ANALYSIS AND DESIGN OF SFRC STRUCTURES

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ABSTRACT

Steel fibres have been used worldwide in the reinforcement of concrete structures for more than four decades. Steel Fibre Reinforced Concrete (SFRC) is well known in several areas of civil engineering as a structural application - underground structures probably represent one of the most important fields of application for SFRC, as well as slope stabilization works.

The development of the new Dramix® 4D and 5D steel fibres, released in 2012 with enhanced mechanical properties, allowed for a remarkable expansion of the fields of application for SFRC structures. It was also possible to improve the structural performance to levels that were previously unattainable. This performance improvement is extraordinary in Serviceability Limit State verifications (namely for crack control), being also very important in Ultimate Limit State verifications, in particular for SFRC solutions combined with traditional rebar reinforcement.

After four years of investigation, a specific software that includes the contribution of steel fibres was developed for structural analysis and design (DIA*Calc*®) in accordance with European standards, namely Eurocode 2.

The present paper highlights the main features of the software, showing also some examples of geotechnical works that incorporate SFRC.

Keywords: Analysis, Design, Concrete, Steel fibres, Reinforcement, Software, DIACalc®

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1. INTRODUCTION

Steel fibres have been used worldwide in the reinforcement of concrete structures for more than four decades. Steel Fibre Reinforced Concrete (SFRC) is well known in several areas of civil engineering as a structural application - underground structures probably represent one of the most important fields of application for SFRC (tunnels, caverns, shafts, etc.), as well as slope stabilization works.

Until recently, steel fibres of the same category of Dramix® 3D, with mean values of yield strength (f_{ym}) of about 1100 MPa, were the most commonly used.

The development of the new Dramix® 4D and 5D steel fibres (see Figures 1 and 2), with enhanced mechanical properties (f_{ym} up to 2300 MPa, with a resistance increase in the post-peak behaviour for 5D fibres - hardening effect), allowed for a remarkable expansion of the fields of application for SFRC structures, also increasing the structural performance to levels that were previously unattainable.

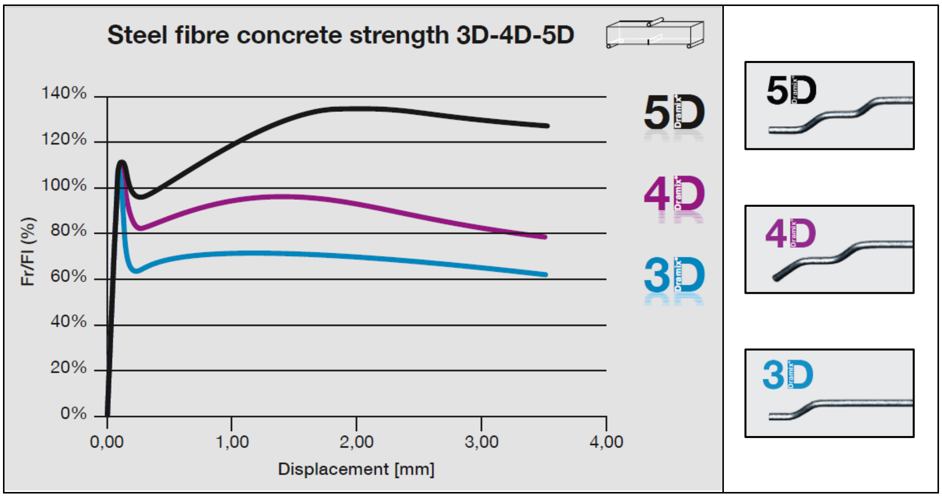


Figure 1. SFRC load-displacement curves for Dramix® fibres 3D, 4D and 5D.

Figure 2 also shows the values of f_{ym} for the most common steel rebars used in Europe, which can be compared with the steel fibre values - it is important to refer that these fibres are made of very high strength steel, in some cases comparable with prestressing steel.

However, the use of high strength steel is not the only reason for the good results achieved with these fibres. In fact, the performance improvement of the referred 4D and 5D steel fibres results mainly from the combination of three factors: 1) the hook's shape; 2) the use of a high ductility wire and 3) the very high tensile strength of the steel.

Taking into account that good SFRC is not just the sum of concrete and fibres, it is clear that laboratory testing plays a very important role in the process of understanding the structural behaviour of SFRC. It is important to refer that the laboratory tests carried out for the characterisation of SFRC structures follow the European standard EN 14651:2005 [1], in order to evaluate the residual flexural tensile strength of SFRC on moulded test specimens.

As an example of these tests, some results on SFRC with 5D 65/60BG steel fibres are shown in Figure 3, concerning the penstock tunnel lining (8 m diameter) in Venda Nova III repowering hydroelectric scheme, in Portugal. Test specimens with ages of 25 days (dosage of 50 kg/m^3) and 30 days (dosage of 65 kg/m^3) were used.

The very good results obtained in the referred tests are mainly due to the good performance of the 5D steel fibres, to the high quality concrete used and, especially, to the very carefully chosen concrete mix.

