Design Guide Line for S&P FRP Systems

Software: www.frp.at

Note: The design models and the "FRP Lamella/FRP Colonna" software are based on the material parameters of the S&P reinforcing fibres and of the S&P adhesive systems. If other components are used, the required FRP cross section and the anchor check provided by the software will no longer be valid. Under these circumstances the system supplier waives all liability.

This software may be used free of charge exclusively for the dimensioning of S&P FRP systems. For all other applications of this software, licence fees are payable to the S&P Clever Reinforcement Company AG. The user agrees to these terms upon installing the software.
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1. Introduction

The structural design and thus the production of structural elements made of reinforced concrete is (RC) based on forces and loads current in codes of the time. However, during the service life of a structure, various circumstances may require that the service loads are changed due to:

- Modification of the structure
- Aging of the construction materials
- Deterioration of the concrete caused by reinforcement corrosion
- Earthquake design requirements; fire design changes
- Upgrading of building codes relating to load bearing capacity or service loads etc.

The consideration of the actual loads resisted by a structure is a necessary prerequisite for the development of a comprehensive rehabilitation concept. Basically, the methods available for the structural strengthening RC structures are as follows:

- Application of cast or sprayed concrete with additional reinforcement
- Placing of additional reinforcement near surface mounted FRP reinforcement
- External post-tensioning
- Installation of supports or additional columns or beams
- Steel plate bonding to increase shear or flexural capacity

An alternative to these traditional methods of strengthening is the use of Fibre Reinforced Polymer (FRP) composites.

2. FRP reinforcing systems

Reinforcing steel and fibre composites exhibit different material behaviours. While steel shows an ideal elastic-plastic behaviour, all FRP systems are linear-elastic materials. This circumstance must be taken into account in design and dimensioning.

The basic fibres of FRP systems are imbedded in a matrix and their arrangement can be either uni-directional or bi-directional. FRP composites are used for the retrofit of existing RC structures.

Stretched sheets

Uni-directional arrangement:
The fibres are bonded to a tight mesh and supplied as a sheet.

The parallel fibres in the sheet are stretched and thus provide a high modulus of elasticity. They are especially suited for increasing the stiffness of an element.
Woven sheets

Bi-directional arrangement:
The arrangement of the fibres is bi-directional. The sheets are produced by weaving.

In the woven sheets the fibres become slightly wave like in form. As a result, these products are less suited for increasing the stiffness of an element. Bi-directional sheets are ideally suited for increasing the ductility of a RC structure. Under loading, the fibres must be stressed before higher forces can be absorbed.

Uni-directional and bi-directional FRP sheets

Cold or thermally curing epoxy resins matrices are used to ensure load transfer from the sheets to the substrate.

Cold curing epoxy resin matrix:
Up to a weight of 400 gm/m² both uni-directional and bi-directional sheets are applied as a dry lay up.
This means:
The cold curing epoxy resin is rolled on to the structural element. The dry sheet is then applied into the matrix.

Stretched and woven sheets with a weight of 400-800 gm/m² are applied as a wet lay up.
This means:
The sheets are impregnated with the epoxy matrix and applied wet to the building component.

Thermally curing epoxy resin matrix:
The uni-directional and bi-directional sheets are impregnated with the thermally curing epoxy adhesive and delivered at controlled low temperatures. Thermal curing is done by applying heat to the epoxy resin on the element. This type of reinforcement is called Prepreg and is typically used in the aviation and sports industry; for the retrofit of structures Prepreg is normally not used.

Prefabricated FRP plates (laminates)

Prefabricated FRP plates are delivered to the job site as a composite (laminate). Impregnation with the matrix and thermal curing is done by the supplier under controlled factory conditions. S&P offers uni- and bi-directional laminates to the individual requirements of the application. The most well known FRP plate used for structural strengthening is the S&P Laminate CFK.
3. Types of fibres for S&P FRP systems

<table>
<thead>
<tr>
<th>Type of fibre</th>
<th>Modulus of elasticity GPa</th>
<th>Tensile strength MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (Carbon)</td>
<td>240 - 640</td>
<td>2'500 – 4'000</td>
</tr>
<tr>
<td>A (Aramid)</td>
<td>120</td>
<td>3'000 – 4'000</td>
</tr>
<tr>
<td>G (Glass)</td>
<td>65 - 70</td>
<td>1'700 – 3'000</td>
</tr>
<tr>
<td>Polyester</td>
<td>12 - 15</td>
<td>2'000 – 3'000</td>
</tr>
<tr>
<td>Steel</td>
<td>210</td>
<td>550</td>
</tr>
</tbody>
</table>

Figure 1: Stress-strain-diagram

S&P manufactures custom-made sheets of either a single fibre type or of fibre combinations (hybrids). The advantages and disadvantages of the various fibres are as follows:

E-glass: Uncoated E-glass corrodes in alkaline environments. Therefore for G-FRP wraps out of E-glass a higher reduction factor on the fibre property is used. E-glass wraps are usually used for enhancement of RC structures in seismic endangered areas.

AR-glass: Alkali-resistant glass is suited also for G-FRP wraps. Because of the higher durability, the reduction factor on the fibre property is any case lower than for E-glass. Therefore AR-glass wraps are often a more economical solution compared to E-glass wraps.

Aramid: Aramid is a very tough material. Aramid sheets are used, as an example, for the manufacture of bullet-proof vests. For RC structures this extreme toughness provides benefits for special applications such as the strengthening of rectangular columns. Ideally, aramid fibres used for this application are prestressed prior to the application. Aramid is especially suited as impact and explosion protection for the retrofit of columns.

Carbon fibres: Carbon fibres provide special benefits when used to increase the flexural capacity:

- High modulus of elasticity (depending on fibre type)
- Minimum coefficient of thermal expansion (approx. 50 times lower than steel)
- Excellent fatigue properties
- Excellent resistance to all types of chemical attack
- Will not corrode
- Freeze/thaw and de-icing salt resistance.
4. S&P FRP sheets for site lamination

The S&P sheets (uni-directional/bi-directional) can be applied as dry and wet lay ups and also as preimpregnated Prepegs. The function of the matrix is to enable the load transfer between the fibres and from the fibres to the substrate. Dimensioning of the reinforcement is based on the net fibre cross section and the net fibre properties only. The theoretical sheet thickness is determined as follows:

\[
\text{Theoretical sheet thickness (net fibre only)} = \frac{\text{fibre weight in the direction of strengthening}}{\text{density of the fibre}}
\]

Due to the application process, the site lamination does not always produce an optimum fibre arrangement. There is also a risk of damage to the fibres while they are being rolled on to the surface. It is therefore recommended that the E-modulus used for the fibres be reduced by an environmental reduction \(y\). The environmental reduction factor is based also on the durability of each fibre type, and on the application (machine controlled, hand lay up).

<table>
<thead>
<tr>
<th>Recommended reduction factor ([y]):</th>
</tr>
</thead>
<tbody>
<tr>
<td>uni-directional (stretched) S&amp;P C-Sheets (y = 1.1-1.2)</td>
</tr>
<tr>
<td>uni-directional (stretched) S&amp;P A-Sheets (y = 1.2-1.4)</td>
</tr>
<tr>
<td>bi-directional (woven) S&amp;P G-Sheets (y = 1.5-1.8)</td>
</tr>
</tbody>
</table>

The theoretical parameters of the S&P sheets for site lamination are as follows.
### 4.1 S&P A-Sheet 120

Sheet of aramid fibre for dry and wet lay up

<table>
<thead>
<tr>
<th>Technical data (unidirectional)</th>
<th>290 g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus [kN/mm²]</td>
<td>120</td>
</tr>
<tr>
<td>Tensile strength [N/mm²]</td>
<td>2900</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fibre weight [g/m²] (main direction)</th>
<th>290</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight per unit area of sheet [g/m²]</td>
<td>320</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>1.45</td>
</tr>
<tr>
<td>Elongation at rupture [%]</td>
<td>2.5</td>
</tr>
</tbody>
</table>

| Design thickness (fibre weight/density) [mm] | 0.20 |
| Theoretical design cross-section 1000 mm width [mm²] | 200 |

| Reduction factor for design (manual lamination/UD sheet) | 1.3 (recommended by S&P) |

| Tensile force of 1000 mm width ultimate [kN] | $\frac{200 \times 2900}{1.3} = 446.2$ |
| Delivery: (Special sheets upon request) | Width: 300 mm | Length roll: 150 m |
| Application: | • Impact protection | • Explosion protection |
### 4.2 S&P A-Strap

Aramide fibre strap for active (prestressed) confinement

<table>
<thead>
<tr>
<th>Technical data of fibre (uni-directional)</th>
<th>S&amp;P A-Strap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity (non twisted)</td>
<td>120 [kN/mm²]</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>2900 [N/mm²]</td>
</tr>
<tr>
<td>Weight of fibre main direction</td>
<td>12 straps of 19.3 g = 290 [g/m²]</td>
</tr>
<tr>
<td>Recommended prestressing force for 12 straps at height 1000 mm</td>
<td>200 [kN]</td>
</tr>
<tr>
<td>Tensile strength (failure) at column length of 1000 mm (12 straps)</td>
<td>580 [kN]</td>
</tr>
<tr>
<td>Delivery in rolls:</td>
<td>Width: 30 mm</td>
</tr>
<tr>
<td></td>
<td>Length: 50 m</td>
</tr>
</tbody>
</table>

**Application:**
- Active embrace reinforcement
- Seismic retrofitting of load-bearing elements
- Special applications
### 4.3 S&P C-Sheet 240

