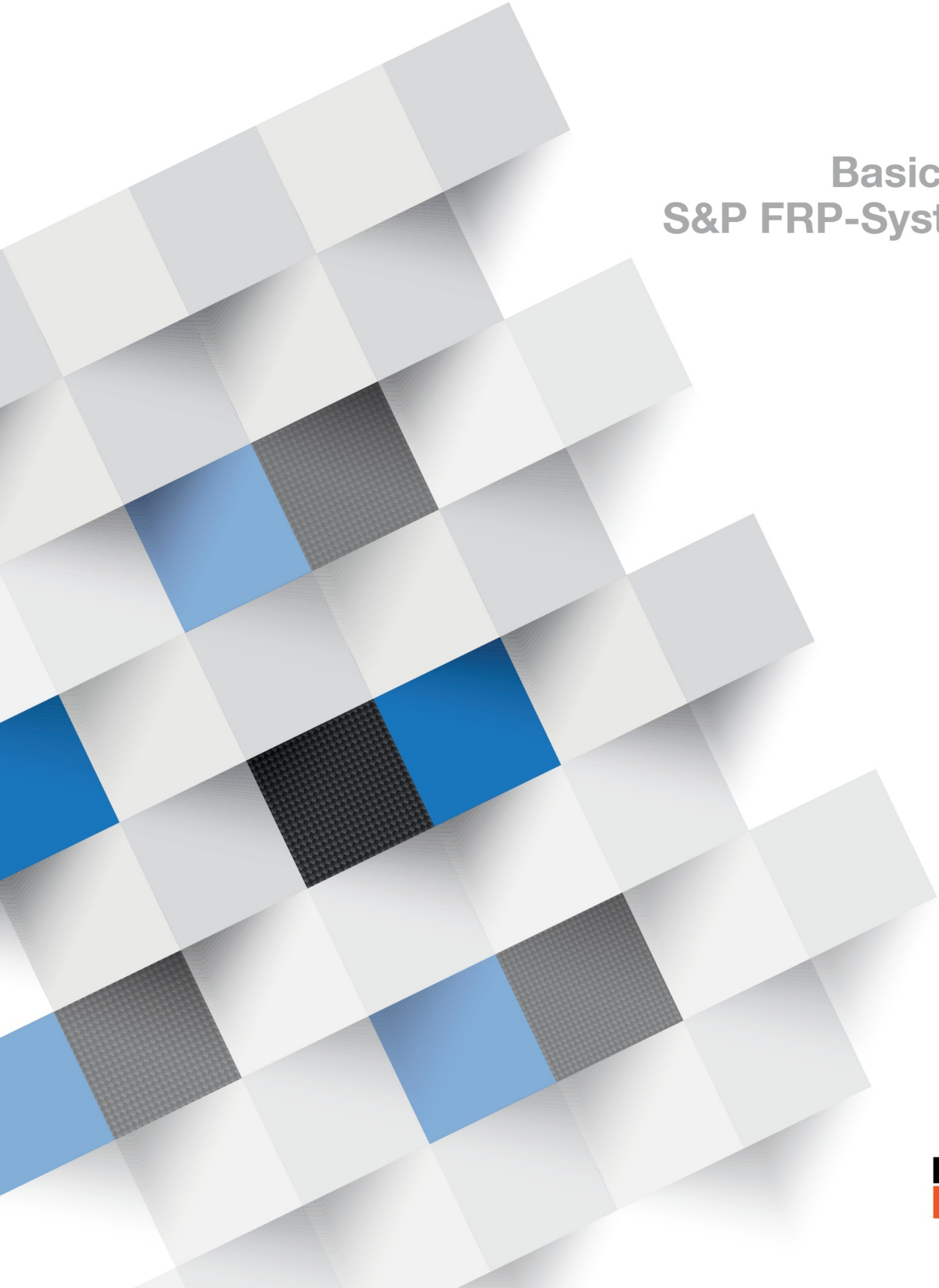
A Simpson Strong-Tie® Company

Basics for S&P FRP-Systems



Content

1. Introduction

Civil structures (steel, concrete, wood) are dimensioned for a given load and produced accordingly. However, during the service life of a structure, various circumstances may require that the service loads are changed due to:

- Modification of the structure
- Ageing 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.

It is also possible to correct calculation or application errors

For the preparation of a comprehensive rehabilitation concept a site survey needs to be performed. For static retrofitting of structures, the following options are possible:

- Modification of the existing supporting structure (new columns, beams, etc.)
- Application of additional reinforcement (slack or pre-stressed)

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

Image 1: S&P C-Laminate

Image 2: S&P A-Sheet 120

Image 3: S&P C-Sheet

Image 4: S&P G-Sheet

2. FRP Reinforcement System

Steel and fibre composites have different physical properties. Whilst steel shows an ideal elastic-plastic material, all FRP systems are linear-elastic. These properties must be taken into account for 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.

2.1 S&P C-Laminate

In the production factory, carbon fibres are impregnated with a resin matrix, thermally cured and delivered to site as a prefabricated composite (laminate). The well-known laminates, which are used in structural reinforcement, are the S&P C-Laminate products and are available in a standard modulus, SM (150/2000), and high modulus, HM (200/2000). These two different types of laminates possess different E-Modulus and elongation at fracture properties. Depending on the application, S&P offer several standard widths and thicknesses.

2.2 S&P Sheets (Stretched and woven Sheets)

2.2.1 Stretched Sheet (uni-directional arrangement)

The fibres are arranged in the longitudinal direction (uni-directional) and stretched. Due to this, the fibres can immediately withstand forces. They are suitable for increasing the bearing capacity with respect to flexural tensile and shear structure components.

During the mechanical production the reinforcement fibres are bonded to a supporting mesh and are available in rolls of various widths and weights.

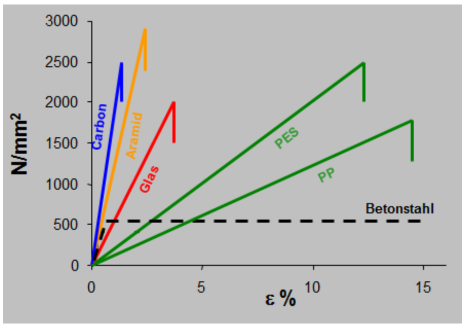
2.2.2 Woven Sheet (bi-directional arrangement)

With a woven sheet the fibres are arranged slightly wavy in both directions (bi-directional), as a result of the weaving process. Due to this, the fibres only begin to withstand forces when they are stretched to a certain elongation. Therefore, woven sheets are ideal if the ductility of a structure needs to be increased.

2.2.3 Epoxy Resin Matrix

As a matrix for transmitting forces from stretched and woven sheets cold hardening epoxy resin is required.
The application of the sheets is dependent on the surface weight either by the dry-lay-up or wet-lay-up method.
For the wet-lay-up method, S&P has developed an impregnation machine (S&P Wet-lay-up Machine) to enable an effortless pre-impregnation of thick sheets.

3. Types of fibres for S&P FRP Systems



Type of fibre	E-Modulus kN/mm²	Tensile strength N/mm²
C (Carbon)	240 – 640	2'650 – 4'500
A (Aramid)	120	2'900
G (Glass)	65 – 73	2'800 – 3'300
PES / PP	< 15	> 1'800
Steel	*205*	*550*

Image 5: Stress-strain diagram

S&P manufacture specific laminates and sheets made from various fibres. The advantages and disadvantages of the various fibres are as follows:

Carbon fibres (C) are industrially produced fibres made from carbonaceous material that comes from the carbonisation of graphite. Individual fibres (filaments) are fixed and wound onto a filament yarn. This base product is worked to produce a stretched or woven sheet. In combination with epoxy resins, carbon fibre reinforced polymers are formed (abbreviation CFRP). Carbon fibres exhibit high strength and stiffness (E-Modulus) in the axial direction. Carbon fibres are corrosion resistant and possess a low density. Carbon fibres also have a negative thermal expansion coefficient in the fibre direction and become shorter when heated.

Aramid fibres (A) are golden-yellow coloured organic synthetic fibres. The fibres are characterised by very high strength, high impact strength, high elongation at break, good vibration resistance and a high resistance to acids and alkalis. They also possess good resistance to heat and fire. The fibres, similar to carbon fibres, have a negative thermal expansion coefficient in the fibre direction. Their specific strength and its modulus of elasticity are significantly lower than those of carbon fibres. The processed fibres are practically indestructible and are often used in various fields such as aerospace, protective clothing, explosion protection etc.

Glass fibres (G) are made from long thing glass fibres. Thin filaments are pulled from melted glass and made into roving's prior to the manufacturing of sheets. Glass fibres are resistant to ageing, weather chemicals and are incombustible. Glass fibres possess isotropic mechanical properties. Glass fibres maintain a linear elasticity until fracture. The high strength of the fibres is due to the large defect-free length in the fibre form. The elongation at break of a single fibre is up to 4.5 percent. Unlike aramid or carbon fibres, glass fibres have an amorphous structure.

AR-Glass (AR = Alkali resistant): Glass fibres developed for use in concrete. These are designed to be largely resistant to alkali environments.

E-Glass (E = Electric): Suitable as a standard fibre for glass fibre reinforced polymers.

4. Technical bases

For the strengthening of engineered structures made from steel or stressed concrete with S&P C-Laminate or S&P sheets S&P design software ‘FRP Lamella’ or ‘FRP Colonna’ is available to engineers. The software programs can be used both for the design of reinforcement measures, as well as the creation of verifiable evidence in the context of structural design. Country applicable Norms are taken into account depending on where the job site is located. In Switzerland the design conforms to Eurocode 2 and SIA 166.

The design fundamentals, important material properties, calculation formulae and design examples are given in the document. The handling and input information is also described n the instruction manual for the design software.

The design models and the software ‘FRP Lamella’/ ‘FRP Colonna’ take into account the specific material properties of the strengthening fibres as well as the adhesive system from S&P. When a system component is changed, the design model created by the software is no longer valid. Under these circumstances, any liability from the system manufacturer is rejected.