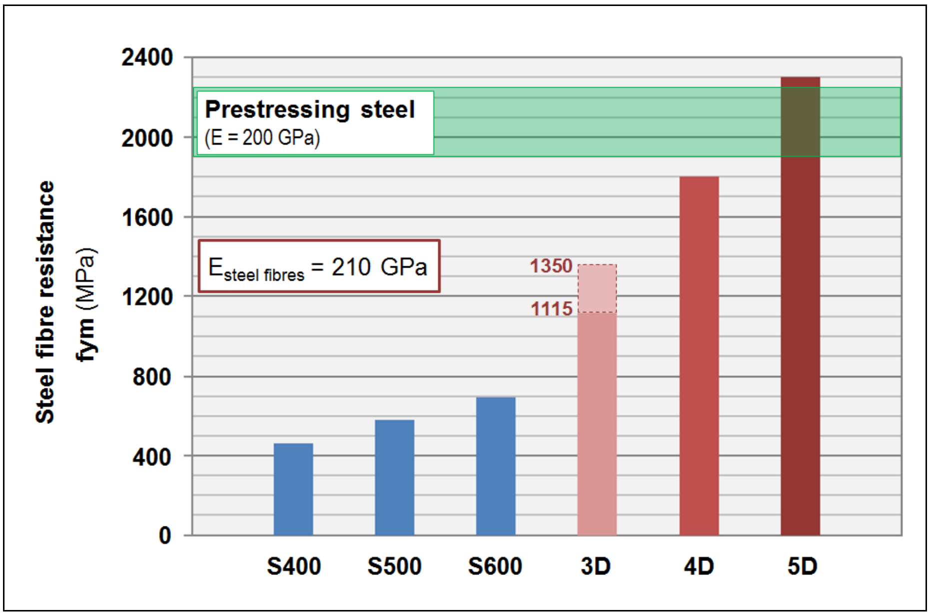


Figure 2. Values of f_{ym} for common steel rebars and for Dramix® steel fibres.

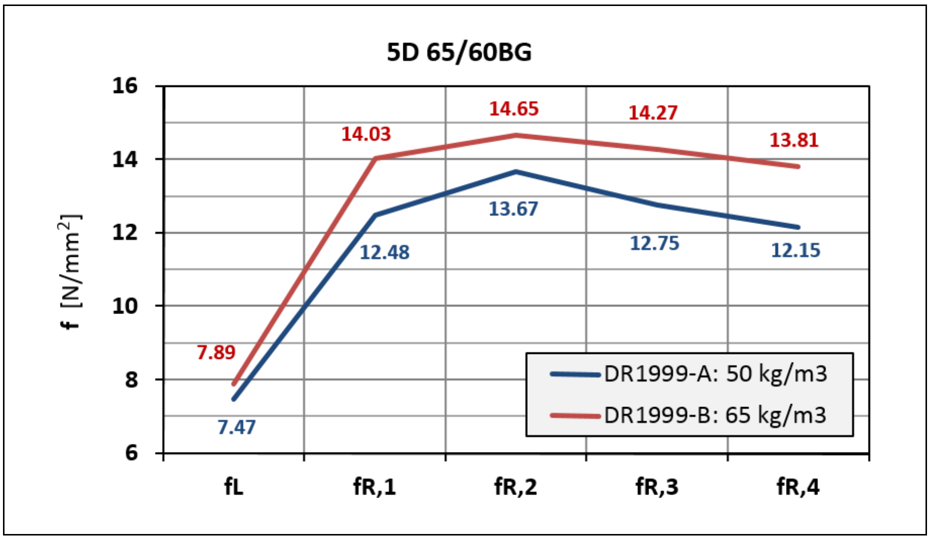


Figure 3. Test results for a SFRC with Dramix® 5D steel fibres.

Despite the obvious improvement of structural performance that can be achieved with the use of SFRC solutions, especially for SFRC solutions combined with traditional rebar reinforcement, there has always been an important lack of engineering calculation tools in the market for design purposes.

In order to overcome this situation, DIACLASE has developed a software for structural analysis and design (DIA*Calc*®) that includes the contribution of steel fibres, for Ultimate Limit State (ULS) and Serviceability Limit State (SLS) verifications.

The present paper highlights the main features of DIA*Calc*®, showing results that correspond to different and independent situations with the sole purpose of illustrating the software's main features and environment.

Some examples of geotechnical works that incorporate SFRC are also presented, in order to illustrate the use of SFRC solutions in the structural domain.

2. ANALYSIS AND DESIGN OF SFRC STRUCTURES WITH DIACALC®

2.1. General

DIA*Calc*® was developed by DIACLASE for analysis and design of concrete structures, considering the following possible structural combinations:

- Plain concrete structures;
- Concrete structures reinforced with conventional rebars;
- Concrete structures reinforced with steel fibres;
- Concrete structures with combined reinforcement (rebars + steel fibres).

The software was developed in accordance with Eurocode 2 [2] and the German standard DAfStb Stahlfaserbeton [3], which is a German extension of the DIN EN 1992-1-1 for SFRC structures. Future developments of the software will take into account other international standards, namely fib Model Code 2010 [4] and ACI standards.

It is an integrated software, intended to be used by engineers to perform complete analysis regarding the following verifications:

- ULS → *Structural resistance*
  - Bending (with or without axial force);
  - Shear;
  - Punching Shear.
- SLS → *Durability*
  - Crack control.

DIA*Calc*® automatically produces complete output results, in six languages, allowing the creation of technical reports almost instantly.

2.2. Ultimate limit state verifications

2.2.1. Bending and shear

The main input data for ULS verifications of bending (with or without axial forces) and shear consists of the following:

- Type of structural element (Solid slab / Plate, Beam, Column);
- Cross-section's geometry;
- Concrete cover;
- Concrete's parameters (compressive strength, including the α_{cc} factor);
- Rebar's parameters (diameter, spacing / no. of bars, yield strength, strain at maximum load);
- SFRC parameters:
  - Defining the residual flexural tensile strength values $f_{R,1k}$ ... $f_{R,4k}$ (see Figure 4, concerning an hypothetical situation for a certain fibre), or using a steel fibre database (type of fibre, dosage);
  - α_{cf} factor for the SFRC tensile strength;
  - Definition of the steel fibres orientation.
- Internal forces (M_{Sd}, N_{Sd}, V_{Sd}).

The stress and strain diagrams used for the ULS analysis are schematically presented in Figure 5. It is important to refer that the steel fibres contribution is not taken into consideration (for bending and shear) when the entire section is in tension.