Sheet of carbon fibre for **dry lay up and wet lay up**

<table>
<thead>
<tr>
<th>Technical data (unidirectional)</th>
<th>200 g/m²</th>
<th>300 g/m²</th>
<th>400 g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus [kN/mm²]</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Tensile strength [N/mm²]</td>
<td>3800</td>
<td>3800</td>
<td>3800</td>
</tr>
<tr>
<td>Fibre weight [g/m²] (main direction)</td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Weight per unit area of sheet [g/m²]</td>
<td>230</td>
<td>330</td>
<td>430</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Elongation at rupture [%]</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
</tr>
<tr>
<td>Design thickness (fibre weight/density) [mm]</td>
<td>0.117</td>
<td>0.176</td>
<td>0.234</td>
</tr>
<tr>
<td>Theoretical design cross-section 1000 mm width [mm²]</td>
<td>117</td>
<td>176</td>
<td>234</td>
</tr>
<tr>
<td>Reduction factor for design (manual lamination/ UD sheet)</td>
<td>1.2 (recommended by S&amp;P)</td>
<td>1.2 (recommended by S&amp;P)</td>
<td>1.2 (recommended by S&amp;P)</td>
</tr>
<tr>
<td>Tensile force of 1000 mm width ultimate [kN]</td>
<td>$117 \times 3800 = 370.5$</td>
<td>$176 \times 3800 = 557.3$</td>
<td>$234 \times 3800 = 744.0$</td>
</tr>
<tr>
<td>Tensile force of 1000 mm width at 0.6% $\varepsilon$ for design [kN]</td>
<td>140</td>
<td>211</td>
<td>282</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Delivery: (Special sheets upon request)</th>
<th>Width: 300 or 600 mm</th>
<th>Length roll: 150 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Flexural enhancement (low quality of substrate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Axial load enhancement of columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Replacement of stirrups in columns</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Different weight of S&P C-Sheet 240 upon request.
### 4.4 S&P C-Sheet 640
Sheet of carbon fibre for **dry and wet lay up**

<table>
<thead>
<tr>
<th>Technical data (unidirectional)</th>
<th>400 g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus [kN/mm²]</td>
<td>640</td>
</tr>
<tr>
<td>Tensile strength [N/mm²]</td>
<td>2650</td>
</tr>
<tr>
<td><strong>Fibre weight [g/m²] (main direction)</strong></td>
<td>400</td>
</tr>
<tr>
<td>Weight per unit area of sheet [g/m²]</td>
<td>430</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>2.1</td>
</tr>
<tr>
<td>Elongation at rupture [%]</td>
<td>0.4</td>
</tr>
<tr>
<td>Design thickness (fibre weight/density) [mm]</td>
<td>0.190</td>
</tr>
<tr>
<td>Theoretical design cross-section 1000 mm width [mm²]</td>
<td>190</td>
</tr>
<tr>
<td>Reduction factor for design (manual lamination/UD sheet)</td>
<td>1.2 (recommended by S&amp;P)</td>
</tr>
<tr>
<td>Tensile force of 1000 mm width ultimate [kN]</td>
<td>( \frac{190 \cdot 2650}{1.2} = 419.6 )</td>
</tr>
<tr>
<td><strong>Tensile force of 1000 mm width at 0.2% ε for design [kN]</strong></td>
<td>203</td>
</tr>
<tr>
<td>Delivery: (Special sheets upon request)</td>
<td>Width: 300 mm</td>
</tr>
<tr>
<td></td>
<td>Length roll: 50 m</td>
</tr>
<tr>
<td>Application:</td>
<td>• External shear strengthening</td>
</tr>
<tr>
<td></td>
<td>• End anchoring of the S&amp;P laminate CFK</td>
</tr>
</tbody>
</table>


### 4.5 S&P G-Sheet E 50/50, S&P G-Sheet AR 50/50

Sheet of E- or AR-glass fibre for **dry lay up**

<table>
<thead>
<tr>
<th>Technical data of fibre (main- and cross direction)</th>
<th>E-glass</th>
<th>AR-glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (kN/mm(^2))</td>
<td>73</td>
<td>65</td>
</tr>
<tr>
<td>Tensile strength (virgin filament) (N/mm(^2))</td>
<td>3400</td>
<td>3000</td>
</tr>
<tr>
<td>Sheet weight (total 350 g/m(^2)) (g/m(^2))</td>
<td>175 in both directions</td>
<td>175 in both directions</td>
</tr>
<tr>
<td>Density (g/cm(^3))</td>
<td>2.6</td>
<td>2.68</td>
</tr>
<tr>
<td>Elongation at rupture (%)</td>
<td>4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Design thickness (fibre weight/density) (mm)</td>
<td>0.067</td>
<td>0.065</td>
</tr>
<tr>
<td>Theoretical design cross-section 1000 mm width (mm(^2))</td>
<td>67 (fibre area only/each direction)</td>
<td>65 (fibre area only/each direction)</td>
</tr>
<tr>
<td>Reduction factor for design (manual lamination / UD sheet)</td>
<td>1.4 (recommended by S&amp;P)</td>
<td>1.4 (recommended by S&amp;P)</td>
</tr>
<tr>
<td>Tensile force of 1000 mm width for design (kN)</td>
<td>(67 \times 3400 = 162.7) each direction</td>
<td>(65 \times 3000 = 139.3) each direction</td>
</tr>
</tbody>
</table>

**Delivery:**
- Width: 670 mm
- Length roll: 50 m

**Application:**
- Explosion protection
- Reinforcing of masonry or historic buildings
- Seismic retrofitting
### Technical data of fibre (main direction)

<table>
<thead>
<tr>
<th></th>
<th>E-glass</th>
<th>AR-glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>73</td>
<td>65</td>
</tr>
<tr>
<td>(kN/mm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength</td>
<td>3400</td>
<td>3000</td>
</tr>
<tr>
<td>(virgin filament)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N/mm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet weight</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>(total 440 g/m²)</td>
<td>in main direction</td>
<td>in main direction</td>
</tr>
<tr>
<td>(g/m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>2.6</td>
<td>2.68</td>
</tr>
<tr>
<td>(g/cm³)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elongation at rupture</td>
<td>4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>(%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design thickness</td>
<td>0.154</td>
<td>0.149</td>
</tr>
<tr>
<td>(fibre weight/density)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical design cross-</td>
<td>154</td>
<td>149</td>
</tr>
<tr>
<td>section 1000 mm width</td>
<td>(fibre area only/</td>
<td>(fibre area only/</td>
</tr>
<tr>
<td>(mm²)</td>
<td>main direction)</td>
<td>main direction)</td>
</tr>
<tr>
<td>Reduction factor for design</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>(manual lamination / UD sheet)</td>
<td>(recommended by S&amp;P)</td>
<td>(recommended by S&amp;P)</td>
</tr>
<tr>
<td>Tensile force of 1000 mm width for design</td>
<td>154 x 3400 = 374.0</td>
<td>149 x 3000 = 319.3</td>
</tr>
<tr>
<td>(kN)</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>main direction</td>
<td></td>
<td>main direction</td>
</tr>
<tr>
<td>Cross direction</td>
<td>10 % of the equal fibre is used in the weft (cross section)</td>
<td></td>
</tr>
<tr>
<td>Delivery:</td>
<td>Width: 670 mm</td>
<td></td>
</tr>
<tr>
<td>(Special sheets upon request)</td>
<td>Length roll: 50 m</td>
<td></td>
</tr>
<tr>
<td>Application:</td>
<td>• Seismic retrofitting of supporting elements using dry lay up</td>
<td></td>
</tr>
</tbody>
</table>

Sheet of E- or AR-glass fibre for **dry lay up**
### 4.7 S&P G-Sheet E 90/10 B, S&P G-Sheet AR 90/10 B

Sheet of E- or AR-glass fibre for **wet lay up**

<table>
<thead>
<tr>
<th>Technical data of fibre (main direction)</th>
<th>E-glass</th>
<th>AR-glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (kN/mm²)</td>
<td>73</td>
<td>65</td>
</tr>
<tr>
<td>Tensile strength (virgin filament) (N/mm²)</td>
<td>3400</td>
<td>3000</td>
</tr>
<tr>
<td>Sheet weight (total 880 g/m²) (g/m²)</td>
<td>800 in main direction</td>
<td>800 in main direction</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.6</td>
<td>2.68</td>
</tr>
<tr>
<td>Elongation at rupture (%)</td>
<td>4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Design thickness (fibre weight/density) (mm)</td>
<td>0.308</td>
<td>0.299</td>
</tr>
<tr>
<td>Theoretical design cross-section 1000 mm width (mm²)</td>
<td>308 (fibre area only/ main direction)</td>
<td>299 (fibre area only/ main direction)</td>
</tr>
<tr>
<td>Reduction factor for design (manual lamination / UD sheet)</td>
<td>1.4 (recommended by S&amp;P)</td>
<td>1.4 (recommended by S&amp;P)</td>
</tr>
<tr>
<td>Tensile force of 1000 mm width for design (kN)</td>
<td>(308 \times 3400 = 748.0) 1.4 main direction</td>
<td>(299 \times 3000 = 640.7) 1.4 main direction</td>
</tr>
<tr>
<td>Cross direction</td>
<td>10 % of the equal fibre is used in the weft (cross section)</td>
<td></td>
</tr>
<tr>
<td>Delivery: (Special sheets upon request)</td>
<td>Width: 670 mm</td>
<td>Length roll: 50 m</td>
</tr>
<tr>
<td>Application:</td>
<td>• Seismic retrofitting of supporting elements using wet lay up</td>
<td></td>
</tr>
</tbody>
</table>
5. Cold curing epoxy resin systems

Figure 2: A structure must be permeable to water vapour from the inside to the outside. VITRUV (Roman architect and engineer, approx. 50 B.C.)

ACI FRP Guideline 440
(Section 8.3.3 Durability)

The effective US Guideline 440 for external FRP strengthening prescribes:

Any FRP system that completely encases or covers a concrete section should be investigated for vapour pressures, and moisture vapour transmission.

When total surface wrapping of concrete is intended, aspects of building physics must be considered. 30-50% of the surface of the RC structure should remain water vapour-permeable. A total surface coverage with an epoxy matrix is therefore not suitable.

