aims in this case would be increasing the bearing capacity and saving the original size and look of the beams under the room. The first goal can be reached in many ways, but the second goal is much more difficult. Strengthening of the structure by welding of additional rebars and by gluing carbon fiber textiles or laminates are the most suitable methods in this case.

In the first method we can meet a lot of difficulties with removing and repairing of the safety layer of concrete. To obtain good cohesion between existing concrete and new safety layer it is necessary to use expensive mixes. Welding can be done only by skilled workers. In this case the strengthening material is cheap, labor is expensive and difficult, and materials for restoration of the safety layer are also expensive. For welding we should always consider the weldability of existing rebars. If existing rebars are unweldable, it is possible to use only one method of strengthening without any influence on the structure – with the use of carbon fiber.

Using carbon fiber we can make strengthening faster, easier and by less skilled worker, and with less amounts of materials. The quality of strengthening is very high. The thickness of carbon fiber strengthening usually is less than 1 mm and the size of the beam will be the same as for the original structure. The main things which should be taken into account in this method are delamination, fast increase of bearing capacity and then appearance of fragile failure risk, and low fire resistance of the composite resin. Also to avoid destruction from the fire adhesive material, carbon fiber material can be covered with a safety layer of concrete or with special paint.

The cost of carbon fiber strengthening is reduced with growth of structure complication in comparison with the traditional method. Applying carbon fiber strengthening is very reasonable for unique and complicated structures.

Calculations, which were made by a guide for strengthening according to SP 52-101-2003 shows high efficiency of the carbon fiber strengthening. However this method of calculation in my mind is not very clear and not well developed. First of all, in many cases we get very high values of ultimate bending moment with small areas of strengthening material, but the strength of the straps is not provided. For an example I will take my beam from appendix 4. The bearing capacity of this beam without any strengthening is 214 kN\*m, but moment from the load is 250 kN\*m. What happens with this beam if we glue one strap (50mm<sup>2</sup>) of Wabo Mbrace 530 strengthening. Calculations, performed by this method, show that we can obtain an ultimate bending moment of about 360 kN\*m, but we have overstraining in the strap. The main question in this case: is it possible to use this reinforcing if we need a bending moment of the improved structure of 250 kN\*m and don't need 360 kN\*m? The second feature of this calculation is reduction of ultimate moment by increasing the number of the strengthening straps, which is shown in part 8 of this thesis. In this calculating method, the ultimate moment directly depends on tension in the strengthening. Tension in the strengthening decreasing with strengthening area growth. This fact leads to the ultimate bending moment reduction. But in a real situation, gluing of additional straps should not cause reduction of bearing capacity or failure under constant load. People, who calculate using this method should take into account these features.

Initially I wanted to write about a wide range of applications of carbon fiber for building construction, but I met with some difficulties in lack of detailed information and absence of experts in this field for guidance. In my thesis I have written mostly about the strengthening of the structures, because it is the most developed and oldest field of application of carbon fibers. I also refrained from tests mostly because the material is very expensive for serious tests, and results of tests, performed by different companies, are available on the web sites and in different articles.

Carbon fiber has good possibilities to become suitable material for many construction purposes. The main things that prevent applying of carbon fiber in building construction, is the lack of experience and knowledge about this material, and its cost, but with an accumulation of experience and reduction of the cost it can become more common.

## **10 SUMMARY**

Carbon fiber has many existing and developing applications such as strengthening of all kinds of structures, usage in precast concrete production, and for bridge construction, production of carbon fiber reinforced plastic profiles, usage as reinforcement in new composite structure, usage as tension elements and many other applications. The application of carbon fibers in all these cases reasonable because of its significant properties and reduction of life-time expenses. The most common use of carbon fiber is for strengthening . Calculation methods exist for carbon fiber strengthening. In this thesis the Interaqua company method is used. Calculations show growth of bearing capacity of the beam up to 90% from the initial condition. In comparison with traditional strengthening, this bearing capacity can be reached with less quantities of materials. Strengthening with carbon fiber does have limitations related to low fire resistance of adhesive and possible delamination and fragile failure, which can occur with high increase of the strengthening area.

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## **REFERENCES**

Askeland, Donald R. 1998. The Science and Engineering of Materials. Third edition. Cheltenham United Kingdom: Stanley Thornes (Publishers) Ltd.

