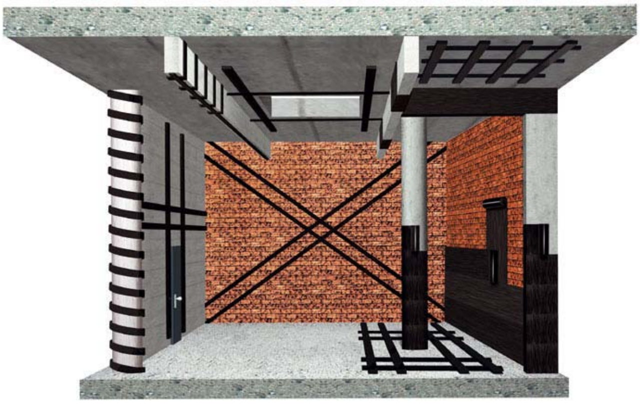
Construction

Sika® CarboDur® FRP Composites



for Repair & Strengthening of Structures.

MARCH 2003

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2. PREAMBLE

2.1. Significance of repair, strengthening and seismic retrofit

The issue of upgrading existing civil engineering infrastructure and building structures poses great importance compared to new construction. Deterioration of bridge decks, beams, girders and columns, buildings and parking structures may be attributed to various reasons and include:

- Durability problems due to poor or inappropriate construction materials.
- Design or construction errors.
- Aggressive environments not properly understood during the design stages.
- Increased loading requirements due to changes of policy or use of structures.
- Increased life-span demands made on ageing infrastructure.
- Exceptional or accidental loading.
- Varying life span of different structural or non-structural components.

Due to the increasing decay of infrastructure and buildings, which is frequently combined with the need for upgrading so that structures can meet more stringent design requirements (e.g. increased traffic volumes on bridges exceeding the initial design loads), the issue of structural renewal has received considerable emphasis over recent throughout the world. At the same time, seismic retrofit has become of equal importance in areas of high seismic risk.

2.2. Definitions

Required Resistance (V_B): is defined as the capacity of the structure after the completion of strengthening interventions.

Available Resistance (V_C): is defined as the capacity of the structure prior to the deterioration due to one or all of the parameters given in §1.1.

Residual Resistance (V_D): is defined as the capacity of the structure after the deterioration due to one or all of the parameters given in §1.1.

Loss of Resistance: is defined as the difference (V_C-V_D).

Repair: is defined as reinstatement of the original characteristics (strength, stiffness, ductility) of the structure. V_D is increased with the repair at least up to the value of V_C.

Strengthening: implies the enhancement of the structure's characteristics beyond the levels envisaged or achieved initially by repair. The resistance becomes equal to V_B or to a predefined percentage of it.

Seismic Retrofit: is used to indicate post earthquake measures. It can be either repair or strengthening.

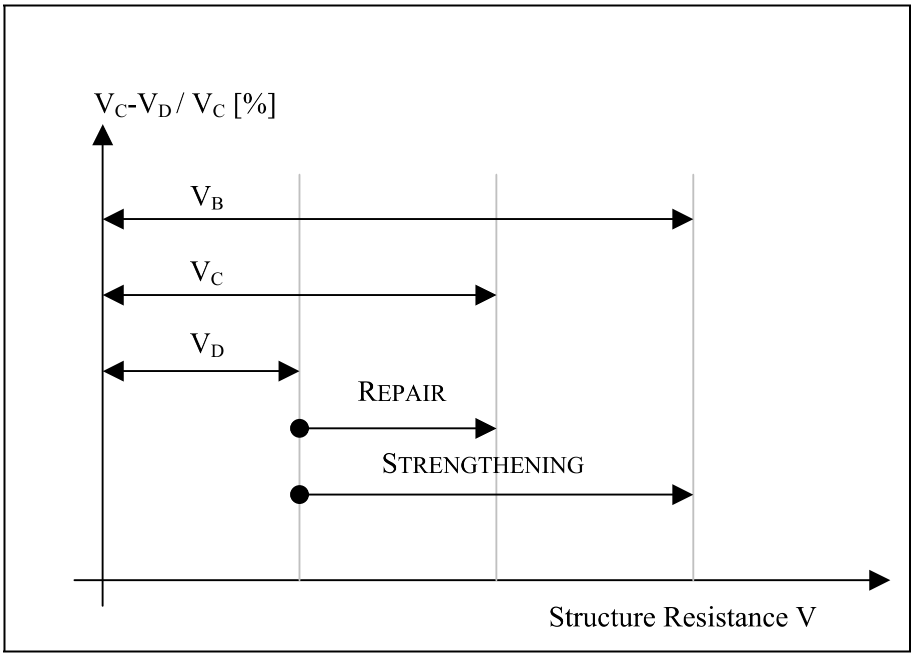


Fig. 1.1 Schematic Representation of V_B, V_C, V_D.

The above figure is a schematic representation of the required (V_B), available (V_C) and residual (V_D) resistance respectively.

2.3. Scope of the manual

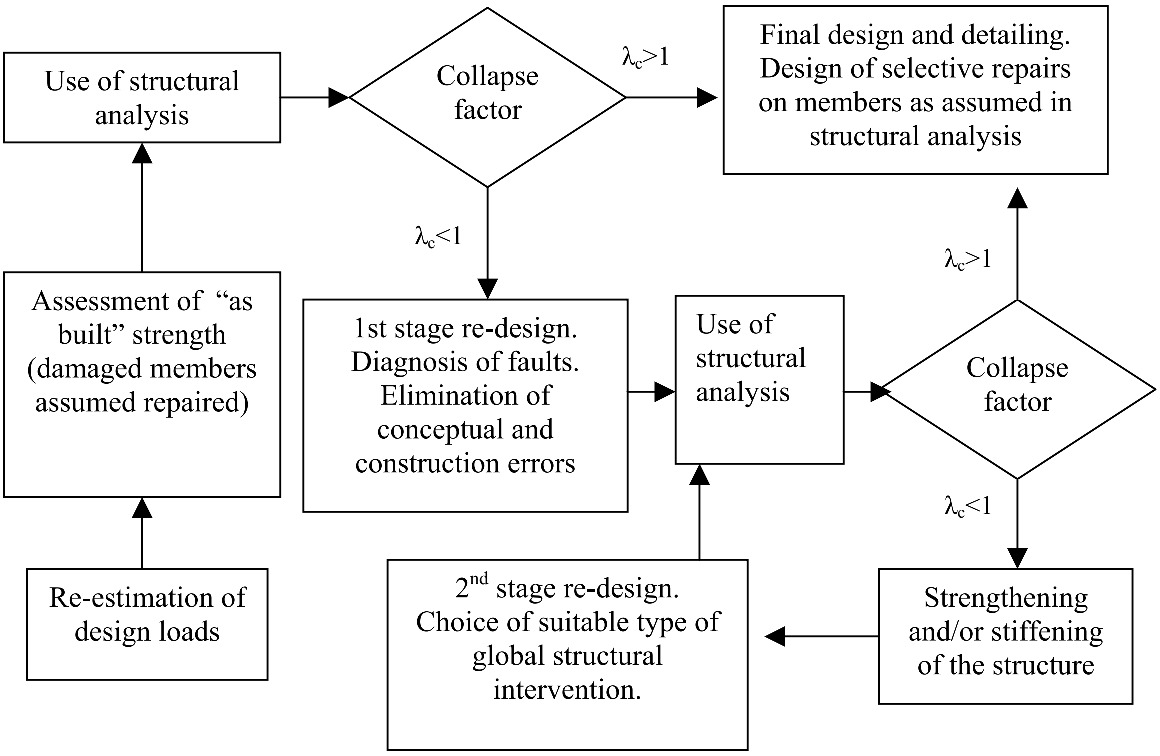
The aim of this manual is to be a useful tool for the Engineer as an overview of repair and strengthening methods using Sika FRP materials. There is a range of composite systems mentioned, for example Sika CarboDur, SikaWrap and SikaDur epoxy resins.

The manual incorporates experience and knowledge gained in the last years through many projects in Greece. Moreover, the manual includes details of application, design guidelines and examples.

3. DESIGN OF STRUCTURAL REPAIR AND STRENGTHENING

Structural damage is very often not identified as such, and cosmetic repairs are undertaken to conceal the obvious defects. Hence, the strategy for repair should involve the actual redesign of the structural requirements so as to achieve an acceptable level of safety. The most common stages of the design of structural repair and strengthening will be briefly mentioned.

A usual flowchart for the redesign of structures is given below:



3.1. Accurate assessment of 'as built' capacity

A prerequisite for any structural intervention is an accurate assessment; not only of the damage levels but also of the original potential of the structure as built. The design capacities are necessarily conservative and therefore 'as built' capacity should be estimated and used in the analysis stage of the repair process.

3.2. Re-estimation of loading

The loads imposed during use are often unknown during the design stages and allowance is made for finishes and live loads for different circumstances. Improved knowledge of the exact level of loading, to which the structure is subjected, can lead to a more precise determination of the forces applied to the critical members.

3.3. Elimination of conceptual or construction errors

The first stage in restoring structural ability to resist expected forces is to ensure that any conceptual and construction errors are rectified. This process may involve correcting abrupt changes in stiffness, irregularities in plan between stiffness and mass, as well as addressing poor detailing, use of inferior materials etc. The elimination of such errors does not necessarily precede any further interventions, but is assumed to take place so that a preliminary analysis can identify the critical members and extent of structural deficiency.

3.4. Prudent choice of structural intervention

Strength and deformation demands on members, identified by reliable structural analysis, will determine the level of strengthening that is required by the structure. Both strength and ductility enhancement might be necessary with the addition of new members or the strengthening of existing ones.

3.5. Selective repair techniques

The design of repairs should take into account the findings made during structural analysis. Improved strength would normally result in the enhancement of stiffness of the same member, and hence, higher forces would be attracted than for an assumed lower stiffness. Similarly, enhancement of ductility in certain locations reduces the rotational stiffness and this may influence the ductility demand in other locations.

Selective types of repair should aim to achieve only enhancement to the desired degree without interfering with other properties, as is often the case in non-selective schemes.

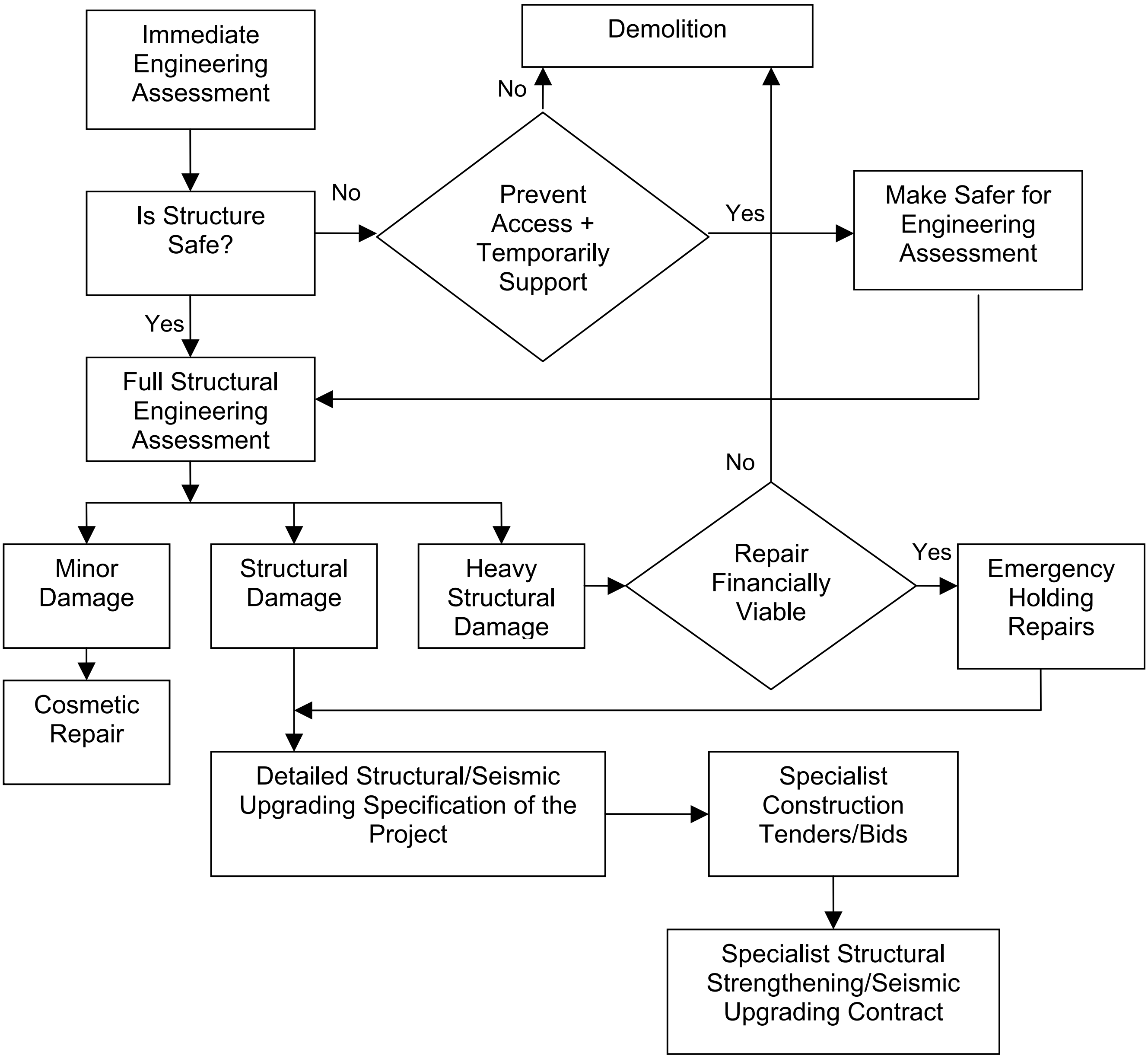
3.6. Strengthening of the structure

Strengthening of the structure is absolutely necessary, if the plastic potential, or servicability limits of the structure, following the initial elimination of errors, is exceeded. Several techniques are used in practice, such as infilling selected bays with reinforced concrete panels or braces, increasing the size of critical members either by extending or jacketing them, and adding new structural elements.

In traditionally designed interventions, the overall deformations are controlled, but a serious disadvantage of strengthening is the possibility of an increase in the imposed forces. This is especially serious at the foundation level, where extensive strengthening may be demanded. Additionally, structural strengthening may result in undesirable interference with the architectural appearance of the structure. High cost and interference with the functionality of the structure can also discourage owners from authorising essential repairs and opting for cheaper purely cosmetic measures.

As a result a comprehensive strengthening strategy should be adopted , its design dependent on the desired outcome.

3.7. Engineering Assessment: Flow Chart of the Process



4. STRUCTURAL REPAIR AND STRENGTHENING TECHNIQUES

4.1. Repair Techniques

Repair techniques can be undertaken to eliminate inherent errors or for the reinstatement of certain elements. The objective is:

1) to restore the structure to its initial desired serviceability and/or
2) to protect the structure from further deterioration.

Repair techniques include:

4.1.1. Resin Injection

Resin injection is the most widely used repair method for sealing minor to medium sized cracks in concrete structures. Flexural cracking is not usually a structural problem, unless the element has been loaded beyond its serviceability and has sustained damage. Sealing flexural cracks can restore the flexural stiffness, but does not increase the flexural capacity beyond its original limit. Hence, more often the sealing of excessive cracks is necessary only appropriate to protect the reinforcement from the environment.

Sealing of shear cracks or cracks associated with bond splitting will again only restore the structural stiffness, but will not address the fundamental problems, which lead to their development in the first instance. Such cracking should therefore be treated not only by this technique, but also by a suitable strengthening technique.

4.1.2. Patch Repair

Patch repair can be used to repair localized areas of damaged or crushed concrete due to accidental overloading. Properly executed repairs can achieve a good bond between the old and new concrete or mortar without the need for dowel connections. In general, the new material is expected to have a higher strength than the original concrete.

4.1.3. Shotcrete / Gunite

This method is normally necessary where a large volume of concrete is to be replaced and where the use of formwork is difficult (e.g. for a beam-column connection). It can be used to replace or increase concrete cover to reinforcement, or replace weak concrete in structural elements. It is also often applied to masonry structures.

However, there can be several drawbacks, such as considerable waste in material due to rebound and wire mesh being needed to avoid drying shrinkage cracks of the high cement concrete mix. The equipment needed, the expertise required and the need for an electricity source may also restrict the use of a repair method.

4.2. Strengthening Techniques

Strengthening techniques should always be associated with an overall re-design strategy. The objective is to increase the load-carrying capacity or stability of a structure in comparison to its previous condition.

The degree of strengthening to be achieved should be associated with a desired safety level. In addition, it should be remembered that in many instances strengthening may adversely affect the structural ductility. This can lead to serious problems, especially in seismic regions where energy dissipation is required.

Strengthening of structural members can involve simple use of stronger materials to replace poor quality or defective materials, or may be more elaborate involving the addition of load-bearing elements on the structure. As with repairs, the problem of interaction between the old and new materials and elements needs to be addressed.
Strengthening techniques include:

4.2.1. Strengthening of the Reinforcement

Inadequate or corroded reinforcement can be replaced by additional reinforcement, by post-tensioning or by externally bonded structural plates. The amount of strengthening to be achieved depends to a large extent on the properties of the existing element. Under-reinforced elements can be strengthened substantially, usually at the expense of ductility, whilst over-reinforced elements cannot be significantly improved without the addition of concrete overlays.

4.2.2. Reinforced Concrete Jacketing

This method requires the unloading of the element to be strengthened, and the removal of the concrete cover. Sufficient new reinforcement can be added in parallel to the existing by suitably designed lapped splices, welding or coupling devices. Care should be taken when welding, since the high temperatures induced may damage the concrete or any adhesives used.

The addition of new bars results in the jacketing of part or the entire reinforced member. This method is very effective for enhancing the strength, stiffness and ductility of a member and is recommended for severely damaged concrete elements.

4.2.3. Externally Bonded Plates or Fabrics

Steel and Carbon Fibre Reinforced Polymer (CFRP) plates are bonded onto concrete surfaces using epoxy resins. This technique is very effective in reducing deflections and crack widths.

A limit to the performance enhancement that can be achieved by this technique is the strength of the substrate surface, since peeling failures take place within the concrete. Creep of the adhesive is also a concern and that is why the adhesive layer should be kept to a minimum. The main advantage of this technique is the achievement of minimum increase in the size of the section after strengthening.

4.2.4. Prestressed Externally Bonded Plates

Prestressing of high strength materials is an effective way of utilizing them structurally. Both bonded and unbonded steel or CFRP tendons can be used. Strengthening by post-tensioning can be designed using conventional post-tensioning design procedures. Care should be taken to limit anchorage slip and to protect the tendons against fire and corrosion. Anchorages can be placed at suitably designed ends, additional supports, existing diaphragms or at new ground locations.

4.2.5. Steel Jacketing

This is a fast and effective technique based on fixing thin steel plates around a structural element. Steel angles are placed at each of the corners of the element and are clamped onto the concrete. The plates are then welded onto these angles and a cast-in-situ concrete jacket or a gunite jacket is added. Enhancement in strength, stiffness and the shear capacity can be achieved by this technique.

4.2.6. Strengthening with Lateral External Tensioning (FRP Jackets)

This technique utilises high strength fibres (glass, carbon or aramid) in the form of flexible fabrics, saturated with an epoxy resin, which allows them to be wrapped around and bond to any element shape. This scheme is useful in the repair and strengthening of elements in seismic regions. It is proven to enhance ductility and increase shear strength of elements to the extent that brittle shear failures are converted into ductile deformation modes. Moreover, the increased stiffness provided is less than that of steel or concrete jacketing.

The structural remediation techniques mentioned above, have various effects on the structural ductility, stiffness and strength. The structural effect for each intervention is given in the following table:

Structural Intervention	Ductility	Stiffness	Strength
Concrete Jacketing	Yes	Yes	Yes
Steel Jacketing	Yes	Yes	Yes
FRP Jacketing	Yes	?	?
Resin Injections	No	Yes	No
Plate Bonding	No	Yes	Yes
External Prestressing	No	Yes	Yes
Shotcrete	Yes	Yes	Yes

Table 2. Effect of structural interventions on the characteristics of the structure.

