FRP-Analysis: Design Software for Sika CarboDur Systems

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

The equations used in this programme are given in the *fib* Bulletin No. 14, July 2001: "Design and use of Externally Bonded FRP Reinforcement for RC Structures".
The following part is explained exactly in the "help – function" of the design – software, incl. the formulas used for calculation and input data.

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 address both the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS).

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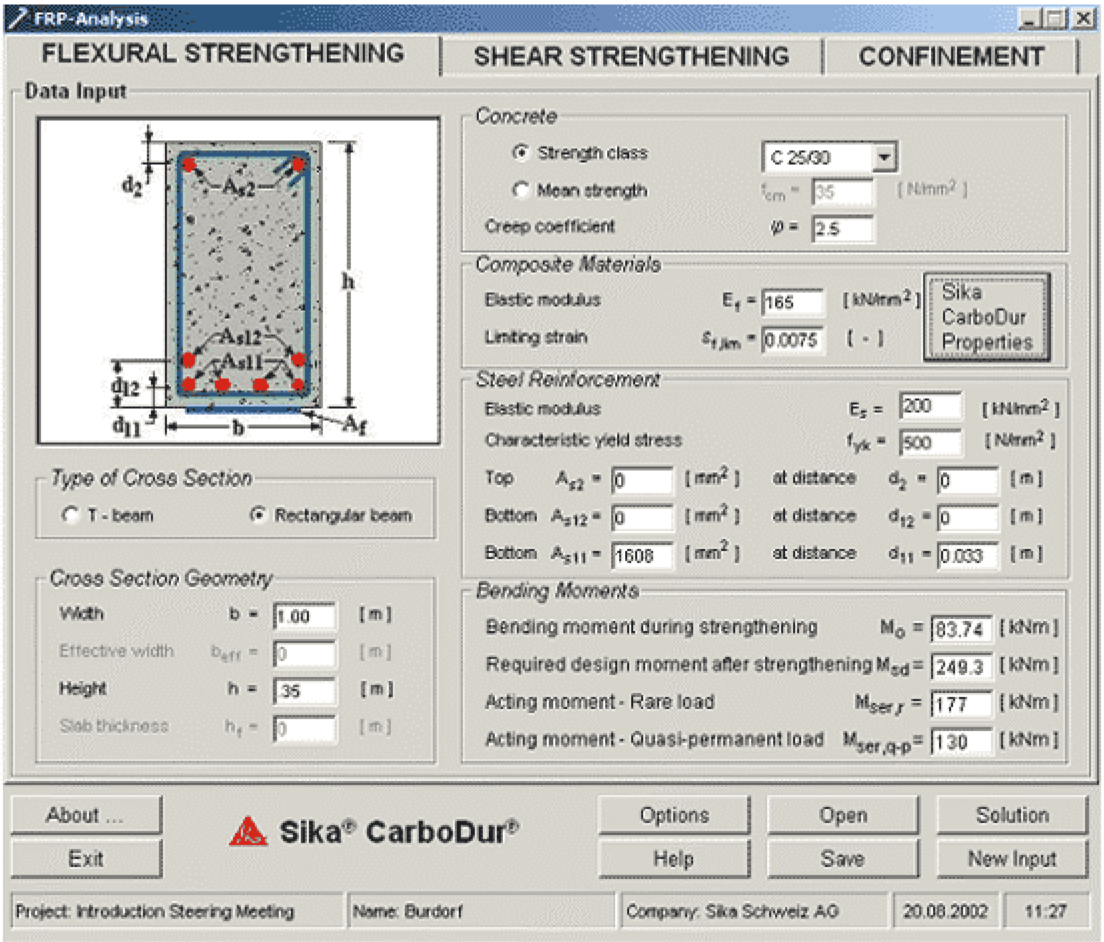