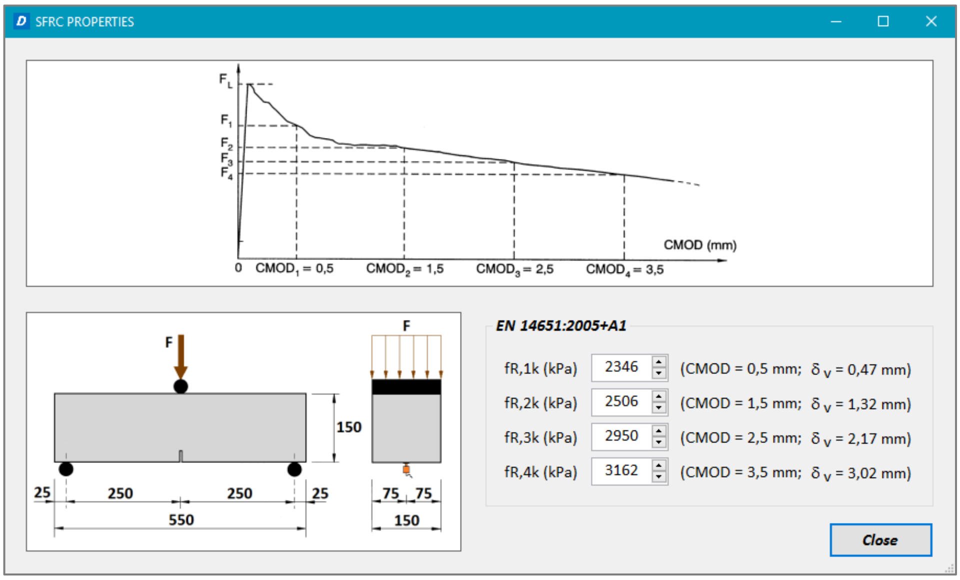


Figure 4. Definition of residual strength values according to EN 14651:2005.

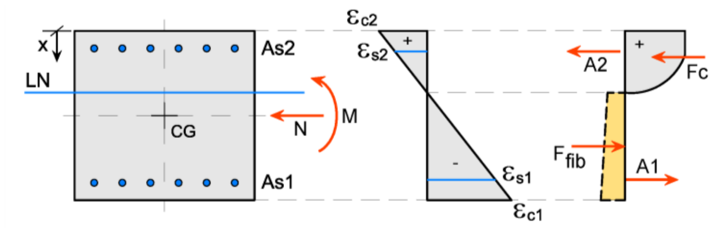


Figure 5. Stress and strain diagrams used in DIA*Calc*® for the ULS analysis.

An example of the main form for bending and shear analysis is presented in Figure 6, for a SFRC solution; the most relevant results are shown in this form, including the *M-N* interaction diagram (which can alternatively be presented as a μ-ν diagram).

For shear verifications of SFRC structures without shear reinforcement, the design shear resistance ($V^f_{Rd,c}$) is calculated as follows:

$$V^f_{Rd,c} = V_{Rd,c} + V_{Rd,cf} \tag{1}$$

Where $V_{Rd,c}$ is the design shear resistance without shear reinforcement and $V_{Rd,cf}$ is the design shear resistance resulting from the steel fibre effect, which is usually very significant.

For shear verifications of SFRC structures requiring shear reinforcement, the design shear resistance ($V^f_{Rd,s}$) is calculated as follows:

$$V^f_{Rd,s} = V_{Rd,s} + V_{Rd,cf} \tag{2}$$

Where $V_{Rd,s}$ is design value of the shear force which can be sustained by the yielding shear reinforcement.

Minimum and maximum reinforcement areas are calculated for bending and shear (taking into account the steel fibre effect, which can be very important, especially for shear), as well as rebar spacing.

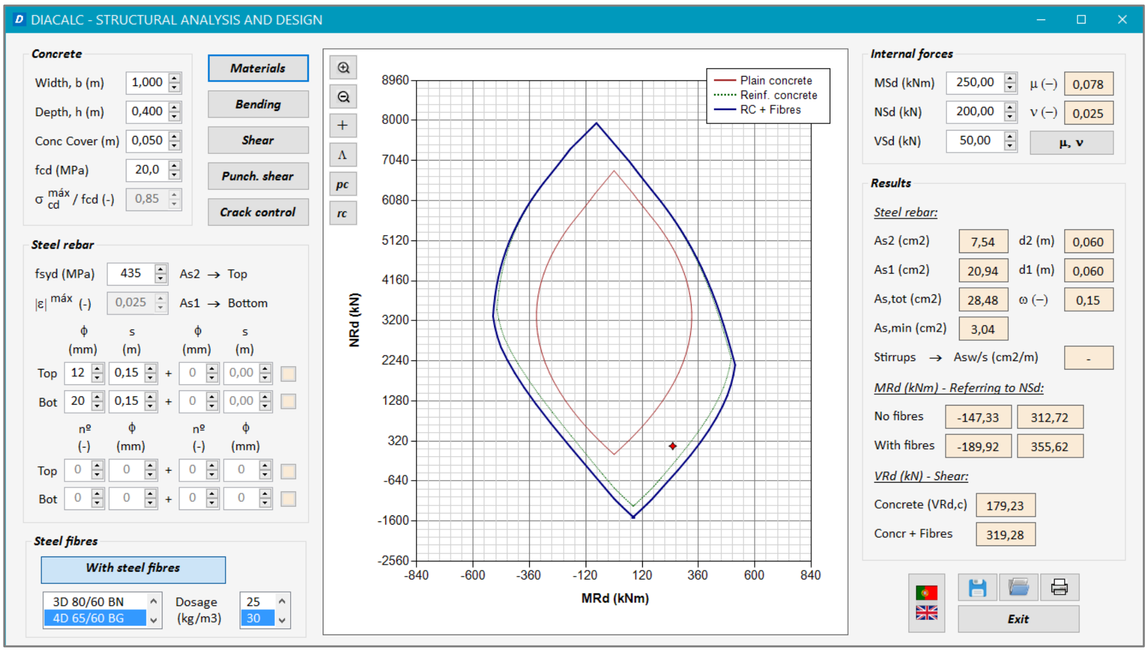


Figure 6. Main form for bending and shear analysis.