S&P Resicem is a newly developed cementitious epoxy matrix. The combined effect of the two binders that have completely different chemical bases, is that the cement particles, due to water vapour pressure, penetrate into the microstructure of the epoxy resin. Thus, the matrix system, which is vapour-proof at the time of its application, becomes vapour-permeable as the water vapour exposure increases. The cement contained in the matrix provides an additional alkali deposit which protects the internal reinforcement against corrosion. The water vapour diffusion coefficient of a FRP confinement (thickness 1 mm) with S&P Resicem will eventually level out at approx. 3'000-5'000. Application is possible to substrates with a higher moisture content.

**Determination of the water vapour-permeability of a coating**

\[
S_d = \mu H_2O \times \text{layer thickness (m)} < 4 \text{ m}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>(\mu H_2O) (FRP thickness 1 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S&amp;P Resicem</td>
<td>(\mu H_2O \approx 3’000 – 5’000)</td>
</tr>
<tr>
<td>S&amp;P Resin 50/55 (epoxy resin)</td>
<td>(\mu H_2O = 1’000’000)</td>
</tr>
</tbody>
</table>

It follows that:

Sd: of a two-layer FRP coating using S&P Resicem, with a total thickness of 0.8 mm (matrix + fibres),

\[
S_d = 4’000 \times 0.008 \text{ (m)} = 3.2 \text{ m} < 4 \text{ m}
\]

With the use of S&P Resicem the water vapour-permeability of the FRP system is guaranteed.
6. S&P C-FRP plates

S&P C-FRP plates are produced by the extrusion method. In a continuous process, the carbon fibres are soaked in epoxy resin and cured through heating. For technical reasons, the extrusion method limits a maximum fibre content to approx. 70%. The elastic properties of a uni-directional composite can be calculated from the performance of the fibres and of the matrix. Since the modulus of elasticity and the tensile strength of the matrix can be neglected for the calculation of the laminate properties, the values are approx. 70% of the values of the carbon fibre.

While the design for manual on-site lamination is based on the theoretical fibre cross section and the parameters of the fibres only, the design for application of prefabricated S&P Laminates CFK is based on the cross section and the parameters of the composite.

The quality control of the S&P Laminate CFK is guaranteed by the manufacturer. The E-modulus and tensile strength of each roll of 150m length is controlled by S&P in house. For each roll a certificate of quality can be delivered on demand.

Figure 3: Installation of S&P Laminates CFK

Because parameters of the laminates are checked by S&P according to the ISO 9001 quality assurance concept. Thus, conversely to manually applied FRP systems, the E-moduli of the laminates do not need to be reduced by an additional reduction factor (y = 1).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity for design</td>
<td>168’000 MPa</td>
<td>205’000 Mpa</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>2’700 – 3’000 MPa</td>
<td>2’400 – 2’600 MPa</td>
</tr>
</tbody>
</table>

Special laminates with a modulus of elasticity of 300’000 MPa can be custom-made to the specific requirements of a project. However, the application is often not economical because of their low effective tensile strength.
7. Prestressed FRP systems

FRP systems can basically be applied in the non-prestressed or prestressed condition. Preliminary tests show that softer materials (glass or aramid fibres) tend to be more suitable for prestressing than high modulus carbon fibres. A high modulus of elasticity of the fibre on the one hand means a lower elongation for a defined prestress level and, on the other, a tendency of premature failure at reduced eccentricities during the prestressing procedure. In order to transmit the tensile forces, prestressing requires the FRP systems to be fixed (locked) at both ends. This is much more difficult with the brittle C and G fibres than with the tough aramide fibres.

Two systems are available for prestressing:

- **S&P A-Strap** (Aramid fibre strap) ➞ For wrapping/confinement of RC columns
- **S&P Laminates CFK** (carbonfiber plate) ➞ For flexural enhancement

![Figure 4: Prestressing of S&P Laminates CFK](image)

![Figure 5: Confinement of column using S&P A-Strap.](image)
8. Substrate requirements for FRP applications

The forces from the FRP are transmitted into the substrate through the modified epoxy matrix. FRP applications require a high quality substrate. The various FRP systems require different substrate conditions.

The S&P G-Sheet (glass fibre sheet) can be applied to substrates with a low surface bond strength. Glass fibre sheets are suited for the retrofit of historic buildings and the enhancement of the total carrying capacity of masonry walls. For the bonding of the S&P C-Sheet and the S&P A-Sheet, however, a bond strength of the substrate of >1.0 MPa is necessary. Prefabricated laminates produce a concentrated load transfer into the substrate. Thus, the application of the S&P Laminate CFK requires a substrate bond strength of 1.5 MPa.

Substrate requirements:

<table>
<thead>
<tr>
<th>Product</th>
<th>Substrate bond strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>S&amp;P C-Sheet / S&amp;P A-Sheet</td>
<td>&gt; 1.0 MPa</td>
</tr>
<tr>
<td>S&amp;P G-Sheet</td>
<td>approx. 0.2 MPa</td>
</tr>
<tr>
<td>S&amp;P Laminates CFK</td>
<td>&gt; 1.5 MPa</td>
</tr>
</tbody>
</table>

In order to transmit the forces from the S&P FRP system into the substrate through effective bond, surface roughening by sand blasting or grinding is required.

Figure 6: Testing of the bond (tensile) strength of the bearing substrate.

Figure 7: Roughening of the surface by sand-blasting or grinding.
9. Bonding and end anchoring of FRP systems

9.1 Confinement of columns

In the case of wrapping RC-columns bonding in the lap area of the FRP is carried out as a hoop directional confinement. The load carrying capacity of the substrate is therefore less important. Large scale tests were conducted at TU Gent (Belgium) with wrapped columns where only the FRP lap zone was bonded with epoxy resin. Tests on the axially loaded columns showed identical results to those systems with full-surface bonding and bonding in the FRP lap zone only.

Bond strengths between FRP layers

- Epoxy adhesive (S&P Resin 50/55) 15 MPa
- S&P Resicem 12 MPa

*Design bond strength* 10 MPa

The required anchoring lengths (overlap of sheet) are deduced from the necessary bonding area.

Example: S&P C-Sheet 240 (300 gm/m²)
Tensile force at width 1’000 mm and limiting design strain 0.6%, see chap. 4.2 ⇒ 211kN

Theoretical anchoring length (overlap of sheet) = \[ \frac{211 \text{ (kN)}}{10 \text{ (MPa)} \times 1'000 \text{ (mm)}} = 21 \text{ mm} \]

S&P recommends the following lap lengths:

<table>
<thead>
<tr>
<th>S&amp;P C-Sheet</th>
<th>150 mm in the fibre direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>S&amp;P A-Sheet</td>
<td>120 mm in the fibre direction</td>
</tr>
<tr>
<td>S&amp;P G-Sheet</td>
<td>100 mm in the fibre direction</td>
</tr>
</tbody>
</table>

9.2 Design for flexural strengthening using S&P Laminates CFK

The bonding of an additional external S&P Laminate CFK on to the tensile stress zone of a structural element subject to bending is carried out with S&P Resin 220 a system approved epoxy resin. Thus, a reinforced concrete structure is produced with an elastic-plastic (steel reinforcement) and a perfectly elastic tensile element (S&P Laminate CFK). Models for the calculation of the flexural capacity of the composite structure and of the anchor lengths were found by means of bond tests.
The maximum bond strength is obtained at an anchoring length of the CFK laminate of 300 mm. Longer anchoring lengths do not contribute to a further increase in bond strength.

The maximum bond strength of a surface applied CFK laminate of width 80 mm is approx. 35-40 kN.

The traditional calculation model for the adhesive bonding of FRP reinforcement to concrete is based on a non-linear brittle fracture mechanics and can be used for any elastic laminate material. The applicability of the traditional models was established by means of bond tests carried out to obtain the General German Approval for S&P Laminates CFK. The bond strengths are transmitted into the substrate between two flexural or shear cracks. Verification of the anchoring of the theoretical laminate end (Point E) is established if the progression of the bending moment curve is positive. The residual tensile strength of the laminate at Point E corresponds to the theoretical bond failure strength of the laminate. In the case of a negative progression of the bending moment curve (moments at support) the laminate is anchored at the point of zero moment, at the required displacement level and anchoring length.

For surface bonded FRP plates, the bond check is the most important verification. The software “FRP Lamella” will verify the anchoring. The software is based on the material parameter of the S&P Laminate CFK and the system approved Resin 220. If other components are used, the required cross section of FRP and the anchor check provided by the Software will no longer be valid. Under these circumstances the system supplier waives all liability.
- Flexural cracks in the area $M$ with high bending moments require a confinement reinforcement to enable the tensile load transfer into the concrete. The concrete thus helps reducing the bending moments.

- In the area $Q$ with varying bending moments the stresses resulting from the tensile force variation are added to the above mentioned confinement reinforcement.

- In the area $V$ of the end anchoring of the external steel strap binder the tensile strength of the laminate is connected to the concrete and transmitted into the internal reinforcement.

The software FRP Lamella provides the required anchor check.

9.3 Anchoring at the ends of the laminates

The design software automatically calculates the required anchor length. In case of anchoring the laminates in a compression zone, no mechanical aid is needed. In the case of steep moment curves, under tension zone, the anchor length of the S&P Laminate CFK as indicated by the design software is often insufficient. In this situation, two alternatives for anchoring at the laminate ends are available.

A) Strengthening of slabs

Premature debonding of the S&P laminates CFK is inhibited by means of two aluminium plates. These produce an active pressure acting against the ends of the laminates and, simultaneously, lead to a radial transfer of the forces into the reinforced concrete cross section. With the use of this type of end anchoring a higher utilisation of the S&P laminates CFK is achieved, particularly in the case of slender RC-elements.
B) Strengthening of beams

The ends of the S&P Laminate CFK are wrapped with the S&P C-Sheet 640. Thus, the forces are transferred into the web of the beam. Tests on bending beams, with and without confinement reinforcement of the laminate ends, have been carried out at the University of Lisbon.