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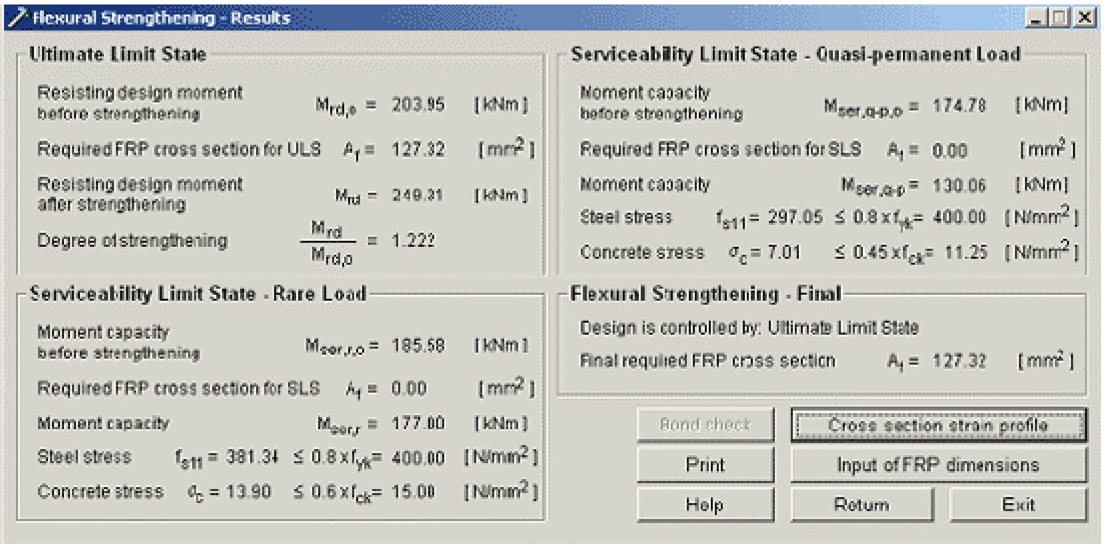
Construction

Ultimate Limit State

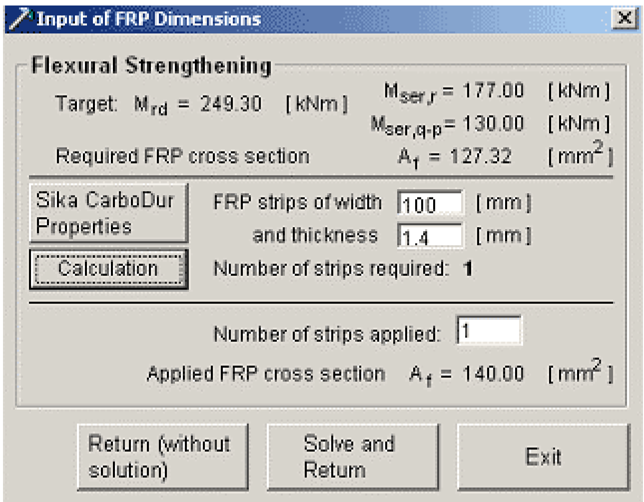
The calculations are based on the assumption that one of the following two desirable failure modes govern the behaviour:

(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_0, that develops in the extreme fibre of the cross section when the strengthening operations take place. This strain is the result of a moment M_0 (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.



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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.**

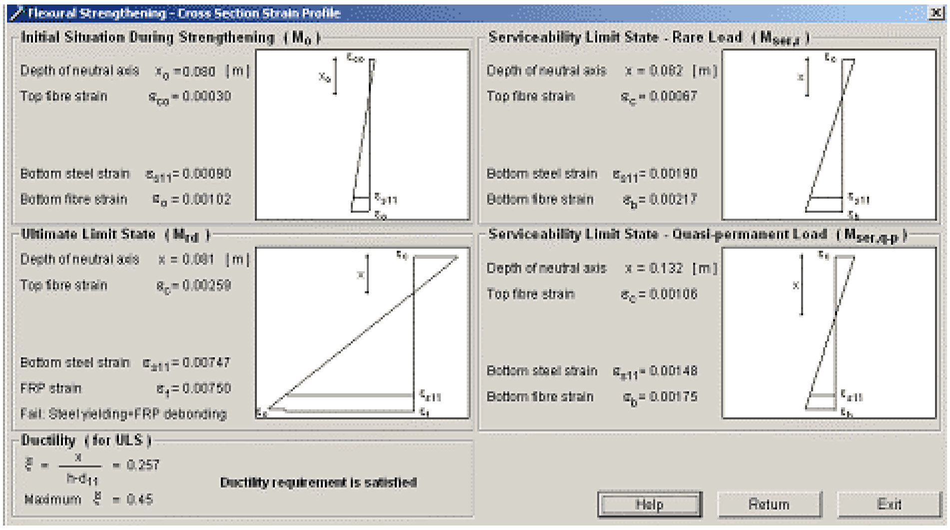
For the case of **Rare Load** the calculations are performed as in the case of the ULS, with the following modifications:

(a) $0.85f_{cd}$ 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 $f_{s1} <= 0.8f_{yk}$ (for steel) and $\sigma_c <= 0.6f_{ck}$, where the stress in the concrete is given by the following stress-strain relationship of concrete (for ε_c less than 0.002):

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

For the case of **Quasi-permanent Load** the calculations are performed as in the case of the ULS, with the following modifications:
(a) $0.85f_{cd}$ 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 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 $\sigma_c <= 0.45f_{ck}$, where the stress in the concrete is calculated with ε_c replaced by $\varepsilon_c/(1+\varphi)$.