2.2.2. *Punching shear*

For punching shear verifications, the following complementary input data (taking in consideration the input data previously defined for bending and shear) is required:

- Geometry of the loaded area;
- Definition of the soil-structure interaction (when applicable);
- Rebar parameters in both directions (diameter, area);
- Loads / Internal forces (independent from the values defined for bending and shear).

An example of the main form for punching shear analysis is presented in Figure 7, for a SFRC solution; the most relevant results are shown in this form, including the graphic that shows the results for all the considered perimeters - from the perimeter of the loaded area (*a=0*) to the perimeter at a distance of *2d* from the loaded area (being "*d*" the mean effective depth of the section).

In Figure 7 it is possible to see the section's resistance without considering the effect of the fibres (green dotted line), as well as the resistance considering the existence of the steel fibres (blue line).

The punching shear verification can include the soil-structure interaction, when applicable, in two different ways, depending on the situation under analysis:

- Calculating the ground pressure distribution using a classical Beam on Elastic Foundation model (BoEF) based on the Winkler solution; the width of the beam and the deformability modulus of the ground are required as direct input values - the remaining input values are internally calculated by the software; Figure 8 shows the results obtained with this approach;
- Defining a mean value for the ground pressure.

For punching shear verifications of SFRC structures without shear reinforcement, the design punching shear resistance ($v^f_{Rd,c}$) is calculated as follows:

$$v^f_{Rd,c} = v_{Rd,c} + v_{Rd,cf} \tag{3}$$

Where $v_{Rd,c}$ is the design punching shear resistance without shear reinforcement and $v_{Rd,cf}$ is the design shear resistance in the critical perimeter limited by the steel fibre effect. $v_{Rd,cf}$ is limited to a maximum value of $0.4 \cdot v_{Rd,c}$ for design purposes, because of the fragile nature of the punching shear failure.

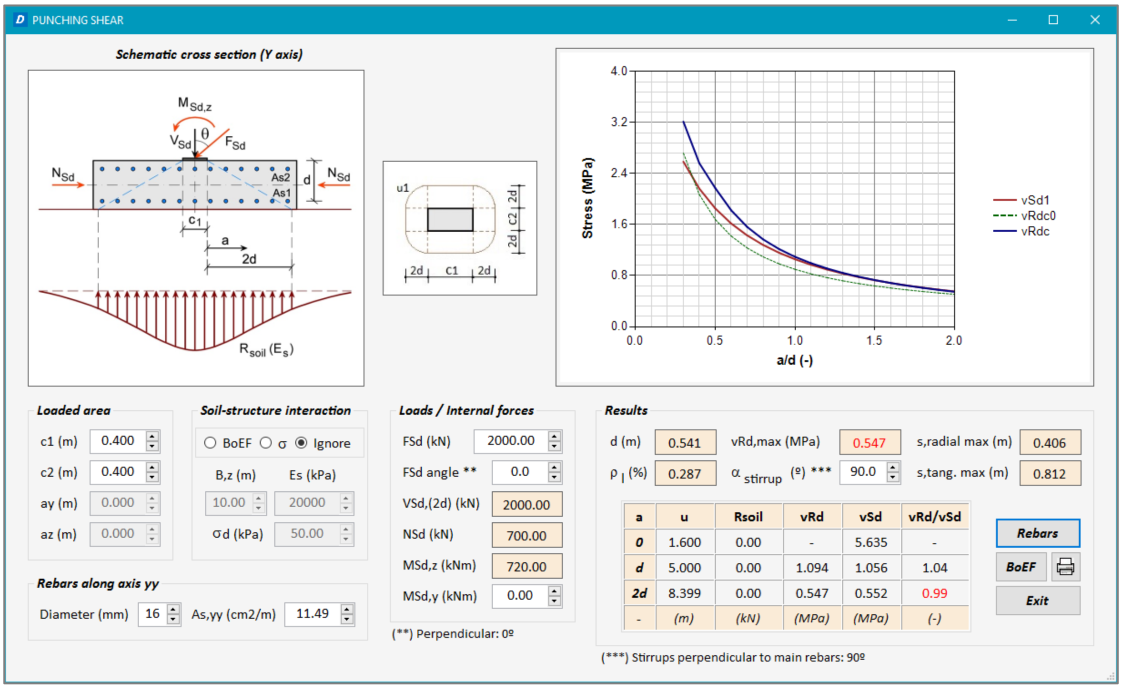


Figure 7. Main form for punching shear analysis.

For punching shear verifications of SFRC structures requiring shear reinforcement, the steel fibre effect is not taken into consideration in the calculation of A_{sw}. The steel fibre effect is also ignored for the calculation of minimum reinforcement areas ($A_{sw,min}$).