Testing arrangement

The test results show that due to the confinement reinforcement of the beam at the ends of the laminates, the bending moment can be increased by approx. 20%.

*Note:* Confinement of the laminate end in this case serves to guarantee the required end anchoring. In addition, the FRP confinement improves the shear capacity of the cross section.

9.4 Near surface mounted S&P Laminates CFK

The S&P Laminate CFK 10/1.4 with a width of 10 mm and a thickness of 1.4 mm is specially designed to be bonded into slots in concrete or timber structures. A concrete saw is used to cut slots approx. 3 mm wide and 10-15 mm deep into the substrate. The slots are filled with the system approved epoxy adhesive, and the S&P Laminates are pressed into the adhesive.
The performance of near surface mounted laminates has been tested at the Technical University in Munich. The test results positively proved that a good and uniform bond exists between the laminate and the concrete. Furthermore, the high tensile strength of the laminate fibres was fully utilized prior to shear failure between laminate and surface.

**Bond tests:**

![Testing arrangement](image)

*Figure 13: Testing arrangement*

Tests: Comparison of slot-applied and surface-applied CFK laminates by means of bond strength tests.

![Results from the tests](image)

*Figure 14: Results from the tests*

**10. Selection of the S&P FRP system**

**10.1 Wrapping of columns**

Low modulus sheets made from glass or aramid fibres are used to increase the ductility of a structural element. As the raw material price of glass fibres is much lower than of A fibres, glass fibre products (S&P G-Sheet 90/10, Types E or AR) are normally used. Aramid sheets (S&P A-Sheet 120) are ideally applied as impact or explosion protection.

The ductility enhancement of the different FRP systems has been verified in push-pull tests. Two FRP wrapped columns were compared to a reference column:

- S&P C-Sheet 240 (E-modulus 240'000 MPa) ⇒ 1.0 kg in the hoop direction
- S&P G-Sheet 90/10 (E-modulus 65'000 MPa) ⇒ 3.6 kg in the hoop direction
As the modulus of elasticity of the G fibre is only approx. 25% of the modulus of the C fibre, the weight of the S&P G-Sheet applied in the test was raised by a factor of four (in the hoop direction).

Figure 15: Pull-Push Test

The test results clearly show the more ductile behaviour of the column wrapped with 4 kg of G fibres in the hoop direction compared to a column confined with 1 kg of C fibres. This is why structural elements in seismically endangered areas are preferably retrofitted with G fibres (see chap. 11).

Because of the high reduction factor of E-glass wraps in practice often 7 kg of E-glass-FRP is replaced by 1 kg of C-FRP.

At the Technical University of Gent (Belgium) large scale tests were carried out on circular columns of height 2.0 m and diameter 400 mm, to which different FRP systems had been applied.

FRP systems:
- S&P C-Sheet 240 (stretched fibres)
- S&P C-Sheet 640 (stretched fibres)
- Carbon/glass hybrid (undulating fibres)
- Glass sheet (undulating fibres)

The increase in axial load capacity obtained from the FRP confinement was measured. In order to achieve an identical increase in axial load capacity, the following fibre quantities were required in the confinement direction:
- S&P C-Sheet 240 (stretched fibres) 1.0 kg of C fibres
- S&P C-Sheet 640 (stretched fibres) 1.6 kg of C fibres
- Carbon/glass hybrid (undulating fibres) 2 - 3 kg of fibres
- Glass sheet (undulating fibres) ≈4.0 kg of G fibres
Wrapping with the S&P C-Sheet 240 is suited for the axial load enhancement of circular columns. With 1 kg of C 240 fibres, applied in the hoop direction, identical values were obtained as with 4 kg of G fibres.

Large scale test on a column with confinement reinforcement of 5 layers of S&P C-Sheet 240:

In the test the FRP confinement provided an increase in axial load capacity of 57%. At ultimate state the wrapped column showed an axial deformation of 11 mm/m. At service state this axial deformation is unfavourable. Thus, the C fibre wrap is used ultimate in order to provide a suitable safety factor. For confined columns a maximum strengthening factor of 1.8-2.0 is therefore realistic.

The static design for axial enhancement of columns is done using the software FRP Colonna.
10.2 Prestressing of axially loaded columns

In order to improve the compressive strength of a rectangular column without large allowable axial compressive strains, the A fibre should be prestressed. Prestressed S&P A-Strap are suited for this field of application. The external prestressing produces a defined hoop effect.

Due to prestressing, cracks in the existing column are closed and premature breaking of the fibres on the edges of the column is likewise prevented. Thus, increasing in compressive strength can be carried out at a minimal axial strain level. Prestressed S&P A-Strap are suited for the enhancement of the serviceability of circular and rectangular columns.

Due to prestressing higher reinforcing levels can be realised.

The new reinforcing concept is confirmed by preliminary test results obtained in cooperation with HTA University of Fribourg (Switzerland) and FH Stuttgart (Germany).

Axial compressive strength tested on unreinforced low cross section columns at HTA University of Fribourg (Switzerland)

Column dimensions:  Side length = 20/20 cm  
Height = 65 cm  
Rounding of edges = 2.5 cm

Figure 20: Reference column Failure at 1'353kN  
Figure 21: Wrapped column (prestressing of S&P A-Strap at 200 kN per m of column height) Failure at 1'718 kN
Interpretation of test:

The compressive strength of the reinforced square column could be increased by 27%, compared to the reference column, without producing large axial strains.

Additional research works on the new strengthening concept will be carried out in future.

10.3 Combined moment and axial load on columns

In the case of both moments and axial load applied to a circular or rectangular column, two types of reinforcing are applied. The additional axial force is absorbed by the FRP wrap (chap. 10.1/10.2). The additional moment is absorbed by a slot- or surface-applied laminate that is placed prior to the FRP confinement. The S&P Laminate CFK is dimensioned for the additional moment effect using the design software.

10.4 Replacement of corroded reinforcement using FRP

In traditional concrete repair, the corroded rebars may be replaced by FRP. Thus, the original safety factor of the constructional element is guaranteed after the repair.

<table>
<thead>
<tr>
<th>Concept:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Remove all spalled concrete.</td>
</tr>
<tr>
<td>- Coating of the cleaned rebars with S&amp;P Resicem (cementitious epoxy resin matrix).</td>
</tr>
<tr>
<td>- Conventional concrete repair using a cementitious mortar (S&amp;P Repcem).</td>
</tr>
<tr>
<td>- <strong>New:</strong> The corroded reinforcement may be replaced with FRP.</td>
</tr>
<tr>
<td>- Final coating of the element (cementitious mortar or vapour permeable coating)</td>
</tr>
</tbody>
</table>
Replacement of corroded vertical rebars with S&P Laminates CFK bonded into slots.

*Note:* With the slot-applied CFK laminate higher forces can be transmitted into the substrate (see chap. 9.5). Thus, the S&P Laminate CFK can be utilised to a higher degree (see chap. 10.6.3). For design purposes a tensile strength of 2'000 MPa is assumed for the slot-applied laminate. This means that approx. 25% of the surface of the corroded internal steel (yield: 500 MPa) are replaced by the slot-applied CFK laminates. The corroded stirrups are replaced by confinement with S&P C-Sheets 240.

*Note:* The S&P C-Sheet 240 is applied to replace the corroded stirrup reinforcement. The maximum spacing between the C-Sheet shall not exceed the internal lever arm of the column (analogy to strut & tie model).
10.5 Seismic upgrading of columns

For the seismic upgrading of columns different FRP systems are used. While in the western part of the United States E-glass wraps (S&P G-Sheet 90/10, Type E) are commonly used, in the seismically endangered zones of East and Middle Europe the alkali-resistant AR-glass (S&P G-Sheet 90/10, Type AR) in combination with the water vapour permeable "Resicem" matrix is usually applied. Aramid fibres (S&P A-Sheet 120) are only used in exceptions because of their high price.

At the Technical University in Porto (Portugal) an investigation into the seismic resistance of carbon fibre based FRP systems was conducted in a series of push-pull tests. To this end, square columns with a side length of 200 mm were reinforced with FRP. S&P Laminates CFK were bonded into slots to improve the longitudinal flexural strength. Partial wrapping was done with the S&P C-Sheet 240. The tests indicated that the maximum displacement angle of 22 mm/m (maximum loading of the testing device) was reached.

![Figure 26: Tests at the Technical University in Porto (Portugal)](image)

The results show that the combined application (into slots and as wrapping) of the high modulus C fibre likewise produces a high reinforcing effect under seismic exposure. *(Note: see chap. 11)*

10.6 Flexural strengthening with non-prestressed C-FRP systems

In addition to the prestressed systems, three non-prestressed FRP systems are available for flexural strengthening:

- Surface bonded S&P Laminates CFK
- S&P C-Sheet 240 (uni-directional C fibre sheet)
- Slot-applied S&P Laminates CFK
10.6.1 Surface bonded S&P Laminates CFK

During tests conducted for the General Approval of the S&P Laminate CFK in France, Germany, UK, Korea etc. the bond of the laminate on beams was investigated. Flexural tests on beams conducted at TU in Braunschweig (Germany) showed that debonding of the laminate from the substrate depends on the strain in the laminate and the plastic strain in the internal rebars. Debonding of the rebars initiated at an elongation of the laminate of approx. 0.65%; this corresponds to 5.7 times the limiting strain of the internal reinforcement. Failure of the beam occurred at an elongation of the laminate of 1.3%.