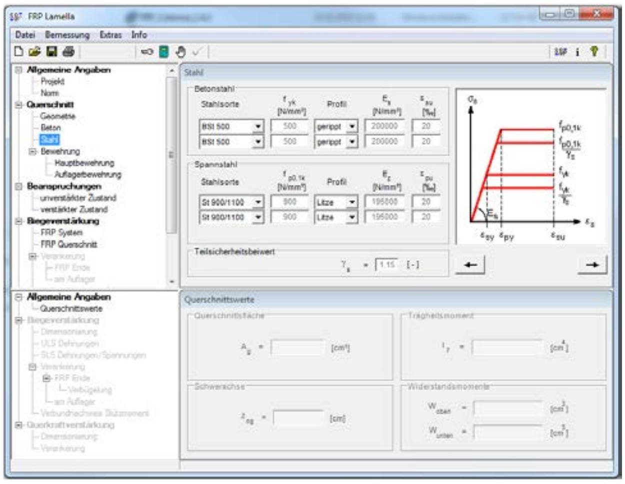


Image 6: FRP Lamella

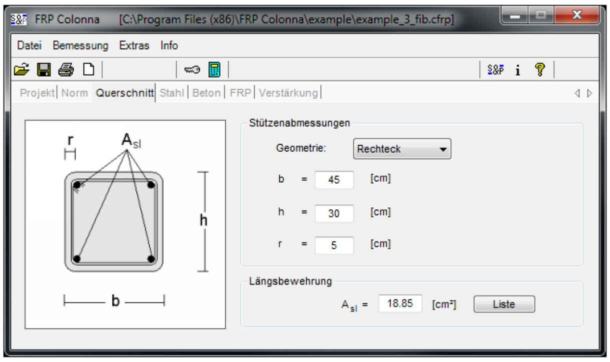


Image 7: FRP Colonna

By downloading the software, the responsible engineer / planner is obliged to use the software exclusively for S&P FRP systems. Otherwise license fees are payable to S&P Clever Reinforcement Company AG.

S&P has taken out liability insurance for engineering services. The responsible engineer /planner is responsible for the accuracy of the input data and information within the assessment.

On request, S&P offers projects for the following services:

- Preparation / specification of reinforcement concept
- Static design
- Development of contract documents
- Quality control at the construction site (bonding tests, compressive strength, evenness, humidity)

4.1 Fundamentals and rules for the design

For a design conforming to SIA 166, the following **principles** are to be observed:

- Safety factor $E_d \leq R_d$
- Failure of bonded reinforcement $E_d = E (G_k, P_k, A_d, \psi_{2i}Q_{ki}, X_d, a_d)$
- Bending tensile strain limit of the bonded reinforcement $\varepsilon_{f,lim,d} \leq 8$ ‰
- Design values of the tangible components from the longitudinal stress
- At $\varepsilon_{f,lim,d} = 2$ ‰ (compression member)
- Bond strength (non-linear to anchoring length)
- Evidence of anchoring in uncracked concrete
- Anchoring of the bending reinforcement at bearing strut-and-tie model
- Detecting the change in tensile strength over 200 mm
- Bonded reinforcement on brickwork is to be anchored in concrete
- Bonded shear reinforcement, only if no shear cracks are present in the unreinforced substrate
- FRP-Systems are tensile members
- Laminate thickness from 1 – 5 mm / Laminate width up to 200 mm

S&P recommendations and **rules** for reinforcement with S&P FRP-Systems:

- Maximum loading of the structure before reinforcement (minimum pre-stress)
- Strain limit $\varepsilon_{f,lim,d}$ *S&P C-Laminate:*
  - Surface bonded 6 - 8 ‰
  - Near surface (slot-applied) 8 bis 10 ‰
  - Pre-stressed 12 ‰ (pre-stress ≤ 6 ‰)
- Strain limit $\varepsilon_{f,lim,d}$ *S&P Sheets:*
  - Bending tensile 8 ‰
  - Supporting 4 ‰
  - Shear force 2 bis 4 ‰
- Edge spacing S&P C-Laminate = Concrete cover of stirrups
- Centre spacing S&P C-Laminate $s_{f,max}$ = 0.2 x Span width
5 x Panel thickness
0.4 x Cantilever
- Maximum of 2 overlapping S&P C-Laminate pieces
- Maximum of 5 overlapping S&P Sheets
- Maximum slot depth concrete cover of the reinforcement minus 5 mm
- Maximum slot width S&P C-Laminate plus 5 mm
- Centre spacing S&P C-Laminate (slot-applied) $s_{f,min} \geq 32$ mm (largest aggregate size in concrete)
- Or slot depth plus slot width
- Corner radius for S&P Sheet wrapping minimum 25 mm
- Distance of the S&P Sheets for shear force = maximum 0.8 x building component height
- Fire protection of $\gamma_{Me,RC} \leq 1.0$
- UV-protection for epoxy adhesive
- Protection from mechanical damage
- Application instructions from the system manufacturer regarding the substrate and the products

5. FRP Systems with S&P C-Laminate

Uni-directional laminates are manufactured either on a double belt press or via a pultrusion method. In a continuous process, the carbon fibres are soaked in epoxy resin and cured through heating. For technical reasons, the pultrusion 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.

Whilst 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 C-Laminate is based on the cross section and the parameters of the composite.

Image 8: Application of an S&P C-Laminate

S&P C-Laminate

The effective characteristics of the S&P C-Laminate can be used for the design.

The characteristics are controlled via an S&P quality control process that conforms to ISO 9001. The S&P C-Laminate characteristic values need not be mitigated by an additional reduction factor **(y = 1.0)**, in contrast to the FRP Sheet / Mesh systems.

For certain projects S&P can produce specialised laminates with a higher E-modulus or larger dimensions.

The theoretical characteristics of the S&P C-Laminate can be seen on the technical data sheet (www.sp-reinforcement.eu).

5.1 Surface applied S&P C-Laminate

The S&P C-Laminate is firmly bonded using the system approved adhesive (S&P Resin 220) and applied to the tensile zone of the section of the structure that is due to be reinforced. Thus, a reinforced concrete structure is produced with an elastic-polymer element (steel reinforcement) and a perfectly elastic tensile element (S&P C-Laminate). Models for the calculation of the flexural capacity of the composite and of the anchor lengths were found by means of bond tests.

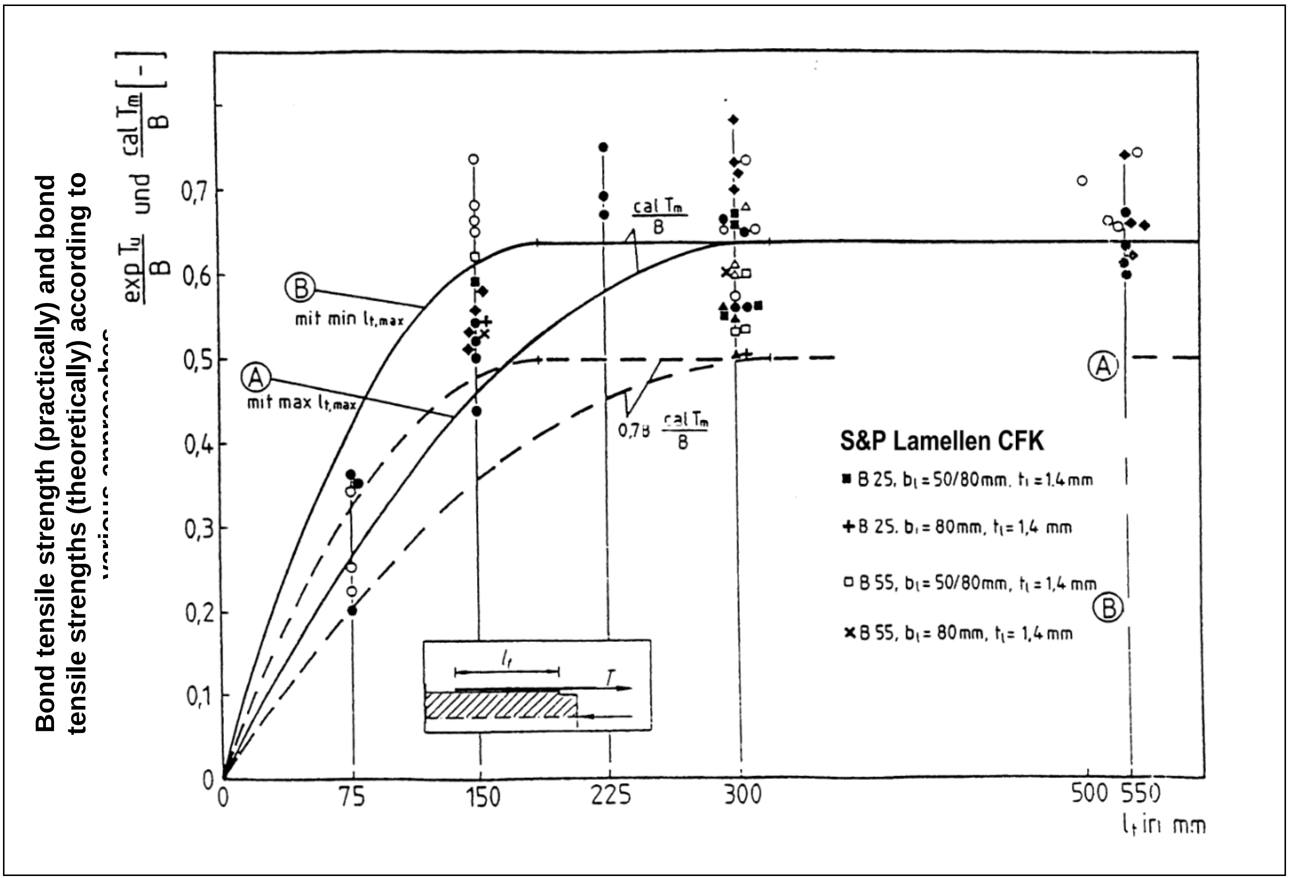


Image 9: Related bond failure forces of all bond tests on S&P C-Laminate, depending on the anchor length (TU Braunschweig, Germany)

The maximum bond strength is obtained at an anchoring length of the S&P C-Laminate of 300 mm. Longer anchoring lengths do not contribute to a further increase in bond strength.