Bascule FRP Composite Footbridge

<http://www.fireco.no/references/Gangbru%20Vesterelven.pdf> (Accessed on 27 of April 2010)

Callister, William D., Jr. 2007. Material Science and Engineering. An introduction. Seventh Edition. USA: John Wiley and Sons, Inc.

Chris Cavette. How products are made. Volume 4. Carbon fiber.

<http://www.madehow.com/Volume-4/Carbon-Fiber.html> (Accessed on 10 of March 2010)

High Performance Insulated Wall Panels

[http://altusprecast.blade7.com/uploads/1137682951/Downloads-PDF-Docs/AG\\_IWP\\_brochure20d.pdf](http://altusprecast.blade7.com/uploads/1137682951/Downloads-PDF-Docs/AG_IWP_brochure20d.pdf) (Accessed on 27 of April 2010)

Hota V.S. GangaRao, Narendra Taly, P.V. Vijay. 2007 Reinforced concrete design with FRP composites. Boca Raton: CRC Press Taylor & Francis Group.

Cherniavsky Vladimir, Khayutin Uliy, Akselrod Evsey, Klevtsov Vladimir, Fatkullin Nikita. 2006. Guide for strengthening of concrete structures by composite materials according to SP 52-101-2003. Moscow: Interaqua LTC

Cherniavsky V., Osmac P. Strengthening of concrete and brick structures by composite materials [http://www.interaqua.biz/stat\\_2.pdf](http://www.interaqua.biz/stat_2.pdf) (Accessed on 13 of April)

From Eyesore to Opportunity: Adapting an Older Building for a New Use  
<http://www.buildings.com/ArticleDetails/tabid/3321/ArticleID/5837/Default.aspx>  
(Accessed on 27 of April 2010)

Morgan, Peter. 2005. Carbon fibers and their composites. Boca Raton: CRC Press Taylor & Francis Group.

Pretopped Precast Double Tees  
[http://altusprecast.blade7.com/uploads/1137682951/Downloads-PDF-Docs/AG\\_TT\\_brochure8b.pdf](http://altusprecast.blade7.com/uploads/1137682951/Downloads-PDF-Docs/AG_TT_brochure8b.pdf) (Accessed on 27 of April 2010)

Sika Construction Document Library.  
[http://www.sika.com/en/solutions\\_products/doc\\_download/constr\\_docu\\_library.html](http://www.sika.com/en/solutions_products/doc_download/constr_docu_library.html)  
(Accessed on 19 of March 2010)

SP 52-101-2003. Code of rules for designing and construction. Concrete and reinforced concrete structures without prestress. 2004. Moscow.

Structure strengthening with composites.  
<http://www.teke.fi/pdf/MSS%20Komposiitratkaisut%20rakenteiden%20vahvistuksiin.pdf>  
(Accessed on 20 of May 2010)

Mechanical properties of carbon fiber from different manufacturers (Morgan, 2005).

Table 1. Properties of cellulose based Fibers

Company	Grade	Specific gravity, kg/m <sup>3</sup>	Tensile strength, N/mm <sup>2</sup>	Tensile modulus, kN/mm <sup>2</sup>
Polycarbon Inc.				
Carbon yarns	C- 5	1400	760	41
	C-10	1420	760	41
	C-20	1440	760	41
Graphite yarns	G-5	1350	720	41
	G-10	1350	660	41
	G-20	1400	660	41
RK Carbon Fibers Grayon				
Carbon yarns	CA 5	1400	820	34
	CA10	1400	820	34
	CA20	1400	820	34
Graphite yarns	RG 5	1400	820	41
	RG 10	1400	820	41
	RG20	1400	820	41