Flexural bending tests on slender slabs showed that premature debonding (partly at a limiting strain of 0.6-0.7%) of the CFK laminate is possible. For this reason, a limiting design strain for CFK laminates of \( \varepsilon = 0.6-0.8\% \) has been defined in internationally recognised Guidelines as well as in the General Approvals for France, Germany etc.

| Limiting design strain of non-prestressed CFK laminates: |
| 0.6 – 0.8% (for flexural strengthening) |

The special end anchorage system inhibits debonding of the S&P laminates CFK. Thus, a higher degree of utilisation of the S&P laminates CFK is achieved.

In the ultimate state, the elongation limit for the static design of end anchored, slackly applied CFK laminates is 0.8 - 1.0% (under flexural stress).

The design software is available for different national code systems (ACI, BS, French Standard, Eurocode 2, DIN 1045 old and new). In the Eurocode 2 version the limiting design strain values for the S&P Laminate CFK as prescribed in the General German Approval are used.

10.6.2 S&P C-Sheet 240

In cases of substrates with a low surface bond strength (<1.5 MPa) or with minimal laminate requirements, it is possible to replace the S&P Laminate 200/2000 by the S&P C-Sheet 240. With the use of the S&P C-Sheet 240 for flexural strengthening the surface for the load transfer into the substrate is raised by a factor of 5 to 10. This allows the product to be applied to surfaces with a bond strength of 1.0 MPa.

As S&P C sheets 240 under flexural stress offer a larger area for the transfer of forces than S&P laminates CFK, higher limits of elongation can be used for the dimensioning.

In the ultimate state, the elongation limit for dimensioning of the S&P C sheet 240 is 0.8 – 1.0 % (under flexural stress).

Dimensioning of the S&P C-Sheet 240 for flexural reinforcement is carried out using the new design software “FRP Lamella”.
10.6.3 Near surface mounted S&P Laminates CFK

Three point load tests with a span of 2.5 m were carried out on various reinforced concrete beams.

Figure 27: Test arrangement

Each sample was either reinforced by a surface-applied CFK laminate 50/1.2 or by two near surface mounted CFK Laminates 25/1.2.

- On test beams A1 and B1 failure occurred due to debonding of the CFK laminate.
- On test beam A2 failure occurred due to tensile fracture of the slot-applied laminate.
- On test beam B2, with a low shear reinforcement made of steel, shear failure occurred in the concrete.

Interpretation of results from test beams A

At equal stiffnesses, the ultimate load was more than doubled using the slot-applied laminate. This is due to the high utilization of the tensile strength of the CFK laminate.

Figure 28: The load-deflection curves of test beams A1 and A2

Interpretation of results from test beams B

The load-deflection curves are almost identical except that the slot-applied CFK laminate exhibited a substantially higher ultimate load.

Figure 29: The load-deflection curves of test beams B1 and B2
Benefits of near surface mounted laminates

- The improved utilization of the laminate permits higher loads to be applied and laminate cross sections to be reduced.
- The quality of the substrate (tensile strength of the surface) is less important. Near surface mounted laminates can also transfer loads into substrates with a low bearing capacity (brickwork, masonry).
- The near surface mounted laminate is more economical than levelling and roughening required for surface-applied laminates.
- The near surface mounted laminate is protected against mechanical damage. Better performance is achieved in the event of a fire, thus reducing the cost of fire protection measures.

An ideal field of application of near surface mounted laminate is the strengthening of the negative moment (moment at support).

In the ultimate state, the elongation limit for dimensioning of slot-applied S&P laminates CFK is 10 – 12 % (under flexural stress).

Dimensioning of slot-applied S&P laminates can likewise be conducted using the new design software “FRP Lamella”.

10.7 External shear reinforcement

Flexural strengthening with S&P Laminates CFK often requires an increase in shear strength. This can be achieved by bonding of S&P C-Sheets 640 around the web of the beam.

The shear force $V_{Sdf}$ in the strengthened condition is shared between the internal steel stirrups and the bonded S&P C-Sheet 640.
The design software distinguishes two cases:

**Case 1:** \( V_{Sdf} > V_{Rd3} \) internal resistance

The internal shear reinforcing **is not sufficient** to absorb the shear force in the strengthened condition \( V_{Sdf} \)

\[ \Delta V = V_{Sdf} - V_{Rd3} \]

\( \Delta V \): Differential shear force (portion of the shear force \( V_{Sdf} \) that is absorbed by the additional FRP shear reinforcing)

or

\[ \Delta V = \frac{(\eta - 1)}{\eta} V_{Sdf} \]

\( \eta \): flexural reinforcing level

In this case, the S&P C-Sheet 640 is designed to fulfil the requirements of the associated strut & tie model and must be anchored in the compression zone.

**Case 2:** The internal shear reinforcement **is sufficient** to absorb the transverse force in the reinforced condition \( V_{Sdf} \).

\[ V_{Sdf} \leq V_{Rd3} \]

\[ \Delta V = \frac{(\eta - 1)}{\eta} V_{Sdf} \]

In this case, the S&P C-Sheet 640 is statically not necessary and a minimum strengthening is dimensioned depending on the flexural reinforcing level. Design is done using the „FRP Lamella“ software.
10.8  Flexural strengthening with prestressed S&P Laminates CFK

S&P has developed a prestressing system for S&P Laminates CFK and has applied for a patent covering the process. The system is exclusively used by a world-wide network of specialized applicators.

During a test series carried out at the University of Fribourg (Switzerland) the behaviour of a concrete slab reinforced with untensioned and prestressed S&P Laminates CFK was investigated. The following is a summary of the ultimate tests performed on the Laminate Type 80/1.2. For a detailed report please contact S&P or the system applicator.
10.8.1 Testing Arrangement

<table>
<thead>
<tr>
<th></th>
<th>Steel longitudinal</th>
<th>FRP</th>
<th>Prestressing stress (N/mm²)</th>
<th>Prestressing force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference LC1</td>
<td>6 Ø 12 (Ø8 s=150)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LC5</td>
<td>6 Ø 12 (Ø8 s=150)</td>
<td>2 S&amp;P Laminate</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LC2</td>
<td>6 Ø 12 (Ø8 s=150)</td>
<td>CFK 150/2000, Type 80/1.2</td>
<td>4.0</td>
<td>640 2x61 = 122</td>
</tr>
<tr>
<td>LC4</td>
<td>6 Ø 12 (Ø8 s=150)</td>
<td>CFK 150/2000, Type 80/1.2</td>
<td>6.0</td>
<td>960 2x92 = 184</td>
</tr>
</tbody>
</table>

10.8.2 Testing results

At service state the test specimens reinforced with prestressed S&P Laminates CKF exhibited a high reduction in the deflection and the crack widths. Due to the predominant prestressing force the concrete cross sections remained in the uncracked condition up to and above the maximum working loads. The ultimate state showed a high increase in the ultimate load, at substantially higher deflection levels compared to LC5 specimens. Samples with untensioned CFK laminates showed an increase in the ultimate state of 32%, while prestressed CFK laminates raised the ultimate state by 82% at a prestress of 4% and by 93% at a prestress of 6%.

Research by University of Fribourg, Switzerland
Table: Failure load / Failure moment

<table>
<thead>
<tr>
<th>S&amp;P Laminate CFK</th>
<th>Concrete slabs</th>
<th>Failure load (kN)</th>
<th>Failure moment (kNm)</th>
<th>Failure moment (% increase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>LC1 Reference</td>
<td>16.4</td>
<td>82.6</td>
<td>100</td>
</tr>
<tr>
<td>2 x 80/1.2</td>
<td>LC5 FRP</td>
<td>24.0</td>
<td>109.4</td>
<td>132</td>
</tr>
<tr>
<td>2 x 80/1.2</td>
<td>LP2 FRP 4‰</td>
<td>35.3</td>
<td>150.1</td>
<td>182</td>
</tr>
<tr>
<td>2 x 80/1.2</td>
<td>LP4 FRP 6‰</td>
<td>37.9</td>
<td>159.4</td>
<td>193</td>
</tr>
</tbody>
</table>

10.8.3 Conclusions

Prestressing of S&P Laminates CFK has a very positive influence on the behaviour of a strengthened RC structure. Deflection and crack formation under working load are reduced. The ultimate moment is substantially increased.

With the lightweight S&P prestressing kits it is possible to prestress the S&P Laminates CFK to an elongation of 6‰. The system has been specially developed for the strengthening of large-span RC-slabs.

There exists a high potential for applications in bridge construction:
- Post-reinforcement of overloaded elements
- External prestressing of bridges with corroded internal prestressing cables
- Repairs to connection joints

In the ultimate state, the elongation limit for dimensioning of prestressed S&P Laminates CFK is 1.2 – 1.3 ‰.
10.9 Special applications using FRP systems

10.9.1 Repairs to historic buildings

Application to low quality substrates

Studies of moisture condition in a historic structure, during Building Physics surveys, must be carried out by an experienced engineer. The selection of G or C fibre systems depends on the quality of the substrate.

Application to steel

Figure 34: Repairs to a vault

Figure 35: FRP strengthening of a truss

Figure 36: Tower Bridge in London
Some of the iron castings of the Tower Bridge in London exhibited corrosion and cracking and thus required retrofitting. As cast iron cannot be welded, strengthening was carried out with the S&P C-Sheet 240.

10.9.2 Applications in timber construction

The special S&P Laminate 10/1.4 is applied into saw notches in the load relieved timber beam.

Figure 37: Example of an application in timber construction

The fundamental principles for the mechanics of FRP retrofitting of timber structures have been elaborated in two dissertations at Technical Universities in Germany and in a thesis at BOKU in Vienna. Design rules have been established in a research carried out at ETH in Zurich.
10.9.3 Fire protection measures for FRP strengthened elements

When strengthening with laminates made of steel of CFK, one must consider that the heat resistance of epoxy based adhesives is limited to temperatures between 60° and 80°C (140° and 180°F). In the event of fire, this leads to a premature failure of the laminate. Therefore, precautions must be taken to protect S&P Laminates CFK against premature failure.