5. INTRODUCTION TO THE USE OF FRP MATERIALS

5.1. Conventional Strengthening Techniques

As already mentioned in § 3.2.3, in situ strengthening of reinforced concrete members (beams, slabs, columns etc.) using externally bonded steel plates and epoxy resins is recognized to be an effective and convenient method of improving performance under loads. The technique has been widely used for both bridges and buildings and for concrete surfaces in tension and compression.

However, strengthening through this technique has the following disadvantages:

- Difficulty in manipulating heavy steel plates at the construction site
- Deterioration of the bond at the steel-concrete interface caused by the corrosion of steel
- Need for scaffolding and temporary support or loading
- Proper formation of joints due to the limited delivery lengths of the steel plates.

Another common conventional technique for the strengthening of RC structures involves the construction of reinforced concrete (either cast in place or shotcrete) jackets around existing elements. Jacketing is clearly quite effective as far as strength, stiffness and ductility is concerned, but:

- It is labour intensive
- It often causes disruption of occupancy
- In many cases it provides RC elements with undesirable weight and increased stiffness [3].

5.2. Fibre Reinforced Polymer (FRP) Composites

The construction difficulties and corrosion problems mentioned above, have led to the substitution of steel plates or other conventional techniques with an alternative solution of Fibre Reinforced Polymer (FRP) composites. These, offer a proven solution since many types of such material have been successfully used for many years in other industries (e.g. aircrafts) and more recently in civil engineering construction.

FRP's consist of a large number of continuous, directionalised non-metallic fibres (usually made of **carbon**, **glass** and **aramid**) with advanced characteristics and bonded together with a resin matrix. The principal stress bearing constituents are the fibres while the resin transfers stresses among fibres and also protects them.

To facilitate their use in construction FRP materials are manufactured in many forms (Fig.4.1) such as:

- thin unidirectional prefabricated strips with thickness in the order of 1mm (Fig.4.1a)
- flexible woven or non-woven fabrics made of fibres in one or two directions (Fig.4.1b)

(a) (b)

Fig. 4.1 Manufactured forms of FRP materials.

Depending on the type of fibre, composite materials are referred to as:

- CFRP (carbon fibre based)
- AFRP (aramid fibre based)
- GFRP (glass fibre based)

In Fig. 4.2, the typical stress-strain diagrams for unidirectional composites under short-term monotonic loading are compared with the corresponding stress-strain diagram for steel.

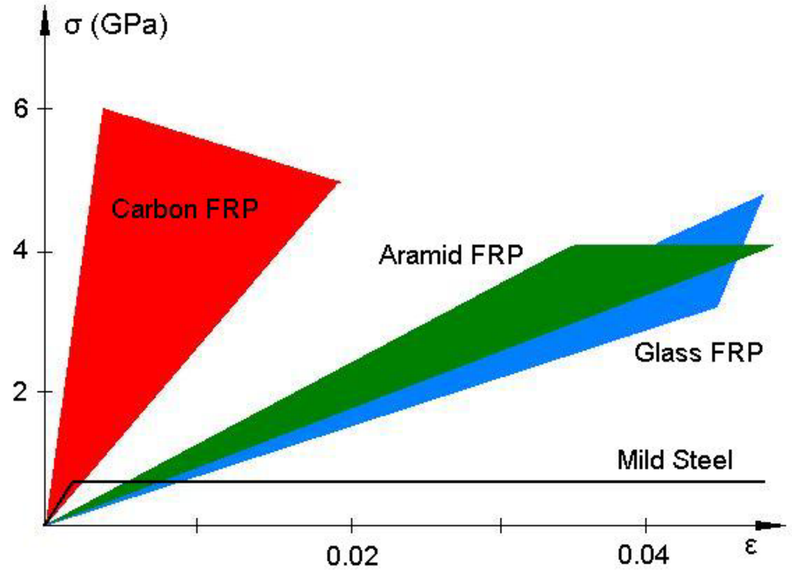


Fig. 4.2 Uniaxial stress-strain diagrams for different unidirectional FRP's [2].

5.3. FRP Constituent Materials

In the following sections the three main constituents namely fibres, adhesives and resin matrices of an FRP strengthening material system will be outlined.

5.3.1. Fibres

The three main types of fibres that are used for strengthening of structures are:

- Carbon
- Aramid
- Glass

It should be recognized that the physical and mechanical properties can vary significantly for a given type of fibre as well of course between the different fibre types. In Table 4.1, the typical properties are provided for the three forms of fibre.

Material	**Elastic Modulus (GPa)**	**Tensile Strength (MPa)**	**Ultimate Tensile Strain (%)**
Carbon	165-700	2100-4800	0.2-2.0
Aramid	70-130	3500-4100	2.5-5.0
Glass	70-90	1900-4800	3.0-5.5

Table 4.1 Typical properties of fibres

Generally, the raw material of *carbon fibres* is either pitch or PAN. Pitch fibres are fabricated by using refined petroleum or coal pitch that is passed through a thin nozzle and hardened by heating. Alternatively, PAN fibres are made of Polyacrylonitrile that is carbonized through burning. Carbon fibres offer general purpose, high strength and elasticity materials. They exhibit alkali, oxide and UV resistance, high fatigue strength and low thermal expansion coefficient.

The structure of *aramid fibre* is anisotropic and gives high strength and medium modulus in the longitudinal direction. Aramid fibres respond elastically in tension but they exhibit non-linear and ductile behaviour under compression; they also exhibit improved toughness, damage tolerance and fatigue characteristics.

Glass fibres for continuous fibre reinforcement are classified into three types: E-glass fibres, S-glass and alkali resistant AR-glass fibres. E-glass fibres, which contain high amounts of boric acid and aluminate, are disadvantageous in having low alkali resistance. S-glass fibres are stronger and stiffer than E-glass, but still not resistant to alkali. To prevent glass fibre from being eroded by cement-alkali, a considerable amount of zircon is added to produce alkali resistance AR glass fibres; such fibres have mechanical properties similar to E-glass. One of the most important aspects of glass fibres is their economy.

The resistance to corrosive factors for the above mentioned types of fibres are given in Table 4.2.

Corrosive Factors	E-glass	AR-glass	Aramid	Carbon
Water Absorption (%, 24 hrs)	-	-	0,05	-
Weak Oxides	LR	HR	HR	HR
Strong Oxides	NR	LR	LR	HR
Weak Alkalines	NR	HR	HR	HR
Strong Alkalines	NR	LR	LR	HR
Temperature	HR	HR	NR	HR
UV Radiation	HR	HR	NR	HR
NR=No Resistance LR=Low Resistance HR=High Resistance				

Table 4.2 Resistance of FRP's to corrosive factors (Pantazopoulou, 1999)

5.3.2. Adhesive

The purpose of the adhesive is to provide a shear load path between the concrete surface and the composite material, so that full composite action may develop. The most common type of structural adhesives is epoxy based, which is the result of mixing an epoxy resin (polymer) with a hardener. Depending on the application demands, the adhesive may contain fillers, softening agents, toughening additives and other constituents.

In the use of epoxy adhesives, three concepts should be taken into account; the *pot life*, the *open time* and the *glass transition temperature* respectively [1].

Pot life represents the time the applicator can work with the adhesive after mixing the resin and the hardener before it starts to harden in the mixing vessel or container.

Open time represents the time that the applicator has at his disposal after the adhesive has been applied to the bond surfaces and before they are joined together.

Glass transition temperature (T_g), represents the temperature level above which the epoxy adhesive changes from a hard, glass-like state to a relatively rubbery condition. This will result in a reduced bond capacity.

5.3.3. Matrix

The matrix for a structural composite material can either be of thermoset or of thermoplastic type, with the former being the most common. The function of the matrix is:

- to protect the fibres against abrasion or environmental corrosion
- bind the fibres together

- distribute the load

The matrix has a strong influence on several mechanical characteristics, such as transverse modulus and strength, shear values and properties in compression.

Epoxy, polyester and vinylester resins are the most common polymeric matrix materials used with high performance reinforcing fibres. They are thermosetting polymers with processibility and chemical resistance. Epoxies have enhanced mechanical properties and outstanding durability whereas polyesters and vinylesters are cheaper.

5.4. FRP Material Safety Factors

Values for the FRP material safety factor γ_f are according to fib bulletin No. 14, and are given in Table 4.3.

FRP type	Application type A(1)	Application type B(2)
CFRP	1.20	1.35
AFRP	1.25	1.45
GFRP	1.30	1.50

Table 4.3 FRP material safety factors γ_f.

Where:

(1) Application of prefab FRP systems (plates) is under normal quality control conditions. Application of wet lay-up systems with all necessary provisions taken to obtain a high degree of quality control on both the application conditions and the application process.

(2) Application of fabric FRP systems is under normal quality control conditions. Application of any system under difficult on-site working conditions.

5.5. Mechanical properties of FRPs

Basic mechanical properties of FRP materials may be estimated if the properties of the constituent materials (fibres and matrix) and their volume fraction are known. This may be accomplished by applying the "*rule of mixtures*" equation as follows:

$$E_f = E_{fib} V_{fib} + E_m V_m \qquad (4.1)$$

$$f_f \approx f_{fib} V_{fib} + f_m V_m \qquad (4.2)$$

where

E_f = Young's modulus of FRP in fibre direction
E_{fib} = Young's modulus of fibres
E_m = Young's modulus of matrix

V_{fib} = Volume fraction of fibres
V_m = Volume fraction of matrix (Note $V_{fib} + V_m = 1$)

f_f = Tensile strength of FRP in fibre direction
f_{fib} = Tensile strength of fibres
f_m = Tensile strength of matrix

Prefabricated strips → The material properties based on the total cross-sectional area can be used in calculations.

In-situ impregnated fabrics → the final FRP thickness and hence the fibre volume fraction may vary due to uncertain resin impregnation. For this reason a calculation based on the FRP properties for the total system (fibres and matrix) and the actual thickness is not appropriate. Therefore, material properties (E_f and f_f) are governed by the fibre properties and the cross-sectional area of the bare fibres. This is due to the fact that the stiffness and strength of the fibres (E_{fib} and f_{fib}) is much greater that those of the matrix (E_m and f_m).

It should be noted that since the FRP properties are based on the total cross-sectional area (fibres and matrix), the stiffness and strength is less than that of the bare fibres. It may be obvious that the strength and stiffness of the total system is not affected, because this reduction is compensated by an increase of the cross-sectional area compared to the cross-sectional area of the fibres. Therefore, there is a strong relation between the fibre volume fraction and the FRP properties to be used in the calculation.

This is shown in Table 4.4. For certain chosen properties of the fibres and the matrix, the effect of the volume fraction of the fibres on the FRP properties is obvious.

Chosen properties for constituent materials of FRP composite:
E_{fib} = 220GPa, f_{fib} = 4000MPa
E_m = 3GPa, f_{fib} = 80MPa

Cross sectional area				**FRP properties**			**Failure Load**	
A_{fib} (mm^2)	**A_m (mm^2)**	**A_f^* (mm^2)**	**V_{fib} (%)**	**E_f [eqs 4.1] (GPa)**	**f_f [eqs 4.2] (MPa)**	**Ultimate Strain (%)**	**KN**	**(%)**
70	0	70	100	220.0	4000	1.818	280.0	100
70	30	100	70	154.9	2824	1.823	282.4	100.9
70	70	140	50	111.5	2040	1.830	285.6	102.0

Table 4.4 Example showing the effect of volume fraction of fibres on the FRP properties(bulletin 14, fib).

For a constant amount of fibres (cross-sectional area = 70 mm^2) the failure load and strain at failure is minimally affected by an increase in the amount of resin. However, the FRP-properties to be used in calculations based on the total cross-sectional area are strongly influenced. Therefore for a comparison of FRP materials it may not be sufficient only to compare values for strength and/or stress-strain relations. It is also important to know the composition of the FRP material to which the given property belongs.

Generally, for in-situ impregnated systems it is convenient to base calculations on:

a) **FRP system properties**. This is possible only when the in-situ impregnated system properties are based on testing.

b) **The fibre properties and fibre cross sectional area**. In this case the second term of equations 4.1 and 4.2 may be ignored and $V_{fib}=1$. The resulting property (e.g. elastic modulus, tensile strength) should be multiplied by a reduction factor (**r**), to account for the efficiency of the fibre-resin system and for the sheet or fabric configuration.

5.6. Comparison of FRP systems: Plates-Fabrics

A difficult task that an Engineer has to confront is the comparison of different FRP systems. Suppose that an Engineer is considering two FRP systems for strengthening a reinforced concrete member and has obtained mechanical properties from the respective manufacturers.

System A: consists of a dry, carbon-fibre unidirectional fabric installed with an epoxy resin using the wet lay-up technique (e.g. SikaWrap 103C with SikaDur 300).
System B: consists of precured carbon-fibre epoxy laminates (e.g. SikaCarboDur S1012) that are bonded to the concrete surface with an epoxy resin (e.g. SikaDur 30).

System A: SikaWrap 103C	System B: Sika CarboDur S1012
Fibre Type: High strength carbon Polymer resin: SikaDur 300 Mechanical Properties (net fibre area) Thickness t_f = 0.34mm Tensile Strength f_f = 3300 N/mm^2 Ultimate tensile strain ε_{fu} = 1.5% Elastic Modulus E_f = 231kN/mm^2 Material safety factor $\gamma_{f,A}$ = 1.35	Fibre Type: High strength carbon Polymer resin: SikaDur 30 Mechanical Properties Thickness t_f = 1.2mm Tensile Strength f_f = 2800 N/mm^2 Ultimate tensile strain ε_{fu} = 1.7% Elastic Modulus E_f = 165kN/mm^2 Material safety factor $\gamma_{f,B}$ = 1.2

Table 4.5 Material properties of two systems.

After reviewing the material data sheets (Table 4.5), the Engineer compares the stiffness and tensile strengths of the two systems. Because the data sheet for the two systems are not at the same base (plates on measurement of the **hole plate-system**, fabric only on **theoretical fibre values**), a comparison of strength is not directly possible (tensile strength of fabric system = approx. 50-80% of theoretical fibre value). The modulus can be approximately compared as 1:1.

It has also to be taken into account, that the quality assurance on site (as for fabric systems) is much lower than the quality control of prefabricated plates in the factory.

Nonetheless, a comparison of the tensile strength and modulus of both systems can be made, by adjusting them with the material safety factor (suggested from fib bulletin No.14), knowing that the difference in tensile strength is more than calculated. The calculations are shown below:

Procedure	*Calculation*
Step 1A – Calculate the tensile strength per unit width of system A $p_{fu} = f_{fu} t_f / \gamma_{f,A}$	$p_{fu}=(3300*0.34)/1.35=831kN/mm$
Step 1B – Calculate the tensile strength per unit width of system B $p_{fu} = f_{fu} t_f / \gamma_{f,A}$	$p_{fu}=(2800*1.2)/1.2=2800kN/mm$
Step 2A – Calculate the tensile modulus per unit width of system A $k_f=E_f t_f/\gamma_{f,A}$	$k_f=(231x10^3x0.34)/1.35=58178N/mm$
Step 2B – Calculate the tensile modulus per unit width of system B $k_f=E_f t_f/\gamma_{f,B}$	$k_f=(165x10^3x1.2)/1.2=165000N/mm$
Step 3 – Compare the two systems Compare the tensile strength	$\frac{p_{fu}(systemB)}{p_{fu}(systemA)} = \frac{2800}{831} \approx 3.0$ ∴three plies of system A are required for each ply of system B for an equivalent **tensile strength**
Compare the stiffness	$\frac{k_f(systemB)}{k_f(systemA)} = \frac{165000}{58178} = 2.8$ ∴three plies of system A are required for each ply of system B for an equivalent **stiffness**

It can be seen from next section (§ 5), the design procedures limit the strain in the FRP material. Therefore, the full ultimate strength of the material is not utilised and should not be the basis of comparison between two material systems. When considering various FRP material systems for a particular application, the **FRP systems should be compared based on equivalent stiffness only**. In addition, each FRP system under consideration should have the ability to develop the strain level associated with the effective strain level required by the application without rupturing, $\varepsilon_{fu}>\varepsilon_{fe}$.

In many instances, it may be possible to vary the width of the FRP strip as opposed to the number of plies (use larger widths for systems with lower thickness and vice versa). In such instances, equivalent stiffness calculations will not typically yield equivalent contributions to the strength of a member. In general, **thinner (lower n t_f) and wider (higher w_f) FRP systems will provide a higher level of strength to a member due to lower bond stresses**. The exact equivalency, however, can only be found by performing complete calculations (e.g. according to ACI Committee 440) for each system.

5.7. Long term durability of FRPs

Correctly installed FRP systems appear to offer the same or improved whole life cycle cost estimates compared to other strengthening systems. Durability of both concrete and FRP is well documented, however the long-term durability of such systems is raising some concerns.

An issue critical to the effectiveness of most FRP structural applications is the FRP-substrate interface. Bond quality is influenced by many factors such as:

- Existing substrate condition
- Substrate preparation
- FRP quality
- Quality of FRP application
- Resin durability

5.7.1. Fire protection

The weakening of the adhesion layer due to the development of high temperatures is the main reason for the failure of externally bonded reinforcement. Hence, fire protection is based on limiting the temperature rise in the adhesive layer.

Sika CarboDur plates can be successfully protected against fire with fire resistant boards. The System was tested in the EMPA fire chamber to an ISO standard. There was virtually no smoke development throughout the period of the test (EMPA Test Report No. 148795,1994).

5.7.2. UV Radiation

Polymeric materials undergo degradation when exposed to sunlight and ultraviolet (UV-A and UV-B) radiation, which can cause dislocation of chemical bonds. This results in a reduction of light transmissibility and colour changes in the composite. Although one could associate this phenomenon as an indication of strength reduction, in reality this is only a surface condition that is not usually indicative of changes in structural integrity or physical damage,

Colour changes and reduced light transmissibility in composites are primarily dependant upon resin matrix and not on reinforcing fibres. As it can be seen from table 4.2, however, only the aramid fibres are affected by UV radiation.

In general, mechanical properties of the composites are only marginally influenced by UV exposure.

Protection against UV radiation is usually achieved by applying a light coloured acrylic or polyurethane based paint. This should be applied while the resin is still “tacky” to the touch. A cured resin surface should be ground before the application of paint.

5.7.3. Fatigue

Carbon FRP exhibits superior fatigue performance to that of steel. The dominant factor in the fatigue of FRP-strengthened beams is the fatigue of existing steel reinforcement.

5.7.4. Creep

Carbon based FRP’s do not creep whilst the creep of glass based FRP is negligible. However the aramid based FRP creep cannot be neglected. As AFRP creeps itself, long-term deformations increase considerably in the case of AFRP-strengthened elements.

Another important issue to consider is the poor behavior of GFRP under sustained loading. Glass fibres exhibit premature tensile rupture under sustained stress (stress rupture). Hence, the tensile strength of GFRP drops to very low values (as low as 20% of max) when the material is subject to permanent tension.

Stress corrosion occurs when the atmosphere or ambient environment is of a corrosive nature, but not sufficiently so that corrosion would occur without the addition of stress. This phenomenon is time, stress level, environment, matrix and fibre related.

Carbon fibre is relatively unaffected by stress corrosion at stress levels up to 80% of ultimate. Aramid and glass fibres are susceptible to stress corrosion.

5.7.5. Impact

Only aramid fibres exhibit a superior impact behavior. The material is used for body armour vests due to their high toughness and high fracture energy. Thus, aramid fibres can be used in cases when there is a need for protecting or strengthening structures which are endangered by explosion like terrorism attacks and require blast mitigation properties. Aramid fibers can also be used in strengthening bridge piers against accidental loading introduced by moving vehicles.

5.7.6. Temperature

Usually FRP strengthening is applied to fractured concrete sections. Thus, the presence of voids in the FRP-concrete interface may not be unusual. In cases of low temperatures and when there is an entrapment of water within those voids, the expansion of water may cause delamination of the FRP at FRP-concrete interface. Hence, the effect of freeze/thaw cycles on the behaviour of strengthened structures must be considered.