Table 2. Properties of PAN based Fibers

Company	Trade name	Tensile strength N/mm <sup>2</sup>	Young's modulus, kN/mm <sup>2</sup>	Filament size, $\mu$ m	Max elongation, %	Density, kg/m <sup>3</sup>	Minimum carbon content, %
AKZO	Fortafil 502,	3800	231	6	1.64	1800	
	506,507,508,509	3450	217	7	1.59	1800	
	510,511,512,513	3800	231	6	1.64	1800	
	555,556	3800	231	6.2	1.65	1800	
Afikim	Acif IS	2500	230	6.8	1.3	1780	93
	HT	2900	230	6.8	1.4	1780	95
	XHT	3300	230	6.8	1.55	1780	95
	HM	2200	335	6.6	0.75	1860	99.5
Cytec	Thornel T300	3750	231	7.0	1.4	1760	92
Carbon	T300C	3750	231	7.0	1.4	1760	92
Fibers LLC	T650/35	4280	255	6.8	1.7	1770	94
	T650/35C	4280	255	6.8	1.7	1770	94
Asahi-Kasei	Hi-Carbolon	4310	230	7.0	1.87	1780	
Fortafil Fibers Inc.	Fortafil 502,	3800	231	6	1.64	1800	
	503,504,505						
	506,507,508,509	3450	217	7	1.59	1800	
	510,511,512,513	3800	231	6	1.64	1800	
Grafil Inc. (Mitsubishi)	Grafil 34-700	4500	234	7	1.9	1800	
	34-700WD	4500	234	7	1.9	1800	
	34-600, 34-	4150	234	7	1.8	1800	

Rayon Co.)	Pyrofil TR40	4700	235	7	2.0	1800	
	TR30S	4410	235	7	1.9	1790	
	TR50S	4900	240	7	2.0	1820	
	TRH50	4900	255	7	1.9	1800	
	MR35E	4410	295	7	1.5	1750	
	MR40	4410	295	6	1.5	1760	
	MR50	5400	290	6	1.8	1800	
	MS40	4610	345	6	1.3	1770	
	HR40	4410	390	6	1.1	1820	
	HS40	4410	450	5	1.0	1850	
Hexcel	AS4	4280	228		1.87	1780	
	AS4C	4350	231	6.9	1.88	1780	94
	AS4D	4690	245	6.7	1.92	1790	
	IM4	4800	276	6.7	1.74	1780	
	IMC	5520	290		1.90	1800	
	IM6	5590	279	5.2	2.00	1760	94
	IM7 (5000 Spec)	5180	276	5.2	1.87	1780	94
	IM7 (5000 Spec)	5520	276	5.2	2.01	1780	94
	IM7 (6000 Spec)	5760	290	5.1	1.99	1790	94
	IM7 (5000 Spec)	5760	292		2.00	1800	94
	IM7 (6000 Spec)						
	IM7C	5520	290	5.4	1.90	1800	94
	IMS	5590	304	5.1	1.84	1790	94
	IM9	6070	290	4.4	2.10		94
	IM9	6140	290	4.4	2.10	1800	
	IMC	5520	290	5.4	1.90	1800	94
	PV36/700	4690	248		1.9		
	PV42/800	5520	290	5.4	1.9	1800	94
	PV42/850	5760	292	4.4	1.97		
UHM	3450	441		0.8	1870		
IPCL	Indcarb 25	Min. 2500	215-240	6.8	1.05-1.40	1780	93
	30	Min. 3000	220-240	6.8	1.25-1.60	1780	95
Kosco	Kosca GP250	2800	220	6.8	1.3	1800	93
	HS300	3300	230	6.8	1.4	1800	95
Tenax Fibers	Tenax HTA	3950	238	7	1.5	1770	
	HTS	4300	238	7	1.5	1770	
	STS	4000	240	7	1.5	1790	
	UTS	4700	240	7	2.0	1800	
	IMS 3131	4120	295	6.4	1.4	1760	
	IMS 5131	5600	290	5.0	1.9	1800	
	HMA	3000	358	6.75	0.7	1770	
	UMS 2526	4560	395	4.8	1.1	1780	
	UMS 3536	4500	435	4.7	1.1	1810	
Textron	Avcarb HC	2070	207		1		88-92
	HCB	1900	262		0.72		99.5
Toho	Besfight HTA	3920	235	7	1.6	1770	
	ST3	4410	235	7	1.9	1770	
	IM400	4310	295	6.4	1.5	1750	

	IM500	5000	300	5.0	1.7	1760	
	HM30	4300	295	6.4	1.5	1750	
	HM35	2740	343	6.7	0.8	1790	
	HM45	3100	441	6.4	0.48	1900	
	UM40	2550	392	6.6	0.65	1830	
Toray*	Torayca T300	3530	230	7	1.5	1760	93
	T300J	4210	230	7.0	1.8	1780	94
	T400H	4410	250	7	1.8	1800	94
	T600S	4310	230		1.9	1790	
	T700S	4900	230	7	2.1	1800	93
	T700G	4900	240		2.1	1800	
	T800H	5490	294	5	1.9	1810	96
	T1000G	6370	294	5	2.2	1800	
	M35J	4700	343	6	1.4	1750	99
	M40J	4410	377	5	1.2	1770	99
	M46J	4210	436	5	1.0	1840	99
	M50J	4120	475	5	0.8	1880	99
	M55J	4020	540	5	0.8	1910	99
	M60J	3820	588	4.7	0.7	1940	99
	M30S	5490	294	6.5	1.9	1730	98
	M40	2740	392	6.5	0.7	1810	99
Zoltek	Panex 33	3800	228	7.2	1.6	1810	94

Table 3. Properties of pitch based carbon fibers.