The maximum **bond force** of a surface applied **S&P C-Laminate** of width 80 mm is approx. **35 – 40 kN** (on a non-cracked concrete substrate).

The traditional calculation model for the adhesive bonding of FRP to concrete is based on non-linear brittle fracture mechanics and can be used for any elastic laminate material.

Between two flexural or shear cracks, the bond forces are transferred respectively into the supporting substrate. With positive bending moments (field moment) the anchorage check is performed in non-cracked concrete. The remaining residual tensile force is to be anchored. With negative bending moments (support moment) the laminate is guided by the torque origin and anchored there with the offset dimension and the bond length. For surface bonded S&P C-Laminate the anchor check must be provided in any case. The S&P developed software "FRP Lamella" makes the corresponding anchorage check for S&P FRP systems.

As part of the S&P C-Laminate approval procedure in France, Germany, England, Korea, etc., laminates were also tested in combination with beam deflection.

Bending tests on slender slabs showed that premature delamination of FRP laminates without end anchorage is possible from an elongation of 6-8 ‰. For this reason the limiting design stress of FRP laminates specified, in nationally and internationally recognized standards and guidelines, is a maximum of 8 ‰.

Recommended design elongation (Elongation limit $\varepsilon_{f,lim,d}$) of surface bonded *S&P CFK-Laminate is a maximum of* 8 ‰, for thin building structures maximum of 6 ‰.

Image 10 / 11 / 12: Various types and sizes of surface applied S&P C-Laminate

5.2 End-anchoring of surface applied S&P C-Laminate

If the bending moment increases steeply near the support or if several sections of S&P C-Laminate have to be glued on top of each other, it is often not possible to provide the anchorage proof. Under these circumstances additional end anchors are required at the end of the S&P C-Laminate.

A) S&P End anchorage system

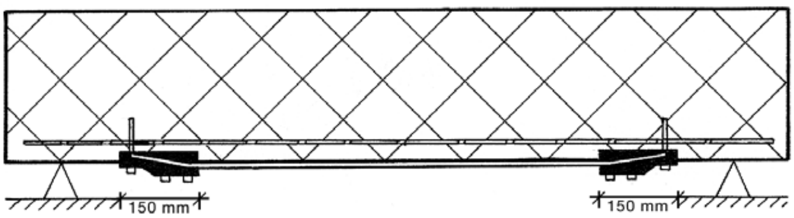


Image 13: Patented S&P End anchorage system

Two aluminium clamps at the end of the laminates prevent the early delamination of the S&P C-Laminate. These special S&P end anchorages guarantee an active contact pressure on the laminate. In addition, due to the forced radius, the laminate forces are optimally introduced into the supporting base.

B) Tests of S&P Anchorages

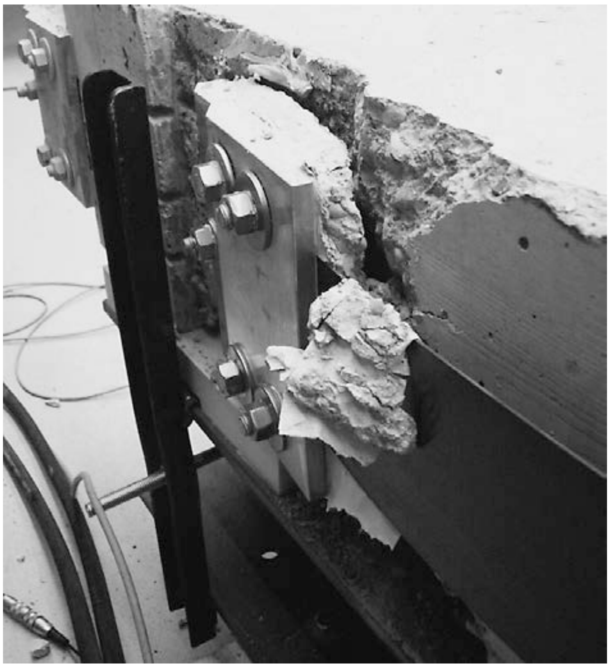


Image 14: Damage of concrete

At the HES-SO Fribourg (CH) and TU Munich (DE), bonding tests were carried out with the S&P anchoring system for slack-bonded S&P C-Laminate. Three different concrete grades and three different laminate dimensions were tested. In the tests, an unreinforced concrete block was used. The failure in all tests was due to concrete fracture. The breaking force depends on the concrete quality and the arrangement of the anchoring plates.

The bond strength of the anchored 80 mm wide S&P C-Laminate is approximately 150 kN.

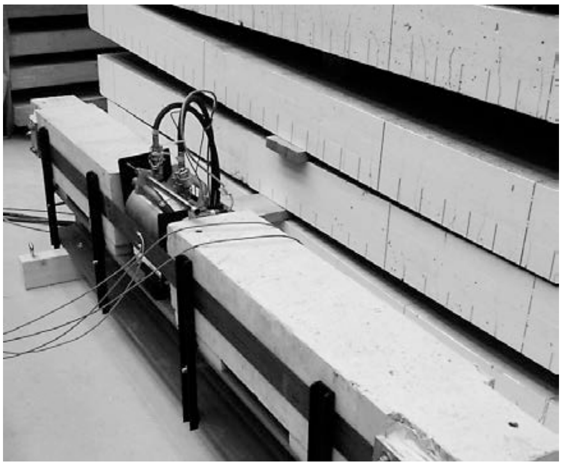


Image 15: Test at the University of Fribourg(CH)

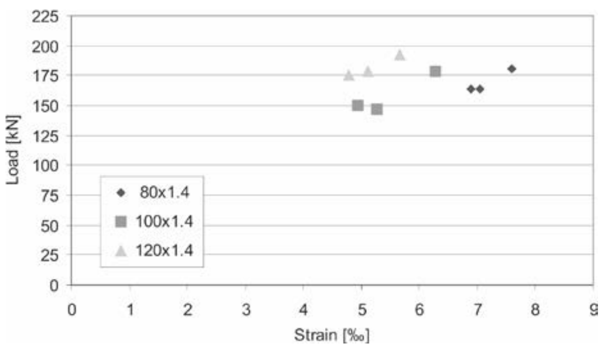
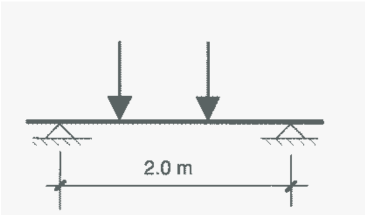


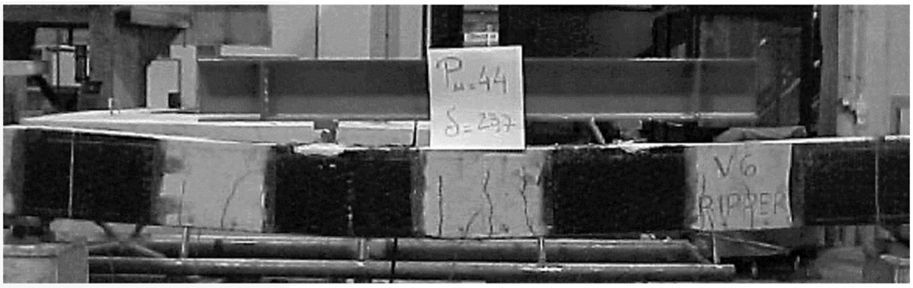
Image 16: Test results (for concrete quality C20/25)

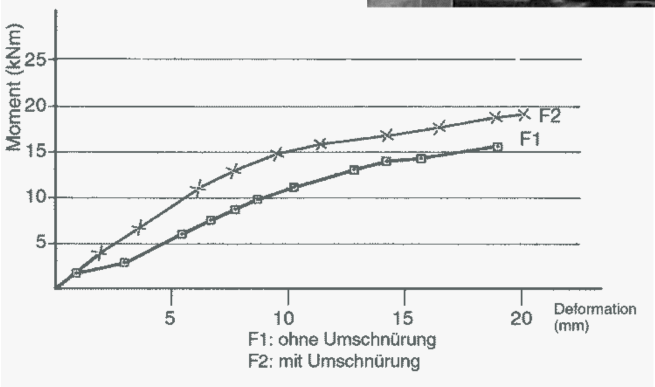
C) End anchoring with S&P C-Sheet 640

The ends of the S&P C-Laminates are wrapped with the S&P C-Sheet 640. An appropriate series of experiments were carried out at the University of Lisbon (PT).

Test arrangement







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

Image 17: Test at the University Lisbon (PT)

Images 18 / 19: End anchored laminates on the ceiling or beam

5.3 Slot applied S&P C-Laminate

The S&P C-Laminates 10/1.4 and 15/2.0 with a width of 10 mm to 20 mm and a thickness of 1.4 mm to 2.8 mm are specially designed to be bonded into slots in concrete or timber structures.

A concrete saw is used to cut slots approx. 5 mm wide and 15 - 25 mm deep into the substrate. The slots are filled with the system approved epoxy adhesive, and the S&P C-Laminates are pressed into the adhesive. For further details, see S&P application instructions (slot applied).

The mode of action of slotted lamellas was thoroughly investigated at the TU Munich (DE), the TU Porto (PT) and the TU Rolla (USA). The load-bearing behaviour was tested with bonding tests. Slotted laminates show a high and robust bonding capacity. There was no failure due to displacement, as with the bonded S&P C-Laminate. **As a result, the high tensile strength of the laminate - up to the failure of the Carbon fibre - can be utilised.**

Various test beams of reinforced concrete were tested at the TU Munich (DE) in a three-point bending test with a support span of 2.5 m.