Static and dynamic stress tests have been carried out on various RC beams strengthened with Sika CarboDur Systems. The beams were subjected to high relative humidity levels and extreme temperatures of –25°C to +40°C. Ice was observed in the cracks during the freeze cycle. Despite this, the subsequent stress tests showed no weakening of the strengthening system.

5.7.7. Moisture

One of the harshest environmental factors for all structural material is the presence of moisture. Carbon and glass fibres are relatively inert to water, while aramid fibres absorb up to 13% by weight of moisture. This has a detrimental effect on tensile strength and can affect the resin-fibre interface.

Additionally , resin matrices will absorb water over a long period of time. The adsorption of water will lead to the reduction of the glass transition temperature and also to resin stiffening. Both of these effects are partially reversible in epoxy resin when the water is removed by drying.

In FRP-concrete strengthening a major concern is the internal pore water pressure. As the FRP system has a secondary effect of sealing the concrete, this internal pressure will locally accumulate. To allow vapour transfer in FRP strengthened members, sufficient zones with no externally bonded FRP may be necessary.

5.7.8. Galvanic Corrosion

Special care has to be taken when carbon fibres are in contact with steel. Carbon fibres act as a noble metal and can establish electrical cells if not electrically insulated from metals. Hence, aluminium and steel will corrode (potential galvanic corrosion) if placed in direct contact with carbon fibres. E-glass or aramid fibres may be applied first as an insulation layer.

5.7.9. Alkalinity/Acidity

As can be seen from Table 4.2, carbon fibres are resistant to both alkali and acid environments while glass and in some instances aramid fibres have no resistance.
A correctly applied resin matrix will isolate and protect the fibres and hence will postpone deterioration.

5.8. Advantages and disadvantages of FRPs

In general, FRP materials when compared to steel, are characterised by:

- Excellent corrosion resistance
- Low weight (1/4 to 1/5 of steel)
- Stiffness tailored to the design requirements
- Satisfactory chemical resistance
- Unlimited availability in geometry and dimensions
- Large deformation capacity
- Excellent fatigue strength and creep/relaxation performance

However, composites can suffer from certain disadvantages, such as:

- Brittle behaviour, i.e. linear elasticity to failure without any significant yielding (no yield plateau) or plastic deformation
- High cost of raw materials (compared on strength basis they become less unfavourable)
- Incompatible thermal expansion coefficients with concrete
- Exposure to high temperatures causes premature bond degradation

Therefore, FRP materials should not be thought as a complete replacement of steel or other materials in structural intervention. Instead, the advantages offered should be evaluated against potential drawbacks, and final decisions regarding their use should be based on consideration of several factors, including not only mechanical performance aspects, but also practicality and long-term durability.

5.9. Possible applications of FRP’s

FRP can be used in a number of external applications, including:

- External Plate Bonding of CFRP plates is already in use on many projects around the world. The lightweight nature of the plates and their originally prepared surfaces, which are suitable for bonding with epoxy resins, make them much easier to use than steel plates. However, anchoring the plate at the ends remains a concern, but a number of techniques are available.

- Wrapping of CFRP, AFRP and GFRP fabrics around structural elements. This technique aims to increase strength and ductility for seismic purposes. However, since this technique works on the principles of confinement, it can be used in cases, where deterioration of the concrete is likely to lead to expansion.

- External pretensioned FRP plates with end anchoring blocks.

6. CARBODUR FRP ANALYSIS SOFTWARE

The aim of this software is to assist the user in calculating the FRP dimensions required to provide (a) flexural strengthening, (b) shear strengthening and (c) confinement. These three topics are treated in the next sections, which present the theoretical basis of the calculations.

The equations used in this program are given in the fib Bulletin No. 14, July 2001: **"Design and use of Externally Bonded FRP Reinforcement for RC Structures"** [1].

6.1. Theoretical Background

6.1.1. Flexural Strengthening

Reinforced concrete elements, such as beams, slabs and columns, may be strengthened in flexure through the use of FRP composites epoxy-bonded to their tension zones, with the direction of fibres parallel to that of high tensile stresses (member axis). The calculations described below address both the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS).

Ultimate Limit State

The calculations are based on the assumption that one of the following two failure modes govern the behaviour:

(a) following yielding of the internal tension steel reinforcement the **concrete crushes** in the compression zone;

(b) following yielding of the internal tension steel reinforcement the **FRP reaches a limiting strain**, $\varepsilon_{f,lim}$, (this is a simplified way to treat debonding of the FRP in areas where flexure dominates the response, e.g. mid-span of simply supported beams).

The first step in the calculations is to find the initial strain, ε_o, that develops in the extreme fibre of the cross section, when the strengthening operation takes place (Fig. 5.1). This strain is the result of a moment M_o (service moment) acting at the critical cross section during strengthening (e.g. due to the self-weight of the structure), and may be calculated based on equilibrium of internal forces and moments. For the example of Fig. 5.1, the results are given below.

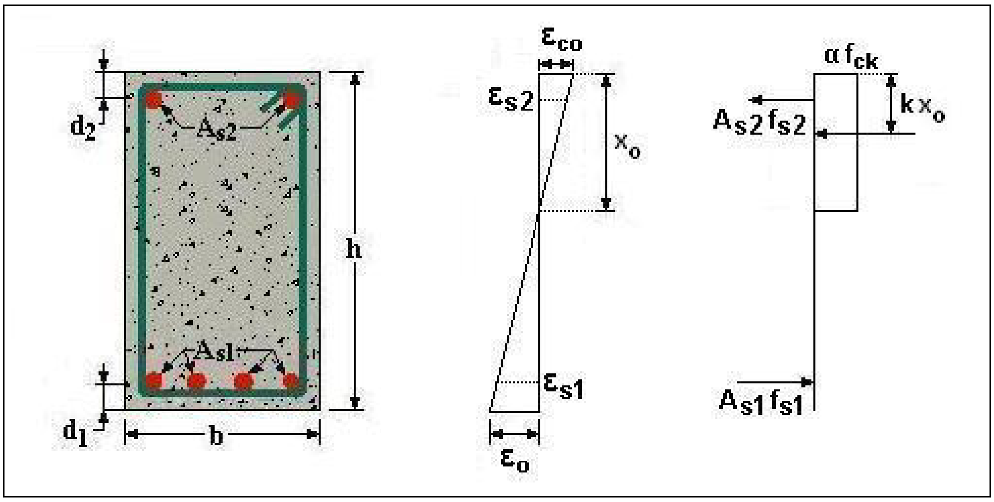


Fig. 5.1 Initial situation – equivalent stress block approach: The moment M_o acting during strengthening results in the development of an initial strain ε_o at the extreme tensile concrete fibre.

Internal force equilibrium (initial situation):

$$\alpha \cdot f_{ck} \cdot b \cdot x_o + A_{s2} f_{s2} = A_{s1} f_{s1} \tag{5.1.1}$$

Moment equilibrium (initial situation):

$$M_o = A_{s1} f_{s1} (h - d_1 - k \cdot x_o) + A_{s2} f_{s2} (k \cdot x_o - d_2) \tag{5.1.2}$$

where x_o is the depth of neutral axis from the extreme compressive fibre and f_{s1}, f_{s2} are the stresses in the bottom and top steel reinforcement, respectively.

$$f_{s1} = \varepsilon_{co} \frac{h - d_1 - x_o}{x_o} E_s \leq f_{yk} \tag{5.1.3}$$

$$f_{s2} = \varepsilon_{co} \frac{x_o - d_2}{x_o} E_s \leq f_{yk} \tag{5.1.4}$$

In the above equations f_{ck} is the characteristic (cylinder) strength of concrete, f_{yd} is the yield stress of steel and α, k are factors determining the location and magnitude of the stress resultant in the concrete compression block. These factors depend on the maximum compressive concrete strain, ε_{co}.

$$\alpha = \begin{cases} 1000\varepsilon_{co}\left(0.5 - \dfrac{1000}{12}\varepsilon_{co}\right) & if \quad \varepsilon_{co} \le 0.002 \\ 1 - \dfrac{2}{3000\varepsilon_{co}} & if \quad 0.002 \le \varepsilon_{co} \le 0.0035 \end{cases} \tag{5.1.5}$$

$$k = \begin{cases} \dfrac{8-1000\varepsilon_{co}}{4(6-1000\varepsilon_{co})} & if \quad \varepsilon_{co} \le 0.002 \\ \dfrac{1000\varepsilon_{co}(3000\varepsilon_{co}-4)+2}{2000\varepsilon_{co}(3000\varepsilon_{co}-2)} & if \quad 0.002 \le \varepsilon_{co} \le 0.0035 \end{cases} \tag{5.1.6}$$

From the numerical solution of equations (5.1.1) and (5.1.2) we calculate the maximum compressive concrete strain, ε_{co}, and the neutral axis depth x_o. Finally, the initial strain ε_o is given as:

$$\varepsilon_o = \varepsilon_{co}\frac{h-x_o}{x_o} \tag{5.1.7}$$

Once ε_o is calculated, the analysis of the critical cross section for the ULS (Ultimate Limit State) is performed on the basis of Fig. 5.2, which shows the strain profile and internal forces at the Ultimate Limit State.

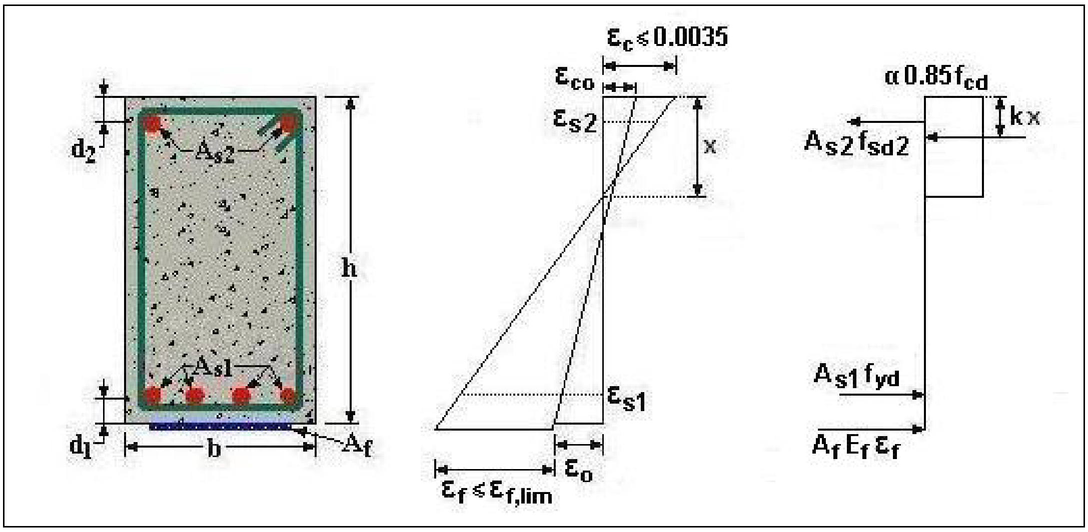


Fig. 5.2 Analysis of rectangular cross section (strain profile and internal forces) for the ultimate limit state in bending.

Internal force equilibrium:

$$\alpha \cdot 0.85 f_{cd} \cdot b \cdot x + A_{s2} f_{sd2} = A_{s1} f_{yd} + A_f E_f \varepsilon_f \qquad (5.1.8)$$

Resisting design moment:

$$M_{rd} = A_{s1} f_{yd} (h - d_1 - k \cdot x) + A_{s2} f_{sd2} (k \cdot x - d_2) + A_f E_f \varepsilon_f (h - k \cdot x) \qquad (5.1.9)$$

where A_f, E_f and ε_f is the cross section area, elastic modulus and strain of FRP reinforcement, respectively. The FRP strain and the stress in the top steel reinforcement are given in terms of the maximum compressive concrete strain, ε_c, and the neutral axis depth as follows:

$$f_{sd2} = \varepsilon_c \frac{x - d_2}{x} E_s \leq f_{yd} \qquad (5.1.10)$$

$$\varepsilon_f = \varepsilon_c \frac{h - x}{x} - \varepsilon_o \leq \varepsilon_{f,\lim} \qquad (5.1.11)$$

Note that the factors α and k in equations (5.1.8) and (5.1.9) are given as before, by eqs. (5.1.5) and (5.1.6), with ε_{co} replaced by ε_c.

The solution of equations (5.1.8) and (5.1.9) is performed numerically through iterations, yielding the required FRP cross section A_f.

Serviceability Limit State

For the SLS (Serviceability Limit State), the analysis of the critical cross section is performed, according to EC2, for the two possible load combinations: Rare load, Quasi-permanent load.

For the case of Rare Load the calculations are performed as in the case of the ULS, with the following modifications:

(a) 0.85fcd in eq. (5.1.8) and in Fig. 5.2 is replaced by f_{ck};
(b) M_{rd} is replaced by the acting moment (under the rare load combination) $M_{ser,r}$;
(c) f_{yd} (the tension steel stress) is replaced by f_{s1};
(d) the stress limitations are $f_{s1} <= 0.8 f_{yk}$ (for steel) and $\sigma_c <= 0.6 f_{ck}$, where the stress in the concrete is given by the following stress-strain relationship of concrete (for ε_c less than 0.002):

$$\sigma_c = \frac{\varepsilon_c \left(2 - \dfrac{\varepsilon_c}{0.002} \right)}{0.002} f_{ck} \tag{5.1.12}$$

For the case of Quasi-permanent Load the calculations are performed as in the case of the ULS, with the following modifications:

(a) $0.85f_{cd}$ in eq. (5.1.8) and in Fig. 5.2 is replaced by f_{ck};

(b) M_{rd} is replaced by the acting moment (under the quasi-permanent load combination) $M_{ser,q\text{-}p}$;

(c) f_{yd} (the tension steel stress) is replaced by f_{s1};

(d) ε_c in eqs. (5.1.5) – (5.1.6) is replaced by $\varepsilon_c/(1+\varphi)$, where φ is the creep coefficient;

(e) the stress limitations are $f_{s1} <= 0.8f_{yk}$ (for steel) and $\sigma_c <= 0.45fck$, where the stress in the concrete is given by equation (5.1.12), with ε_c replaced by $\varepsilon_c/(1+\varphi)$.

Bond check

For user-defined dimensions of the FRP cross section geometry (n strips of width b_f and thickness t_f placed in m layers, n/m should be an integer if m > 1) the programme calculates the maximum force, $N_{bd,max}$, that can be carried by the total number of strips, and the associated bond length, $l_{bd,max}$, before debonding of the external reinforcement initiates at the ends (anchorage zone), see Fig. 5.3. These calculations are based on the following equations:

$$l_{bd,\max} = 0.6 \sqrt{\frac{E_f (m t_f)}{f_{ctd}}} \tag{5.1.13}$$

$$N_{bd,\max} = \frac{n}{m} \cdot 0.5 \cdot k_b b_f \sqrt{E_f (m t_f) f_{ctd}} \tag{5.1.14}$$

where:

$$k_b = \max \left(1, 1.06 \cdot \sqrt{\frac{2 - \left(\dfrac{b_f}{b/(n/m)} \right)}{1 + (\dfrac{b_f}{400})}} \right) \tag{5.1.15}$$

b = beam width [note that b/(n/m) equals the spacing of strips if the number of layers >1]

f_{ctd} = design value of the tensile strength of the substrate in N/mm^2, that is the tensile strength of concrete near the surface

$l_{bd,max}$ is in mm, $N_{bd,max}$ is in N, b_f and t_f are in mm, E_f is in N/mm^2.

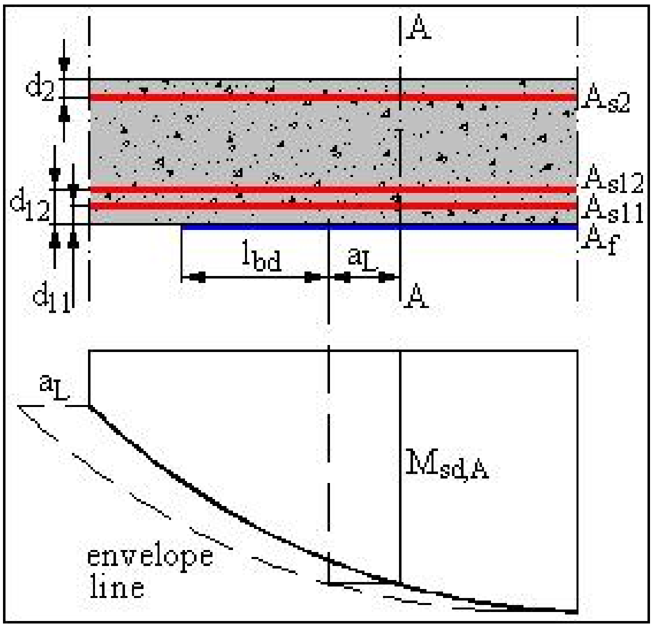


Fig. 5.3 Bending moment envelope line and definition of bond length corresponding to section A.

At each cross section (for example A), equilibrium and strain compatibility equations yield the tensile force $N_{fd,A}$ carried by each strip. If this force does not exceed $N_{bd,max}$, then the bond check is verified, that is failure of the anchorage is not expected, provided that the appropriate bond length l_{bd} will be available. The bond length corresponding to $N_{fd,A}$ is calculated as follows:

$$l_{bd,A} = l_{bd,\max}\left[1-\sqrt{1-\left(\frac{N_{fd,A}}{N_{bd,\max}}\right)}\right] \qquad (5.1.16)$$

As mentioned above, $N_{fd,A}$ is the tensile force carried by the FRP. This is calculated by multiplying the cross sectional area A_f by the product of elastic modulus times strain, $E_f\varepsilon_f$, where ε_f results through cross section equilibrium and compatibility. The equations in this case are identical to those used in the ULS, with the provision that the tensile steel reinforcement may not be yielding. Hence the same formulas used for the ULS apply, with:

(a) M_{rd} replaced by the design value of the bending moment acting at section A, $M_{sd,A}$;

(b) f_{yd} replaced by f_{sd1};

(c) ε_o taken approximately equal to that corresponding to Mo, times the reduction factor ($M_{sd,A}/M_{sd}$). This implies the assumption that the bending moment during strengthening at cross section A, $M_{o,A}$, is equal to M_o (acting at the critical section) reduced by the factor $M_{sd,A}/M_{sd}$ (note that M_{sd} is acting at the critical section).

6.1.2. Shear Strengthening

Shear strengthening of RC members using FRP may be provided by bonding the external reinforcement with the principal fibre direction as parallel as practically possible to that of maximum principal tensile stresses, so that the effectiveness of FRP is maximised. For the most common case of structural members subjected to lateral loads, the maximum principal stress trajectories in the shear-critical zones form an angle with the member axis that may be approximately 45°. However, it is normally more practical to attach the external FRP reinforcement with the principal fibre direction perpendicular to the member axis (Fig. 5.4).

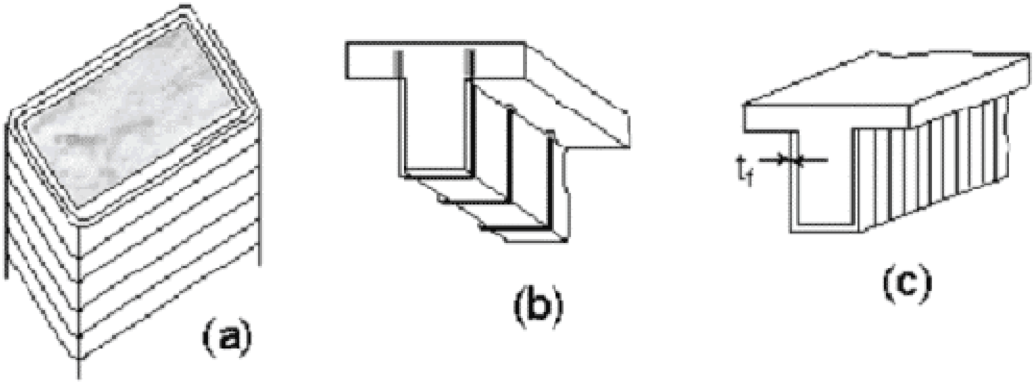


Fig. 5.4 Examples of shear strengthening with: (a) closed (properly anchored) jackets; (b) discrete strips anchored in the compression zone; and (c) open jackets.

