Validation

FRP RC Studio

Platform validation manual

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1. Introduction

This manual documents the reliability of the FRP RC Studio platform, as required by Eurocode 0 (EN 1990). The application enables the design of concrete structural elements reinforced with FRP bars. The reference codes supported in the Standard version are CNR-DT 203 R1 and Eurocode 2 (EN 1992-1-1).
The first chapter presents the theoretical framework of the calculation methodology; the second chapter reports the case study proposed by CNR-DT 203 R1 (appendix G, sections 17.1.2 and 17.1.3), comparing the results obtained from the platform with those provided by the code.
The percentage differences between the results:

$$percentage\ \ difference\ \ (DP) = 100 \times \left[\frac{Results\ \ "\ \ FRP\ \ RC\ \ Studio"}{Results\ \ CNR\ \ DT\ \ 203\ \ R1} - 1 \right]$$

are reported in tabular form for ease of consultation, adopting the following rating scale:
if 0% ≤ DP < 0.1% → results in perfect agreement with independent results;
if 0.1% ≤ DP < 5% → results in excellent agreement with independent results;
if 5% ≤ DP < 10% → results in good agreement with independent results.

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2. Theoretical framework of the calculation methodology

The design of concrete structural elements reinforced with FRP bars requires flexural analyses to compute the ultimate resisting moment (ULS) and flexural analyses to check the maximum stresses, the crack opening and the maximum deflection (SLS).

The design is completed with the ULS shear verifications, both without and with shear-resisting elements.

In the Standard version, the platform provides the flexural analyses to compute the ultimate resisting moment (ULS) and to check the maximum stresses (SLS). The following section reports the theoretical references needed for the development of the calculation.

2.1 Model used to compute the ULS resisting moment

The model used to evaluate the ULS resisting moment is based on the following assumptions:

- plane sections remain plane up to failure, with a linear distribution of the normal strains for the compressed concrete and the tensioned FRP bars;
- no tensile strength of the concrete;
- negligible contribution of the FRP bars subjected to compressive stresses;
- parabola-rectangle constitutive law for the concrete;
- linear-elastic-to-failure constitutive law for the FRP bars.

The concrete strength is defined in accordance with the provisions of Eurocode 2 (EN 1992-1-1), while the design strength of the FRP bars follows the indications of CNR-DT 203 R1.

In the calculation, the concrete section is analysed using a fibre model, with a regular 20×20 grid discretisation. For generic shapes, the base grid is geometrically adapted along the outer or inner edges, truncating the perimeter cells into triangles or trapezoids. Each fibre is placed at the centroid of its own cell and is assigned the corresponding values of area and moment of inertia in the local directions x, y and xy, as well as the parabola-rectangle constitutive law described above. All the FRP bars are likewise modelled as fibres, each placed at its own geometric centre and assigned the linear-elastic-to-failure law.
The resisting moment is computed through an adaptive incremental nonlinear static analysis under displacement control, applying a constant axial force with a Lagrange constraint on the direction and magnitude of the curvature.
Convergence of each step is considered achieved when at least one of the following four tolerance conditions is satisfied (absolute or relative to the first iteration of the step):

- Force residual (absolute or relative threshold)
- Displacement increment (absolute or relative threshold)

The analysis stops when the first fibre reaches the failure condition dictated by its constitutive law. The resisting moment is the bending moment, evaluated about the geometric centroid, that the section is able to balance at the attainment of failure.

2.2 Model used to compute the SLS stresses

For the calculation of the SLS stresses, the same fibre model described in section 2.1 is used; the concrete, however, is assigned a linear-elastic law. For the quasi-permanent combination, its elastic modulus is reduced to account for creep effects through the following relationship:

$$E_{c,eff} = \frac{E_c}{1+\varphi(t,t_0)}$$

where:

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$E_{c,eff}$ is the effective elastic modulus of the concrete,
E_c is the elastic modulus of the concrete,
$\varphi(t, t_0)$ is the viscosity coefficient.

To evaluate the stress state, the external actions are imposed and a Newton–Raphson iteration is performed on the 3 section DOFs to find the strain state that satisfies sectional equilibrium.