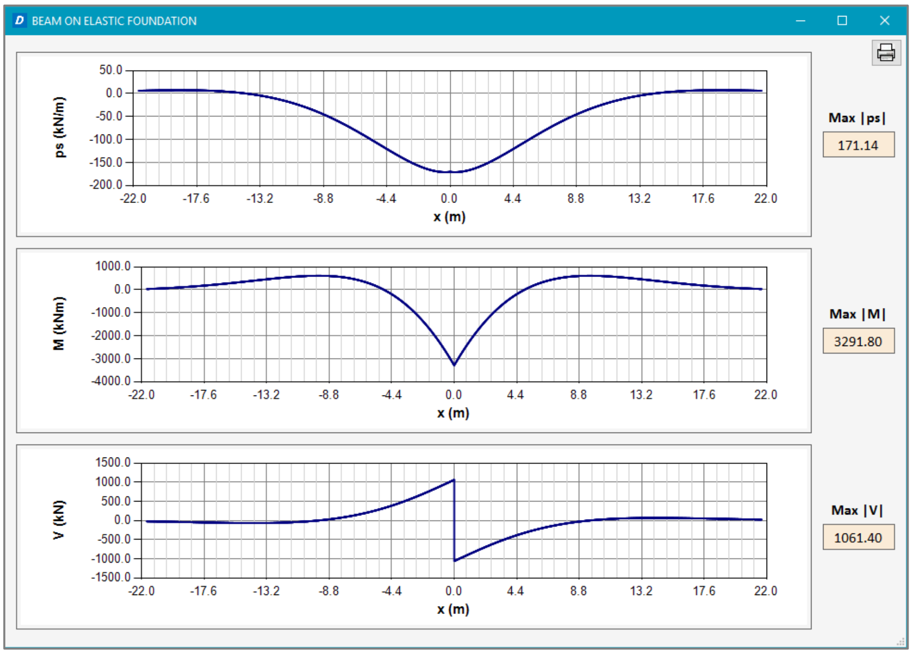


Figure 8. Results from a soil-structure interaction analysis with a BoEF model.

A solution is provided automatically by DIA*Calc*® whenever punching shear reinforcement is necessary, by calculating the reinforcement areas and defining a geometrical distribution of the rebars according to the reinforcement detailing rules of Eurocode 2 [2]. A cruciform pattern solution is presented in Figure 9.

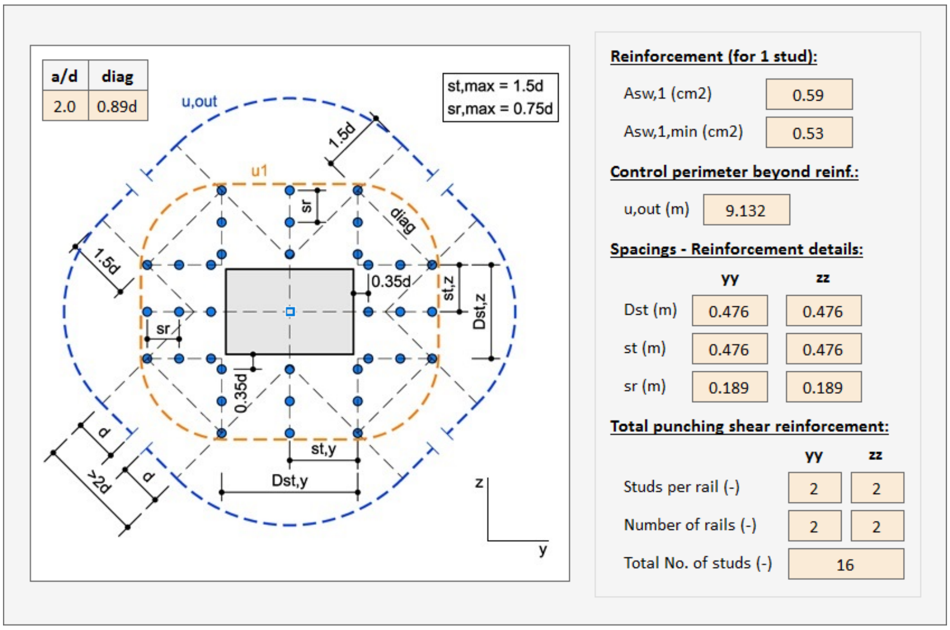


Figure 9. Example of a solution presented for the punching shear reinforcement.

2.3. Serviceability limit state verifications

In order to perform crack control analysis, the following complementary input data (taking in consideration the input data previously defined for bending and shear) are required - see Figure 10:

- Internal forces (M_k, N_k - independent from the values defined for bending and shear);
- Duration of loading;
- Bond properties of the rebars;
- Concrete age;
- Cement class (R, S, N).

For the crack width (w_k) evaluation, the following expression is used:

$$w_k = s_{r,max} \cdot \left(\varepsilon_{sm}^{f} - \varepsilon_{cm}\right) \tag{4}$$

Where $s_{r,max}$ is the maximum crack spacing, ε_{sm}^{f} is the mean strain in the reinforcement under the relevant combination of loads (taking into consideration the steel fibre effect when applicable), and ε_{cm} is the mean strain in the concrete between cracks.

The steel fibres effect is very important regarding crack control, for the evaluation of the required minimum reinforcement area and also for the calculation of the crack width.

In order to obtain the crack width and the crack spacing for a specific combination of loads, the strains and stresses in the cross section are calculated by the software through an exact analysis - results are given for the concrete (section's top and bottom) and also for the top and bottom rebar levels (when applicable).

Figure 10 shows an example of the results obtained for a crack control analysis for a SFRC solution. The results allow for the comparison of the steel fibre effect in the solution being analysed, including the strains and stresses in the section (post-cracking results), as well as the evaluation of the neutral axis position.