Closed jackets (Fig. 5.4a) or properly anchored strips (Fig. 5.4b) are always preferable to open jackets (Fig. 5.4c), as in the latter case the FRP can debond prematurely and may therefore be of reduced effectiveness.

The external FRP reinforcement may be treated in analogy to the internal steel (accepting that the FRP carries only normal stresses in the principal FRP material direction), assuming that at the Utimate Limit State in shear (concrete diagonal tension) the FRP develops an effective strain in the principal material direction, $\varepsilon_{f,e}$ which is, in general, less than the tensile failure strain, ε_{fu}. The effective strain depends on the degree of FRP debonding when the shear capacity of the RC is reached, that is on the type of anchorage (properly anchored FRP, e.g. closed jackets, versus poorly anchored FRP, i.e. open jackets). Hence, the shear capacity of a strengthened element may be calculated as follows (e.g. in Eurocode 2 format):

$$V_{Rd} = \min\left(V_{cd} + V_{wd} + V_{fd}, V_{Rd2}\right) \qquad (5.1.17)$$

where V_{fd}, the contribution of FRP to the member's shear capacity, is given by the following expression.

$$V_{fd} = 0.9 \cdot \varepsilon_{fd,e} \cdot E_f \rho_f \cdot bd(1 + \cot a)\sin a \qquad (5.1.18)$$

In the above equation E_f is the elastic modulus of FRP, b is the width of the cross section, d is the static (or effective) depth, α is the angle between the principal FRP fibre orientation and the longitudinal axis of the member, $\varepsilon_{fd,e}$ is the design value of the effective FRP strain and ρ_f is the FRP reinforcement ratio, equal to $(2t_f/b)\sin\alpha$ for continuously bonded FRP of thickness t_f, or $(2t_f/b)(b_f/s_f)$ for FRP reinforcement in the form of strips or sheets of width b_f (perpendicular to the fibre orientation) at a spacing s_f (axis to axis of strips along the member axis). Equation (5.1.18) may be calculated for the thickness of FRP required to provide a shear resistance equal to V_{fd}.

The effective FRP may be estimated as follows:

- Fully wrapped or properly anchored CFRP or GFRP:

$$\varepsilon_{fd,e} = \min\left[\frac{k \cdot 0.17\varepsilon_{fu}\left(\dfrac{f_{cm}^{2/3}}{E_f \rho_f}\right)^{0.3}}{\gamma_{f,f}}, \frac{\varepsilon_{f,\lim}}{\gamma_{f,1}}\right] \qquad (5.1.19a)$$

- Fully wrapped or properly anchored AFRP:

$$\varepsilon_{fd,e} = \min\left[\frac{k \cdot 0.048\varepsilon_{fu}\left(\dfrac{f_{cm}^{2/3}}{E_f \rho_f}\right)^{0.47}}{\gamma_{f,f}}, \frac{\varepsilon_{f,\lim}}{\gamma_{f,1}}\right] \qquad (5.1.19b)$$

- Open FRP jackets (e.g. side or U-shaped sheets):

$$\varepsilon_{fd,e} = \min\left[\frac{k \cdot 0.17\varepsilon_{fu}\left(\dfrac{f_{cm}^{2/3}}{E_f \rho_f}\right)^{0.3}}{\gamma_{f,f}}, \frac{k \cdot 0.65 \cdot 10^{-3}\left(\dfrac{f_{cm}^{2/3}}{E_f \rho_f}\right)^{0.56}}{\gamma_{f,b}}, \frac{\varepsilon_{f,\lim}}{\gamma_{f,1}}\right]$$

(5.1.20)

In the above, f_{cm} is the mean compressive strength of concrete in N/mm^2, E_f is measured in kN/mm^2, k is a constant relating the characteristic to the mean value of the effective FRP strain (default: k = 0.8) and γ_f is the FRP material safety factor. The γ_f factor depends on the type of FRP material as well as on the failure mode governing shear design. The first term in eqs. (5.1.19a), (5.1.19b) and (5.1.20) corresponds to FRP fracture (when the member's shear capacity is reached), hence the use of $\gamma_{f,f}$ (= 1.20 for CFRP, 1.25 for AFRP, 1.30 for GFRP), the second term in eq. (5.1.19) corresponds to FRP debonding, hence the use of $\gamma_{f,b}$ (= 1.30), and the last term is taken (with $\gamma_{f,l}$ = 1.25) if it is desired to limit the FRP strain in order to maintain the integrity of concrete and secure activation of the aggregate interlock mechanism.

In cases where the cross section is circular (usually in columns) the contribution of FRP (closed jacket) to shear capacity is regulated by the tensile strength of the FRP jacket, but may be limited to a maximum value corresponding to excessive expansion of the concrete due to aggregate interlock at inclined cracks. By limiting the concrete expansion , that is the radial strain to a maximum value, ε_{max}, the FRP shear capacity calculated as:

$$V_{fd} = \frac{\varepsilon_{\max}}{\gamma_f} E_{fu} \rho_f \frac{1}{2} \frac{\pi D^2}{4} \cot\theta \qquad (5.1.21)$$

where D is the column diameter, ρf the volumetric ratio of FRP and θ is the angle formed by the inclined cracks and the column axis. Experimental evidence suggests that ε_{max} is in the order of 0.006.

6.1.3. Confinement

The main objectives of confinement are:

(a) to enhance concrete strength and deformation permission,
(b) to provide lateral support to the longitudinal reinforcement
(c) to prevent the concrete cover from spalling.

In the case of circular columns, these goals can be achieved by applying external FRP jackets, either continuously over the entire surface or intermittently as strips. In the case of rectangular columns, the confinement can be provided with rectangular-shaped reinforcement, with corners rounded before application. Note that rectangular confining reinforcement is less effective (but still possible) as the confinement action is mostly located at the corners and a significant jacket thickness needs to be used between corners to restrain lateral expansion and rebar buckling.

The stress-strain response of FRP-confined concrete is illustrated schematically in Fig. 5.5. The graph displays a near bilinear response with a sharp softening and a transition zone at a stress level that is close to the strength of unconfined concrete, f_{co}. After this stress the tangent stiffness changes a little, until the concrete reaches its ultimate strength f_{cc} when the jacket reaches tensile failure at a stress $f_{f,e}$ and a corresponding strain $\varepsilon_{fu,e}$, which is, in general, less than the uniaxial tensile strength εfu.

This reduction is attributed to several factors, including: (a) the triaxial state of stress in the FRP (due to axial loading and confining action, but also due to bending, e.g. at corners of low radius); and (b) the quality of execution (potential local ineffectiveness of some fibres due to misalignment, and overstressing of others, damaged fibres at sharp corners or local protrusions etc).

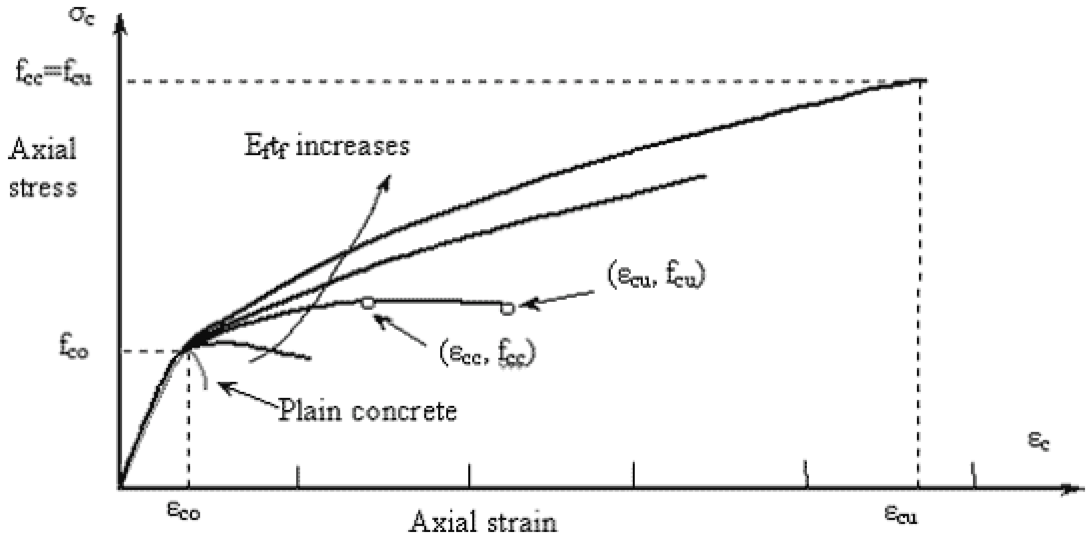


Fig. 5.5 Stress-strain curves for plain (unconfined) and FRP-confined concrete.

For rectangular cross sections with dimensions b and h (b>=h), Fig. 5.6, the effect of FRP confinement may be calculated based on the following expressions for the confined concrete strength f_{cc} and the corresponding strain ε_{cu}:

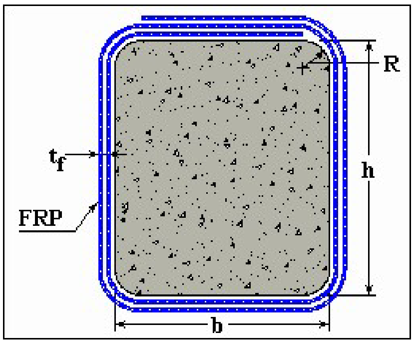


Fig. 5.6 Rectangular cross section with radius R at corners.

$$f_{cc} = E_{\sec,u} \cdot \varepsilon_{cu} \geq f_{co} \tag{5.1.22}$$

$$\varepsilon_{cu}=\varepsilon_{co}\left[1+5(\alpha_1\alpha_2-1)\right]\left[\frac{E_{cc}\left(E_{co}-E_{\sec,u}\right)}{E_{\sec,u}\left(E_{co}-E_{cc}\right)}\right]^{1-\frac{E_{cc}}{E_{co}}} \qquad (5.1.23)$$

where

$$E_{\sec,u}=\frac{E_{co}}{1+2\beta\varepsilon_{fu,e}} \qquad (5.1.24)$$

$$\beta=\frac{E_{co}}{f_{co}}-\frac{1}{\varepsilon_{co}} \qquad (5.1.25)$$

$$E_{cc}=\frac{\alpha_1\alpha_2 f_{co}}{\varepsilon_{co}\left[1+5(\alpha_1\alpha_2-1)\right]} \qquad (5.1.26)$$

$$\alpha_1=2.254\cdot\sqrt{1+7.94\frac{\sigma_{1,b}}{f_{co}}}-2\frac{\sigma_{1,b}}{f_{co}}-1.254 \qquad (5.1.27)$$

$$\alpha_2=1-\left[0.6\left(\frac{h}{b}\right)^2-1.4\frac{h}{b}+0.8\right]\cdot\sqrt{\frac{\sigma_{1,b}}{f_{co}}} \qquad (5.1.28)$$

$$\sigma_{1,b}=\frac{2t_f}{h}k_e\cdot f_{f,e} \qquad (5.1.29)$$

$$k_e=1-\frac{(b-2R)^2+(h-2R)^2}{3A_g} \qquad (5.1.30)$$

(Confinement effectiveness coefficient)

E_{co} = initial elastic modulus of concrete, ε_{co} = 0.002 (strain corresponding to f_{co}), A_g = gross sectional area of concrete = bh-(4-π)R_2.

Note that for circular cross sections of diametre D confined with strips of width b_f at a spacing s_f, k_e is given as follows:

$$k_e=\left[1-\frac{\left(s_f-b_f\right)}{2D}\right]^2 \qquad (5.1.31)$$

6.2. Use of CarboDur FRP Analysis Software

6.2.1. General

The software package FRP-Analysis may be employed as a user friendly, simple and reliable design tool for the selection of FRP dimensions to provide flexural strengthening, shear strengthening or confinement of reinforced concrete sections. Essentially, the software is divided into two procedures. The first is related to definitions of input data, solution options and print options, whereas the second involves presentation of results, selection of appropriate number of FRP strips or layers and printing of information. Between the two distinct procedures lies the numerical solutions algorithm.

Sika® CarboDur®
Composite
Strengthening Systems

A Software for the Design with Sika CarboDur Composite Strengthening Systems to increase the Flexural, Shear and Confinement Strength of Reinforced Concrete Structures, based on the *fib* Bulletin 14.

The program was developed in collaboration with the Department of Civil Engineering, University of Patras, Greece.

When the program starts, the user is asked to provide "Data Input" for one of the following three cases: *flexural strengthening (ULS and SLS)*, *shear strengthening* or *confinement*. When all data is provided, the user may either proceed to the "Solution" or initialise the input parameters through the "New Input" option. During the data input process, the program checks the validity of input parameters and provides warnings if incorrect actions are taken. Through a series of "Options" the user may define print-related information, or even change the default values for FRP material safety factors. Finally, the commands "Open" and "Save" provide the opportunity to the user to track the various strengthening projects, whose input data are loaded and saved by demand.

By clicking "Solution", the program's "heart", the problem solving procedure is activated. When the procedure is completed, results are provided in terms of the FRP cross sectional area (in case of flexural strengthening) or total FRP thickness (in case of shear strengthening or confinement) required for a given problem. In the case of flexural strengthening, additional information is provided regarding the degree of strengthening (moment capacity after strengthening divided by that before strengthening), the strain profile (e.g.

neutral axis depth, concrete, steel and FRP strains) during strengthening as well as that after strengthening, the ductility, the failure mode, the acting moment before strengthening (at the SLS) and the maximum achievable acting moment (at the SLS). Finally, the user has the option to input dimensions of actual FRP products (e.g. thickness and width of strips in the case of flexural strengthening, thickness of each layer in the case of shear strengthening or confinement) and the program responds with the calculation of number of strips or layers and the corresponding capacity (flexural, shear or confinement).

6.2.2. Flexural Strengthening

DATA INPUT

The user is required to provide input as described in the following:

Type of Cross Section

The option "T-beam" is selected for T-shaped cross sections or "Rectangular beam" for rectangular sections. The last option also includes slab sections.

Cross Section Geometry

Width b: input the width in m.

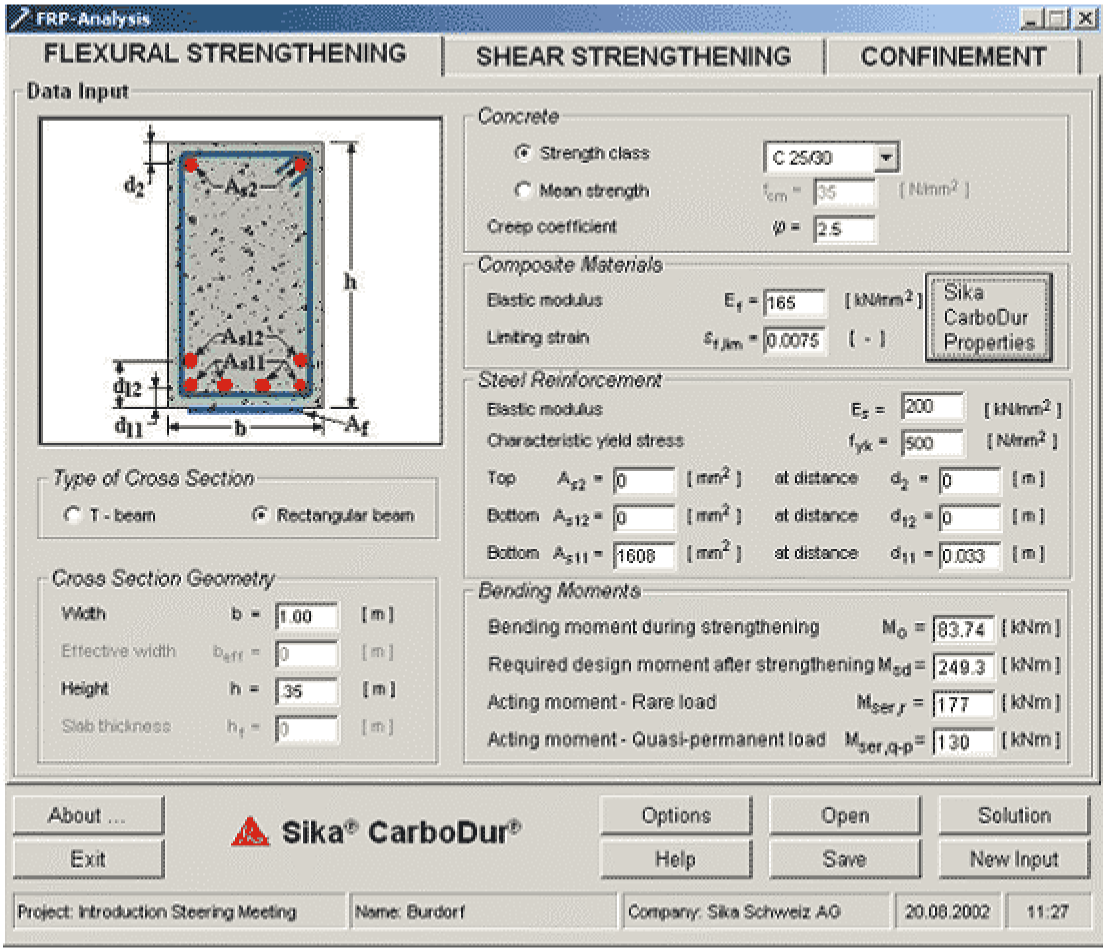
Height h: input the height in m.

Effective width b_{eff}: input the effective width in m (only in the case of T-beams).

Slab thickness h_f: input the slab thickness in m (only in the case of T-beams).

Concrete

The user has the option either to select the strength class of concrete (if known) or to input the mean strength (f_{cm}) in N/mm2. The assumed relationship between the two is: $f_{ck} = f_{cm} - 1.64 \times 5$. Moreover, the user has the option to input the creep coefficient (estimated according to EC2 procedures), which is used in the Serviceability Limit State verification for quasi-permanent loads. The default value of 2.5 is assumed here.



Data Input

Concrete

● Strength class C 25/30

○ Mean strength f_{cm} = 35 [N/mm²]

Creep coefficient φ = 2.5

Composite Materials

Elastic modulus E_f = 165 [kN/mm²]

Limiting strain $\varepsilon_{f,lim}$ = 0.0075 [-]

Steel Reinforcement

Elastic modulus E_s = 200 [kN/mm²]

Characteristic yield stress f_{yk} = 500 [N/mm²]

Top A_{s2} = 0 [mm²] at distance d_2 = 0 [m]

Bottom A_{s12} = 0 [mm²] at distance d_{12} = 0 [m]

Bottom A_{s11} = 1608 [mm²] at distance d_{11} = 0.033 [m]

Type of Cross Section

○ T - beam ● Rectangular beam

Cross Section Geometry

Width b = 1.00 [m]

Effective width b_{eff} = 0 [m]

Height h = 35 [m]

Slab thickness h_f = 0 [m]

Bending Moments

Bending moment during strengthening M_0 = 83.74 [kNm]

Required design moment after strengthening M_{sd} = 249.3 [kNm]

Acting moment - Rare load $M_{ser,r}$ = 177 [kNm]

Acting moment - Quasi-permanent load $M_{ser,q\text{-}p}$ = 130 [kNm]

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Composite Materials

By clicking the button "Sika CarboDur Properties", characteristics of the various CarboDur systems are provided for consultation.

Elastic modulus E_f: Input the elastic modulus of FRP in kN/mm² (provided by the material supplier).

Limiting strain $\varepsilon_{f,lim}$: Input the limiting strain of the FRP (non-dimensional data !). Beyond this value, the FRP may debond in the areas of high bending moments (flexural cracks). Suggested (default) value = 0.008.

Steel Reinforcement

Elastic modulus E_s: Input the elastic modulus of the longitudinal steel reinforcement in kN/mm². The default value is 200 kN/mm².

Characteristic yield stress f_{yk}: Input the characteristic yield stress of the longitudinal steel reinforcement in N/mm², e.g. 500 for steel S500.

Top As_2: Input the total cross sectional area of the steel reinforcement in the compression zone (if present) (in mm2).