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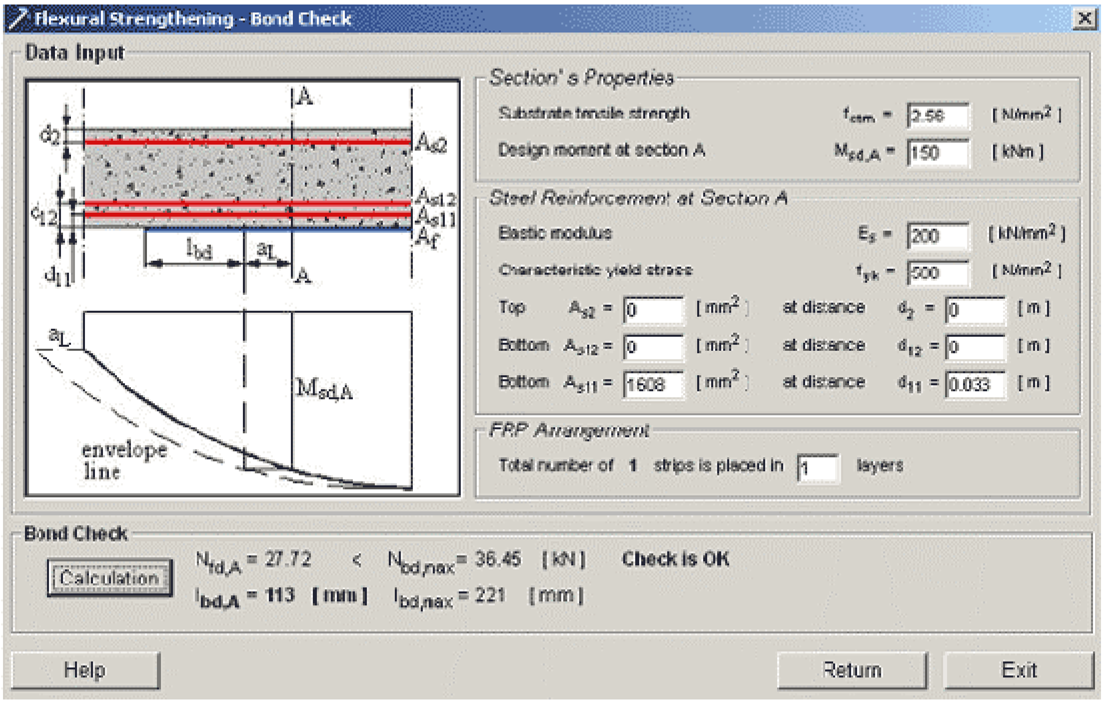
Bond check

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).



At each cross section (say 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.

It was mentioned above that $N_{fd,A}$ 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 M_o, 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).

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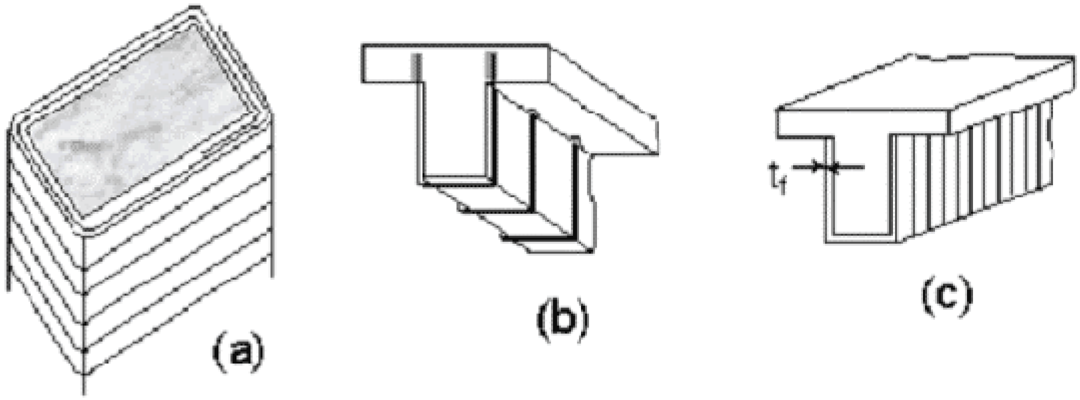
2. Shear strengthening

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 taken roughly equal to 45°. However, it is normally more practical to attach the external FRP reinforcement with the principal fibre direction perpendicular to the member axis.