Company	Trade name	Tensile strength, N/mm <sup>2</sup>	Young's modulus, kN/mm <sup>2</sup>	Filament size, $\mu\text{m}$	Max elongation, %	Density, kg/cm <sup>3</sup>	Minimum fiber content, %
Amoco	Thornel P25	1380	159	11	0.90	1.90	
	P55S	1900	379	10	0.50	2.00	97
	P75	2100	517	10	0.40	2.00	99
	P100	2410	758	10	0.32	2.16	99
	P100S	2070	758	10	0.27	2.16	99
	P100HTS	3620	724	10	0.50	2.17	99
	P120	2410	827	10	0.29	2.17	99
	P120S	2240	827	10	0.29	2.17	99
	K1100X	3100	966	10	0.30	2.20	
Ashland Oil Mitsubishi	Dialead K133	2350	441		0.53	2.08	
Kasei	K135	2550	539		0.47	2.1	
	K137	2650	637		0.42	2.12	
	K139	2750	735	10	0.37	2.14	
	K223	2840	225	10	1.21	2.00	
	K321	1960	176		1.08	1.90	
Nippon	Granoc	3830	520	10	0.7	2.14	
	XN70A	3630	720	10	0.5	2.16	
	XN80A	3630	785	10	0.5	2.17	

Graphite Fiber Corp.	XN85A	3630	830	8.5	0.4	2.17	
	YS50A <sup>[2]</sup>	3830	520	7	0.7	2.14	
	YS70A	3630	720	7	0.5	2.16	
	YS90A	3630	880	7	0.4	2.19	
	YS50	3730	490	7	0.8	2.09	
	YS60	3530	590	7	0.6	2.12	
	YS70	3530	690	7	0.5	2.14	
	YS80	3530	785	7	0.5	2.15	
	YT-50-10S	4050	490	6	0.8		
Osaka Gas	Donacarbo	3000	500	9	0.6	2.10	
Petoca	Carbonic HM50	2750	490	10	0.56	2.16	
	HM60	2940	588	10	0.50	2.17	
	HM70	2940	686	10	0.43	2.18	
Tonen Corp.	Forca FT500	3000	500	10	0.6	2.14	
	FT700	3300	700	10	0.5	2.16	

Costs and Relative Costs for Engineering materials.  
(William D. Callister, Jr. 2007).

Material / Condition	Cost (\$US/kg)	Relative Cost
<b>PLAIN CARBON AND LOW ALLOY STEELS</b>		
Steel alloy A36		
• Plate, hot rolled	0,50-0,90	1
• Angle bar, hot rolled	1,15	1,6
Steel alloy 1020		
• Plate, hot rolled	0,50-0,60	0,8
• Plate, cold rolled	0,85-1,45	1,6
Steel alloy 1040		
• Plate, hot rolled	0,75-0,85	1,1
• Plate, cold rolled	1,3	1,9
Steel alloy 4140		
• Bar, normalized	1,75-1,95	2,6
• H grade (round), normalized	2,85-3,05	4,2
Steel alloy 4340		
• Bar, annealed	2,45	3,5
• Bar, normalized	3,30	4,7
<b>STAINLESS STEELS</b>		
Stainless alloy 304		
• Plate, hot finished and annealed	2,15-3,50	4
Stainless alloy 316		
• Plate, hot finished and annealed	3,00-4,40	5,3
• Round, cold drawn and annealed	6,2	8,9
Stainless alloy 440A		
• Plate, annealed	4,40-5,00	6,7
Stainless alloy 17-7PH		
• Plate, cold rolled	6,85-10,00	12
<b>CAST IRONS</b>		
Gray irons (all grades)		
• High production	1,20-1,50	1,9
• Low production	3,3	4,7
Ductile irons (all grades)		
• High production	1,45-1,85	2,4
• Low production	3,30-5,00	5,9
<b>ALUMINUM ALLOYS</b>		
Alloy 1100		
• Sheet, annealed	7,25-10,00	12,3
Alloy 2024		
• Sheet, T3 temper	8,80-11,00	14,1
• Bar, T351 temper	11,35	16,2
Alloy 6061		
• Sheet, T6 temper	4,40-6,20	7,6