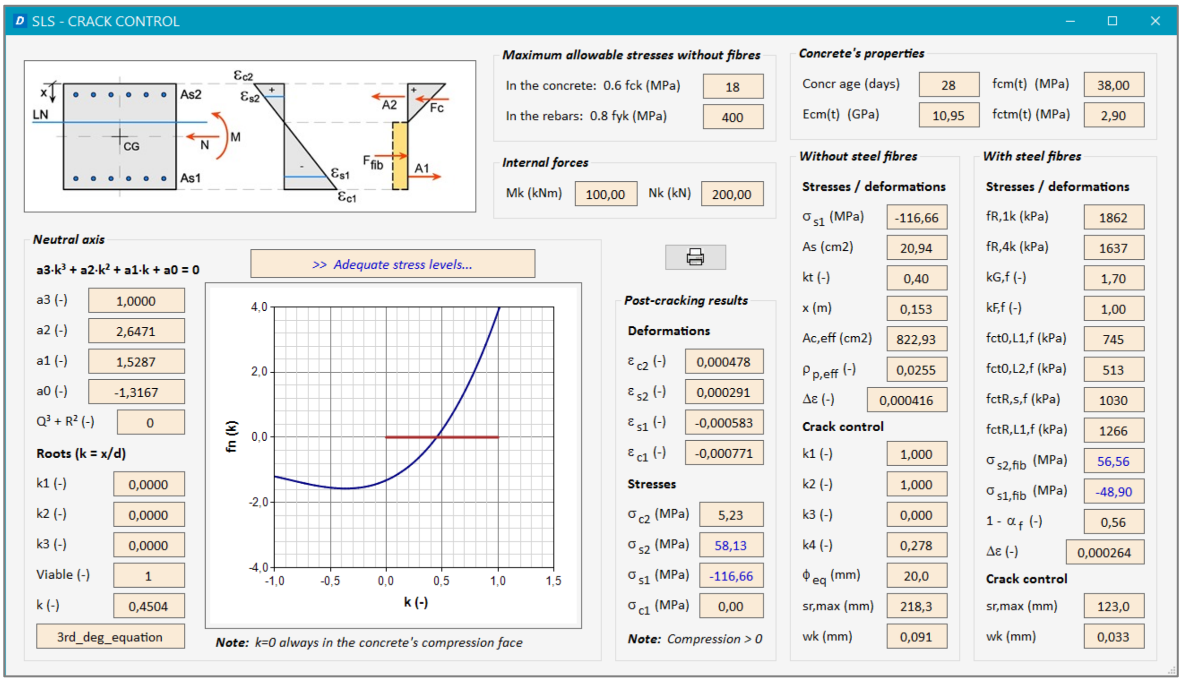


Figure 10. Example of the results obtained for a crack control analysis.

2.4. Output results

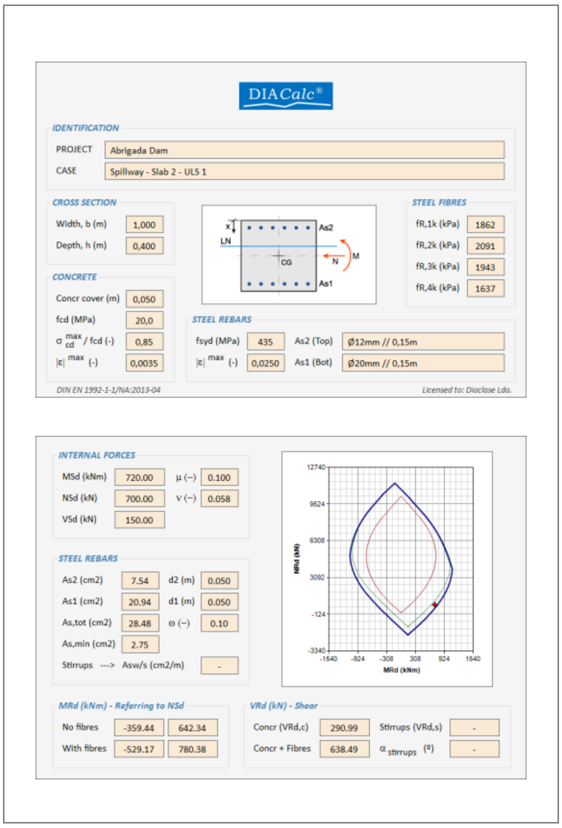
The output results are produced automatically, regarding all the relevant information for each verification, in order to easily create technical reports:

- Bending and Shear:
  - Including the interaction diagram (M-N or μ-ν).
- Punching shear:
  - Including the graph *a/d* vs. (v_{Sd}, v_{Rd});
  - Including the punching shear reinforcement definition, when applicable;
  - Including the beam on elastic model results, when applicable.
- Crack control:
  - Including the graphical definition of the neutral axis.

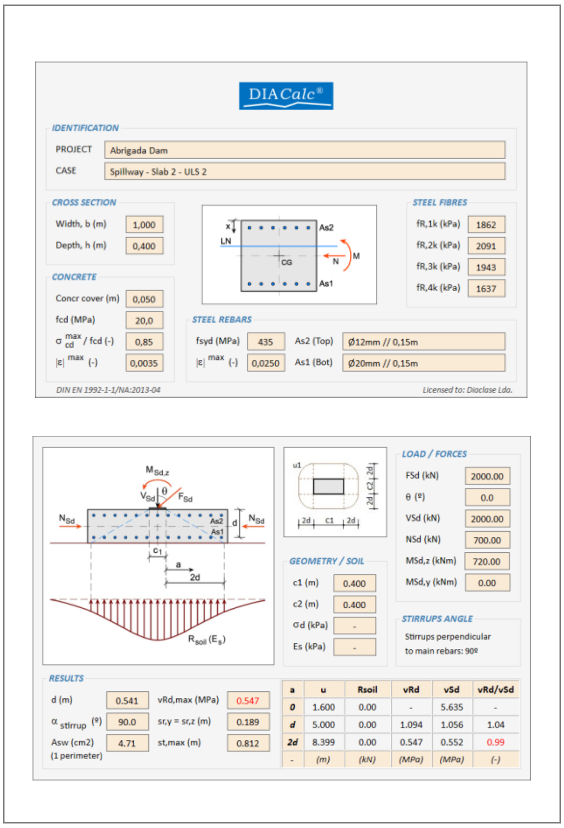
Six languages are available for the output results: English, French, German, Italian, Portuguese and Spanish. Future developments of the software will include additional languages.