In the event of failure of the CFK laminate, the residual safety factor $\gamma$ determines the necessary measures required for fire protection. The S&P design Software automatically outputs the residual safety factor in the case of failure of the S&P Laminate CFK.

### Residual safety in the event of laminate failure

<table>
<thead>
<tr>
<th>$\gamma &gt; 1.0$</th>
<th>$S &lt; 1.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire resistance ensured by internal reinforcement</td>
<td></td>
</tr>
<tr>
<td>Conventional fire protection for internal reinforcement only</td>
<td></td>
</tr>
</tbody>
</table>

**Example: Fire protection plates**

Concrete ceiling

<table>
<thead>
<tr>
<th>Fire resistance</th>
<th>A = 100 mm (D)</th>
<th>A = 200 mm (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 30</td>
<td>2 x 20 mm</td>
<td>2 x 20 mm</td>
</tr>
<tr>
<td>F 60</td>
<td>2 x 40 mm</td>
<td>2 x 30 mm</td>
</tr>
<tr>
<td>F 90</td>
<td>&gt; 110 mm</td>
<td>2 x 40 mm</td>
</tr>
<tr>
<td>F 120</td>
<td>&gt; 110 mm</td>
<td>&gt; 110 mm</td>
</tr>
</tbody>
</table>

Please contact the S&P Technical Service for detailed documentation.
11. Seismic retrofitting of reinforced concrete columns and frames using FRP

11.1 Reinforced concrete columns

11.1.1 Strengthening methods for reinforced concrete columns

The earthquake resistance of many of the older RC columns is too low: Their flexural strength and ductility are not sufficient. On the one hand, these shortcomings are due to the fact that the lap splice lengths of the internal rebars are too short and, on the other, that the anchoring length of the internal rebars of adjacent structural elements is too short. Typical overlapping in the compression zone, with a length of 20 times the cross section of the rebars, is not sufficient to transmit all the post-elastic forces from the reinforcing rebars. Under seismic action insufficiently anchored rebars show an unacceptable behaviour. When exposed to cyclical bending moments and potential additional tensile loads, these structures are subject to premature failure. This becomes especially critical in the case of foundation connections: If the projecting reinforcement exhibits too little overlapping, under seismic action it may form an undesirable plastic hinge. Unfortunately, this type of deficient construction detail is frequently found in older buildings and bridges. Often, also the transverse strength of RC structures is insufficient.

A solution to enhance these deficiencies of supporting elements is the confinement. The earthquake resistance of a column with confinement reinforcement on its connections is improved due to the radial stresses. For the confinement (wrapping) of existing structures various methods are available. Three different strengthening methods were compared in large-scale tests:

- Steel jackets
- Concrete casing
- FRP confinement

The traditional methods with steel and concrete are well known and will therefore not be discussed.

11.1.2 Reinforced concrete columns retrofitted with FRP jackets

During the last years the performance of reinforced concrete columns retrofitted with FRP jackets has been verified in several scientific studies. Design concepts for the dimensioning of FRP confinements are available (e.g. M.J.N. Priestley, F. Seible, G.M. Calvi, "Seismic design and retrofit of bridges").

The confinement of columns with a rectangular cross section is more difficult than that of a column with a circular cross section. The radial stresses are concentrated at the corners. In order to achieve a defined confinement force (radial confinement), S&P has developed a prestressing system. Prestressing produces a defined three-dimensional stress level. In the case of non-prestressed FRP jackets, the three-dimensional stress level is only achieved when transverse strain of the concrete occurs. Prestressing increases the reinforcing efficiency of the FRP reinforcement. With this new method sufficient radial stress can thus be provided in the case of columns with a rectangular cross section.
Unlike steel jackets, FRP reinforced columns do not show any reduction in performance. Additional tests showed that with FRP confinements potential shear failure can be avoided very effectively. Uni-directional confinement (horizontal) of columns with FRP jackets does not affect the vertical stiffness of the element, an essential part of seismic strengthening. Dimensioning of the FRP confinement is basically identical to the dimensioning adopted for steel stirrups. The limiting design strain of FRP is assumed as approx. 50% of the breaking elongation of the fibre. The high safety factor guarantees that the shearing mechanism of the reinforced concrete column is not reduced by excessive concrete strains.

The FRP confinement acts in two ways:
• Under tensile loading the effect of the FRP confinement on the plastic hinge region of the column is that the overlapping of the reinforcement, or of the anchoring of the longitudinal reinforcement respectively, is strengthened, and the post-elastic behaviour of the reinforcing bars can thus be fully utilised.
• Under compressive loading of the plastic hinge region the confinement prevents buckling of the longitudinal reinforcement as well as spalling of the concrete cover.

11.1.3 Confinement to improve flexural ductility

The primary aim of the confinement is the enhancement of the flexural ductility. Columns with insufficient internal stirrup reinforcement cannot sustain large non-elastic rotations in the plastic hinge region. FRP confinements are suited to increase the flexural ductility of such supporting elements. Tests on circular columns retrofitted with FRP clearly indicated that they are able to increase the ductility more effectively than conventional steel jackets. The reason for this is the linear-elastic behaviour of the FRP confinement. Seismic response can cause steel jackets to undergo tangential deformation. On unloading residual plastic strains remain in the jackets. The effectiveness of the steel jacket is therefore reduced for each successive seismic response, and for each new load cycle higher hoop strains are required. Due to the linear-elastic behaviour of FRP there is no cumulative damage. Successive cycles cause similar hoop strains. This improved behaviour compared to steel jackets is taken into account in the dimensioning concepts for FRP confinement that have been deduced from testing programmes.

Circular columns

The maximum concrete compressive strain $\varepsilon_{cu}$ of the column can be calculated as follows:

$$\varepsilon_{cu} = 0.004 + \frac{2.5\rho_s f_{FRP} \varepsilon_{FRP}}{f_{cc}}$$

[M.J.N. Priestley, F. Seible, G.M. Calvi]

The ratio of volumes of the confinement $\rho_s$ of a circular column is defined as follows:

$$\rho_s = \frac{4t_{FRP}}{D}$$
\( f_{\text{FRP}} \) and \( \varepsilon_{\text{FRP}} \) are the maximum stress and strain in the FRP confinement.

The concrete compressive strength \( f'_{cc} \) of a confined reinforced concrete column is defined as follows:

\[
f'_{cc} = f'_c \left[ 2.254 \sqrt{1 + \frac{7.94f'_l}{f'_c}} - \frac{2f'_l}{f'_c} - 1.254 \right]
\]

[M.J.N. Priestley, F. Seible, G.M. Calvi]

In the formula \( f'_c \) represents the characteristic concrete compressive strength and \( f'_l \) the effective lateral confinement stress (stress of the theoretical fibre cross section).

From the expressions for \( \varepsilon_{cu} \) and \( \rho_s \), the required confinement strength \( t_{\text{FRP}} \) (theoretical fibre thickness of the FRP confinement) can be deducted:

\[
t_{\text{FRP}} = \frac{0.1(\varepsilon_{cu} - 0.004)Df'_c}{f_{\text{FRP}}\varepsilon_{\text{FRP}}}
\]

Rectangular columns

Push-pull tests on rectangular columns retrofitted with GFRP likewise indicated an increase in ductility. Figure 41 shows a rectangular column retrofitted with GFRP after failure. In the test a displacement ductility (failure) of \( \mu_\Delta = 8 \) was reached. This corresponds to a displacement angle of approx. 4%.

Displacement ductility factor \( \mu_\Delta = \frac{\text{displacement at ultimate}}{\text{displacement at firstyield}} \)

---

![Image](image-url)
In several test series it could be shown that with rectangular cross sections compared to circular columns with an identical cross section an increase in ductility of approx. 50% is obtained.

The maximum concrete compressive strain $\varepsilon_{cu}$ of the rectangular column is calculated as follows:

$$\varepsilon_{cu} = 0.004 + \frac{1.25 \rho_s f_{FRP} \varepsilon_{FRP}}{f_{cc}}$$

[M.J.N. Priestley, F. Seible, G.M. Calvi]

The ratio of volumes of the confinement $\rho_s$ of a rectangular column is defined as follows:

$$\rho_s = 2t_{FRP} \left[ \frac{b + h}{bh} \right]$$

In the formula $b$ and $h$ represent the dimensions of the cross section.

From the expressions for $\varepsilon_{cu}$ and $\rho_s$, the theoretical required FRP confinement thickness can likewise be deducted:

$$t_{FRP} = \frac{0.4(\varepsilon_{cu} - 0.004)f_{cc}}{f_{FRP} \varepsilon_{FRP}} \left[ \frac{bh}{b + h} \right]$$

**Confinement area**

In Table 1 the required confinement areas (l) are indicated. Distinction is made between one-sided or double-sided restraint of the columns. $L_a$ and $L_b$ represent the distances from the support to the centre of moments.

<table>
<thead>
<tr>
<th>Restraint of the column</th>
<th>Cross section of the column</th>
<th>Column length</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-sided</td>
<td>D</td>
<td>L</td>
<td>$D \leq l \leq 0.25 L$</td>
</tr>
<tr>
<td>Double-sided: $M_a$</td>
<td>D</td>
<td>$L_a$</td>
<td>$D \leq l \leq 0.25 L_a$</td>
</tr>
<tr>
<td></td>
<td>$M_b$</td>
<td>$L_b$</td>
<td>$D \leq l \leq 0.25 L_b$</td>
</tr>
</tbody>
</table>

Table 1: Confinement area

### 11.1.4 Confinement to improve the lap splices of the internal reinforcement

The load transfer from the steel reinforcement into the concrete leads to the formation of micro-cracks in the concrete that will reduce the bond between steel and concrete. Retrofitting with FRP jackets, and with prestressed FRP systems in particular, enhances this bond.
Dimensioning is carried out as follows:

\[
\rho_s = 2 \left[ \frac{A_b f_s / \mu p l_s - f_s}{0.0015 E_{\text{FRP}}} \right]
\]

- \( f_a \): active hoop stress
- \( A_b \): surface of the longitudinal reinforcement
- \( f_s \): stress in the longitudinal reinforcement
- \( \mu \): coefficient of friction (1.4)
- \( p \): area of influence of the fractured surface in the lap splice region
- \( l_s \): length of the lap splice

The prestressed S&P A-Strap is specially suited for this field of application. Sheets with a low modulus of elasticity, such as sheets made of G fibres, are less suited for these applications.