The stresses computed for the concrete and for the FRP bars are finally compared with the limits set by Eurocode 2 (EN 1992-1-1) and CNR-DT 203 R1.

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3. Case study from CNR-DT 203 R1

The flexural verification example at ULS and SLS proposed in appendix G of CNR-DT 203 R1 is reported below.

3.1 Case study description

A beam with a rectangular section is analysed, characterised by the following geometry:

- total height h = 600 mm,
- concrete cover (mechanical) c = 40 mm,
- effective depth d = 560 mm

A C30/37 concrete class is assumed, with:

- fck = 30 MPa
- fcm = fck + 8 = 38 MPa
- fctm = 2.9 MPa
- Ec = 32837 MPa

Glass-fibre (GFRP) bars of class E45/850 are assumed, characterised by a characteristic tensile strength f_{ftk0} = 850 MPa and a mean elastic modulus E_f = 45 GPa, with a nominal diameter d_b = 14 mm. Exposure condition 2 (dry external environment), in which the element is directly exposed to solar radiation, is assumed.

The section is subjected to the following actions:

- ULS: MEd = 123.6 kNm
- SLS quasi-permanent: MEd,qp = 54.22 kNm
- SLS characteristic: MEd,c = 85.94 kNm

3.2 Definition of the case study in the FRP RC Studio platform

3.2.1 Project settings

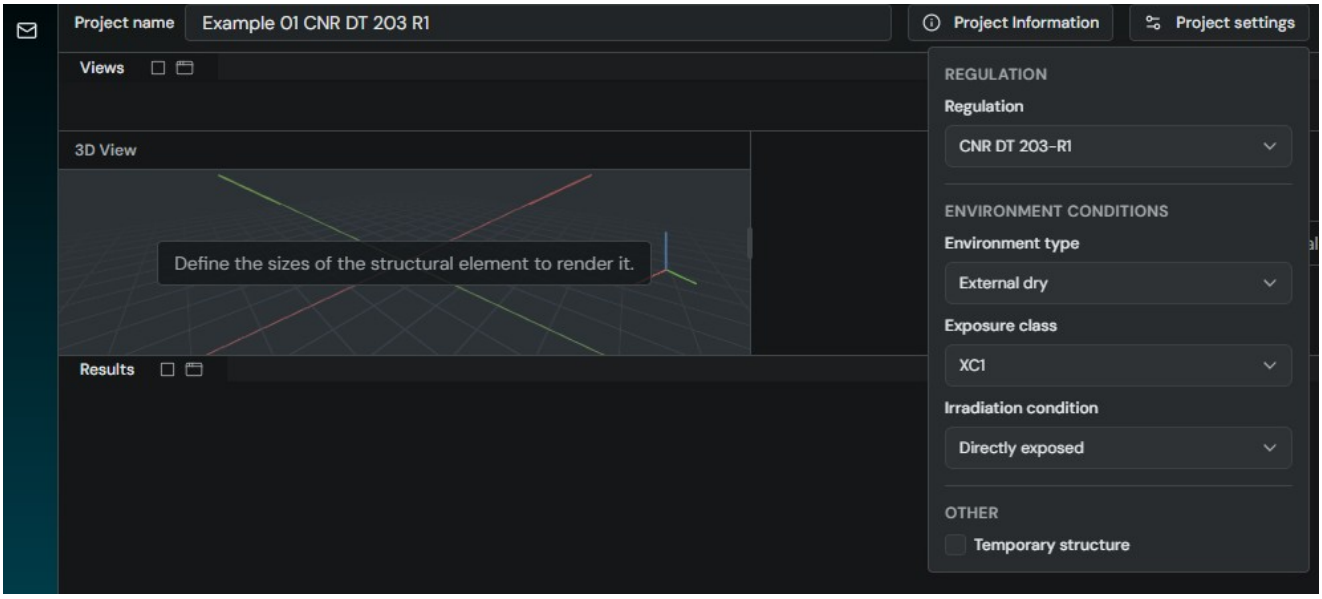


Figure 1 *— Project settings and environmental conditions*

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3.2.2 Material definition

Concrete

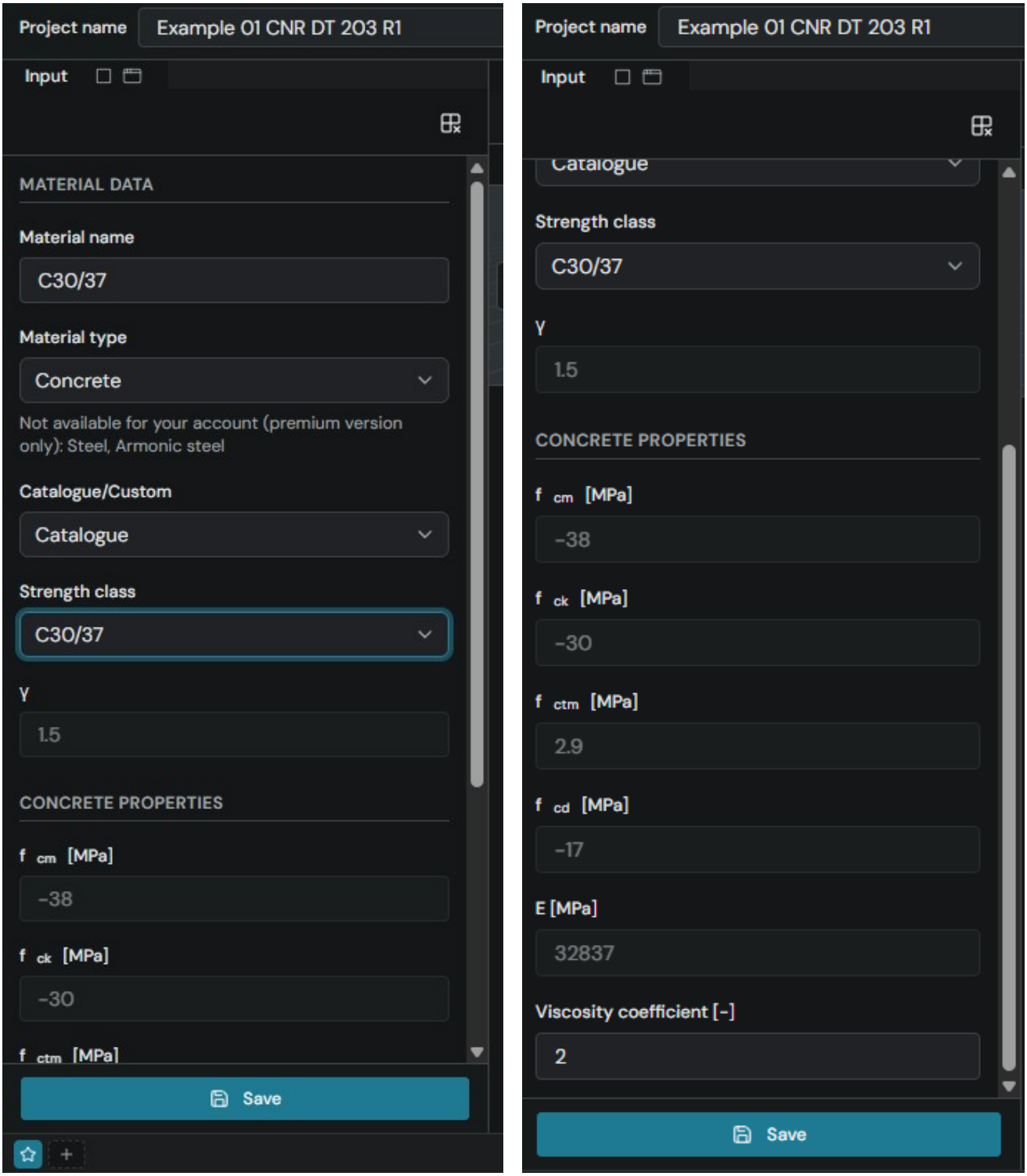