One S&P C-Laminate 50 / 1.2 mm was glued onto the surface or two slot applied S&P C-Laminate 25 / 1.2 mm slit (same cross-section).

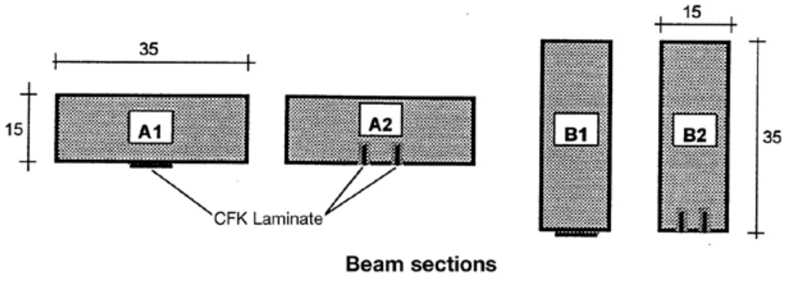


Image 20: Test arrangement

- On test beams A1 and B1 failure occurred due to de-bonding 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

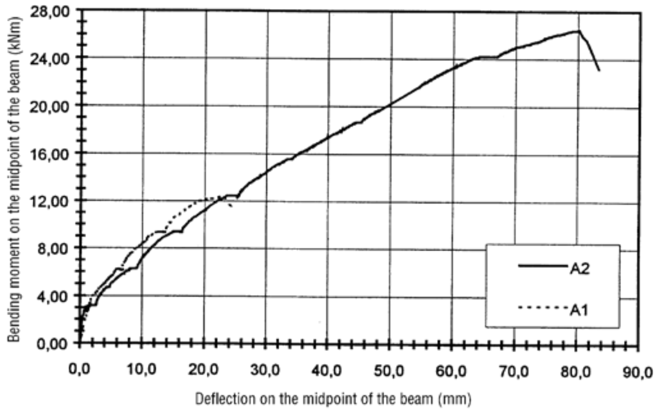


Image 21: The load-deflection curves of test beams A1 and A2

Interpretation of results from test beams A

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

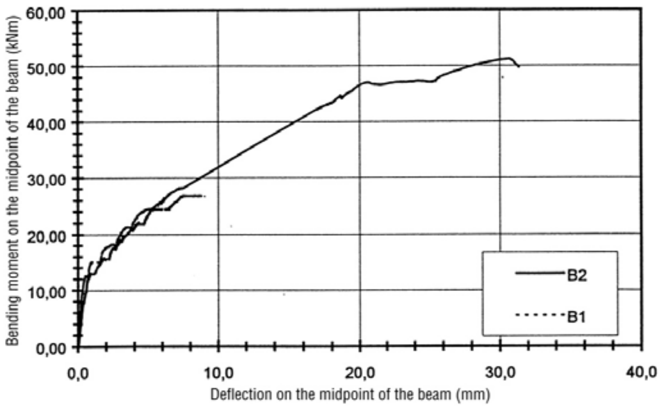


Image 22: The load-deflection curves of test beams B1 and B2

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.

Benefits of slot-applied S&P C-Laminate

– As larger forces can be anchored, the S&P C-Laminate is better utilised; thus a smaller laminate cross-section is required.

– The anchorage length at negative moments is reduced.

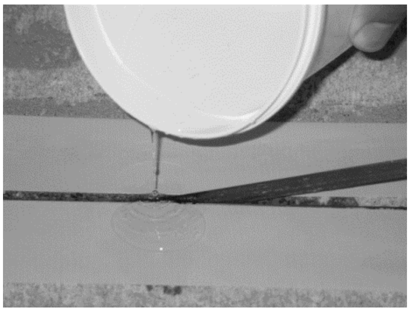
– The slot applied laminate is more economical than levelling and roughening required for surface applied laminates.

– The slot applied laminate is protected against mechanical damage.

The ideal application area for slot-applied S&P C-Laminates is ceiling surfaces (negative/support moments). Vertical applications (walls/columns) are also possible. Dimensioning of slot-applied S&P C-Laminates can be conducted using the design software FRP Lamella.

Recommended design elongation (Elongation limit $\varepsilon_{f,lim,d}$) of slot applied *S&P C-Laminates is maximum* 8 until 10 ‰.





Images 23 / 24 / 25: slot-applied C-Laminates in concrete

5.4 Pre-stressed S&P C-Laminate

S&P has developed a pre-stressing system for S&P C-Laminate. This system is used exclusively by a worldwide network of specialised applicators in co-operation with S&P application engineers.


Images 26 / 27: Patented S&P Pre-stressing System (aluminium)

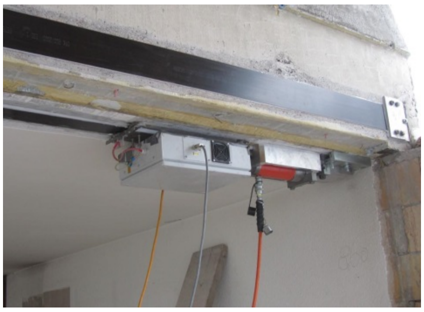


Image 28: Pre-stressing with Gradient-Anchoring

5.4.1 Slab tests

Concrete slabs with slack S&P C-Laminates, as well as concrete slabs reinforced with pre-stressed S&P C-Laminates were tested by the HES-SO Fribourg (Switzerland). The following diagrams show the experimental setup and a short overview of the results.

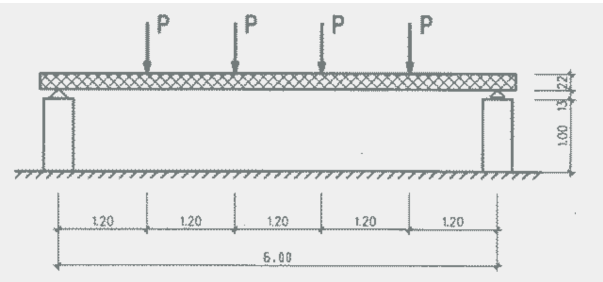


Image 29: Test arrangement

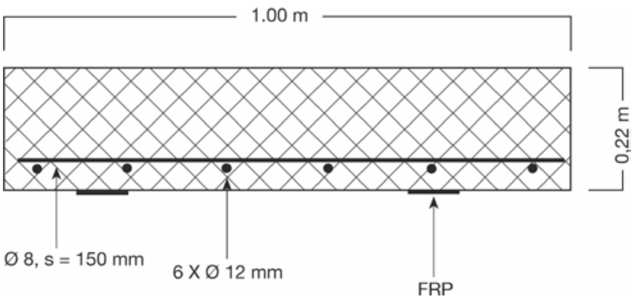


Image 30: Cross section of the concrete slab

	Steel longitudinal	cross	**FRP**	**Pre-stressing** ‰	**Pre-stressing** (N/mm²)	**Pre-stressing force** (kN)
Reference LC1	6 Ø 12	(Ø8 s =150)	none	-	-	-
LC5 FRP	6 Ø 12	(Ø8 s =150)	2 S&P C-Laminates 150/2000, Type 80/1.2 mm	-	-	-
LP2 FRP 4 ‰	6 Ø 12	(Ø8 s =150)		4	640	122
LP4 FRP 6 ‰	6 Ø 12	(Ø8 s =150)		6	960	184

Table 1: Graphical representation of the test

Test results

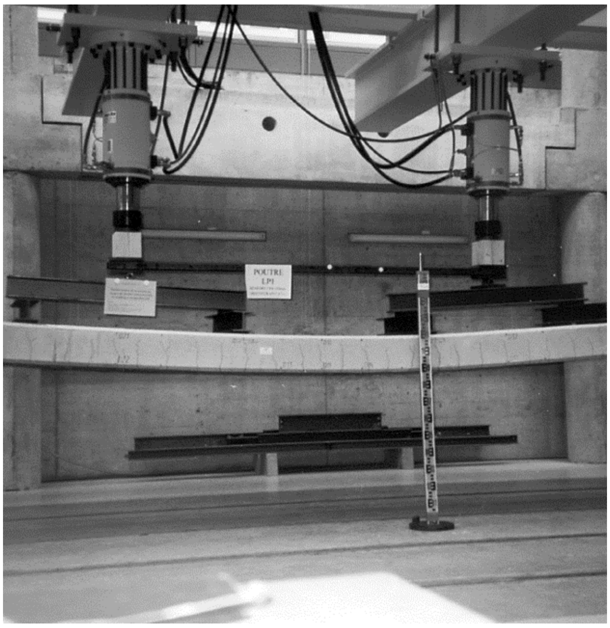


Image 31: Testing facility HES-SO Fribourg (CH)

The test slabs reinforced with pre-stressed S&P C-Laminates show a greatly reduced deflection rate and thinner crack widths following the experimentation. As a result of the superimposed normal force, the concrete cross sections remain in a non-cracked state far beyond the maximum load.
The fracture only occurred with greatly increased loads and higher deflections.
The increase in the breaking resistance was 32% for the test slabs reinforced with slack S&P C-Laminates. For the pre-stressed S&P C-Laminates, the increase was 82% (pre-stressing 4 ‰) and 113% (pre-stressing 6 ‰).
The properties of the slab were increased even further with pre-stressed S&P C-Laminates in comparison to slack S&P C-Laminates.

S&P C-Laminate	**Concrete slabs**	**Failure load** (kN)	**Failure moment** (kNm)	**Elongation at failure (‰)**	**Failure moment** (%)
none	Reference LC1	16.4	82.6	-	**100**
2 x 80/1.2 mm	LC5 FRP	24.0	109.4	6.0	**132**
2 x 80/1.2 mm	LP2 FRP 4 ‰	35.3	150.1	13.7	**182**
2 x 80/1.2 mm	LP4 FRP 6 ‰	42.6	176.4	14.9	**213**

Table 2: Slab test results

Conclusion

Pre-stressing of S&P C-Laminates 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 pre-stressing kits it is possible to pre-stress the S&P C-Laminates to an elongation of 6‰. The system has been specially developed for the strengthening of large-span RC-slabs.