• Bar, T651 temper	6,1	8,7
Alloy 7075		
• Sheet, T6 temper	9,00-9,70	13,4
Alloy 356		
• As cast, high production	4,40-6,60	7,9
• As cast, custom pieces	11	15,7
• T6 temper, custom pieces	11,65	16,6
<b>COPPER ALLOYS</b>		
Alloy C11000 (electrolytic tough pitch), sheet	4,00-7,00	7,9
Alloy C17200 (beryllium-copper), sheet	25,00-47,00	51,4
Alloy C2600Q (cartridge brass), sheet	3,50-4,85	6
Alloy C36000 (free-cutting brass), sheet, rod	3,20-4,00	5,1
Alloy C71500 (copper-nickel, 30%), sheet	8,50-9,50	12,9
Alloy C93200 (bearing bronze)		
• Bar	4,50-6,50	7,9
• As cast, custom piece	12,2	17,4
<b>MAGNESIUM ALLOYS</b>		
Alloy AZ31B		
• Sheet (rolled)	11	15,7
• Extruded	8,8	12,6
Alloy AZ91D (as cast)	3,8	5,4
<b>TITANIUM ALLOYS</b>		
Commercially pure		
• ASTM grade 1, annealed	28-65	66,4
Alloy Ti-5A1-2,5V	90-130	157
Alloy T1-6A1-4V	55-130	132
<b>PRECIOUS METALS</b>		
Gold, bullion	9500-10250	14100
Platinum, bullion	11400-14400	18400
Silver, bullion	170-210	271
<b>REFRACTORY METALS</b>		
Molybdenum		
• Commercially pure, sheet and rod	85-115	143
Tantalum		
• Commercially pure, sheet and rod	390-440	593
Tungsten		
• Commercially pure, sheet	77,5	111
• Commercially pure, rod (72-% in, dia.)	97-135	166
<b>MISCELLANEOUS NONFERROUS ALLOYS</b>		
Nickel 200	19-25	31,4
Inconel 625	20-29	35
Monel 400	15,5-16,5	22,9
Haynes alloy 25	85,5-103,5	135
Invar	17,25-19,75	26,4
Super invar	22,00-33,00	39,3
Kovar	30,75-39,75	50,4
Chemical lead		
• Ingot	1,2	1,7

• Plate	1,55-1,95	2,5
Antimonial lead (6%)		
• Ingot	1,5	2,1
• Plate	2,00-2,70	3,4
Tin, commercial purity (99,9+%), ingot	6,85-8,85	11,2
Solder (60Sn-40Pb), bar	5,50-7,50	9,3
Zinc, commercial purity		
• Ingot	1,2	1,7
• Anode	1,65-2,45	2,9
Zirconium, reactor grade 702 (plate)	44,00-48,50	66,1
<b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b>		
Diamond		
• Natural, <sup>1</sup> / <sub>k</sub> carat, industrial grade	36000-90000	90000,00
• Synthetic, 30-40 mesh, industrial grade	18750,00	27000,00
• Natural, powder, 45 /xm, polishing abrasive	5000	7100
<b>POLYMERS</b>		
Butadiene-acrylonitrile (nitrile) rubber		
• Raw and unprocessed	2,90	4,10
• Extruded sheet ('A-Vs in, thick)	9,90-10,50	14,60
• Calendered sheet ('A-Vs in, thick)	8,40	12,00
Styrene-butadiene (SBR) rubber		
• Raw and unprocessed	1,20	1,70
• Extruded sheet ('A-Vs in, thick)	7,60-12,20	14,10
• Calendered sheet ('A-'A in, thick)	6,80	9,70
Silicone rubber		
• Raw and unprocessed	5,50	7,90
• Extruded sheet ('A-Vs in, thick)	12,60-26,20	27,70
• Calendered sheet ('A-Vs in, thick)	31,50-38,50	50,00
Epoxy resin, raw form	3,00-4,00	5,00
Nylon 6,6		
• Raw form	4,40-6,00	7,40
• Extruded	9,40	13,40
Phenolic resin, raw form	6,50-12,00	13,20
Poly(butylene terephthalate) (PBT)		
• Raw form	4,00	5,70
• Sheet	9,75	13,90
Polycarbonate (PC)		
• Raw form	4,85-5,30	7,30
• Sheet	7,00-10,00	12,10
Polyester (thermoset), raw form	1,50-4,40	4,20
Polyetheretherketone (PEEK), raw form	90,00-110,00	143
Polyethylene		
• Low density (LDPE), raw form	1,20-1,35	1,80
• High density (HDPE), raw form	1,00-1,70	1,90
• Ultrahigh molecular weight (UHMWPE), raw form	3,00-8,50	8,20
Poly(ethylene terephthalate) (PET)		
• Raw form	1,90-2,10	2,90
• Sheet	3,30-7,70	7,90