At distance d_2: Input the distance from the centroid of As_2 to the extreme compressive fibre of the cross section (in m).

Bottom As_{12}: Input the total cross sectional area of the second layer (if present) of steel reinforcement in the tension zone (in mm²).

At distance d_{12}: Input the distance from the centroid of As_{12} to the extreme tensile fibre of the cross section (in m).

Bottom As_{11}: Input the total cross sectional area of the first layer of steel reinforcement in the tension zone (in mm^2).
At distance d_{11}: Input the distance from the centroid of As_{11} to the extreme tensile fibre of the cross section (in m).

Bending Moments

Bending moment during strengthening M_o: Input the bending moment applied to the cross section during strengthening (service moment), that is the moment that develops (e.g. due to gravity loads) when the strengthening process takes place (in kNm).
Required design moment after strengthening M_{sd}: Input the design value of the resisting bending moment after strengthening, (in kNm) for the Ultimate Limit State verification.

Acting moment - Rare load $M_{ser,r}$: Input the bending moment acting at the critical cross section due to the rare load combination of the Serviceability Limit State (in kNm).

Acting moment - Quasi-permanent load $M_{ser,q-p}$: Input the bending moment acting at the critical cross section due to the quasi-permanent load combination of the Serviceability Limit State (in kNm).

Commands

Solution: The program checks for input errors and provides the solution.

New Input: All input data values may be initialized through this command.
Help: Activates the help facility.
Options: Activates the options described in Section 5.2.5.
Save: Saves all the input data in a file.
Open: Accesses a data file, where input data may have been saved.
About: Activates the program's introductory window.
Exit: Exits the program.

Information Line

The following information is shown: Project Name Company Date Time

The first three items of information are provided by the user through “Options”, “General”, whereas the latter two details, the date and time, are automatically provided by the system.

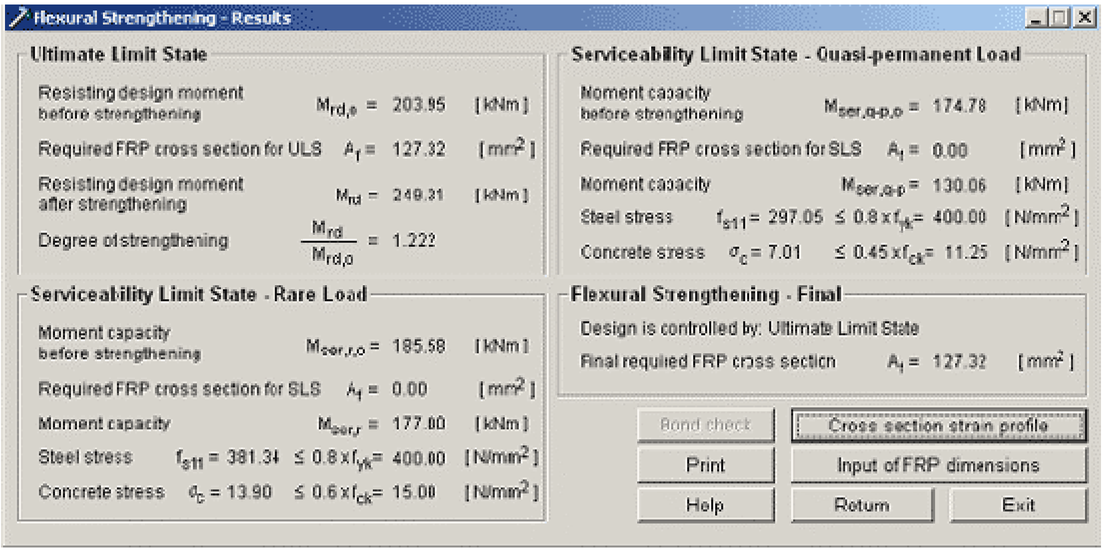
*****General Remarks*****

For each value input provided by the user the program checks that this value is “reasonable” (e.g. not too high, not too low) and provides a warning if this is not the case. Warnings are also provided if the user inputs wrong characters (e.g. a letter instead of a number) or if they forget to complete a box. Additional checks are made by the program, the corresponding warnings provided, if a combination of values does not make sense (e.g. the effective width of a slab cannot be less than the beam's width).

When "Solution" is selected, the program performs a number of checks. Warning messages are provided when the required design moment after strengthening is too high (so that the section cannot be strengthened, no matter how much FRP is provided) or too low (that is less than the resisting design moment before strengthening).

RESULTS

Upon completion of the solution process, the "Results" window provides the following.



Ultimate Limit State

Resisting design moment before strengthening $M_{rd,o} = 203.95$ [kNm]

Required FRP cross section for ULS $A_f = 127.32$ [mm^2]

Resisting design moment after strengthening $M_{rd} = 249.31$ [kNm]

Degree of strengthening $\frac{M_{rd}}{M_{rd,o}} = 1.222$

Serviceability Limit State - Rare Load

Moment capacity before strengthening $M_{ser,r,o} = 185.58$ [kNm]

Required FRP cross section for SLS $A_f = 0.00$ [mm^2]

Moment capacity $M_{ser,r} = 177.00$ [kNm]

Steel stress $f_{s11} = 381.34 \leq 0.8 \times f_{yk} = 400.00$ [N/mm^2]

Concrete stress $\sigma_c = 13.90 \leq 0.6 \times f_{ck} = 15.00$ [N/mm^2]

Serviceability Limit State - Quasi-permanent Load

Moment capacity before strengthening $M_{ser,q\text{-}p,o} = 174.78$ [kNm]

Required FRP cross section for SLS $A_f = 0.00$ [mm^2]

Moment capacity $M_{ser,q\text{-}p} = 130.06$ [kNm]

Steel stress $f_{s11} = 297.05 \leq 0.8 \times f_{yk} = 400.00$ [N/mm^2]

Concrete stress $\sigma_c = 7.01 \leq 0.45 \times f_{ck} = 11.25$ [N/mm^2]

Flexural Strengthening - Final

Design is controlled by: Ultimate Limit State

Final required FRP cross section $A_f = 127.32$ [mm^2]

Ultimate Limit State

Resisting design moment before strengthening $M_{rd,o}$: This is the value of the resisting design moment calculated without the use of FRP.

Required FRP cross-section for ULS A_f: Total FRP cross sectional area to be added to the tension face in order to verify the ULS.

Resisting design moment after strengthening M_{rd}: This is the value of the resisting design moment corresponding to the above FRP cross section A_f. Note that this value might be slightly different from the one input by the user, due to round-off measures.

Degree of strengthening $M_{rd}/M_{rd,o}$: The ratio of the resisting design moment after strengthening to that before strengthening.

Serviceability Limit State - Rare Load

Moment capacity before strengthening $M_{ser,r,o}$: This is the value of the moment capacity calculated without the use of FRP. A warning will be provided if the bending moment during strengthening M_o is higher than $M_{ser,r,o}$.

Required FRP cross-section for SLS A_f: Total FRP cross sectional area to be added to the tension face in order to verify the SLS for the Rare Load combination.

Moment capacity $M_{ser,r}$: Value of the moment capacity corresponding to the above FRP cross section A_f. Note that this value might be slightly different from the one input by the user, due to round-off measures.

Steel stress fs_{11}: Stress in the extreme tension steel reinforcement for the SLS verification under the Rare Load combination.

Concrete stress σ_c: Maximum stress in the concrete for the SLS verification under the Rare Load combination.

Note that for the SLS verification under the Rare Load combination either the steel or the concrete stress has reached its respective limiting value. For the steel stress the limiting value is $0.8f_{yk}$ and for the maximum concrete stress the limiting value is $0.6f_{ck}$. If $M_{ser,r}$ is lower than $M_{ser,r,o}$, no FRP is needed for the SLS verification under the Rare Load combination, and in this case none of the above materials reaches its respective limiting value.

Serviceability Limit State - Quasi-permanent Load

Moment capacity before strengthening $M_{ser,q\text{-}p,o}$: This is the value of the moment capacity calculated without the use of FRP. A warning will be provided if the bending moment during strengthening Mo is higher than $M_{ser,q\text{-}p,o}$.

Required FRP cross-section for SLS A_f: Total FRP cross sectional area to be added to the tension face in order to verify the SLS for the Quasi-permanent Load combination.

Moment capacity $M_{ser,q\text{-}p}$: Value of the moment capacity corresponding to the above FRP cross section A_f. Note that this value might be slightly different from the one input by the user, due to round-off errors.

Steel stress fs_{11}: Stress in the extreme tension steel reinforcement for the SLS verification under the Quasi-permanent Load combination.

Concrete stress σ_c: Maximum stress in the concrete for the SLS verification under the Quasi-permanent Load combination.

Note that for the SLS verification under the Quasi-permanent Load combination either the steel or the concrete stress has reached its respective limiting value. For the steel stress the limiting value is $0.8f_{yk}$ and for the maximum concrete stress the limiting value is $0.45f_{ck}$. If $M_{ser,q\text{-}p}$ is lower than $M_{ser,q\text{-}p,o}$, no FRP is needed for the SLS verification under the Quasi-permanent Load combination, and in this case none of the above materials reaches its respective limiting value.

Flexural Strengthening - Final

Design is controlled by: the Limit State controlling the design (corresponding to the maximum of the three A_f values, calculated for ULS, SLS - Rare Load, SLS - Quasi-permanent Load) is provided here.

Final required FRP cross section A_f: The maximum of the three A_f values (calculated for ULS, SLS - Rare Load, SLS - Quasi-permanent Load) is provided here.

Commands

Cross section strain profile: Activates a window with the deformation characteristics of the cross section, both graphically and with numbers.

Initial Situation During Strengthening (M_o)

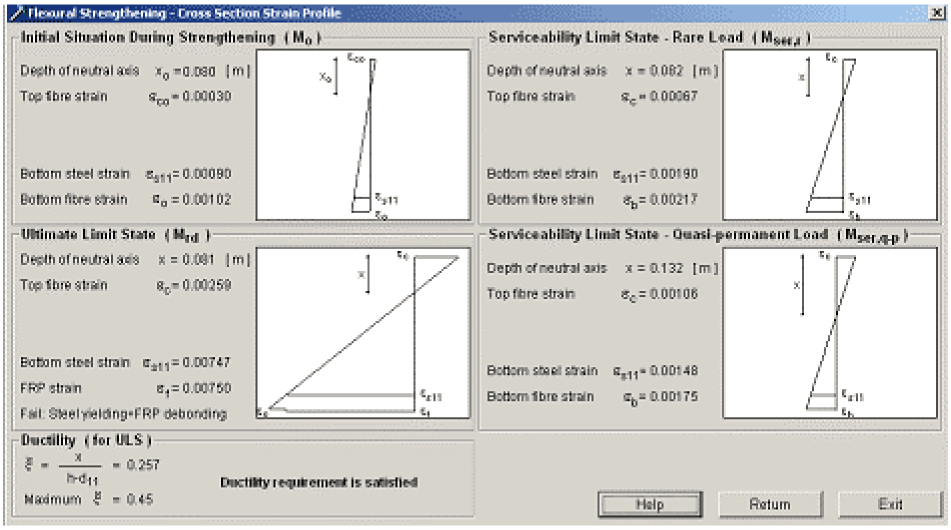
- Depth of neutral axis: depth of neutral axis in m, during strengthening (due to M_o).
- Top fibre strain: strain in the extreme concrete compressive fibre during strengthening (due to M_o).
- Top steel strain: strain in the top steel reinforcement during strengthening (due to M_o).
- Bottom steel strain: strain in the bottom steel reinforcement during strengthening (due to M_o).
- Bottom fibre strain: strain in the extreme concrete tensile fibre during strengthening (due to M_o).

Ultimate Limit State (Mrd)

- Depth of neutral axis: depth of neutral axis (in m) when M_{rd} is reached.
- Top fibre strain: strain in the extreme concrete compressive fibre when M_{rd} is reached. If this value equals 0.0035, compressive crushing of the concrete occurs.
- Top steel strain: strain in the top steel reinforcement when M_{rd} is reached.
- Bottom steel strain: strain in the bottom steel reinforcement when M_{rd} is reached.

- FRP strain: strain in the FRP when M_{rd} is reached. If this value equals the limiting strain $\varepsilon_{f,lim}$ (default = 0.008), debonding of the FRP occurs.

- Fail: The failure mode assosiated to ULS is reported.



Flexural Strengthening - Cross Section Strain Profile

Initial Situation During Strengthening (M_0)

Depth of neutral axis x_0 = 0.080 [m]
Top fibre strain ε_{c0} = 0.00030
Bottom steel strain ε_{s11} = 0.00090
Bottom fibre strain ε_0 = 0.00102

Serviceability Limit State - Rare Load ($M_{ser,r}$)

Depth of neutral axis x = 0.082 [m]
Top fibre strain ε_c = 0.00067
Bottom steel strain ε_{s11} = 0.00190
Bottom fibre strain ε_b = 0.00217

Ultimate Limit State (M_{rd})

Depth of neutral axis x = 0.081 [m]
Top fibre strain ε_c = 0.00259
Bottom steel strain ε_{s11} = 0.00747
FRP strain ε_f = 0.00750
Fail: Steel yielding+FRP debonding

Serviceability Limit State - Quasi-permanent Load ($M_{ser,q-p}$)

Depth of neutral axis x = 0.132 [m]
Top fibre strain ε_c = 0.00106
Bottom steel strain ε_{s11} = 0.00148
Bottom fibre strain ε_b = 0.00175

Ductility (for ULS)

$\xi = \frac{x}{h-d_{11}} = 0.257$
Maximum ξ = 0.45

Ductility requirement is satisfied

Ductility (for ULS)

The ratio of neutral axis depth is calculated and compared with the maximum value provided by EC2. A statement is provided related to the ductility requirement.

Serviceability Limit State - Rare Load ($M_{ser,r}$)

- Depth of neutral axis: depth of neutral axis (in m) corresponding to $M_{ser,r}$.

- Top fibre strain: strain in the extreme concrete compressive fibre corresponding to $M_{ser,r}$.

- Top steel strain: strain in the top steel reinforcement corresponding to $M_{ser,r}$.

- Bottom steel strain: strain in the bottom steel reinforcement corresponding to $M_{ser,r}$.

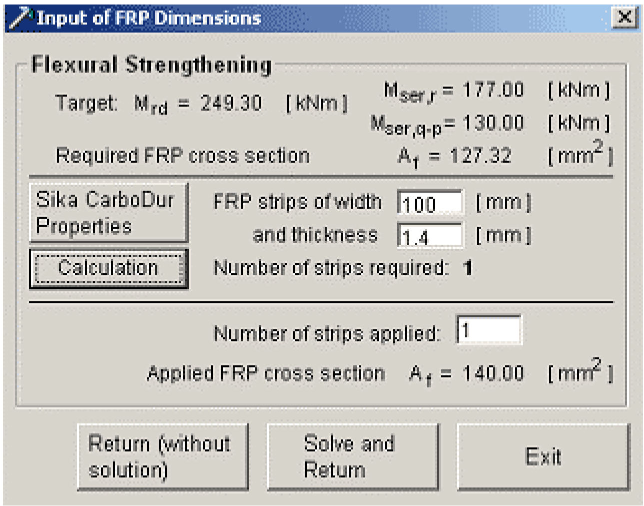
- Bottom fibre strain: strain in the extreme concrete tensile fibre corresponding to $M_{ser,r}$.

- FRP strain: strain in the FRP corresponding to $M_{ser,r}$.

Serviceability Limit State - Quasi-permanent Load ($M_{ser,q-p}$)

- Depth of neutral axis: depth of neutral axis (in m) corresponding to $M_{ser,q\text{-}p}$.
- Top fibre strain: strain in the extreme concrete compressive fibre corresponding to $M_{ser,q\text{-}p}$.
- Top steel strain: strain in the top steel reinforcement corresponding to $M_{ser,q\text{-}p}$.
- Bottom steel strain: strain in the bottom steel reinforcement corresponding to $M_{ser,q\text{-}p}$.
- Bottom fibre strain: strain in the extreme concrete tensile fibre corresponding to $M_{ser,q\text{-}p}$.
- FRP strain: strain in the FRP corresponding to $M_{ser,q\text{-}p}$.

Input of FRP dimensions: Activates a window where the user may input the dimensions (width and thickness, in mm) of FRP materials (values refer to a single strip) to be used for the specific strengthening project. By clicking the button Sika CarboDur Properties, characteristics of the various CarboDur systems are provided for consultation. By clicking Calculation, the number of strips required and the corresponding FRP area (final cross section) are calculated. The user has the option to override the required number of strips, by providing the applied number in the appropriate field.



Target: M_{rd} = 249.30 [kNm]

$M_{ser,r}$ = 177.00 [kNm]

$M_{ser,q\text{-}p}$ = 130.00 [kNm]

Required FRP cross section A_f = 127.32 [mm^2]

FRP strips of width 100 [mm]

and thickness 1.4 [mm]

Number of strips required: 1

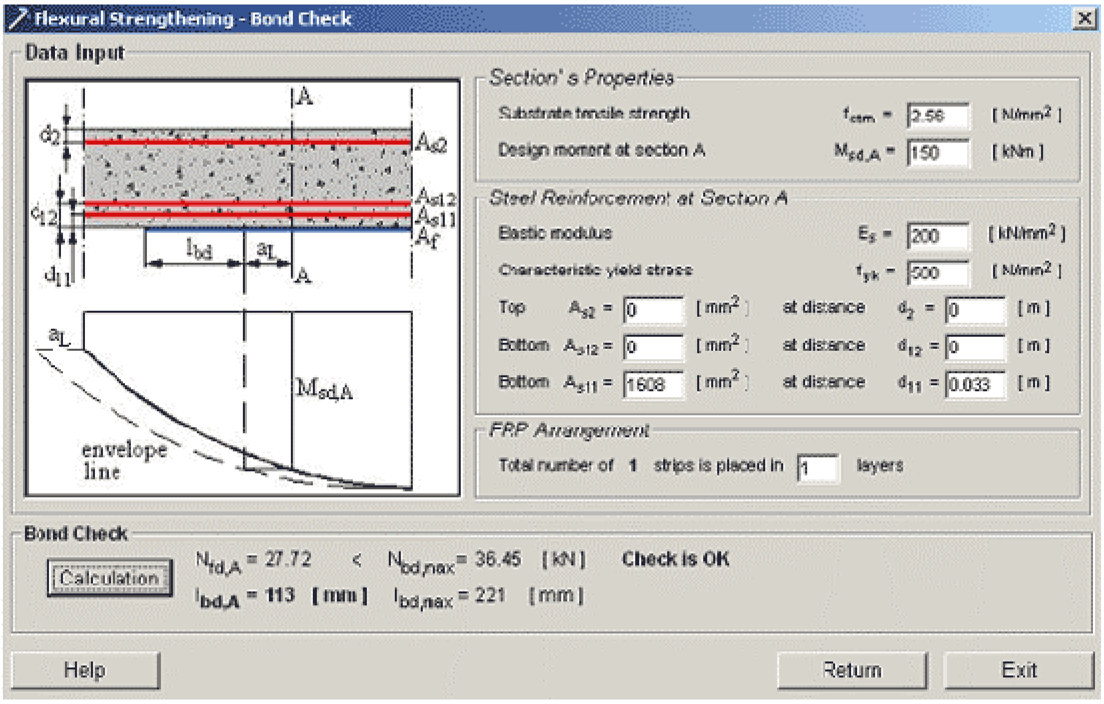
Number of strips applied: 1

Applied FRP cross section A_f = 140.00 [mm^2]

Solve and return: The window “Results” is activated with updated information, based on the new applied FRP cross section. Note that ALL values are updated (e.g. even if the SLS controls, values corresponding to the ULS are provided too, and vice versa). The FRP area is now called “applied”.

Return (without solution): The window “Results”, as it was before the input of FRP dimensions, is activated again.

Bond Check: When the user has selected the FRP dimensions and the number of strips (n), this button activates a window where the bond check is performed.