5.4.2 Testing of RC beams

A research programme was carried out at the ST University in Gliwice (Poland). This pro- gram analysed the behaviour of RC beams strengthened flexurally with S&P C-Laminate. The beams were strengthened with non-tensioned and pre-stressed FRP laminates. The research showed the relationship between the use of different pre-stressing forces and effectiveness of strengthening. This is only a short summary of the tests performed on full- scale (8 meters long) RC beams using laminate type 90/1.4.

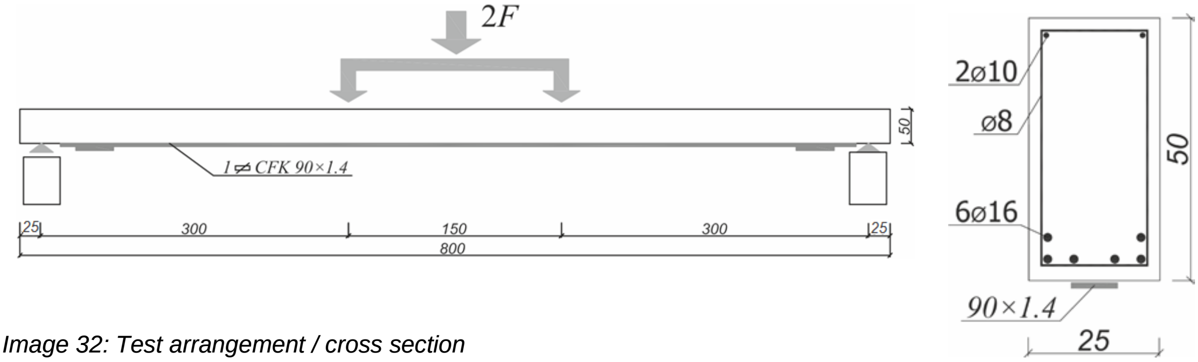


Image 32: Test arrangement / cross section

RC Beams	Steel	S&P C-Laminate	Pre-stressing ‰	Pre-stressing (N/mm²)	Pre-stressing force (kN)
Reference B1		none	-	-	-
B4 C FRP	6 Ø 16mm (fy=340N/mm²)	S&P C-Laminate 150/2000 Typ 90/1.4 mm	-	-	-
B1 C-FRP 3 ‰			3	495	62
B6 C-FRP 6 ‰			6	990	125

Table 3: Graphical representation of the test

Test results

The reinforced beams have a tremendous increase in flexural strength in the fracture state. The beams with pre-stressed S&P C-Laminates have a lower deflection rate under the same load as the beams with slack S&P C-Laminates. For all the reinforced beams, a sharp reduction in crack width was observed. The failure of a beam with pre-stressed S&P C-Laminates can be recognised at an early stage (high deformation). The increase in the fracture resistance was 32% compared to the reference beam for the test bars reinforced with slack S&P C-Laminates. For the pre-stressed S&P C-Laminates, the load increase was 42% with a pre-stressing of 3 ‰ and 58% with a pre-stressing of 6 ‰.

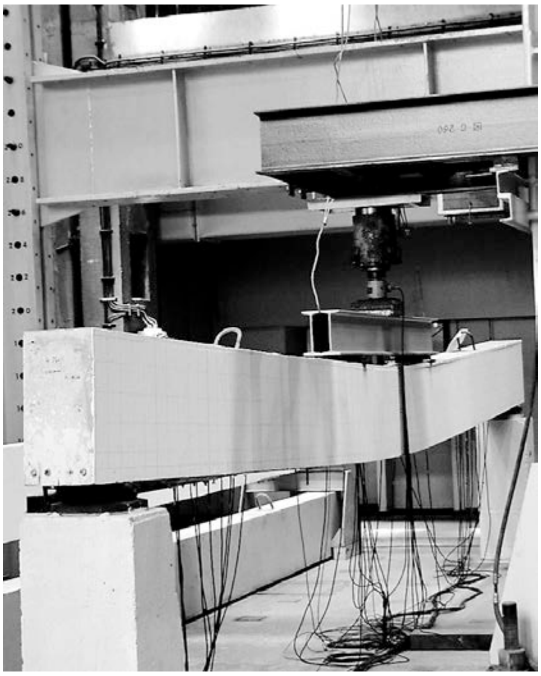
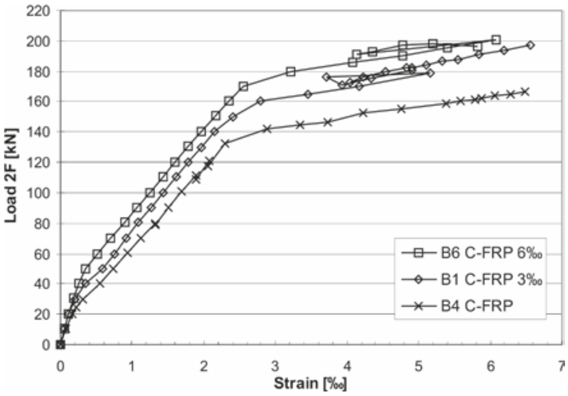
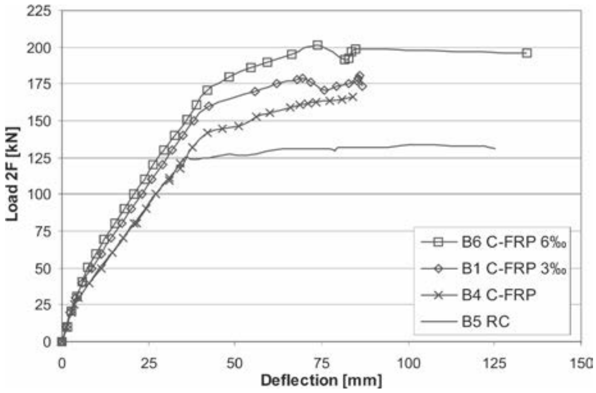


Image 33: Research by University Gliwice (PL)

S&P C-Laminate	RC beams	Failure load (kN)	Failure moment (kNm)	Failure moment (%)
keine	B5 Referenz	122	204	**100**
90/1.4 mm	B4 C-FRP	166	270	**132**
90/1.4 mm	B1 C-FRP 3 ‰	179	289	**142**
90/1.4 mm	B6 C-FRP 6 ‰	202	323	**158**

Table 4: Results failure force / failure moment





Images 34 / 35: Test results: Strain in the laminate and deflection of elements

Conclusions

Similarly as for RC slabs, a very positive influence of pre-stressing beams with S&P C-Laminate was observed. The investigated beams strengthened with FRP laminates exhibited a reduction in deflections and crack widths. The ultimate load is significantly increased. Low modulus S&P C-Laminates are used for pre-stressing.

Recommended design elongation (Elongation limit $\varepsilon_{f,lim,d}$) for pre-stressed S&P C-Laminates is maximum 12 ‰ (Pre-stressing through elongation 4 - 6 ‰).

Many applications in construction are possible with pre-stressed S&P C-Laminates:

- Reinforcement of overloaded structures
- External reinforcement of structures with corroded internal tension cables
- Refurbishment of coupling joints
- Deflection limitation
- Reduction of crack widths

5.5 Masonry strengthening using S&P C-Laminates

Masonry is cost-effective and is a global form of construction. Thanks to good physical building properties of masonry, it will continue to be used in the future. The strength of masonry is subject to great variations due to different stone and mortar qualities. The reinforcement of masonry in advance for seismic stress plays an increasingly important role in the construction of buildings.

For the reinforcement of masonry, S&P C-Laminates or S&P Sheets (see chapter 6) can be used. In the case of reinforcement with S&P C-Laminates, the introduction of the force should be duly taken into account.

S&P C-Laminates 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 S&P C-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 36). As a result of the de-bonding of the C-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 C-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 36, 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 C-Laminate has been applied to one side of the wall only.

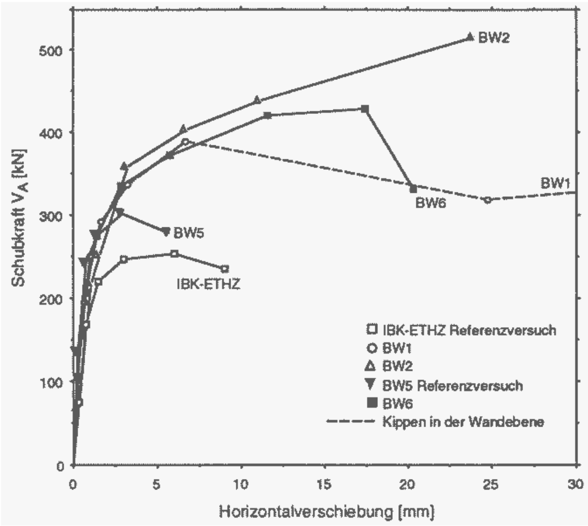


Image 36: Comparison of FRP reinforced masonry with reference sample

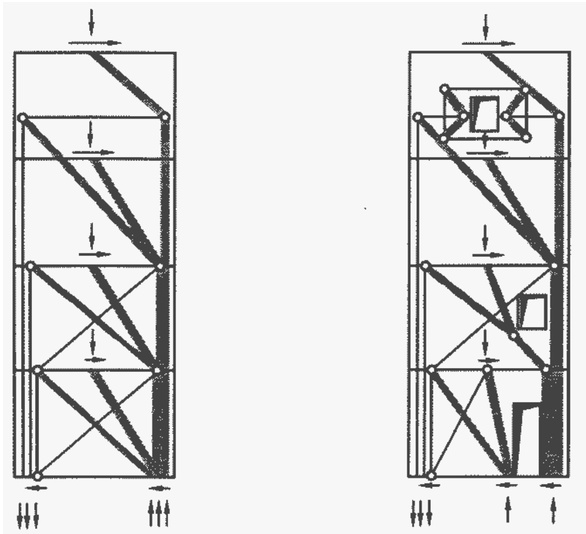


Image 37: Load bearing wall with and without openings

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. 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 and V_y. The requirements for the critical load bearing walls in the lower floors differ from those in the upper floors. Figure 37 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.