Poly(methyl methacrylate) (PMMA)		
• Raw form	2,40	3,40
• Calendered sheet	4,20	6,00
• Cell cast	5,85	8,40
Polypropylene (PP), raw form	0,85-1,65	1,80
Polystyrene (PS), raw form	1,00-1,10	1,50
Polytetrafluoroethylene (PTFE)		
• Raw form	20,00-26,50	33,20
• Sheet	38,00	54
Poly(vinyl chloride) (PVC), raw form	1,40-2,80	3,00
<b>FIBER MATERIALS</b>		
Aramid (Kevlar 49), continuous	31,00	44,30
Carbon (PAN precursor), continuous		
• Standard modulus	31,50-41,50	52,10
• Intermediate modulus	70,00-105,00	125
• High modulus	175,00-225,00	285
E-glass, continuous	1,90-3,30	3,70
<b>COMPOSITE MATERIALS</b>		
Aramid (Kevlar 49) continuous-fiber, epoxy prepreg	55,00-62,00	84,00
Carbon continuous-fiber, epoxy prepreg		
• Standard modulus	40,00-60,00	71,00
• Intermediate modulus	100,00-130,00	164,00
• High modulus	200,00-275,00	340,00
E-glass continuous-fiber, epoxy prepreg	22,00	31,40
<b>WOODS</b>		
Douglas fir	0,54-0,60	0,80
Red oak	2,55-3,35	4,2

## Calculating tool interface overview.

Исходные данные/Reference data					
Название/name	Российское обозначение / Russian sign	Европейское обозначение / European sign	Величина/value	Другие значения/ Other values	Единицы измерения/ Units of measure
Бетон/Concrete					
Класс бетона/Class of the concrete			B25		
	$R_{b,n}; R_{b,ser}$		18,5		МПа/MPa
	$R_{bt,n}; R_{bt,ser}$		1,55		МПа/MPa
	$R_b$	$f_{cd}$	14,5		МПа/MPa
	$R_{bt}$		1,05		МПа/MPa
	$E_b$		30		ГПа/GPa
Коэффициенты условий работы бетона по п. 5.1.10 СП 52-101-2003/Factors of working conditions by p. 5.1.10 of СП 52-101-2003	$\gamma_{b1}$		1		-
	$\gamma_{b2}$		1		-
	$\gamma_{b3}$		1		-
	$\gamma_{b4}$		1		-
Размеры и геометрические данные/dimensions and geometrical data					
Сечение/Cross-section	b	b	300		мм/mm
	h	h	600		мм/mm
Защитные слои по табл. 8.1 СП 52-101-2003/ Safety layers by t. 8.1 of СП 52-101-2003	a		20		мм/mm
	a'		20		мм/mm

Армирование/Reinforcement				
Продольная арматура/Longitudinal reinforcement				
Класс арматуры/Class of steel		A500		
	$R_{s,n} ; R_{s,ser}$	500		МПа/MPa
	$R_s$	435		МПа/MPa
	$R_{sw}$	300		МПа/MPa
	$R_{sc}$	435		МПа/MPa
	$E_s$	200		ГПа/GPa
	$d_s$	20		мм/mm
	$d'_s$	18		мм/mm
	$n_s$	3		шт./pcs.
	$n'_s$	0		шт./pcs.
	$A_s$	942,54		мм <sup>2</sup> /mm <sup>2</sup>
	$A'_s$	0		мм <sup>2</sup> /mm <sup>2</sup>

Действующие нагрузки/existing loads				
Полная/full	M		250	кН*м/kN*m
	M1		0	кН*м/kN*m