**Confinement area**

If strengthening of the lap splices is the only reason for the FRP confinement, a wrap above the lap splice is of no use. It only becomes necessary if the lap splice is not located in a plastic hinge region.

**11.1.5 Confinement for external shear strengthening**

FRP confinements, similarly to steel jackets, are very efficient in improving the shear resistance of a building component. Since FRP exhibits a linear-elastic behaviour until failure, the design value adopted for external steel reinforcement has to be slightly modified. A limiting design strain of the FRP of 0.2-0.3% has to be used. For this type of application the S&P C-Sheet 640 with a breaking elongation of 0.4% is ideally suited.

Post-reinforcement of the shear resistance can be calculated as follows:

**Circular columns**

\[
V_{\text{FRP}} = \frac{\pi}{2} t_{\text{FRP}} f_{\text{FRP}} D \cot \theta
\]

\[ [\text{M.J.N. Priestley, F. Seible, G.M. Calvi}] \]

- \( D \): cross section of the column
- \( \theta : 35^\circ \)

**Rectangular columns**

\[
V_{\text{FRP}} = 2 t_{\text{FRP}} f_{\text{FRP}} h \cot \theta
\]

- \( h \): column dimension in parallel to the shear stress
- \( \theta : 35^\circ \)
Confinement area

In the case of reduced shear resistance, the FRP confinement should be applied to the plastic hinge regions at a height of 2D for circular columns, or 2h for rectangular columns respectively.

11.1.6 Flexural strength of the column

As a result of the confinement of a column, its flexural stiffness is increased and it is thus subject to higher forces. This is a critical issue and needs careful attention. The increase in flexural strength depends on the elected strengthening method, the material parameters and the shape of the columns.

Table 2 shows the increase in flexural strength of a column as a function of the elected strengthening method.

<table>
<thead>
<tr>
<th>Column</th>
<th>Reinforcing</th>
<th>Steel</th>
<th>Concrete</th>
<th>FRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>Plastic hinge</td>
<td>10 - 20</td>
<td>20 - 50</td>
<td>0 - 5</td>
</tr>
<tr>
<td></td>
<td>Shear</td>
<td>20 - 40</td>
<td>25 - 75</td>
<td>0 - 5</td>
</tr>
<tr>
<td>Rectangular</td>
<td>Plastic hinge</td>
<td>20 - 40</td>
<td>20 - 50</td>
<td>0 – 10</td>
</tr>
<tr>
<td></td>
<td>Shear</td>
<td>40 - 70</td>
<td>25 - 75</td>
<td>0 – 5</td>
</tr>
</tbody>
</table>

*Table 2: Increase in flexural strength (%)*

FRP retrofitting causes a substantially lower increase in flexural strength compared to the application of steel jackets or concrete casing.

11.1.7 Comparison of strengthening methods

A comparison of the different strengthening methods is given in Table 3. The results demonstrate the favourable behaviour of FRP confinements compared to conventional procedures. The main benefit of the FRP confinement is the minimal increase in flexural strength, despite its high capacity in improving ductility. As a result, the FRP retrofitted structural element is not subject to additional forces, and premature failure of the framework is thus prevented.

A defined three-dimensional stress condition is obtained using the prestressed S&P A-Strap. Prestressing provides an increase in concrete compressive strength, without producing large axial compressive strains in the load bearing element. Due to the increased compressive strength higher loads can be transmitted.

The application of FRP confinements is fast and easy. Down times are therefore substantially reduced. Furthermore, FRP jackets are thin and require less adaptation of adjacent building components.
Table 3: Comparison of reinforcing methods

<table>
<thead>
<tr>
<th>Strengthening method</th>
<th>Increase in weight</th>
<th>Dimension reduction</th>
<th>Radial stresses</th>
<th>Increase in flexural strength</th>
<th>Application</th>
<th>Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel jackets</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Concrete casing</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>--</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>FRP confinement</td>
<td>+</td>
<td>+</td>
<td>++*</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

* Prestressing without problems

### 11.2 Reinforced concrete frames

For a correct design of seismically endangered structures the structural engineer must be aware of the typical types of damage caused by earthquakes. The most frequent failure modes of reinforced concrete frames are described below.

**"Short Column"**

Shear cracking in the concrete occurring at an early stage can be caused by an insufficient transverse load bearing capacity in the beam/column connections, or the beam/slab connections respectively. This crack formation causes the internal stirrup reinforcement to open and thus leads to failure of the element. The application of FRP jackets to improve the transverse load bearing capacity on the potential plastic hinge regions of the column can prevent this failure mode. Since in addition the overall ductility of the structure must be taken into account, the woven S&P G-Sheet 90/10 or the prestressed S&P A-Strap are specially suited for this type of application. FRP confinement with high modulus C fibres is less suited for this application as the requirements regarding the overall ductility of the structure would be fulfilled to a lesser degree.
Weak junction points

Junction points that are too weak or those with insufficient load capacity due to reduced cross sections cause further failure modes. Insufficient lap splice lengths of the longitudinal reinforcement at the ends of the columns lead to an additional frequent failure mode. Strengthening can be achieved by CFK laminates applied into longitudinal slots or to the surface, with additional wrapping of S&P G-Sheet 90/10 or the prestressed S&P A-Strap over the junction points.

Figure 40: Weak junction point

Plastic hinge regions

Due to insufficient shear reinforcement bending beams can exhibit failure in the plastic hinge regions, as shown in Figure 44. Retrofitting is carried out using the high modulus S&P C-Sheet 640 as confinement reinforcement.

A further failure mode is the insufficient flexural strength of the beam at mid-span, or near the supports respectively. In this case S&P Laminates CFK are applied into slots or to the surface.

Figure 41: Shear failure in a plastic hinge region

Methodology of retrofitting with FRP

In numerous research studies it has been verified that retrofitting of reinforced concrete in the plastic hinge regions provides enhanced load capacity and thus improves the ductility of the reinforced concrete frame. The effectiveness of the S&P G-Sheet or S&P A-Sheet in enhancing the ductility has been verified in push-pull tests. The tests further show that GFRP or AFRP provides a higher increase in ductility than a C fibre jacket. This is due to the higher ultimate strain of the glass fibre. Ideally suited for seismic retrofitting of columns are systems that cause either an increase in hoop stresses on the plastic hinge regions or over the entire length of the column.
Figure 42: Retrofitting of a reinforced concrete frame

Large-scale tests indicate that G- or AFRP confinements provide better technical benefits and are more economical than steel jackets. In the case of FRP confinement of the entire column or on its ends, concrete failure occurs at larger strains. The reduction of transverse strains provided by the FRP confinement also serves as reinforcement against buckling of the longitudinal reinforcement.

Prior to the confinement with FRP, structural repair of cracks in the substrate should be carried out using epoxy resin injection.

12. Explosion and impact protection using S&P FRP systems

12.1 Explosion protection

Damage to structures incurred during wars or caused by explosions is frequent. Explosion protection is also a requirement of the chemical industry. While explosions in industrial buildings can be estimated and the necessary protection thus be designed, estimating the effects of a bomb is impossible. Traditional industrial buildings are often insufficiently reinforced. Masonry structures with little reinforcement are likewise seen in practice. Such structures offer only a minimal resistance to explosion hazards. Conventional strengthening methods using steel are costly and their application is time-consuming. FRP provides a time saving and economical solution.
The S&P G-Sheet 50/50 has been specifically developed for this field of application. The sheet with a 50% glass content in the longitudinal and the transverse direction can be applied in several layers. S&P offers also prefabricated GFK laminates for the same purpose. The prefabricated S&P GFK laminates have been tested and approved as protective structural elements by NATO. The GFK laminates are structurally glued on to the existing building component using the S&P Resin 220 (Epoxy Resin).

Bi-directionally applied aramid fibres (S&P A-Sheet 120) are likewise suited as explosion protective measure. Due to the favourable mechanical properties of the aramid fibres, and especially their excellent behaviour across the fibre direction, they are ideally suited for this field of application. The high fibre price is often a hindrance to the application of this fibre type. However, AFRP is able to increase the explosion resistance of masonry by a factor of 5 to 10. The related test reports are available from the A fibre manufacturers.

12.2 Impact protection

The design of columns of for example highway bridges, in practice is often insufficient to sustain the impact of vehicles. The column may not be able to absorb the horizontal loads created by the impact of a truck which could lead to a bridge collapse. Conventional strengthening methods, such as concrete casing, are unsuitable because of lacking space and for aesthetical reasons. Furthermore, concrete casing requires long traffic down times. An alternative strengthening method is provided by AFRP confinements. The performance of AFRP retrofitted circular columns during the impact of vehicles has been tested by the fibre manufacturers in UK. The AFRP was arranged in orthogonal directions, the weight of the sheet layers being 290 gm/m². Currently, a similar testing programme is conducted at HTA University of Fribourg (Switzerland) on columns with a square cross section. The tests simulate the impact on a bending beam.

The impact of a 30-ton truck at a speed of 75 km/h represents a static load of 1'500 kN that hits the column at approx. 0.75 to 1.5 m above the road surface, plus an additional load of 750 kN hitting the column at approx. 1 to 3 m above surface.
The test results show that the energy absorption of columns reinforced in both directions (longitudinal and transverse) is substantially higher than of unwrapped columns. C- and GFRP provided barely any increase in energy absorption. The brittle C and G fibres exhibited premature failure due to their insufficient transverse load bearing capacity. The tough aramid fibre, however, was able to yield to the high deformation of the column due to its inherent transverse load bearing capacity.