Images 38 / 39 / 40: Reinforcement of masonry (seismic) with S&P C-Laminates anchored in the concrete substrate

6. FRP Systems with S&P Sheets (stretched/woven)

The S&P Sheets (uni-directional/bi-directional) can be applied as dry and wet lay ups. 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 nett fibre properties only.
The theoretical sheet thickness is determined as follows:

net fibre cross section

$$\text{Theoretical sheet thickness} = \frac{\text{fibre weight in the direction of strengthening}}{\text{density of the fibre}}$$

Site lamination does not always produce an optimum fibre arrangement because of the application process. 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 properties used for the fibres be reduced by an environmental reduction factor [y].

The recommended **reduction factor (y)**:
For S&P C-Sheet **y = 1.2**
For S&P A-Sheet **y = 1.3**
For S&P G-Sheet **y = 1.4**

The theoretical parameters of the S&P Sheets for site lamination can be downloaded under www.sp-reinforcement.eu.

6.1 Vapour permeable S&P Epoxy System

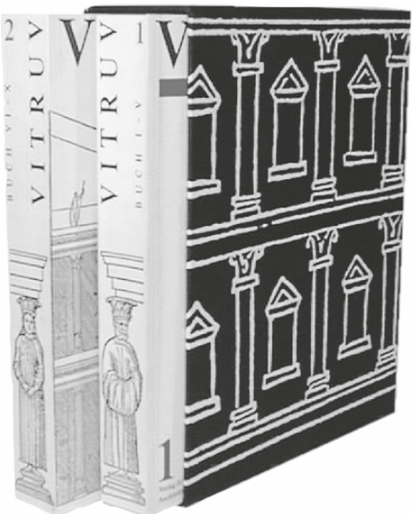


Image 41: A structure must be permeable to water vapour from the inside to the outside. (VITRUV Roman architect and engineer, approx. 50 B.C.)

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 specially developed cementitious epoxy saturant. The combined effect of the two binders that have completely different chemical bases, is that the cement particles 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 onto a substrate with up to 12 % moisture content.

Determination of the water vapour-permeability of a coating

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

S_d: Water vapour diffusion resistance of the layer
μH_2O: Water vapour diffusion coefficient of the coating

S&P Resicem	μH_2O = 3‘000 – 5‘000	(FRP thickness of approx. 1 mm)
S&P Resin 50/55 (epoxy resin)	μH_2O = 1‘000‘000	(FRP thickness of approx. 1 mm)

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

S_d = 4‘000 x 0.0008 = $\underline{3.2\ m < 4\ m}$ ✓
With the use of S&P Resicem the water vapour-permeability of the FRP system is guaranteed.

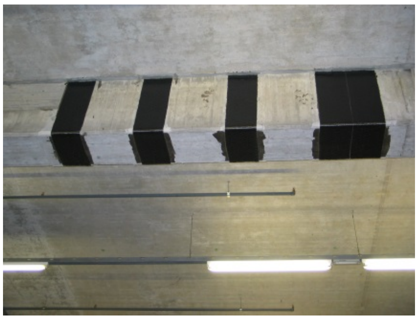
6.2 Reinforcement of beams

In the course of flexural reinforcement of reinforced concrete structures, the shear resistance of the component must also be checked as a rule. According to the standard SIA 262, the transverse force is to be transmitted through the reinforcement (steel, CFRP) (no concrete involvement).

If a shear reinforcement is required, S&P can offer the S&P C-Sheet 640. This scrim contains fibres with an extremely high modulus of elasticity of 640 kN/mm². For the dimensioning, a maximum elongation of 2 ‰ is calculated. This means that the S&P C-Sheet 640 transmits the full lateral force at maximum 2 ‰ strain - in analogy with the existing steel reinforcement - to the bearing component. A higher elongation of the sheets can lead to the premature failure of the component because shear failure occurs with little deformation (no flow range as in the case of bending tensile failure).

The S&P design software "FRP Lamella" calculates the required positions and the relevant distances of the S&P Sheets. Depending on the design situation, the additional transverse force reinforcement must be anchored in the pressure zone. This can be done either with ceiling slits or steel anchors.
In the event of subsequent breakouts for doors, windows, recesses, etc., the severed shear reinforcement in these areas of the structure shall be compensated with S&P C-Sheet 640 or S&P C-Sheet 240.

For more information please refer to the application instructions.


Images 42 / 43 / 44: *Complete or partial reinforcement of steel reinforced beams with S&P C-Sheet 640 with anchorage in the pressure zone*

6.3 Reinforcement of flexural and tensile elements

If a bending reinforcement with S&P C-Laminates is not possible, S&P C-Sheet 240 can be used instead. The main application area is on substrates with a reduced adhesive tensile strength (fctH of 1.0 to 1.5 N / mm²). The number of layers can be calculated with the technical characteristics of the S&P C-Laminates. Another application of the S&P C-Sheet 240 is the anchoring of S&P C-Laminates in the area of ceiling decks, edges and walls. In these cases, the S&P C-Sheet 240 can be applied with a minimum radius (≥ 25 mm) around any corners. See the S&P Application Guide for further details.

Image 45: Underside of deck application

Image 46: Application as end anchorage

6.4 Wrapping of columns

S&P sheets made from carbon, glass or aramid fibres are used for the reinforcement of round and rectangular pressure members. The choice of the fibres used is determined by the engineer according to the static requirements, as well as the economic efficiency of the project. In principle, the following fibres are proposed for the following requirements:

Increase of ductility:	**Glass fibre fabric**	**S&P G-Sheet**
Bearing capacity:	**Carbon fibre scrim**	**S&P C-Sheet**
Explosion / Impact resistance:	**Aramid fibre scrim**	**S&P A-Sheet**

The application areas and their effects have been scientifically tested in various tests. The following illustrations show the pull-push test with FRP systems and their results:

Two FRP wrapped columns were compared to a reference column:

- S&P C-Sheet 240 (E-modulus 240 kN/m^2) => 1.0 kg/m^2 in the hoop direction
- S&P G-Sheet 90/10 (E-modulus 65 kN/m^2) => 3.6 kg/m^2 in the hoop direction

Since the E-modulus of the glass fibre is only about 25% of the E-modulus of the carbon fibre, the 3.6-fold surface weight (in the wrapping direction) of the G-Sheet 90/10 was applied for the comparison.

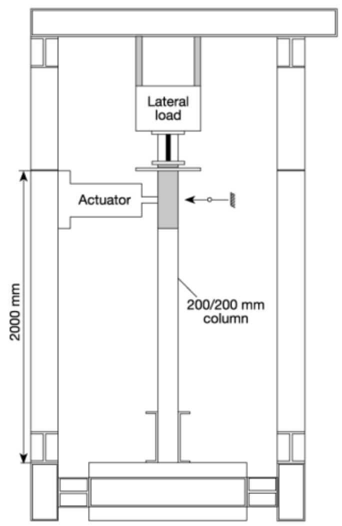
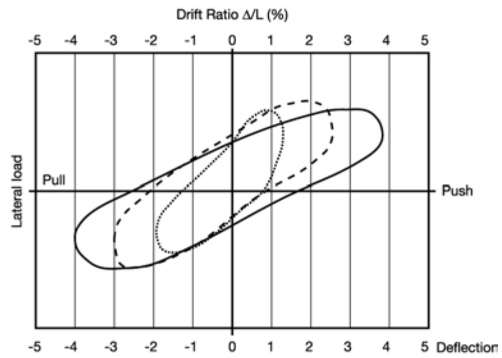


Image 47: Pull-Push Test



…… *Reference column*
\- - - *Column wrapped with S&P C-Sheet 240*
—— *Column wrapped with S&P G-Sheet 90/10*

Image 48: Results from a pull-push test

The test results clearly show that a reinforcement made with glass fibres offers more ductility compared to the reinforcement carried out with carbon fibres. This is why structural elements in seismically endangered areas are preferably retrofitted with G fibres.

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* (scrim)	with 1.0 kg/m^2 fibre content horizontal
	- *S&P C-Sheet 640* (scrim)	with 1.6 kg/m^2 fibre content horizontal
	- Glass Sheet (fabric)	with 3.6 kg/m^2 fibres horizontal