The output results can be presented in the International System of Units (SI); the Imperial System of Units will also be considered in future developments.

As an example of the output layouts created by DIA*Calc*®, Figure 11 shows some results concerning Bending and Shear and also Punching shear.



Bending and Shear



Punching shear

Figure 11. Output results - Reports.

3. FIELDS OF APPLICATION FOR SFRC STRUCTURES

3.1. General

SFRC structures are very interesting for civil engineering works, especially due to the exceptional mechanical properties of the 4D and 5D steel fibres, which allow for the design of more competitive solutions in several areas, such as:

- Underground structures (caverns, tunnels, shafts);
- Hydraulic structures (dams, power plants, canals);
- Earth retaining structures (including diaphragm walls);
- Foundations (including piles);
- Slope stabilisation works;
- Pavements (industrial, harbour, clad racks, rafts);
- Prefabricated structures (tunnel linings, tubular structures).

Furthermore, SFRC is also suitable for the use of special concrete solutions, namely:

- Underwater concrete;
- Steel fibre reinforced self-compacting concrete;
- High strength concrete.

In the present paper some examples of the use of SFRC solutions will be presented regarding underground structures (temporary and permanent works), as well as slope stabilisation works. The first author was the designer for all the presented projects, except for the Lee Tunnel.

3.2. Underground structures

3.2.1. Road tunnel (Faial-Cortado tunnel; Owner: RAMEDM)

The Faial-Cortado tunnel (see Figure 12) is located in the north shore of Madeira Island, with a length of 3168 m and a width that varies from 9.6 m to 20.4 m [5]. The works were completed in 2004.

Figure 12. Faial-Cortado tunnel.

SFRC was used in all the primary linings, together with steel welded mesh, in order to obtain a solution that was able to comply with significant internal forces; Dramix® 3D 45/35BL steel fibres were used, with dosages varying from 30 to 40 kg/m^3.

3.2.2. Cavern (Socorridos pumping station; Owner: EEM)

The cavern of the Socorridos pumping station (see Figure 13) is located in Madeira Island, with a total height of 26.5 m, a width of 12 m and a length of 42 m [6]. The works were completed in 2005.

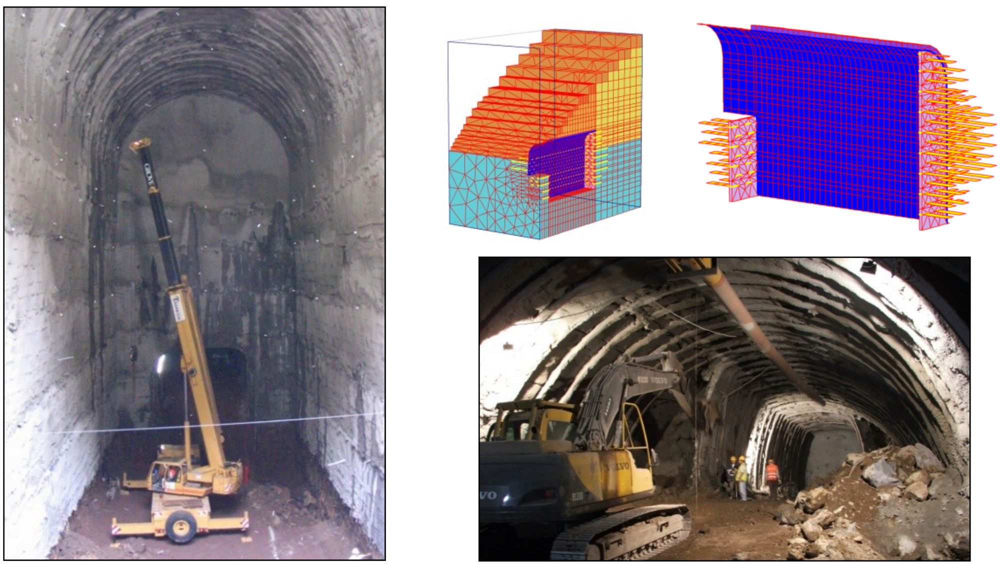


Figure 13. Socorridos pumping station.

SFRC was used in the primary lining, together with steel welded mesh, in order to obtain a solution that was able to comply with significant internal forces; Dramix® 3D 45/35BL steel fibres were used, with a dosage of 50 kg/m^3.

3.2.3. Hydraulic tunnels (Socorridos water storage network; Owner: EEM)

The Socorridos water storage network tunnels (see Figure 14) are located in Madeira Island, with a total length of 1250 m and a height of 7 m, for a storage of 40,000 m^3 of water [6]. The year of completion of the works was 2005.

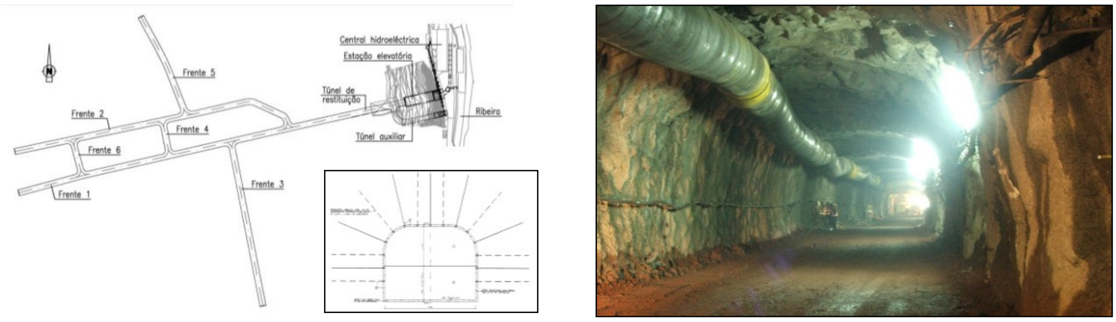


Figure 14. Socorridos water storage network.