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

The option “Closed jacket” or “Open jacket” is selected, depending on 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 perfect anchorage of the FRP in the compression zone may be considered of the closed-type too. This is the case, for instance, with the 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 take a solution, calculated by linear interpolation between “Closed jacket” and “Open jacket”, that is to run the programme for both cases and adopt the value by linear interpolation. Consult also the technical datasheet and design recommendation of this product.

Closed jackets or properly anchored strips are always preferable compared with open jackets, as in the latter case the FRP is debonding prematurely and is, therefore, 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 ultimate 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 according to Eurocode 2.

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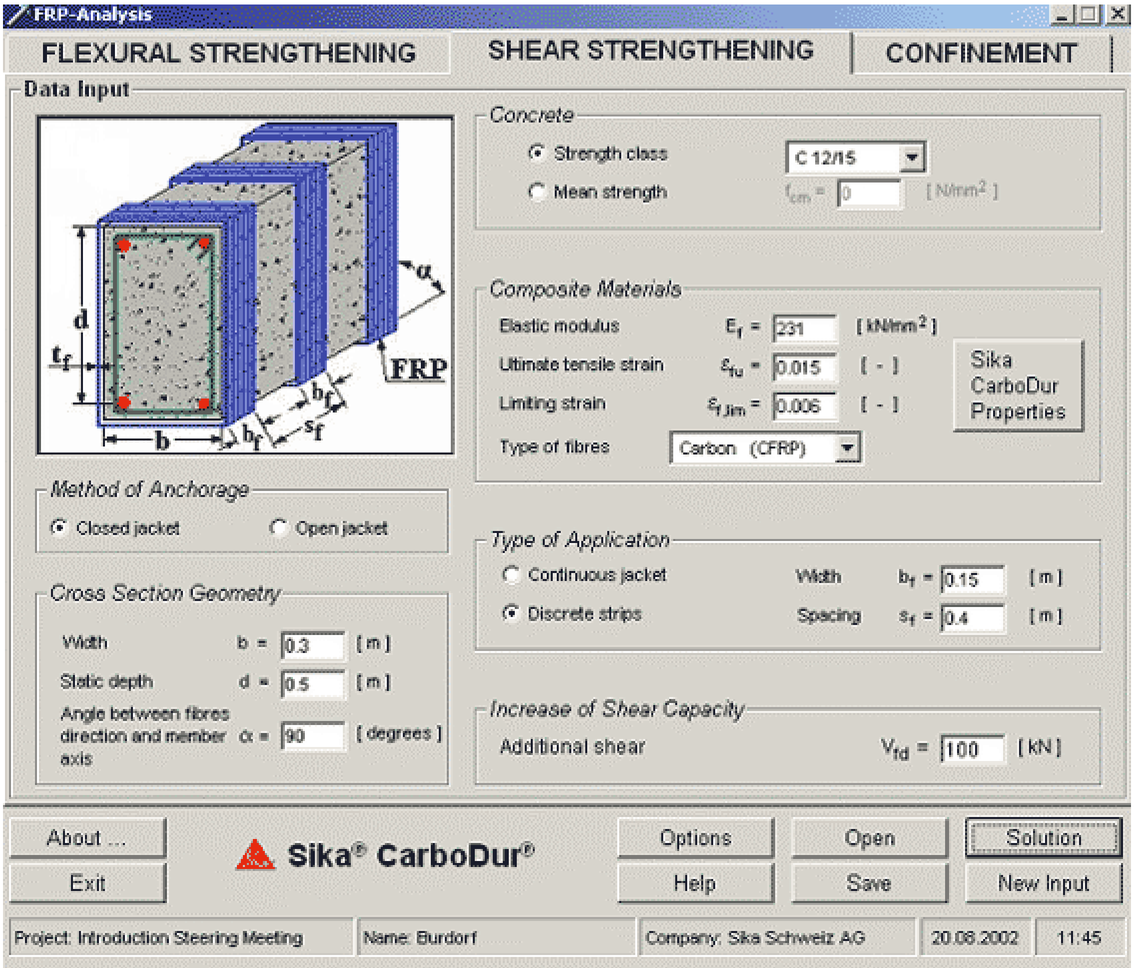
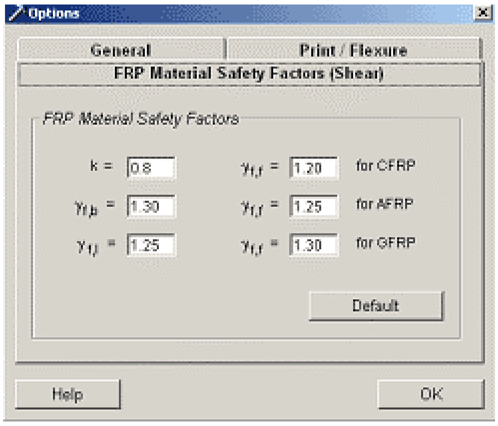
Input:
V_{fd} is the contribution of FRP to the member's shear capacity. E_f is the elastic modulus of FRP, b is the width of the cross section, d is the static (or effective) depth, α is the angle between the principal FRP fibre orientation and the longitudinal axis of the member, $\varepsilon_{fd,e}$ is the design value of the effective FRP strain and ρ_f is the FRP reinforcement ratio, equal to $(2tf/b)\sin\alpha$ for continuously bonded FRP of thickness tf, 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).