Расчет балки по СП 52-101-2003/Calculating the beam according to СП 52-101-2003					
Название/Name	формула/Formula	Результат/ Result	Единицы измерения/ units of measure	Примечание/ Notes	
	$x = \frac{R_s A_s - R_{sc} A'_s}{R_y b} = 94,254$	94,254	мм/mm		
	$\varepsilon_{s,el} = \frac{R_s}{E_s} = 0,002175$	0,002175			
	$\varepsilon_{b,ult} = 0,0035$	0,0035			
	$\xi_R = \frac{0,8}{1 + \frac{\varepsilon_{s,el}}{\varepsilon_{b,ult}}} = 0,49339207$	0,49339207			
	$\xi = \frac{x}{h_0} = 0,16535789$	0,16535789		<	$\xi_R$
	$M_{ult} = R_y b x (h_0 - 0,5x) + R_{sc} A'_s (h_0 - a) = 214,380492$	214,380492	кН*м/kN*m		Strengthening is required

Продольное усиление(Углеволокно)/Longitudinal strap(Carbon fiber)					
Название/name	Российское обозначение / Russian sign	Европейское обозначение / European sign	Величина/ value	Другие значения/ Other values	Единицы измерения/ Units of measure
	R <sub>f</sub>		4800		МПа/МПа
	E <sub>f</sub> ; E <sub>ft</sub>		230		ГПа/GPa
	g <sub>f</sub>		1,1		-
Environmental factor	C <sub>f</sub>		0,95		-
Thickness of strap	t <sub>f</sub>		0,167		мм/mm
Number of layers	n		5		шт./pcs.
Max. elongation	ε <sub>f</sub>		0,0208696		-
Width of strap	b <sub>f</sub>		300	271	мм/mm

Расчет усиления балки с использованием ФАП по СП 52-101-2003/Calculating the beam using CFRP strengthening according to СП 52-101-2003

Название/Name	формула/Formula	Результат/ Result	Единицы измерения/ units of measure	Примечание/ Notes
Design elongation	$\varepsilon_n = \varepsilon_f * C_f / g_f =$ $n E_n t_f =$	0,01802372 192050	>180000	
	$k_m = \begin{cases} \frac{1}{60\varepsilon_{ft}} \left( 1 - \frac{nE_n t_f}{360000} \right) \leq 0,9 & \text{for } nE_n t_f < 180000 \\ \frac{1}{60\varepsilon_{ft}} \left( 1 - \frac{90000}{nE_n t_f} \right) \leq 0,9 & \text{for } nE_n t_f \geq 180000 \end{cases} = 0,49136376$			
	$\varepsilon_{fu} = \varepsilon_n * k_m = 0,0088562$ $\sigma_{fu} = E_f \varepsilon_{fu} = 2036,92615$		МПа/МПа	
	$\omega = 0,85 - 0,008R_b = 0,734$			
	$\xi_{Rf} = \frac{\omega}{1 + \frac{R_f}{0,002E_f} \left( 1 - \frac{\omega}{1,1} \right)} = 0,29676353$			
	$A_f = n b_f t_f = 226,285$		мм <sup>2</sup> /мм <sup>2</sup>	
	$x = \frac{R_{fu} A_f + R_s A_s}{R_s b} = 200,213962$		мм/mm	
	$\xi_f = \frac{x}{h} = 0,33368994$	>	ξ <sub>гр</sub>	OK
	$\xi = \frac{x}{h_0} = 0,34519649$	<	ξ <sub>г</sub> = 0,493392	OK

$$\sigma_f = \frac{0,002 E_f}{1 - \frac{\omega}{1,1}} \left( \frac{\omega}{\xi_f} - 1 \right) = 1658,52809$$

МПа/МПа	<	$\sigma_{fu}$
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OK
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$$M_{uit,cf} = A_f \sigma_f (h - 0,5x) + A_s R_s (h_0 - 0,5x) = 380,268305$$

кН*м/кН*м	>	M
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OK
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**Эффективность усиления/Strengthening efficiency**

$$\frac{M_{uit,cf} - M_{uit}}{M_{uit}} \cdot 100\% = 77,38008762 \quad \% \quad \text{With carbon fibers}$$

$$\frac{M_{uit,s} - M_{uit}}{M_{uit}} \cdot 100\% = 205,7375309 \quad \% \quad \text{With steel rebars}$$