Image 49: Point of failure

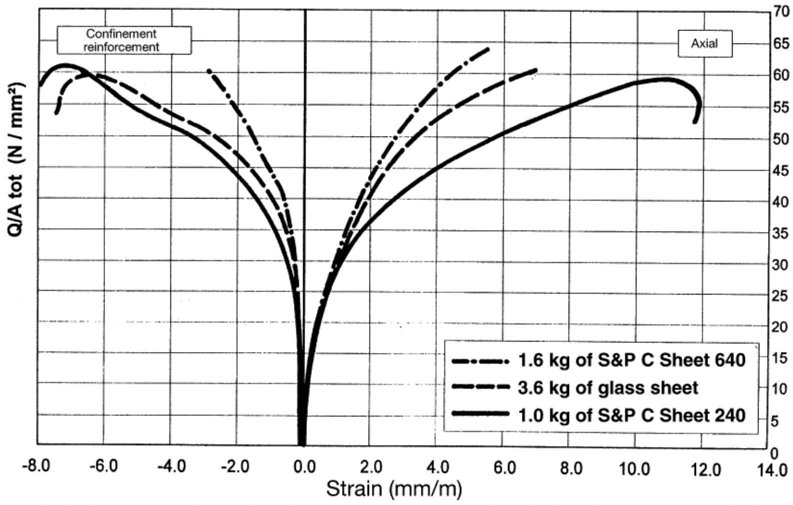
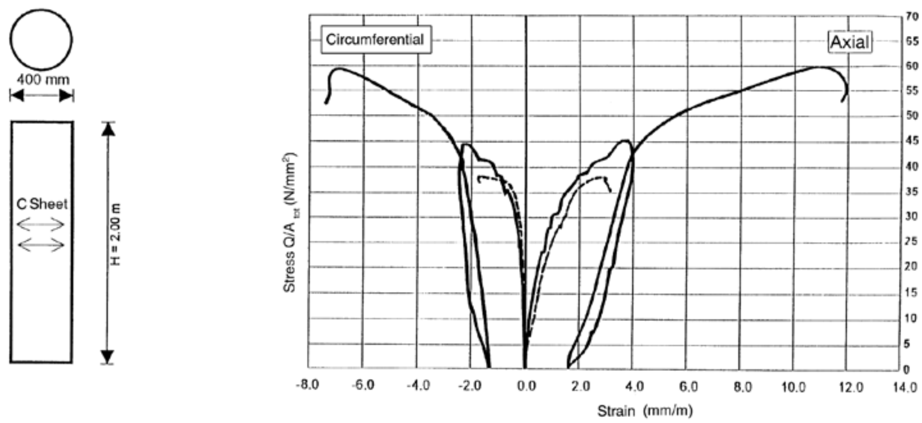


Image 50: Test results TU Gent (B)

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 3.6 kg of G fibres.

Results of the reference column (without reinforcement) and the column with confinement reinforcement of 5 layers of *S&P C-Sheet 240* (5 x 200 g/m^2 = 1 kg/m^2):



		%
------ Reference column	38 N / mm²	100
——— 5 layers of S&P C Sheet 240 GPa 200 gr/m²	60 N / mm²	157

Image 51: Results from the tests at TU Gent (B)

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 at ultimate state in order to provide a suitable safety factor. For confined columns a maximum strengthening factor of 1.8-2.0 is therefore realistic.

During the last few years, the practice of FRP-strapped steel concrete columns has been demonstrated by several scientific studies. Various design bases for the design of FRP wraps are available (e.g., Seismic Design and Retrofit of Bridges by M.J.N. Priestley, F. Seible and G.M. Calvi).

FRP wrapping of rectangular columns is more problematic than wrapping of rounded columns. Further experiments showed that with FRP wraps, a possible shear failure can be prevented very effectively. FRP wraps only minimally increase the bending resistance.

Numerous research work has shown that wrapping the reinforced concrete - in the areas which act as plastic joints - increases the load bearing capacity and the ductility of reinforced concrete frames. Experiments have also shown that GFRP can achieve a greater increase in ductility than a CFRP system. This is due to the higher elongation at fracture value of the glass fibre.

Images 52 / 53: Confinement of columns with S&P C-Sheet

Image 54: Wall reinforcement - S&P G-Sheet

6.5 Seismic reinforcement

Many older concrete structures have too little earthquake resistance. In this case, the ductility or the bending resistance of the pressure members (columns) is insufficient. This is particularly evident in the area of the reinforcement overlaps, as well as in the end regions of the columns. Specifically, plastic hinges form in the anchoring zones leading to the failure of the component. Another breaking mechanism is the buckling of the longitudinal reinforcement. Reinforcement with FRP wraps have proven themselves in practice and are used successfully. The S&P software "FRP Colonna" is used to support the design.

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

Insufficient, transverse, load-bearing capacity in the beam/column or beam/slab connections can cause shear cracking in the concrete at an early stage of loading. 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 the overall ductility of the structure must be taken into account also, the woven S&P G-Sheet 90/10 or the pre-stressed 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 over- all ductility of the structure would be fulfilled to a lesser degree.

Image 55: “Short Column”

Image 56: Weak junction point

Weak junction points

Junction points that are too weak or those with insufficient load capacity because of reduced cross sections can be subject to other 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 pre-stressed S&P A-Strap over the junction points

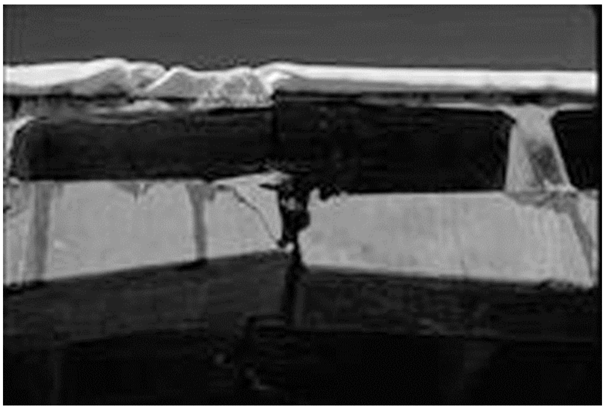


Image 57: Shear failure in a plastic hinge region

Plastic hinge regions

Beams subject to flexure with insufficient shear reinforcement can exhibit failure in the plastic hinge regions, as shown in the Figure 37. 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. In this case S&P C-Laminates are applied into slots or onto the surface.

Methodology of retrofitting with FRP

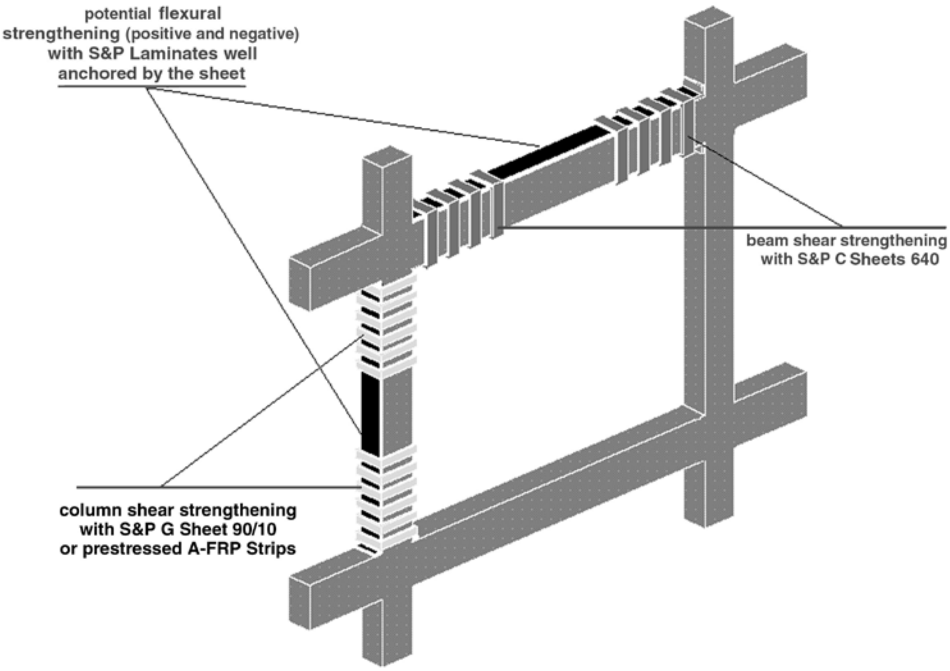


Image 58: Retrofitting of a reinforced concrete frame

Large-scale tests indicate that G- or A-FRP confinements provide better technical benefits and are more economical than steel jackets. In the case of FRP confinement of the entire column or at its ends, concrete failure occurs at larger strains. The reduction of transverse strains provided by the FRP confinement also helps to minimise 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.

As described in Chapter 5, masonry structures can be reinforced with S&P Sheets. S&P G-Sheets are the most suitable if an increase in ductility of the structure is the primary.

6.6 Explosion and impact protection

6.6.1 Explosion protection

Structures can be frequently damaged by exposure to explosions or the effects of bombs. Protection against explosion can also be a requirement of the chemical industry. Whilst 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.

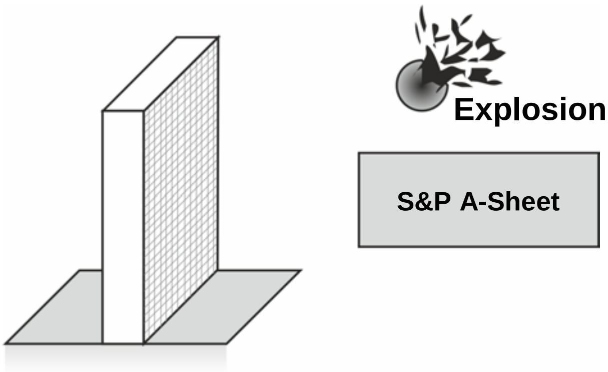


Image 59: Protection of constructional elements subject to explosion hazards

Bi-directionally applied aramid fibres (S&P A-Sheet 120) are likewise suited as an explosion protection measure. The favourable mechanical properties of the aramid fibres, and especially their excellent behaviour transverse to the fibre direction, make them ideally suited for this 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.

6.6.2 Impact protection

The design of a column for a highway bridges, in practice, can give rise to insufficient capacity against vehicle impact. The column may be unable to absorb the horizontal loads generated by impact of a lorry, which could lead to a bridge collapse. Conventional strengthening methods, such as concrete casing, may be unsuitable because of lack of space and for aesthetical reasons. Furthermore, concrete casing requires traffic restrictions for a lengthy construction period. A-FRP confinements provide an alternative and more beneficial strengthening method. Tests carried out by the fibre manufacturers in the UK have proved the performance of A-FRP for retrofitting circular columns against vehicle impact. The layers of A-FRP were arranged in orthogonal directions with a sheet weight of 290 gm/m^2. A similar testing programme is underway at HTA University of Fribourg (Switzerland) on columns with a square cross section. The tests simulate the impact on a bending beam.