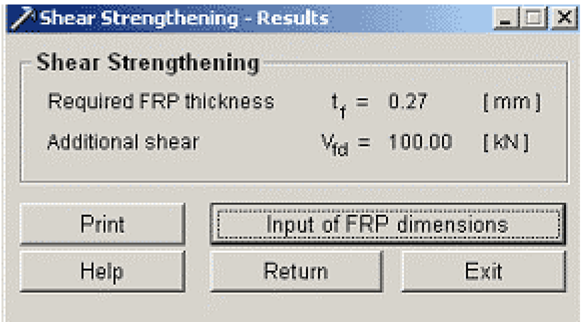


In the above, f_{cm} is the mean compressive strength of concrete in N/mm2, E_f is taken in kN/mm2, k is a constant relating the characteristic to the mean value of the effective FRP strain (default: k = 0.8) and γ_f is the FRP material safety factor. The γ_f factor depends on the type of FRP material as well as on the failure mode governing shear design.
The first term (described in eqs. (1.3.3a), (1.3.3b) and (1.3.4) in the help function) 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. (1.3.3 of help function) corresponds to FRP debonding, hence the use of $\gamma_{f,b}$ (= 1.30), and the last term is

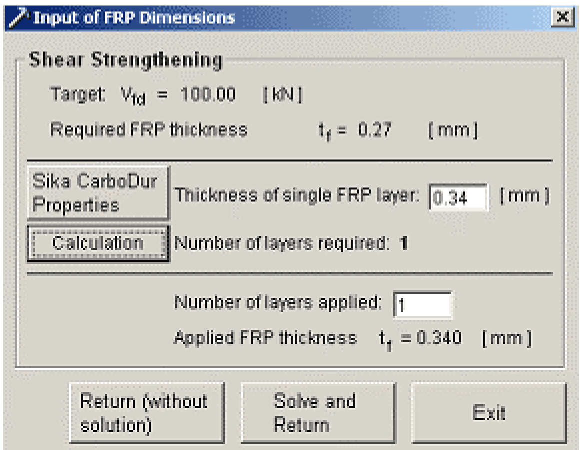


taken (with $\gamma_{f,l}$ = 1.25) if it is desired to limit the FRP strain in order to maintain the integrity of concrete and secure activation of the aggregate interlock mechanism. It should be noted that these FRP material factors may be changed through **"Options".**

The thickness of FRP required to provide a shear resistance equal to V_{fd} will be calculated.



After the input of the effective thickness of the FRP – layer, the number of layers and the effective reinforcing shear capacity can be calculated.