Информация о дополнительных арматурных стержнях для классического усиления /Information about additional reinforcing bars for traditional strengthening.				
Продольная арматура/Longitudinal reinforcement				
Класс арматуры/Class of steel		A500		
	$R_{s,n} ; R_{s,ser}$	500		МПа/МПа
	$R_{s,add}$	435		МПа/МПа
	$R_{sw}$	300		МПа/МПа
	$R_{sc}$	435		МПа/МПа
	$E_{s,add}$	200		ГПа/ГПа
	$d_{s,add}$	20		мм/мм
	$n_{s,add}$	6		шт./pcs.
	$A_{s,add}$	1885,08		мм <sup>2</sup> /мм <sup>2</sup>

Расчет традиционного усиления по СП 52-101-2003/Calculating of traditional strengthening according to СП 52-101-2003				
формула/Formula	Результат/Result	Единицы измерения/ units of measure	Примечание/ Notes	
$x = \frac{R_s A_s + R_{s,add} A_{s,add} - R_{sc} A'_s}{R_b b} =$	282,762	мм/мм		
$\xi = \frac{x}{h_0} =$	0,487521	<	$\xi_R$	OK
$M_{uit,s} = R_b b x (h_0 - 0,5x) + R_{sc} A'_s (h_0 - a') =$	655,4416	кН*м/кН*м	OK	

APPENDIX 4.

Ultimate bending moment of the beam, calculated for the same area of strengthening material.

Area, mm <sup>2</sup>	Materials							
	MapeWrap C UNIAX 300/10, TS=4800 MPa, YM=230 Gpa		Wabo Mbrace 530, TS=3517 MPa, YM=372 GPa		S&P C Sheet 640, TS=2650 MPa, YM=640 Gpa		Reinforcing steel A500, TS=500 Mpa, YM=200 Gpa	
	Size	Ult. Moment, kH*m	Size	Ult. Moment, kH*m	Size	Ult. Moment, kH*m	Size	Ult. Moment, kH*m
0		214,4		214,4		214,4		214,4
28,3	0,167X169	268,7	0,165X171	311,6	0,19X149	395,47	1 d6	223,6
50,2	0,167X301	291,1	0,165X304	358,6	0,19X265	495,5	1 d8	228,8
56,6	2X0,167X169	302,3	2X0,165X171	369,1	2X0,19X149	518,8	2 d6	230,1
78,5	2X0,167X235	315,2	2X0,165X238	395,9	2X0,19X207	586,5	1 d10	235,6
84,8	3X0,167X169	329,9	3X0,165X171	401,6	3X0,19X149	602,2	3 d6	236,6
100,5	2X0,167X301	321,5	2X0,165X304	411,9	2X0,19X265	635,6	2 d8	240,4
113,1	4X0,167X169	359,2	4X0,165X171	417,5	4X0,19X149	656,7	4 d6	243,1
141,4	5X0,167X169	378,1	5X0,165X171	422	5X0,19X149	690,1	5 d6	249,6
150,8	3X0,167X301	342,5	3X0,165X304	421,7	3X0,19X265	697,5	3 d8	252
157,1	4X0,167X235	369,4	4X0,165X238	420,9	4X0,19X207	701,5	2 d10	253,7
169,7	6X0,167X169	359,4	6X0,165X171	418,49	6X0,19X149	707,5	6 d6	256,1
201,1	4X0,167X301	367,9	4X0,165X304	408	4X0,19X265	712,5	4 d8	263,6
226,2	5X0,167X271	380,3	5X0,165X274	395,6	4X0,19X298	708,1	2 d12	269,9
235,6	6X0,167X235	347,1	6X0,165X238	390,3	6X0,19X207	704,9	3 d10	271,8
251,3	5X0,167X301	375,3	5X0,165X304	381	5X0,19X265	697,8	5 d8	275,2
301,6	6X0,167X301	322,6	6X0,165X304	346	6X0,19X265	663,8	6 d8	286,8
314,2	8X0,167X235	F.f	8X0,165X238	F.f	8X0,19X207	653,2	4 d10	289,94
339,3		F.f		F.f	6X0,19X298	629,3	3 d12	296
603,2		F.f		F.f		F.f	3 d16	357,6
942,5		F.f		F.f		F.f	3 d20	436,9
1472,7		F.f		F.f		F.f	3 d25	561,6
1885,1		F.f		F.f		F.f	6 d20	655,4