Section' s Properties

Substrate tensile strength f_{ctm} = 2.56 [N/mm^2]

Design moment at section A $M_{sd,A}$ = 150 [kNm]

Steel Reinforcement at Section A

Elastic modulus E_s = 200 [kN/mm^2]

Characteristic yield stress f_{yk} = 500 [N/mm^2]

Top A_{s2} = 0 [mm^2] at distance d_2 = 0 [m]

Bottom A_{s12} = 0 [mm^2] at distance d_{12} = 0 [m]

Bottom A_{s11} = 1608 [mm^2] at distance d_{11} = 0.033 [m]

FRP Arrangement

Total number of 1 strips is placed in 1 layers

Bond Check

$N_{fd,A}$ = 27.72 < $N_{bd,max}$ = 36.45 [kN] **Check is OK**

$l_{bd,A}$ = 113 [mm] $l_{bd,max}$ = 221 [mm]

__Section's Properties__

- Substrate tensile strength f_{ctm}: Input the mean value of the concrete tensile strength near the surface (in N/mm^2). The default value is calculated based on the characteristic value of the compressive strength. However, more realistic values could be obtained through pull-off testing.

- Design moment at section A $M_{sd,A}$: Input the bending moment acting in cross section A (in kNm). The calculations will provide the required bond length l_{bd} corresponding to this particular cross section, that is, how far from this section the FRP should extend, in addition to the horizontal displacement of the bending moment, Diagram aL.

__Steel Reinforcement at Section A__

- Elastic modulus E_s: Input the elastic modulus (in kN/mm^2) of the longitudinal steel reinforcement crossing section A. The default value is that provided for the critical cross section verifications.

- Characteristic yield stress f_{yk}: Input the characteristic yield stress (in N/mm^2) of the longitudinal steel reinforcement crossing section A. The default value is that provided for the critical cross section verifications.

- Top As_2: Input the total cross sectional area of the steel reinforcement in the compression zone (if present) of section A (in mm^2). The default value is that provided for the critical cross section verifications.

- At distance d_2: Input the distance from the centroid of As_2 to the extreme compressive fibre of the cross section A (in m). The default value is that provided for the critical cross section verifications.

- Bottom As_{12}: Input the total cross sectional area of the second layer (if present) of steel reinforcement in the tension zone of section A (in mm^2). The default value is that provided for the critical cross section verifications.

- At distance d_{12}: Input the distance from the centroid of As_{12} to the extreme tensile fibre of the cross section A (in m). The default value is that provided for the critical cross section verifications.

- Bottom As_{11}: Input the total cross sectional area of the first layer of steel reinforcement in the tension zone of section A (in mm^2). The default value is that provided for the critical cross section verifications.

- At distance d_{11}: Input the distance from the centroid of As_{11} to the extreme tensile fibre of the cross section A (in m). The default value is that provided for the critical cross section verifications.

FRP Arrangement

Total number of n strips is placed in m layers: The number of strips n has been calculated from the previous process. Given this number, the user will decide upon the number of layers m. For instance, if a total of two strips are needed, and they do not fit next to each other, they will be placed one on the top of the other, so that m=2. The number of layers m should be provided here as input by the user. Note that if m>1, the total number of strips divided by the number of layers should be an integer, so that the strips can be divided evenly. If this condition is not fulfilled, the user is warned by a message, so that a new selection of FRP dimensions should be made resulting in n/m=integer.

Calculation

By clicking Calculation, the program provides the total tensile force carried by FRP in section A, $N_{fd,A}$, the corresponding value of the maximum force, $N_{bd,max}$, so that debonding (anchorage failure) does not occur, the bond length, $l_{bd,max}$, corresponding to $N_{bd,max}$ and, if the bond check is OK, ($N_{fd,A}<N_{bd,max}$), the bond length required to transmit the force $N_{fd,A}$. If the bond check is NOT OK, a number of suggestions are provided: the user should increase the FRP cross-section (this solution is not so likely to be successful), and/or use a mechanical anchorage at the FRP ends.

Help: Activates the help facility.

Return: Activates the Data Input window, should modifications to the input data be required.

Print: A printout of the results is obtained.

Exit: Exits the program.

6.2.3. Shear Strengthening

DATA INPUT

The user is required to provide input as described in the following.

Method of Anchorage

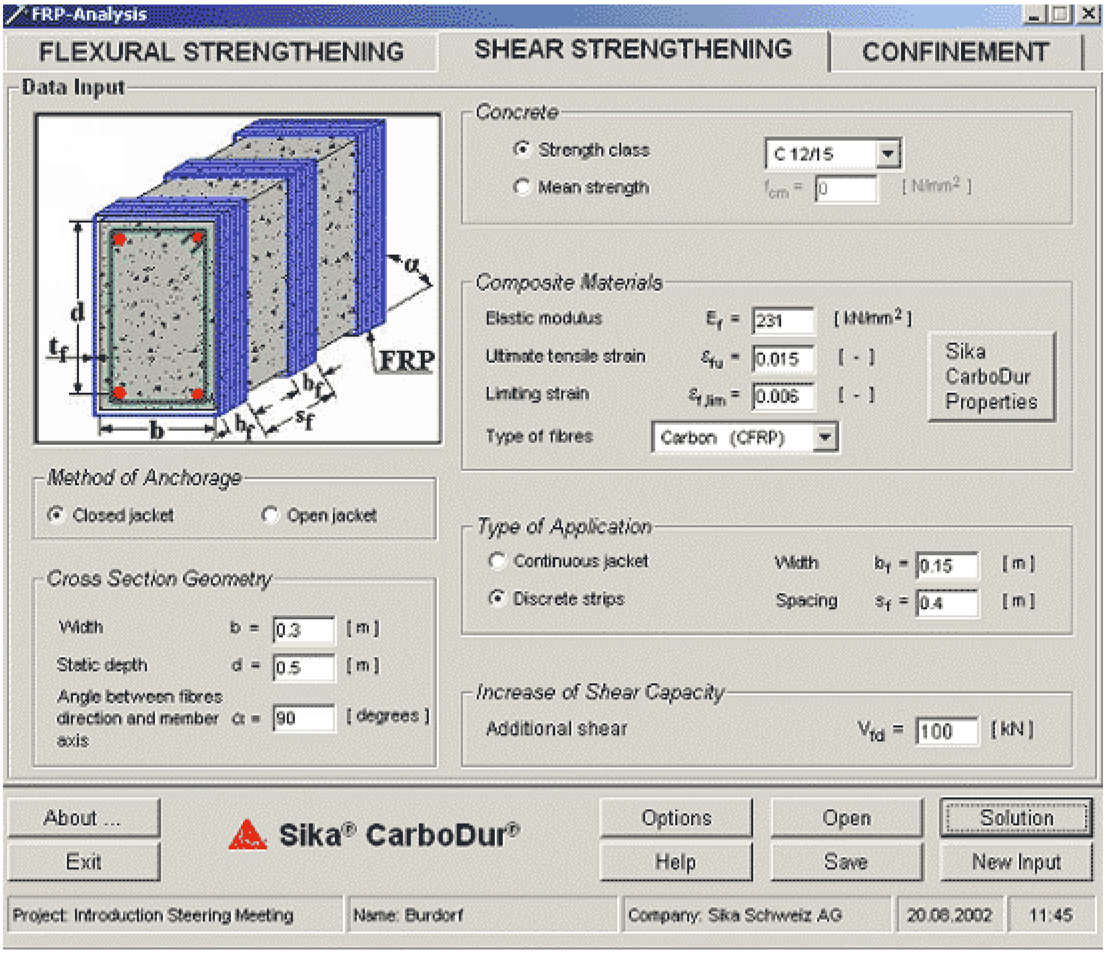
The option “Closed jacket” or “Open jacket” is selected, dependent upon the type of strengthening system used. Shear strengthening of columns where all four sides are accessible is typically of the closed-type. Moreover, shear strengthening of T-beams with mechanical anchorage systems that ensure optimal securing of the FRP in the compression zone, may be considered of the closed-type too. This is the case, for instance, with the Sika CarboShear elements, if sufficient anchorage length is available through the slab. For these particular elements, if the anchorage length is less than 300 mm, it is recommended to accept a solution calculated by linear interpolation between “Closed jacket” and “Open jacket”, that is to run the program for both cases and adopt the value by linear interpolation. Consult also the technical datasheet and design recommendation of this product.

Cross Section Geometry

Width b: Input the width in m.

Static depth d: Input the static (or effective) depth, that is the distance from the centroid of the tension steel reinforcement to the extreme compressive fibre, in m.

Angle between fibres direction and member axis: Input the angle (degrees) formed between the principal fibre direction in the FRP and the axis of the RC member. In most cases this angle is 90 degrees.



Data Input

Concrete
● Strength class C 12/15
○ Mean strength f_{cm} = 0 [N/mm^2]

Composite Materials
Elastic modulus E_f = 231 [kN/mm^2]
Ultimate tensile strain ε_{fu} = 0.015 [-]
Limiting strain $\varepsilon_{f,lim}$ = 0.006 [-]
Type of fibres Carbon (CFRP)
Sika CarboDur Properties

Method of Anchorage
● Closed jacket ○ Open jacket

Type of Application
○ Continuous jacket
● Discrete strips
Width b_f = 0.15 [m]
Spacing s_f = 0.4 [m]

Cross Section Geometry
Width b = 0.3 [m]
Static depth d = 0.5 [m]
Angle between fibres direction and member axis α = 90 [degrees]

Increase of Shear Capacity
Additional shear V_{fd} = 100 [kN]

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Concrete

The user has the option either to select the strength class of concrete (if known) or to input the mean strength in N/mm^2. The assumed relationship between the two is: $f_{ck} = f_{cm} - 1.64 \times 5$.

Composite Materials

By clicking the button "Sika CarboDur Properties", characteristics of the various CarboDur systems are provided for consultation.

Elastic modulus E_f: Input the elastic modulus of FRP in kN/mm2 (provided by the material supplier).

Ultimate tensile strain ε_{fu}: Input the ultimate tensile strain (failure strain) of the FRP (non-dimensional quantity). Typically this is provided by the material supplier.

Limiting strain $\varepsilon_{f,lim}$: Input the limiting strain of the FRP (non-dimensional quantity). Exceeding this value would imply significant cracks and hence reduced contribution from the concrete to the shear capacity as a result of reduced aggregate interlock. Suggested (default) value = 0.006.

Type of fibres: Select the type of fibres for the FRP material. This is related to material safety factors.

Type of Application

The use of continuous jacket or discrete strips may be selected here. In the latter case the width and spacing (axis to axis) of the strips should be provided (in m). The spacing should be such that a potential shear crack should cross at least one strip. As a general rule, a maximum spacing of 0.8 x d is adopted here.

Increase of Shear Capacity

Additional shear Vfd: Input the shear force (in kN) to be carried by the FRP.

Commands

Solution: The program checks for input errors and provides the solution.
New Input: All input data values may be assigned through this command.
Help: Activates the help facility.
Options: Activates the options described in Section 5.2.5.
Save: Saves all the input data in a file.
Open: Opens a data file, where input data may have been saved.
About: Activates the programme's introductory window.
Exit: Exits the programme.

Information Line

The following information is shown: Project Name Company Date Time

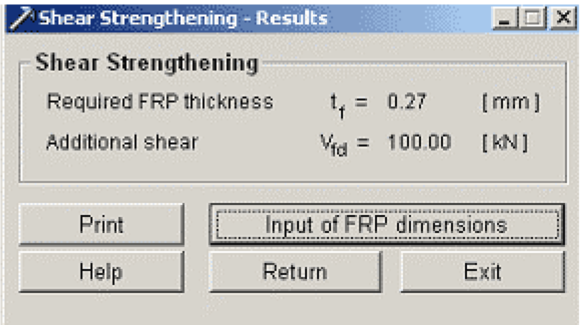
The first three items of data are provided by the user through "Options", "General", whilst the latter two items, namely the date and time are automatically provided by the system.

****General Remarks****

For each input value provided by the user the program checks if this value is "reasonable" (e.g. not too high, not too low) and provides a warning if this is not the case. Warnings are also provided if the user inputs wrong characters (e.g. a letter instead of a number) or if they forget to complete a box. Additional checks are made by the program, (with the corresponding warnings provided), if a combination of values does not make sense, e.g. the spacing of discrete strips cannot be less than their width.

RESULTS

Upon completion of the solution process, the "Results" window provides the following.



Shear Strengthening

Required FRP thickness t_f = 0.27 [mm]

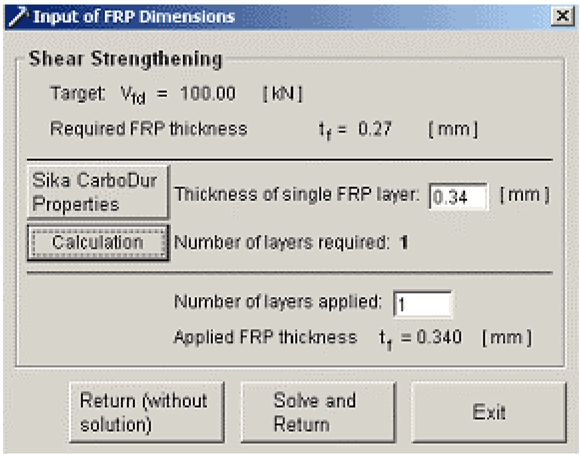
Additional shear V_{fd} = 100.00 [kN]

Required FRP thickness t_f: The total thickness of the FRP jacket is provided.

Additional shear V_{fd}: This is the value of the force corresponding to the FRP jacket of thickness t_f. Note this value might differ from that input by the user, due to round-off measures.

Commands

Input of FRP dimensions: Activates a window where the user may input the thickness (in mm) of a single layer of the FRP material to be used for the specific strengthening project. By clicking the button Sika CarboDur Properties, properties of the various CarboDur systems are provided for consultation. By clicking Calculation, the number of layers required is determined. The user has the option to override the required number of layers, by providing the applied number, in the appropriate field.



Shear Strengthening

Target: V_{fd} = 100.00 [kN]

Required FRP thickness t_f = 0.27 [mm]

Thickness of single FRP layer: 0.34 [mm]

Number of layers required: 1

Number of layers applied: 1

Applied FRP thickness t_f = 0.340 [mm]

Solve and return: The window "Results" is activated with updated information, based on the new FRP thickness. Note that the FRP thickness is now called "applied".

Return (without solution): The window "Results", as it was before the input of FRP dimensions, is activated again.

Help: Activates the help facility.

Return: Activates the Data Input window, should modifications to the input data be required.

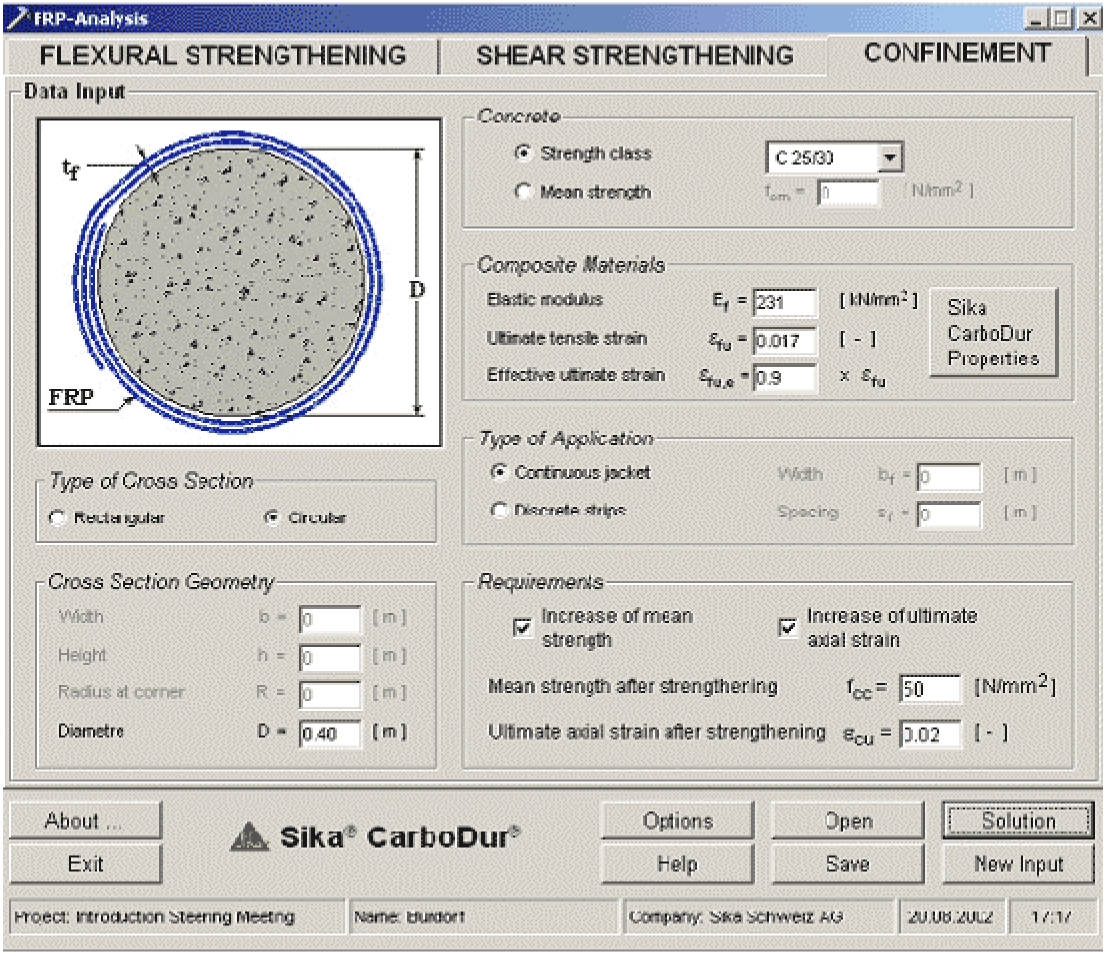
Print: A printout of the results is obtained.

Exit: Exits the program.

6.2.4. Confinement

DATA INPUT

The user needs to provide input as described in the following.



Concrete
● Strength class: C 25/30
○ Mean strength f_{cm} = 0 [N/mm²]

Composite Materials
Elastic modulus E_f = 231 [kN/mm²]
Ultimate tensile strain ε_{fu} = 0.017 [-]
Effective ultimate strain $\varepsilon_{fu,e}$ = 0.9 x ε_{fu}

Type of Cross Section
○ Rectangular ● Circular

Type of Application
● Continuous jacket Width b_f = 0 [m]
○ Discrete strips Spacing s_f = 0 [m]

Cross Section Geometry
Width b = 0 [m]
Height h = 0 [m]
Radius at corner R = 0 [m]
Diametre D = 0.40 [m]

Requirements
☑ Increase of mean strength ☑ Increase of ultimate axial strain
Mean strength after strengthening f_{cc} = 50 [N/mm²]
Ultimate axial strain after strengthening ε_{cu} = 0.02 [-]

Project: Introduction Steering Meeting | Name: Burdorf | Company: Sika Schweiz AG | 20.08.2002 | 17:17

Type of Cross Section

The option “Rectangular” is selected for rectangular cross sections, whilst “Circular” is selected for circular sections.

Cross Section Geometry

Width b: Input the width in m (for rectangular cross sections).

Height h: Input the height in m (for rectangular cross sections).

Radius at corner R: Input the radius at the corners of the cross section in m (for rectangular cross sections).

Diametre D: Input the diametre in m (for circular cross sections).

Concrete

The user has the option either to select the strength class of concrete (if known) or to input the mean strength in N/mm². The assumed relationship between the two is: $f_{ck} = f_{cm} - 1.64 \times 5$.

Composite Materials

By clicking the button "Sika CarboDur Properties", properties of the various CarboDur systems are provided for consultation.

Elastic modulus E_f: Input the elastic modulus of FRP in kN/mm^2 (provided by the material supplier).

Ultimate tensile strain ε_{fu}: Input the ultimate tensile strain (failure strain) of the FRP (non-dimensional quantity!). Typically provided by the material supplier.

Effective ultimate strain $\varepsilon_{fu,e}$: Input a reduction factor (default = 0.9) which multiplies the ultimate tensile strain of the FRP to give the effective ultimate strain in the circumferential direction. This reduction is related to the multiaxiality of stresses in the FRP and the quality of execution.