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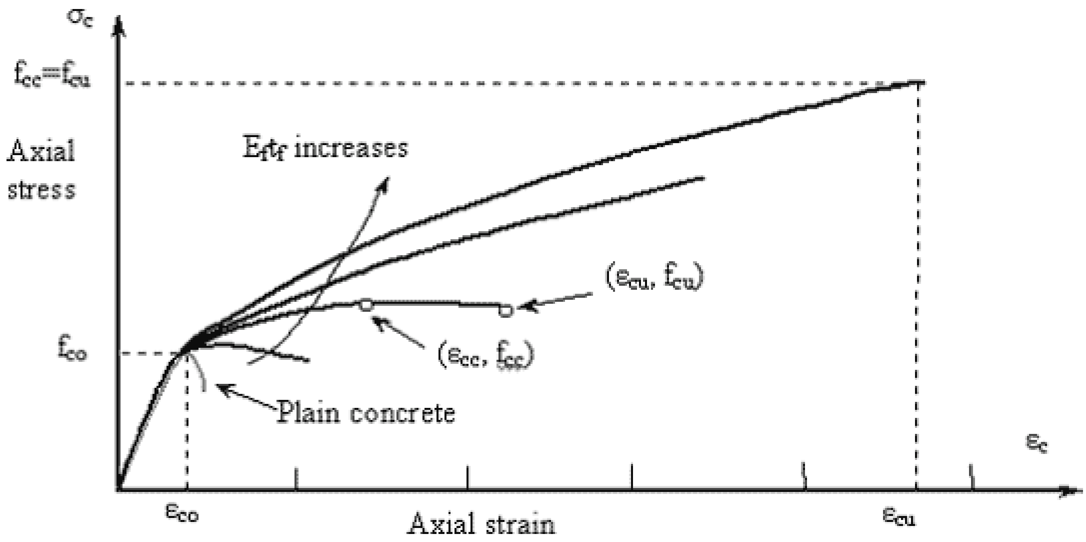
3. Confinement

The main objectives of confinement are:

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

In case of circular columns, these goals can be achieved by applying external FRP jackets, either continuously all over the surface or discontinuously 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 dilation and rebar buckling.
The stress-strain response of FRP-confined concrete is illustrated schematically in the following picture:



The figure displays a nearly bilinear response with a sharp softening and a transition zone at a stress level that is near 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 uni-axial tensile strength ε_{fu}. This reduction is attributed to several reasons, including:

(a) the tri-axial 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 over-stressing of others; damaged fibres at sharp corners or local protrusions etc).