Test arrangement:

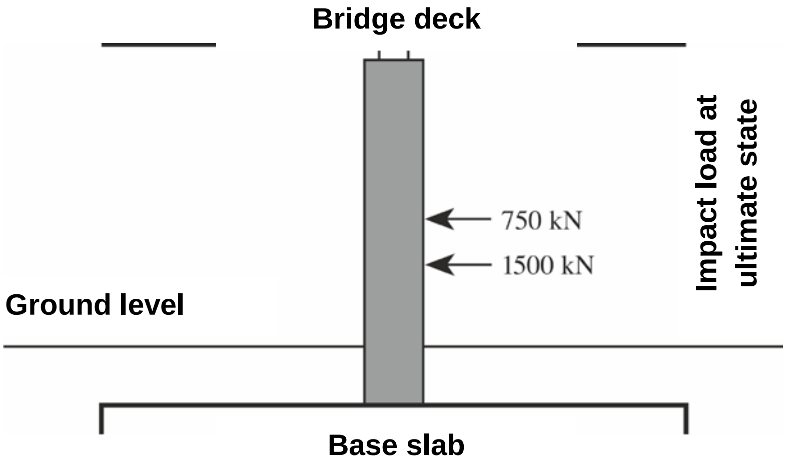


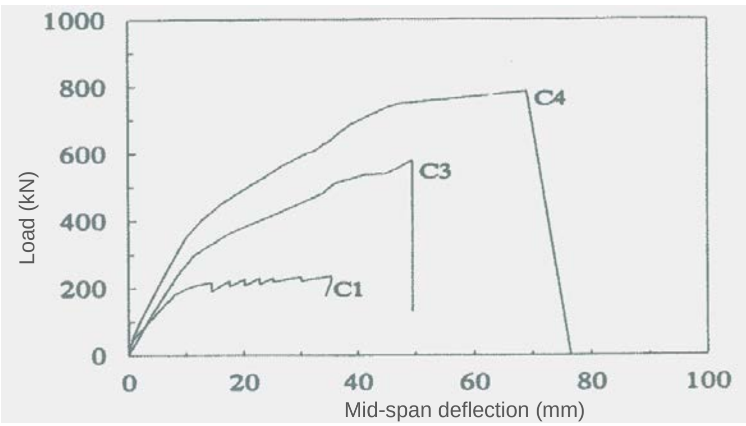
Image 60: Highway column sustaining a horizontal impact

The test results showed that the energy absorption of columns reinforced in 2 directions (longitudinal and transverse) can be substantially higher than that of unwrapped columns. However different fibre types behaved in different ways. C- and G-FRP provided barely any increase in energy absorption. The brittle C and G fibres failed prematurely because of their insufficient transverse load bearing capacity. The tough aramid fibre however, with its inherent transverse load bearing capacity, was able to yield with the high deformation of the column.

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

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

Table 5: Test results obtained by DUPONT UK (manufacturer of aramid fibres)



C1: Reference column

C3: 2 longitudinal layers
+ 2 transverse layers

C4: 3 longitudinal layers
+ 2 transverse layers

Image 61: Load-deflection diagram

7. Fire protection measures

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. In the event of fire, this leads to a premature failure of the laminate.

The global residual safety (γ Me, RC) in the case of failure of the reinforcement with S&P C-Laminates is critical for the determination of fire protection measures.
The S&P design program determines the remaining residual safety when the S&P C-Laminates fail.

Residual safety in the event of laminate failure

$\gamma_{Me,RC} > 1.0$

⇩

Fire resistance ensured by internal reinforcement
Structural safety in the event of fire

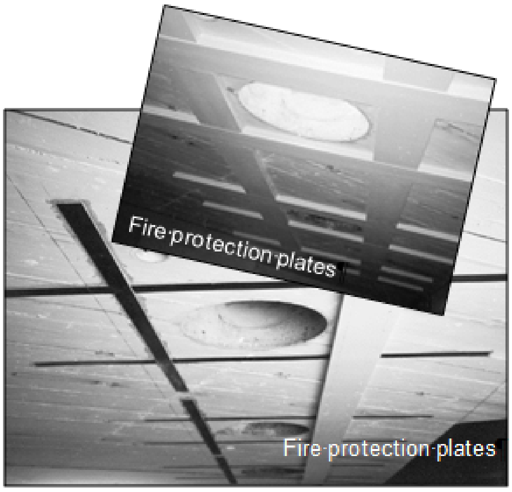
⇩

Conventional fire protection for internal reinforcement only

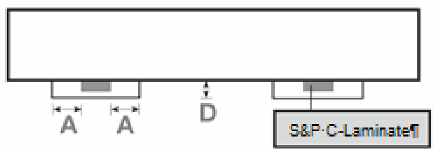
$\gamma_{Me,RC} < 1.0$

⇩

Additional protective measures are required!



Example: Fire protection plates



Fire resistance	A = 100 mm (D)	A = 200 mm (D)
R 30	2 x 20 mm	2 x 20 mm
R 60	2 x 40 mm	2 x 30 mm
R 90	> 110 mm	2 x 40 mm
R 120	> 110 mm	> 110 mm

8. Quality assurance

When FRP reinforcement is applied, quality assurance should be duly taken into account. The responsible project author (civil engineer) must already define in the planning phase which tests are necessary to determine the static measures. The selected examinations and quality controls are to be listed in the performance list.

The site construction manager, as well as the application sub-contractor, must under all circumstances ensure that the work processes are carried out according to the static design. In all cases, supporting components may not be removed until the FRP reinforcement has been applied and the responsible civil engineer has given the consent.

8.1 Substrate

8.1.1 Determination of compressive strength

The scope of the test shall be selected in such a way as to provide sufficient information on the distribution of the compressive strength of the supporting base. Critical areas, especially in the area of anchorage, must be examined with particular care. A possible test method is the removal of cores and the subsequent testing of the drilled cores in the laboratory. Often, however, it is sufficient to determine the compressive strength with the concrete rebound hammer.

8.1.2 Determination of bond strength

The adhesive tensile strength of the supporting base is decisive in the selection of the FRP reinforcement system. This is because tensile forces from the FRP system are introduced into the bearing base via shear stresses.

Depending on the FRP reinforcement system used, the following target values for the substrate are recommended:

FRP strengthening system	**Min. adhesive tensile value of the substrate f_{ctH}**
S&P G-Sheet	> 0.2 N/mm^2
S&P C-Sheet / S&P A-Sheet	> 1.0 N/mm^2
S&P C-Laminate	> 1.5 N/mm^2

Table 6: min. adhesive tensile strength of the substrate f_{ctH}

8.1.3 Substrate preparation

The supporting base for FRP reinforcement systems must be clean, free of dust, oil and grease. In the case of concrete, the cement laitance must be removed completely with sand or shot blasting, as well as grinding. Paints, insulation materials or wood linings must also be removed. The preliminary work must be carried out so that the grain structure of the concrete is not damaged (no staking). Any larger cracks must be closed with force.

8.1.4 Substrate levelness

Application tests have shown that freshly applied S&P C-Laminates on largely uneven surfaces become detached from the concrete. The high bending stiffness of the laminate causes the laminate to stretch immediately after pressing. Adhesion of the fresh adhesive is not sufficient to hold the laminate on the concrete surface. In regions of the substrate where depressions are present, air bubbles and hollow spaces form in the adhesive under the laminate. These imperfections weaken the bond and this can be very dangerous in the area of end anchors. Curvatures that press the FRP products against the concrete are not objectionable.

There should be no unevenness > 5 mm when holding a 2 m long metal plate onto the substrate. Irregularities of < 1 mm are permissible on a test section of 30 cm. Only system-tested levelling mortars may be used for re-profiling.

8.1.5 Substrate moisture content

When using S&P epoxy based resins (for example S&P Resin 55 HP/220/230), the maximum water content of the substrate is 4%. For S&P resins with cement additives (for example S&P Resicem HP), the maximum water content is 12%. When a higher water content is present, the substrate must be allowed to dry accordingly.

8.1.6 Dew point temperature

The dew point temperature must be determined before applying FRP systems. For this, the relative humidity and the air temperature are measured. The associated dew point temperature can be determined from this. To assess the risk of condensation forming, it is to be compared with the temperature of the substrate. This must be at least 3° C higher than the dew point temperature.

8.2 S&P FRP Materials

The S&P FRP materials (laminates, sheets, adhesive) are subject to ongoing quality control measures (ISO 9001). The technical data sheets provide information on the relevant characteristic values. For the application of S&P FRP systems, application instructions are available to the user. S&P offer practical courses every year, or on request, to all civil engineers and applicators.

The technical data sheets are available on www.sp-reinforcement.eu.

8.3 Control during application

Various protocols are available to the user for the ongoing control of the application. This allows for the continuous recording of values.

8.3.1 Bond

The quality of the bond of applied FRP reinforcement is of utmost importance. The bond can be tested by adhesion tests. As a rule, test laminates are adhered to the substrate. The adhesion tensile strength is measured with a suitable testing device. The fracture is usually apparent within the supporting substrate.

With this method, it is possible to examine the long-term behaviour. For example, further adhesive tensile tests can be carried out every 10 years.

8.3.2 Cavities

FRP systems are to be tapped to reveal any cavities after bonding. Cavities which are located in the middle area of the FRP system may be filled with an injection resin with light pressure.

If cavities are present at the edges of the system (anchorage area of the FRP System), the FRP products must be removed and re-applied.

8.4 Working safety

During the application of S&P Systems, the information and guidelines within the safety data sheets and application guidelines are valid (www.sp-reinforcement.eu).

Carbon fibres and epoxy resins can cause skin irritation. Therefore we recommend a consistent use of:

- Headgear
- Safety goggles with side protection according to EN 166
- Protective mask with dust filter during application
- Long sleeved workwear
- Safety gloves according to EN 374
- Closed shoes

Precautionary measures in case of danger, first aid, proper disposal, etc., must be observed!

8.5 References

S&P have carried out more than 20 years of research and development work, including various experiments and material tests. Relevant documents and results can be viewed at S&P Switzerland.