SFRC was used in the primary and final linings, not only to comply with demanding criteria of resistance and durability, but also to ensure that the tunnels would be watertight; Dramix® 3D 45/35BL steel fibres were used, with a dosage of 50 kg/m^3.

3.2.4. Hydraulic tunnel (Tideway Lee Tunnel project; Owner: Thames Water)

The Tideway Lee Tunnel was constructed at East London (see Figure 15), integrated in the London's sewage system. It comprises five shafts of various depths (68 m to 86.5 m) and diameters (20 m to 38 m), and one tunnel with a unique and innovative secondary lining design [7].

The Lee Tunnel is a 6.9 km long tunnel with a finished internal diameter of 7.2 m, being the largest to date steel fiber only reinforced tunnel in Great Britain. The works were completed in January 2016.

The design and fabrication of the traditional reinforcement in such a tunnel as the Lee Tunnel would have been a major logistical challenge to the construction team at the jobsite - an estimated 17000 tons of traditional reinforcing bar would have had to have been delivered, stored, transported underground and fixed into position - with iron workers working at height off work platforms.

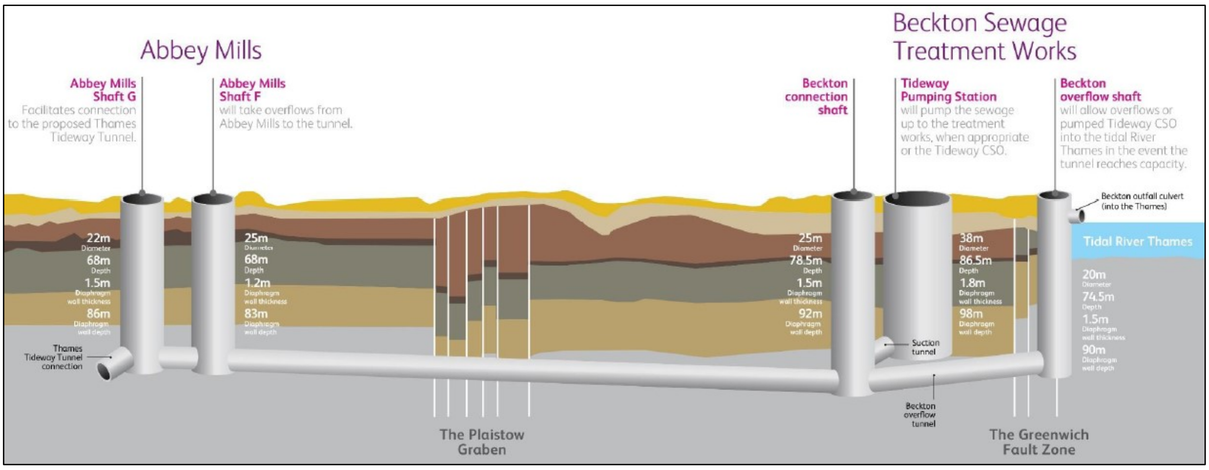


Figure 15. General layout of the Lee tunnel.

In this case, the standard traditional reinforcement was replaced with a Dramix® 5D 65/60BG steel fibre solution for the secondary tunnel lining (see Figure 16), with a dosage of 40 kg/m^3.

No reinforcement bars were used at all, eliminating the very large and difficult logistical challenge that would have been placed before the contractors underground team.

The referred final lining consisted of 350 mm thick precast concrete segments, with a specified strength of 60 MPa.

Figure 16. Secondary tunnel lining.

3.3. Slope stabilisation works

In March 2011 a massive slope failure (more than 50 m high) occurred close to the village of Arco de São Jorge, in Madeira Island, causing the destruction of the main road of the island's north shore (ER101) over more than 80 m.

The slope failure occurred inside a volcanic crater with a diameter of 2.4 km, with very unfavourable geotechnical characteristics, resulting in a 123 m high slope stabilisation solution - see Figures 17 and 18.

SFRC was used in the concrete facing, in order to assure an adequate resistance level and also to comply with the demanding durability criterion that was defined for this slope; Dramix® 3D 65/35BG steel fibres were used, with a dosage of 25 kg/m^3. The works were completed for RAMEDM in November 2011.

Figure 17. Slope failure close to the village of Arco de São Jorge.

Figure 18. Slope stabilisation works.

4. CONCLUSIONS

The development of the new Dramix® 4D and 5D steel fibres allowed for a remarkable expansion of the fields of application for SFRC structures in civil engineering.

Taking into consideration that there has been an important lack of engineering calculation tools in the market for SFRC solutions, DIACLASE has developed an integrated software for design purposes (DIA*Calc*®), mainly based in Eurocode 2 and including the contribution of steel fibres, in order to carry out the relevant ULS and SLS verifications.

The use of SFRC solutions has proven to be very effective in ULS verifications, especially concerning shear (stirrups become often unnecessary for slabs and shells, which is very useful in underground works) and also for punching shear (which is interesting, as an example, for anchored walls). For bending, the increase in resistance can usually vary from 20% to 50%, which is also interesting in many situations.

Despite the referred advantages in ULS verifications, the use of SFRC solutions has proven to be extraordinary regarding crack control, with very significant reductions concerning the crack opening values. This is a matter of great importance, because it directly influences the structures durability.

Despite the importance of the existence of calculation tools for the design of SFRC structures, the technical knowledge and the experience in dealing with SFRC should also be taken into consideration, to assure adequate levels of safety not only in the design phase but also during construction.

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