Type of Application

The use of continuous jacket or discrete strips may be selected here. In the latter case the width and spacing (axis to axis!) of the strips should be provided (in m). A warning is provided if the user specifies discrete strips as a means of confining rectangular cross sections. The effectiveness of confinement in this case is limited, and hence not recommended.

Requirements

The user has the option to select (a) increase of the concrete strength from f_{co} (= f_{cm}) to f_{cc} or (b) increase of the concrete ultimate strain to a value ε_{cu}, or both.

Mean strength after strengthening f_{cc}: Input the strength of FRP-confined concrete (target value after strengthening) in N/mm^2.

Ultimate axial strain after strengthening ε_{cu}: Input the ultimate axial strain of FRP-confined concrete (target value after strengthening), expressed as a dimensionless value.

Commands

Solution: The program checks for input errors and provides the solution.
New Input: All input data values may be assigned through this command.
Help: Activates the help facility.
Options: Activates the options described in Section 5.2.5.
Save: Saves all the input data in a file.
Open: Opens a data file, where input data may have been saved.
About: Activates the program's introductory window.
Exit: Exits the program.

Information Line

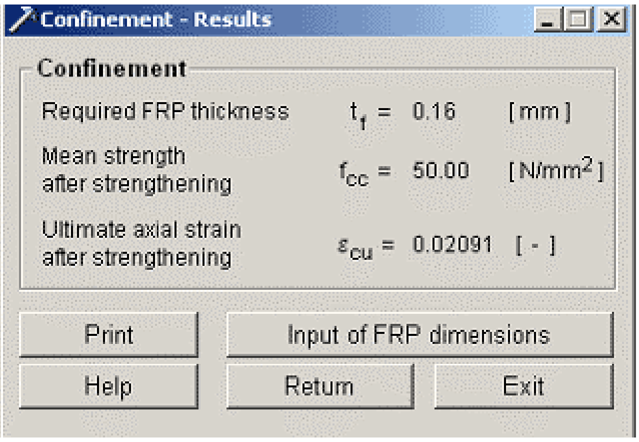
The following information is shown: Project Name Company Date Time

The first three items of data are provided by the user through “Options”, “General” whilst the two latter items , namely the date and time are automatically provided by the system.

General Remarks
For each input value provided by the user the program checks if this value is a “reasonable” one (e.g. not too high, not too low) and provides a warning if this is not the case. Warnings are also provided if the user inputs wrong characters (e.g. a letter instead of a number) or if he/she forgets to fill a box. Additional checks are made by the program (and the corresponding warnings are provided) if a combination of values does not make sense (e.g. the radius at the corners of a rectangular section cannot be more than half of the small side).

RESULTS

Upon completion of the solution process, the “Results” window provides the following.



Confinement - Results

Confinement

Required FRP thickness t_f = 0.16 [mm]

Mean strength after strengthening f_{cc} = 50.00 [N/mm^2]

Ultimate axial strain after strengthening ε_{cu} = 0.02091 [-]

Required FRP thickness t_f: The total thickness of the FRP jacket is provided.

Mean strength after strengthening f_{cc}: This is the value of the strength of FRP-confined concrete corresponding to the FRP jacket of thickness t_f. Note that this value might differ that one input by the user due to: (a) round-off (only slight variations are expected in this case); (b) the option “Ultimate axial strain after strengthening” has been selected as the FRP thickness is controlled by this requirement (i.e. larger FRP thickness is required to satisfy the strain requirement than the strength).

Ultimate axial strain after strengthening ε_{cu}: This is the value of the ultimate axial strain of FRP-confined concrete corresponding to the FRP jacket of thickness t_f. Note that this value might differ from that input by the user due to: (a) round-off (only slight variations are expected in this case); (b) the option “Mean strength after strengthening” has been selected as the FRP thickness is controlled by this requirement (i.e. larger FRP thickness is required to satisfy the strength requirement than the strain).

Commands

Input of FRP dimensions: Activates a window where the user may input the thickness (in mm) of a single layer of the FRP material to be used for the specific strengthening project. By clicking the button Sika CarboDur Properties, properties of the various CarboDur systems are provided for consultation. By clicking Calculation, the number of layers required is calculated. The user has the option to override the required number of layers, by providing the applied number in the appropriate field.

Solve and return: The window “Results” is activated with updated information, based on the new FRP thickness. Note that the FRP thickness is now called "applied".

Return (without solution): The window “Results”, as it was before the input of FRP dimensions, is activated again.

Help: Activates the help facility.
Return: Activates the Data Input window, should modifications to the input data need be required.
Print: A printout of the results is obtained.
Exit: Ends the program.

6.2.5. Options

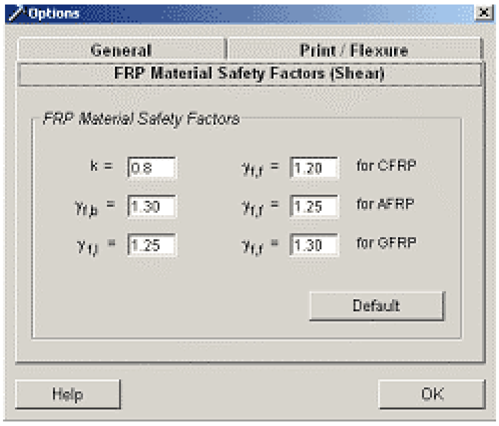
General

Names for the user, the company and the project may be provided through this option. A choice can be made as to whether these details should be included in the printout or not.

Print/Flexure

“Print Options” includes the “Print Setup” (type of printer, properties, paper etc.) and the “Fonts” (font, style, size), to be selected for the printout.

“Flexural Strengthening”: If the box “Solution for desirable failure modes only” is ticked (strongly recommended), the program will provide a solution (for the ULS) only if one of the two desirable failure modes (steel yielding + concrete crushing, steel yielding + FRP at limiting strain) is activated. If this is not possible, a warning will inform the user that the cross section is over-reinforced. If the box “Solution for desirable failure modes only” is not ticked, the program will provide a solution regardless of the failure mode (which could be of the concrete crushing type, without yielding of the tension steel reinforcement).



k = 0.8

$\gamma_{f,b}$ = 1.30

$\gamma_{f,j}$ = 1.25

$\gamma_{f,f}$ = 1.20 for CFRP

$\gamma_{f,f}$ = 1.25 for AFRP

$\gamma_{f,f}$ = 1.30 for GFRP

FRP Material Safety Factors

These factors are described in §5.1.2. The default values given here may be modified by the user.

6.2.6. Printing

A printout of both the user's input and the calculation results can be obtained through the window "Results". By using the window "Options" the user may select print the print setup and fonts.

The printout contains the following information, independently of the strengthening chosen (flexural, shear or confinement):
(a) user and project name, date & time (by demand);
(b) type of strengthening;
(c) type and geometry of cross section;
(d) material properties (concrete, steel and composite materials);
(e) type of application;
(f) strengthening requirements;
(g) required FRP dimensions (cross sectional area or thickness).

In cases of flexural strengthening, the moment capacity corresponding to every limit state, as well as the stresses in the concrete and steel (corresponding to SLS), and the governing failure mode is also printed. Moreover, information on the "cross section strain profile" for every limit state is given, if the user selects to see it at the solution stage. Finally, if the user selects the option "Input of FRP dimensions", the applied FRP dimensions as well as the number of strips or layers are printed. If the "Bond check" is performed, the corresponding results are also printed.

7. CARBODUR FRP SOFTWARE EXAMPLES

7.1. Flexural Strengthening Example

Let us suppose a 5 metre simply supported RC beam of figure 6.1. The beam is designed for a permanent action g_d = 15 kN/m and a varible action q_d = 30 kN/m. The purpose of the strengthening is to increase the variable design action to 70 kN/m. (Concrete C20/25, Steel S500). Assume FRP plates 1.2mm thick and 80mm width, with an Elastic modulus E_f = 165 Gpa (Sika CarboDur S812).

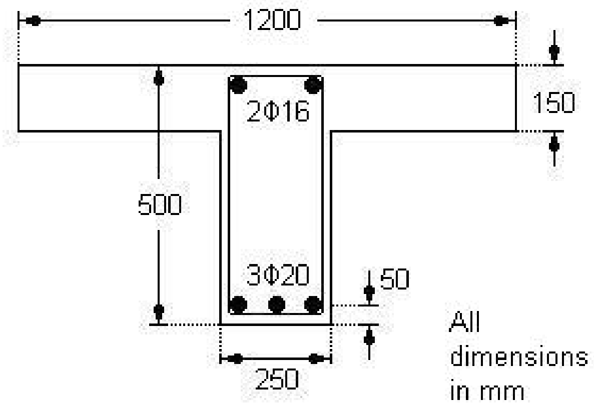


Fig. 6.1 Dimensioned Cross section of a T-beam.

Solution

From Fig.6.1 we calculate: A_s= 940mm^2, A'_s = 400mm^2, H = 500mm, d = 450mm, d_2 = 40mm.

The bending moment during strengthening (M_o) is: $M_o = wL^2/8 = 15x5^2/8$ = 46.9 kNm. Solving the equations 5.1.1, 5.1.2, 5.1.3 and 5.1.4 we calculate: ε_{co} = 0.00012 and x_o = 76mm. Therefore, from equation 5.1.7 we calculate ε_o = 0.00067.

The required design moment after strengthening (M_{Rd}) is: $M_{Rd} \geq 85x5^2/8$ = 265 kNm. Initially, we assume that FRP will reach the limiting strain $\varepsilon_{f,lim}$, i.e. ε_f = 0.008. Solving the equations 5.1.8, 5.1.9, 5.1.10 and 5.1.11 with unknowns ε_c, x and A_f we determine that , ε_c = 0.00150, x = 74mm and A_f = 148,87mm^2.

Hence, for this strengthening scheme we require a total width of FRP of 148,87/1.2 = 124,06 mm. We choose 2 plates of 80mm width each $\Rightarrow A_f$ = 2x80x1.2 = 192 mm^2 > 148,87 mm^2.

Note: The initial assumption that the FRP reaches the limiting strain (before the crushing of concrete) is not in contradiction with the results of the analysis. Hence, it is not necessary to make the calculations for the failure mechanism that is characterised by concrete crushing (ε_c = 0.0035 and ε_f < 0.008).

7.2. Shear Strengthening Example

Let us suppose a RC rectangular column 250x400 mm, shown in fig. 6.2, with concrete strength 18MPa. The additional shear that the column will receive is 135 kN. Assume a CFRP fabric with elastic modulus E_f = 230 GPa, an ultimate tensile strain ε_{fu} = 0.017 and a thickness t_f = 0.12 mm (SikaWrap 230C).

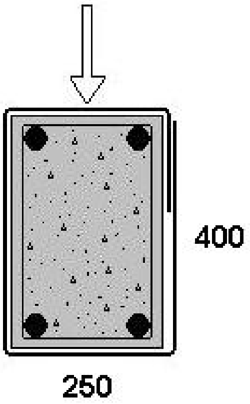


Fig. 6.2 Cross section of a rectangular column.

Solution

Let us assume 2 layers of the fabric: t_f = 2x0.12 = 0.24 mm
ρ_f = 2x0.24/250 = 0.0019.

From equation 5.1.19a we calculate:

- $[0.8 \times 0.17 \times 0.017 \times (18^{2/3} / 230 \times 0.0019)^{0.3}] / 1.2 = 0.0053$
- (0.006/1.25) = 0.0048

Therefore $\varepsilon_{fd,e}$ = 0.0048.

Hence, equation 5.1.18 we have: V_{fd} = 174,43 kN > 135 kN.

7.3. Confinement Example

Let us assume a RC rectangular cross section 250x500 mm, shown in figure 6.3, with concrete strength f_{co} = 20MPa and elastic modulus E_{co} = 27GPa.

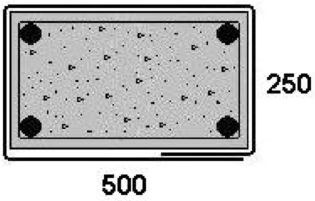


Fig. 6.3 Cross section of a rectangular element.

Assume that for the confinement of the element we use two different material fabrics a) Glass FRP with elastic modulus E_{fib}=76 GPa, f_{fk} =2300 MPa, ε_{fu} = 0.028 and thickness t_f = 0.17mm (SikaWrap 430G) and b) Carbon FRP with elastic molulus E_{fib} = 231GPa, f_{fk}= 4100 MPa, ε_{fu} = 0.017 and t_f =0.12mm (SikaWrap 230C). Also assume a tensile strength reduction of 5% in respect to the characteristic tensile strength of fibres f_{fk}.

Requirements: 1) to increase the mean strength f_{cc} to 35MPa and 2) to increase the ultimate axial strain (from 0.0035-0.004 of unconfined concrete) to 0.025.

Solution

The design tensile strength is $f_{fd} = \frac{f_{fk}}{\gamma_f} \cdot \frac{\varepsilon_{fue}}{\varepsilon_{fum}}$ where the ratio $\frac{\varepsilon_{fue}}{\varepsilon_{fum}}$ normally equals 1, as the effective ultimate FRP strain ε_{fue} expected in-situ will not significantly differ from the mean strain ε_{fum} obtained through uniaxial tensile testing, and as small variations are accounted for in the FRP material safety factor γ_f.

Therefore for GFRP we have: f_{fd} = 0.95x(2300/1.5)x1= 1457 MPa and,

For CFRP we have, respectively: f_{fd} = 0.95x(4100/1.35)x1= 2885 MPa

Assuming that the radius at corner will be 2cm, the gross sectional area of concrete A_g = 1246.5 and from equation 5.1.30 we establish a confinement effectiveness coefficient = 0.32.

Substituting the above values in equations 5.1.22 to 5.1.29 we calculate:

f_{cc}=35MPa

GFRP: Required FRP thickness t_f = 0,75⇒ 5 layers of fabric.
CFRP: Required FRP thickness t_f = 0,41 ⇒ 4 layers of fabric.

ε_{cu} = 0.025

GFRP: Required FRP thickness t_f = 0,08⇒ 1 layers of fabric.
CFRP: Required FRP thickness t_f=0,18 ⇒ 2 layers of fabric.

Note: From the above results it is obvious that to increase strength the CFRP fabrics require less layers than the GFRP options. Alternatively to increase strain the GFRP fabrics need fewer layers than the CFRP.

8. CARBODUR FRP DETAILING RULES

8.1. Flexural Strengthening

Flexural strengthening is provided by:

- Prefabricated CFRP plates,

or

- Axially oriented flexible fabrics

These are bonded and cured in-situ on the tensile faces of the element (e.g. in the bottom faces for simply supported beams, in top faces for beams over internal supports).
In the anchorage zones no additional transverse reinforcement is required if adequate anchorage is provided by bond stresses and debonding is resisted by concrete tensile stresses.

8.1.1. Recommendations

- Maximum spacing s_f between parallel plates or fabrics = $\min(0.2\ell, 5h, 0.4\ell_c)$ where ℓ= span length, h= total depth, ℓ_c=length of cantilever.
- Minimum distance to the edge of a beam = concrete cover to existing reinforcement.
- It is strongly recommended that lap joints of strips should be avoided; actually they are not necessary since FRP can be delivered in the required length. Joints are allowed only in cases of static loading and they are provided in sections where the maximum tensile force in the EBR does not exceed 60% of the tensile force at ultimate.
- Crossing of strips is allowed, with simultaneous bonding in the crossing area.
- Peeling-off of FRP is avoided by minimising concrete unevenness. The permissible unevenness of prefabricated plates and flexible fabrics is given in Table 7.1.

FRP type	**Permissible unevenness on a 2.0 m base (mm)**	**Permissible unevenness on a 0.3 m base (mm)**
Prefabricated Plates	10	4
Flexible Fabrics	4	2

Table 7.1 Allowable values of unevenness of the concrete surface.

8.1.2. Multiple Layers

- For prefabricated plates, maximum recommended layers = 3.
- For axially-oriented flexible fabrics, maximum recommended layers = 5.
- For several layers of prestressed plates there is a reduction of prestressing due to the successive release of prestressing forces.

8.1.3. Anchorage Zones

- In cases of span strengthening of simply supported beams, the distance between the face of the support and the end of the strip should be less than 50mm.
- In cases of strengthening over supports of continuous beams or slabs, FRP should be anchored in the compression zone.
- Longitudinal FRP can be anchored with the use of flexible fabrics or prefabricated L-shaped plates (Fig.7.1). These anchors are used as external stirrups and are not considered to be part of the shear reinforcement but are responsible for preventing early peeling-off.

Fig. 7.1 Anchorage of longitudinal FRP with prefabricated carbon L-shaped plates.

8.2. Shear Strengthening

Shear strengthening is provided by:

- Prefabricated CFRP L-shaped plates or,

or

- Axial or biaxial oriented flexible fabrics

The key issue in this technique is the appropriate anchorage of either the fabric or the plate. Proper anchorage means a fully wrapped or a system that is properly anchored in the compression zone, as shown in Fig. 7.2.

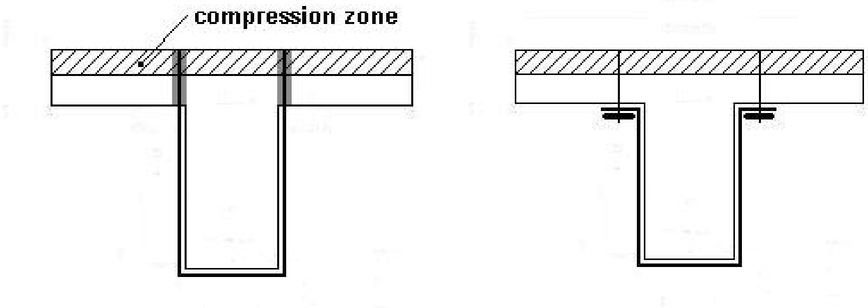
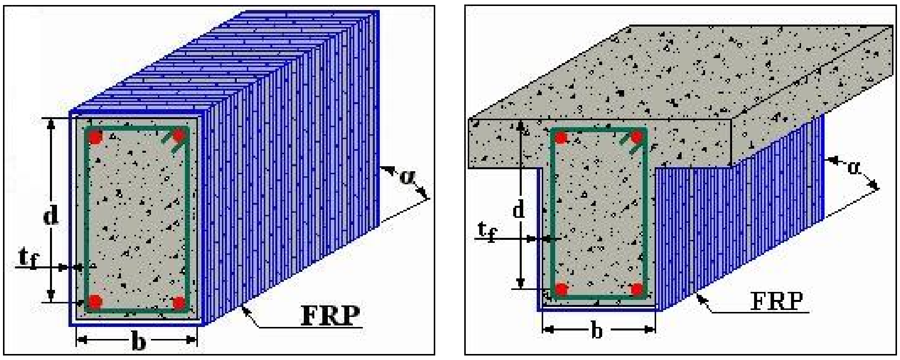


Fig. 7.2 Anchorage in the compression zone

8.2.1. Recommendations

- Externally bonded shear reinforcement covers four sides (fully wrapped) or three sides (U-shape wrap) (Fig. 7.3a, 7.3b) of the element and in some cases only two sides (prefabricated plates).



(a) (b)

Fig. 7.3 Shear strengthening on (a) four, and (b) three sides of the element using FRP fabrics

- For improved performance and where practically possible, use the whole height of the compression zone.
- The use of plates at the sides of a beam is not recommended as there is a lack of anchorage in both the compression and tension zones.
- In cases of insufficient anchorage in the compression zone, the usable height (inner lever arm) has to be reduced, in order that the member has a fictitious lower ultimate bending resistance (Fig. 7.4).
- FRP effectiveness increases as the fibers direction becomes closer to the perpendicular of the diagonal shear crack.
- In cases where discrete strips of small width are used (Fig. 7.5), the maximum spacing s_f should be equal to 0.8 d.

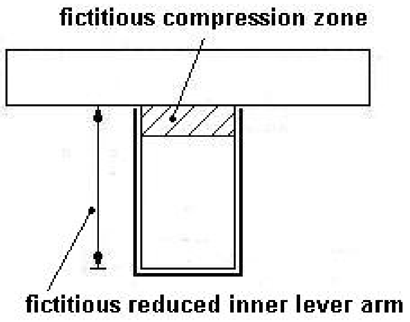


Fig. 7.4 No anchorage: reduction of the useable height for bending resistance.