In various test series conducted in UK the behaviour of three AFRP wrapped circular columns has been investigated. The results can be summarised as follows:

<table>
<thead>
<tr>
<th>Column</th>
<th>Number of sheet layers</th>
<th>Max. load [kN]</th>
<th>Max. deflection [mm]</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0</td>
<td>233</td>
<td>34</td>
<td>Plastic forces in the internal reinforcement and subsequent compressive strain of the concrete</td>
</tr>
<tr>
<td>C3</td>
<td>2</td>
<td>580</td>
<td>50</td>
<td>Failure of the longitudinal fibres</td>
</tr>
<tr>
<td>C4</td>
<td>3</td>
<td>785</td>
<td>69</td>
<td>Failure of the longitudinal fibres</td>
</tr>
</tbody>
</table>

*Table 4: Test results obtained by DUPONT UK (manufacturer of aramid fibres)*

A graphical description of the results is shown in Figure 48.

*Figure 45: Load-deflection diagram*

In the test the longitudinal aramid fibres were utilised up to failure. Due to the confinement in the transverse direction premature buckling of the longitudinal fibres was avoided.

Conclusions:
- The flexural capacity of a column with longitudinal and hoop directional AFRP wrap can be substantially improved.
- The energy absorption is made possible by the high flexural capacity.
- Traditional design concepts can be utilised.
- Aramid fibres are suited for retrofitting against collision impacts caused by vehicles.
13. Seismic retrofitting of masonry using S&P FRP systems

Masonry is an economical construction material that is used on a world-wide basis. Due to its favourable building physical properties masonry will be widely utilised also in future. Due to varying stone and mortar properties, quality and strength of brickwork are subject to considerable fluctuation. The role of seismic upgrading of masonry in building maintenance is gaining increasing importance.

In the past various methods of masonry strengthening have been developed:
- Retrofitting using reinforced sprayed concrete and sprayed mortar layers
- External prestressing to increase the load bearing capacity
- Application of steel reinforcements (bracing of the reinforced concrete frame)

The drawbacks of the traditional methods are as follows:
- The increase in overall weight of the building will lead to a proportional increase in the relevant earthquake forces.
- As a result of bond problems in the contact region of masonry and sprayed mortar the reinforcing effect is partially reduced.
- The interior space will be reduced.
- External prestressing systems cause additional compressive loads. This will often lead to an overloading of the masonry in the lower floors of a multi-storey building.
- Reinforcing systems using steel mats and steel frames are subject to corrosion and require adequate protection.
- Stiffening with steel frames, while providing a substantial increase in resistance, is problematical from an esthetical point of view and requires extensive application logistics.

With the utilisation of FRP, all the above listed drawbacks are largely avoided. FRP repairs require less space and do not corrode.

13.1 Masonry strengthening using the S&P G-Sheet 50/50

Strengthening of masonry with glass sheets is adequate in cases where the primary requirement is the increase in ductility of a load bearing wall and where the enhancement of the bearing capacity is less important. Seismic retrofitting of load bearing walls should aim at an even distribution of the cracks over the entire wall surface. Enhancement of the ductility means that the cracks should be able to open already under minimal seismic action. The S&P G-Sheet 50/50 made of low modulus glass fibres is suited for this field of application. The thus reinforced masonry wall is not subject to additional forces.

Strengthening with the S&P G-Sheet 50/50 is carried out on one side of the masonry only (inside or outside). Due to the water vapour permeable S&P Resicem matrix the coating can be applied to the entire surface. The water vapour diffusion coefficient of S&P Resicem is \( \mu_{H2O} = 3'000 – 5'000 \).
13.2 Masonry strengthening using S&P Laminates CFK

S&P Laminates CFK are able to be bonded diagonally to an existing masonry wall and anchored in the adjacent concrete elements. Tests conducted at EMPA Switzerland indicate that the tensile strength of a slot-applied CFK laminate, width 50 mm and thickness 1.2 mm, can be anchored at a depth of 25-30 cm into an adjacent concrete element. Masonry that has been thus reinforced exhibits an elastic behaviour of up to approx. 2/3 of the maximum shear force $V_{A,max}$ (see also Figure 49). As a result of the debonding of the CFK laminate caused by the load transfer from the masonry, the deformation in the upper strain levels can be heavily increased without causing any substantial increase in the bearing capacity. The brick walls possess large deformation reserves that contribute to a high ductility. The earthquake resistance of the CFK laminate strengthened wall (sample BW6) could be raised by a factor of 4.3 compared to an unreinforced wall (reference sample BW5). As shown in Figure 49, the ductility of the wall could be raised by a factor of over 3, with a proportional increase in the bearing capacity by a factor of 1.4. The CFK laminate has been applied to one side of the wall only.

![Figure 46: Comparison of FRP reinforced masonry with reference sample](image)

![Figure 47: Load bearing wall with and without openings](image)

13.3 Load bearing wall systems

The horizontal earthquake resultant $Q_{acc}$ which is of triangular distribution, the self weight and the live loads on the floor levels, all have to be diverted through the load bearing walls (Figure 50). The earthquake resultant $Q_{acc}$ causes high shear forces in the walls of the lower floors, in combination with low vertical loads. As a result of this unfavourable relation between vertical load and shear force, the load capacity is often exceeded. The flexural resistance, by contrast, is usually sufficient. Therefore, the lower floors require a reinforcement that diverts the high shear forces through diagonals subject to tensile and compressive loads.

Detailing of the reinforcement mainly depends on the force combination of $M_z$, $N_x$ und $V_y$. The requirements for the critical load bearing walls in the lower floors differ from those in the upper floors. Figure 50 shows how the resultants are led around openings. The necessary reinforcement can be designed as a concentrated S&P Laminate CFK or a distributed S&P G-Sheet. Special attention must be paid to the anchoring of the laminates and the areas of the load bearing walls that are subject to maximum compressive loads. The example clearly shows that this method of defining stress fields is suited for universal use.
## 14. S&P FRP product overview

<table>
<thead>
<tr>
<th>Modulus of elasticity</th>
<th>Tensile strength at break</th>
<th>Modulus of elasticity</th>
<th>Tensile strength at break</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 150 GPa</td>
<td>2'500 N/mm²</td>
<td>&gt; 200 GPa</td>
<td>2'500 N/mm²</td>
</tr>
<tr>
<td>Width/thickness mm/mm</td>
<td>Tensile force at elongation of 0.6/0.8 %</td>
<td>Width/thickness mm/mm</td>
<td>Tensile force at elongation of 0.6/0.8 %</td>
</tr>
<tr>
<td>50/1.2</td>
<td>58/77 x 10⁶ N</td>
<td>50/1.4</td>
<td>84/112 x 10⁶ N</td>
</tr>
<tr>
<td>50/1.4</td>
<td>67/90 x 10⁶ N</td>
<td>80/1.4</td>
<td>134/179 x 10⁶ N</td>
</tr>
<tr>
<td>80/1.2</td>
<td>92/123 x 10⁶ N</td>
<td>80/1.4</td>
<td>134/179 x 10⁶ N</td>
</tr>
<tr>
<td>80/1.4</td>
<td>108/143 x 10⁶ N</td>
<td>100/1.4</td>
<td>168/224 x 10⁶ N</td>
</tr>
<tr>
<td>100/1.2</td>
<td>115/154 x 10⁶ N</td>
<td>100/1.4</td>
<td>168/224 x 10⁶ N</td>
</tr>
<tr>
<td>100/1.4</td>
<td>134/179 x 10⁶ N</td>
<td>120/1.4</td>
<td>201/259 x 10⁶ N</td>
</tr>
</tbody>
</table>

* special dimensions upon request
Delivery in rolls of 150 m or ready-to-use
(unroll set available upon request)

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### Levelling mortar for FRP systems:
- S&P Repcem (Mineralic based levelling mortar)
- S&P Resin 230 (Levelling mortar)

### Adhesive for S&P Laminates CFK:
- S&P Resin 220 (Epoxy Resin)

### Adhesives for S&P Sheets:
- S&P Resicem (impregnation vapour-permeable)
- S&P Resin Epoxy 55 (impregnation dry lay up)
- S&P Resin Epoxy 50 (impregnation wet lay up)

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### Upon request:
- Special adhesive for wet substrates
- Special adhesive for low temperatures
15. Literature / Product names

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- Taerwe L., Matthys S., Universität Gent: Inrijgen van Betonkolommen met vezelcomposietlaminaat.
- Allgemeine bauaufsichtliche Zulassung Deutschland-236.12-54 für S&P Lamellen CFK
- Deutsches Institut für Bautechnik: Gutachten Nr. 98/0322 Ingenieurbüro Prof.Dr.Ing.Dr.Ing.E.h.F.S. Rostasy, Braunschweig
- Bemessungsdiskette BOW Ingenieure, Braunschweig
- Procédé „Carbone CFK“, Dossier SOTEX No. Ex 1443
- T. Pauly and M.J.N. Priestley: Seismic design of reinforced concrete and masonry buildings
- M.J.N. Priestley, F. Seible and G.M. Calvi: Seismic design and retrofit of bridges
- T. Ripper, J. Scherer: "AVALIAÇÃO do DESEMPENHO de PLÁSTICOS ARMADOS com FOLHAS UNIDIRECCIONAIS de FIBRAS de CARBONO como ELEMENTO de REFORÇO de VIGAS de BETÃO ARMADO", IBRACON 41st Congress, 1999, Salvador, Bahia, Brasil.
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• Mander, J.B., Priestley, M.J.N. and Park, R. – Seismic Design of Bridge Piers - Research Report 84-2, Department of Civil Engineering, University of Canterbury, New Zealand, 442 pp,1984
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