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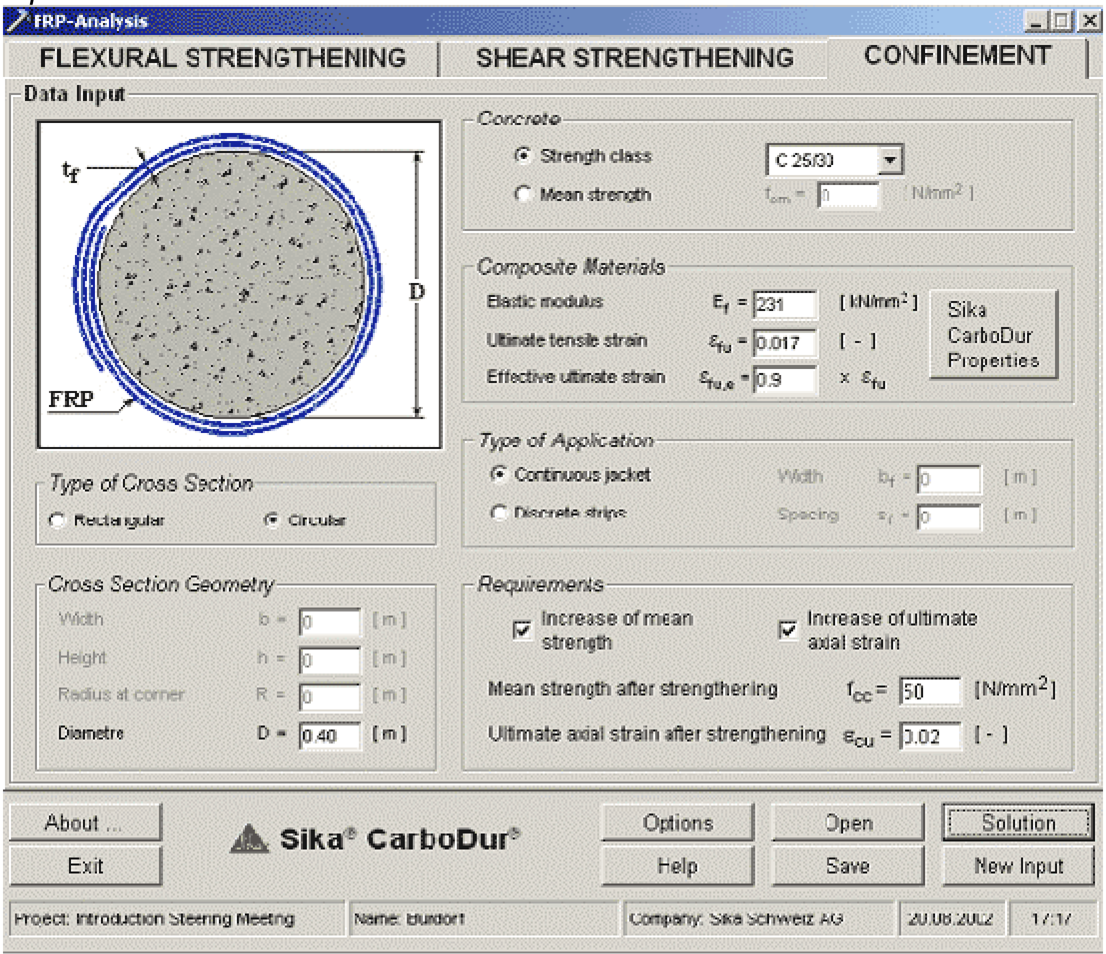
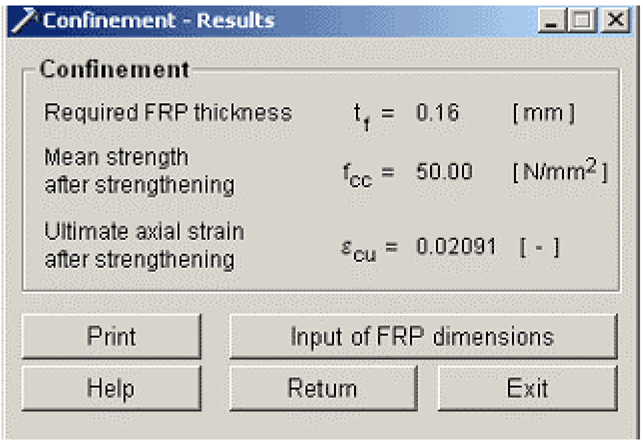
Input:



- Mean strength after strengthening $\mathbf{f_{cc}}$: This is the value of the strength of FRP-confined concrete corresponding to the FRP jacket of thickness t_f.
- Ultimate axial strain after strengthening $\boldsymbol{\varepsilon_{cu}}$: This is the value of the ultimate axial strain of FRP-confined concrete corresponding to the FRP jacket of thickness t_f.

The total required thickness t_f of the FRP jacket is provided. Upon completion of the solution process, the “Results” window provides the following:



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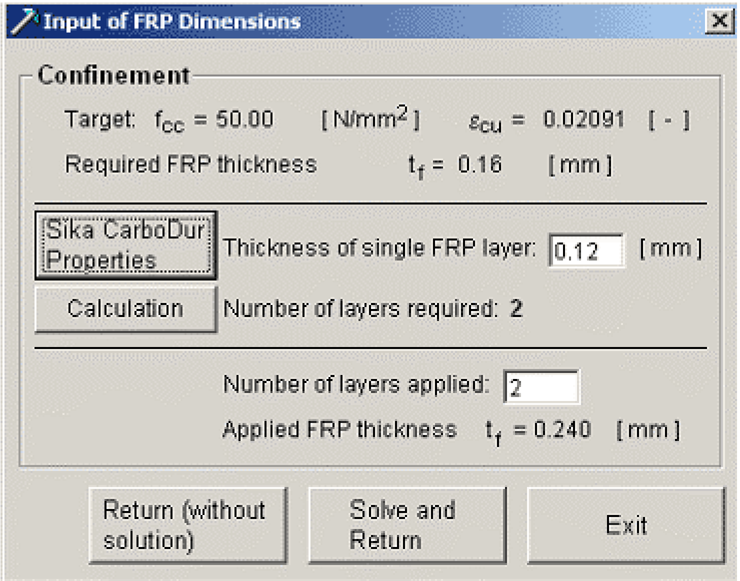

For details please consult the help – function of the design – software or the *fib* document.

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