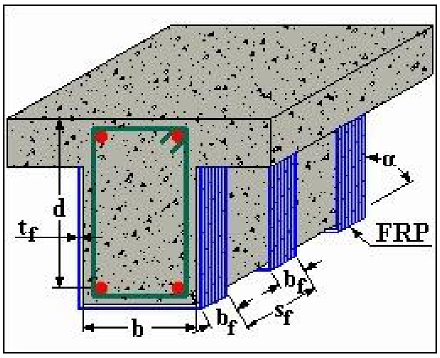


Fig. 7.5 Shear strengthening with discrete strips.

8.3. Confinement

Confinement is generally applied to members in compression and is provided by circumferential-oriented flexible fabrics.

8.3.1. Recommendations

- Sharp corners on rectangular columns should be rounded to minimum radius of 10 mm in order to avoid stress concentrations in the fabric.
- Both horizontally and spirally running fibres can achieve effective confinement.
- The maximum number of superimposed layers = 20-25.
- For rectangular members with a large aspect ratio (e.g. pier walls), FRP jackets should be restrained through the use of dowels or bolts in order to achieve effective confinement.
- In cases of high magnitude eccentric compressive loads, longitudinally directed fibres can be applied. Proper anchorage of these fibres is recommended.

- When strengthening columns, excessive flexural strength in the plastic hinge region due to FRP confinement, may possibly result in undesired moment and shear forces in footings and cap beams. Therefore a gap of 30-50mm is left between the column and the footing and/or cap beam face.

8.4. Moisture Issues

In general, when structures are located in an extremely humid environment or in direct contact with water (e.g. part of quay-, bridge- or dam structures) full wrapping of the structure's elements should be avoided. Whereas, in a dry environment of low humidity (e.g. indoor structures) the total surface of the element can be wrapped. In any other circumstances, special investigation is required.

As already mentioned on §4.7.7, in order to avoid entrapping moisture inside concrete members the following recommendations should be adopted.

8.4.1. Recommendations

- In cases of flexural strengthening a small gap should be left between the plates or the fabrics.
- In cases of shear strengthening a gap every 300mm should be left exposed.
- In cases where a gap is needed for avoiding excess flexural strength in the plastic hinge regions, water should be prevented from seeping in between the FRP and the concrete surface by sealing the gap with a water barrier such as an epoxy resin compound.

9. SIKA SYSTEMS & TECHNOLOGIES

9.1. Sika Technologies in Action

In the following the, for each structural requirement a solution is provided through the use of Sika products.

Structural Requirements	**Sika System Solutions**
Structural Bonding of Cracked Reinforced Concrete Members	SikaDur® Epoxy Injection Systems
Replace Areas of Mechanically Damaged Concrete	Sikament® and Viscocrete® Admixtures
	Sika® Machine Applied Repair Mortars
Bonding Anchors and additional Reinforcement into Hardened Concrete	SikaDur® Epoxy Bonding Systems
Confinement of Structural Members to increase Load Bearing Capacity and Ductility	SikaWrap® Composite Fabric Systems
Flexural Strengthening	Sika® CarboDur® Composite Plates and SikaWrap® Fabric Systems
Shear Strengthening	Sika® CarboShear® Stirrups and SikaWrap Composite Systems

9.2. CarboDur FRP Systems

In 1994, Sika introduced FRP materials into the field of structural strengthening. Three different systems exist in the product range:

- The Sika CarboDur System
- The SikaWrap System
- The Sika CarboShear L System

An overview for all systems is given below.

9.2.1. Sika CarboDur System

The Sika CarboDur System consists of factory pultruded carbon plates, which are bonded to substrates on site with SikaDur 30 structural epoxy adhesive. CarboDur plates are produced in a number of different widths and thickness (Table. 8.1) and in four different Elastic Moduli, S (XS), M, H and UH respectively (Fig 8.1 and 8.2).

Sika® CarboDur®	Width (mm)	Thickness(mm)	Cross Sectional Area (mm^2)
XS514	50	1.4	70
XS1014	100	1.4	140
XS1214	120	1.4	168
XS1514	150	1.4	210
S512	50	1.2	60
S612	60	1.2	72
S812	80	1.2	96
S1012	100	1.2	120
S1212	120	1.2	144
S1512	150	1.2	180
S614	60	1.4	84
S914	90	1.4	126
S1014	100	1.4	140
S1214	120	1.4	168
M514	50	1.4	70
M614	60	1.4	84
M914	90	1.4	126
M1014	100	1.4	140
M1214	120	1.4	168
H514	50	1.4	70
UH514	50	1.4	70

Table 8.1 Types of Sika CarboDur Plates

	Sika CarboDur Plate				
	Type XS	**Type S**	**Type M**	**Type H**	**Type UH**
E-modulus (kN/mm^2)	165	165	210	300	400
Tensile Strength (N/mm^2)	>2200	>2800	>2800	>1300	>1800
Strain at failure (%)	>1.35	>1.7	>1.35	>0.45	>0.45

Fig 8.1 Mechanical properties of Sika CarboDur Plates

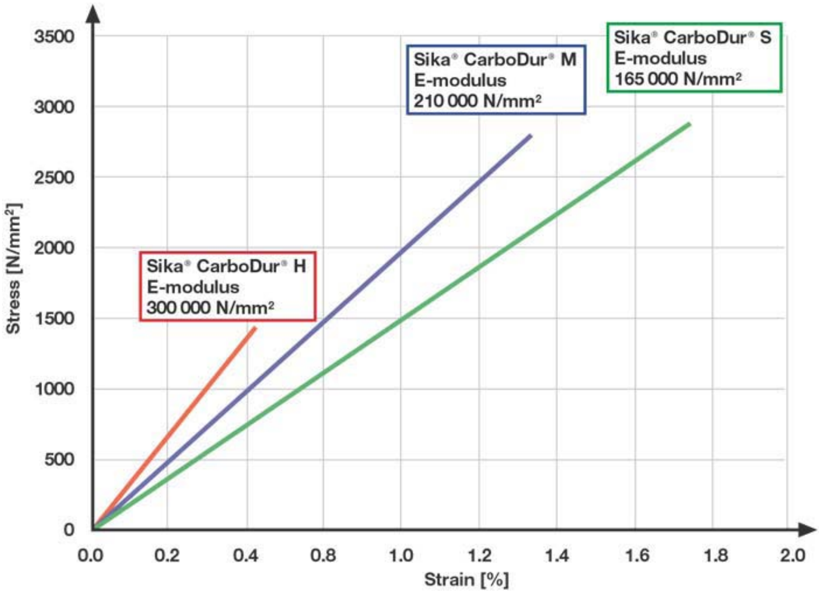


Fig 8.2 Stress-Strain diagram of Sika CarboDur Plates S,M and H

One of the advantages of Sika CarboDur plates is that they can be prestressed before bonding. This reduces the risk of plates peeling off due to concrete shear failure in the tension zone, thus increasing the structural safety. The prestressing force in the plate relieves the strain from internal steel reinforcement and reduces deflection and crack widths.

9.2.2. SikaWrap System

The SikaWrap system consists of flexible fabrics which are laminated and bonded to substrates on site using SikaDur structural epoxy resins.

SikaWrap systems can be applied by two different processes according to the client requirements and site conditions. These are known as the “wet” and “dry” process respectively:

- In the wet process the SikaWrap fabric is impregnated with SikaDur-300 epoxy resin manually or in a saturator machine (Fig. 8.3) and then is applied “wet” to the sealed substrate.

- In the dry process the dry SikaWrap fabric is applied directly into the SikaDur-330 resin which has been applied uniformly onto the concrete surface.

Either the Sika “wet” or “dry” process can achieve equal performance on site.

SikaWrap fabrics are produced with carbon and glass fibres in one or two directions. The SikaWrap fabric range is shown in Table 8.2

Fig 8.3 Saturator Machine for the SikaWrap “Wet” process.

SikaWrap® Fabrics	**Areal Weight (g/m²)**	**Tensile E-Modulus (kN/mm²)**	**Tensile Strength (N/mm²)**	**Strain at break of fibres (%)**	**Nominal Thickness (mm)**	**Process**
Glass Fabrics						
100G	935	76	2300	2.8	0.36	Wet
107G	955	76	2300	2.8	0.35	Wet
430G	445	76	2300	2.8	0.17	Dry
Aramid Fabrics						
300A	300	100	2880	2.8	0.21	Dry/Wet
450A	450	100	2880	2.8	0.31	Wet
Carbon Fabrics						
103C	610	230	3900	1.5	0.34	Wet
160C 0/90	160	230	3800	1.5	0.045	Dry
200C	200	230	3900	1.5	0.11	Dry
Hex230C	220	231	4100	1.7	0.12	Dry
300C	300	230	3900	1.5	0.17	Dry/Wet
201C	200	230	4900	2.1	0.11	Dry
231C	230	230	4900	2.1	0.13	Dry
301C	300	230	4900	2.1	0.17	Dry/Wet
200C NW	200	230	3900	1.5	0.11	Wet
300C NW	300	230	3900	1.5	0.17	Wet
300C HiMod NW	300	640	2600	0.4	0.14	Wet
400C HiMod NW	400	640	2600	0.4	0.19	Wet

Table 8.2 Range of SikaWrap Fabrics

9.2.3. Sikadur Adhesives and Impregnating Resins

SikaDur-30

The SikaDur 30 is a high modulus, high strength structural epoxy paste adhesive used for external bonding of steel and CarboDur plates.

The main features of SikaDur 30:

- Application temperature range +10…+35°C
- No primer is required , acts as primer and adhesive

- Resistant to low concentrations of acids and alcalis as well as oil

SikaDur 330
The SikaDur 330 is a proven mid-viscosity impregnation resin for the “dry” application method. It is not suitable for tightly woven (e.g. 103C, 107G) and non-woven (e.g. 300C HiMod NW) fabrics.

The main features of SikaDur 330:

- Application temperature range +10 to 35°C
- No primer is required , acts as primer and impregnating resin
- Resistant to low concentrations of acids and alcalis as well as oil
- Tacky surface after curing: coating or application of further layers has to be done carefully according to the procedures provided in product data sheets.

SikaDur 300
The SikaDur 300 is a low viscosity impregnating epoxy resin, designed especially for use with the saturator and the wet application method. For this reason, the pot life is in the range of 3 to 5 hours, depending on temperature. SikaDur 300 can be used in general for every SikaWrap fabric, but is recommended for the saturation of tightly woven and non-woven fabrics.

The main features of SikaDur 300:

- Extreme pot life and slow curing
- Application temperature range +15 to +40°C.
- Resistance to low concentrations of acids and alkalis as well as oil.

9.3. CarboDur Complementary Systems

9.3.1. CarboShear L System

Sika CarboShear L-shaped plates (Fig. 8.4) are manufactured for use as externally applied shear reinforcement and therefore to complement the prefabricated CarboDur plates.

Fig 8.4 CFRP L-Shaped Plates "CarboShear L".

The L-shaped plates afford the benefits of all CFRP products and use SikaDur 30 epoxy adhesive for bonding. They are manufactured in three different types as it is shown in Table 8.3.

Type	Leg Length (mm)	Width (mm)	Thickness (mm)
4/20/50	200 resp. 500	40	1.4
4/30/70	300 resp. 700	40	1.4
4/50/100	500 resp. 1000	40	1.4

Elastic Modulus	Tensile Strength
120 kN/mm^2	126 kN/40mm

Table 8.3 Types and Mechanical Properties of CarboShear L

9.3.2. CarboHeater

Sika has developed a CarboHeater System (Fig. 8.5) which reduces the curing time of adhesives. This system takes advantage of the electrical conductivity of carbon fibres. It uses special equipment to pass an electric current through CFRP plates during the strengthening process. The control unit allows the desired curing temperature to be maintained within a narrow range.

Fig 8.5 Fast Curing using Sika Heating Device.

The main advantages of controlled curing are:

- Increased glass transition temperature of adhesives
- Fast curing of adhesives at low temperatures
- Application even under dynamic loads

From an experimental program in EMPA test laboratories it was identified that the full curing of SikaDur 30 at 70°C is achieved in 3 hours.

8.3.3 Prestressed FRP

Post-strengthening in tension of reinforced concrete structures using externally bonded CFRP plates is state of the art technology . For the ultimate load capacity the useful plate strain in the optimal scenario, under approval max ε_L = 8‰. This strain is only the 50% of the guaranteed elasticity of the CFRP plate used. The limitation on useful tendon strain mainly results from the limited load capacity of the bond and the limited tensile strength of the concrete layers near the surface.

If the high load capacity and elasticity of the tendon were to be used economically, i.e. above the 8‰ range, the additional strain would have to be put into it before actual application on the structure. The tendon has therefore to be prestressed.

The prestressed CFRP plate combines the advantages of the bonded CFRP plate strengthening with those of conventional prestressing. The tensioned CFRP plate superimposes compressive stress in the tensile zone of the cross-section, thus reducing tensile stress in steel reinforcement under service load and consequently reducing crack width and deflection (Fig. 8.6). For calculation of the load-bearing capacity, the tensile force in the tensioned CFRP plate is added to the tensile strength of the steel.

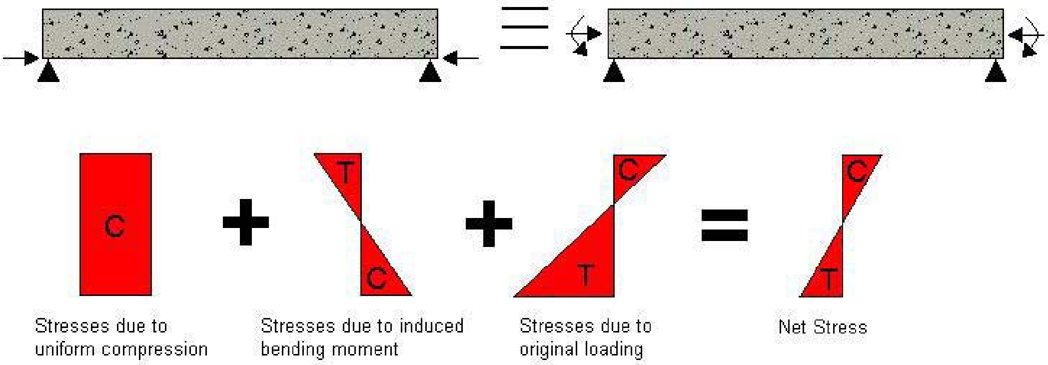


Fig 8.6 Principle of Prestressing.

Sika has developed two prestressed systems in collaboration with the consulting engineers Leonhardt, Andrä & Partners and StressHead AG. These are the Sika Leoba Carbodur (SLC I and II) and Sika-StressHead, respectively (Fig. 8.6). Properties of both systems are shown in Table 8.4.

System	Sika LC II	Sika StressHead
Sika CarboDur plate	V914	V624
Cross-section	126 mm^2	144 mm^2
Tensioning force	200 kN	220 kN
Pretensioning strain	9.0 ‰	9.5 ‰
Tensioning anchor	Leoba LC II	StressHead 220

Table 8.4 Properties of Sika Prestressed Systems.

Fig 8.7 Sika Prestressed Systems; (a) Sika Leoba CarboDur II and (b) Sika-StressHead.

The advantages of prestressed Sika CarboDur CFRP plates compared to prestressing steel are:

- Easy prestressing of existing structures
- Low weight for easy handling
- Low loss of prestress due to higher initial tensile strain
- Compact because of thin sections
- Comparable stress level for CFRP plates and prestressing steel
- No stress corrosion cracking risk
- Corrosion resistant tendons
- Bonded or non-bonded to structures

Moreover, the advantages compared to CFRP plates applied without pretensioning are:

- Optimal use of the high tensile strengths of the Sika CarboDur plates
- 30% to 50% less plates required
- Optimal cost/performance ratio for strengthening of concrete structures
- Increased serviceability: reduction of crack width, tensile steel strain and corrosion

- Strengthening effect can also be “appropriate” for dead and permanent load
- Reduction of tensile strain of existing reinforcement
- Possibility of structural strengthening despite low substrate temperatures and high humidity and without special measures being required.
- Plate thickness up to 2.4 mm
- Short end-anchors for the plates.

10. CARBODUR FRP CASE STUDIES

10.1. EURIPOS BRIDGE, CHALKIDA

During January 1998, the movable historic bridge of Chalkida was repaired. Flexural cracks had appeared at both ends of the bridge deck. The repair technique applied included sealing of cracks with SikaDur 52 epoxy resin injection method and followed by bonding of Sika CarboDur S1012 plates perpendicular to the direction of cracks to avoid excessive cracking of concrete (Fig.9.1).

Fig. 9.1 Down side of Euripos Bridge Deck.

10.2. KATERINI BRIDGE, NATIONAL ROAD KATERINI-THESSALONIKI

In May 2000, a bridge on the national Katerini-Thessaloniki road was strengthened against increased traffic loads. For this work, the CarboDur S1212 was chosen. CarboDur plates were bonded onto bridge beams as is shown in Fig. 9.2. Application of CarboDur was enhanced with the use of CarboHeater.

Fig. 9.2 Katerini Bridge and Strengthened Deck.

10.3. SPORTS INSTALLATION, ATHENS

A Sports Stadium in the center of Athens was strengthened in September 2000 (Fig 9.3). More specifically, each tier span was strengthened against flexure and the ends against shear (Fig.9.4). For the flexural and shear strengthening Sika CarboDur S1012 and SikaWrap Hex-230C were used. For the concrete repair, Sika MonoTop mortars were used.

Fig. 9.3 Sport Stadium during Strengthening.

Fig. 9.4 Shear and Flexural Strengthening of Stadium Tiers.

10.4. HOTEL BUILDING, CRETE

Due to a change of use in a Hotel, in January 1999, beams had to be decreased by their static depth 20 to 25 cm (initial static depth ~ 100 cm). The beams were strengthened with Sika CarboDur S1012 against flexure and with SikaWrap Hex-230C against shear (Fig. 9.5).

Fig. 9.5 Shear and Flexural Strengthening of a beam.

10.5. TRADITIONAL HOUSE, ATHENS

In May 2001, a wooden roof to a traditional house has been strengthened using Sika CarboDur plates S1012 for flexure, as is shown in Fig. 9.6.

Fig. 9.6 Flexural Strengthening of a Wooden Roof.

10.6. TOBACCO FACTORY, KILKIS

In May 2002, the upgrade of flexural loading capacity of a slab was carried out in a tobacco factory. For the flexural strengthening, the Sika CarboDur S512 plates were used (Fig. 9.7).

Fig. 9.7 Flexural Strengthening of a Slab.

10.7. GALIKOS RIVER BRIDGE, KILKIS

In May 2002, the bridge deck slab of Galikos River bridge required reinforcing to alleviate sagging due to low design. The strengthening of the upper side (tensile zone) of the bridge deck slab was performed with Sika CarboDur S1012 (Fig. 9.8).

Fig. 9.8 Strengthening of Bridge Deck Slab over the Bridge Columns.

10.8. MASONRY HOUSE, THESSALONIKI

In September 2002, the shear load capacity of a masonry building was upgraded. Cracks in masonry were filled with Sika injections and then substrates were leveled with Sika MonoTop mortars. The strengthening involved Sika CarboDur S812 plates (Fig. 9.9).

Fig. 9.9 Shear Load Capacity Upgrade of a Masonry Building.

10.9. COMMERCIAL COMPLEX, ATHENS

In June 2002and due to a change of use , general rehabilitation of a multi-storey block of shops and offices was undertaken. Works included flexural strengthening of slabs and beams with Sika CarboDur S1012, S812 and S512 and shear strengthening of beams with SikaWrap-300C HiMod NW (Fig. 9.10).

Fig. 9.10 Flexural and Shear Strengthening of Beams and Slabs.

10.10. RETIREMENT HOME, IOANNINA

During January 2003, the refurbishment of a retirement home took place in Ioannina. Repair of concrete surfaces was achieved using Sika MonoTop mortars and the confinement of columns and joints with SikaWrap Hex-230C (Fig.9.11).

Fig. 9.11 SikaWrap Hex-230C Confinement of Columns and Joints.