Figure 2 *— Concrete material definition (C30/37)*

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FRP Rebars

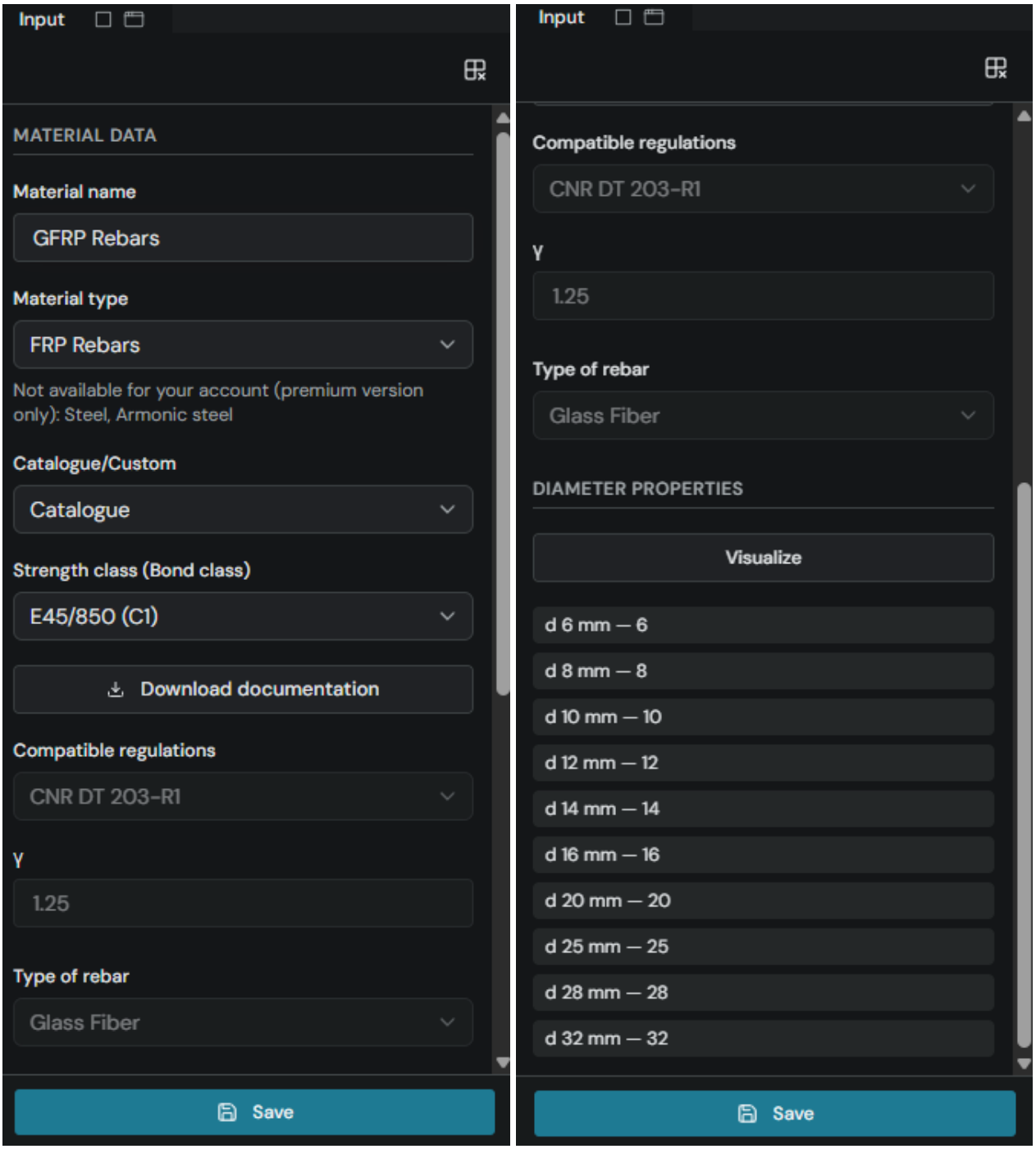


Figure 3 *— FRP material definition (GFRP E45/850)*

3.2.3 Section definition

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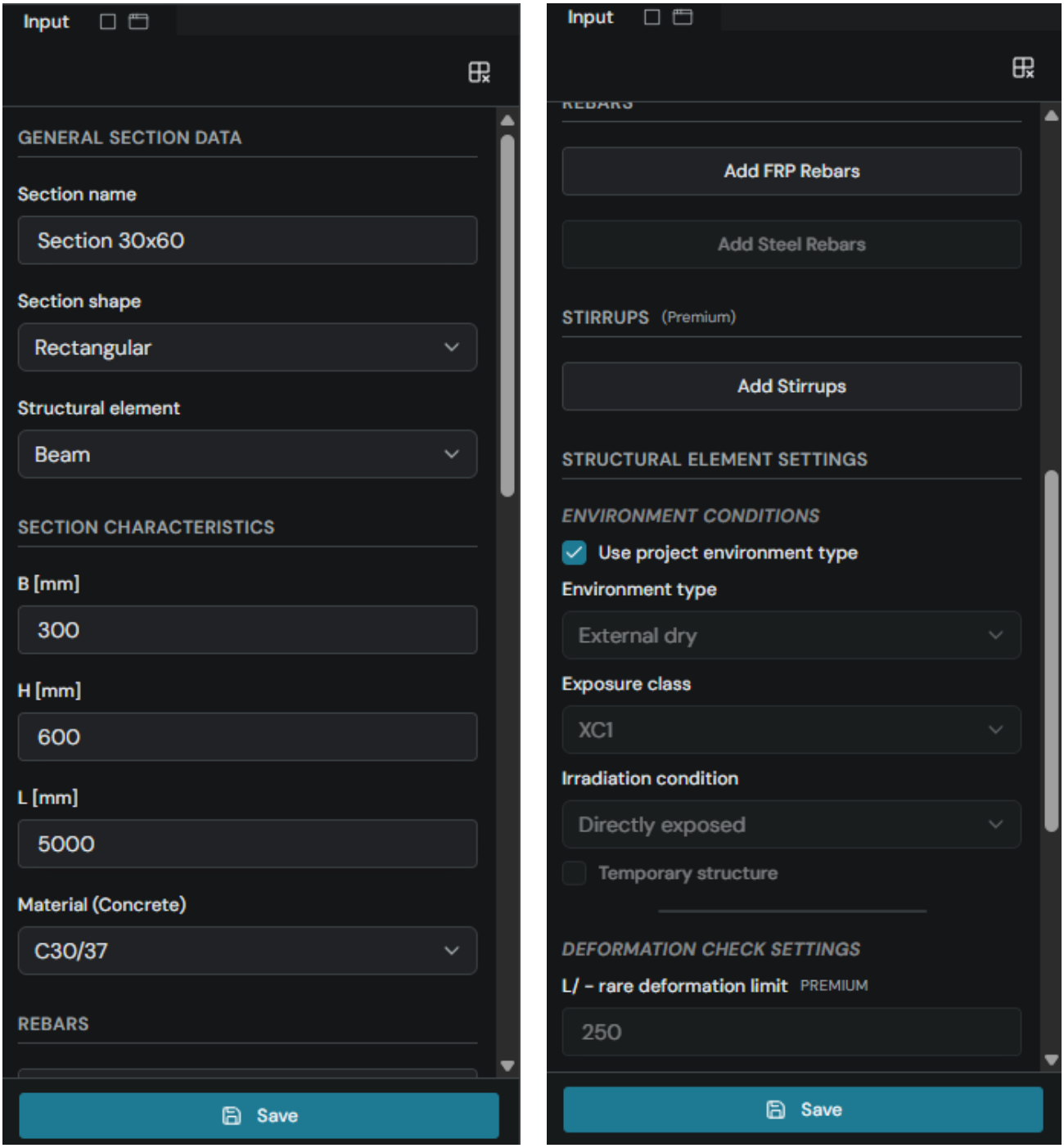


Figure 4 *— Section definition — geometry data*

The bars defined through the “Add FRP Rebars” button are reported below:

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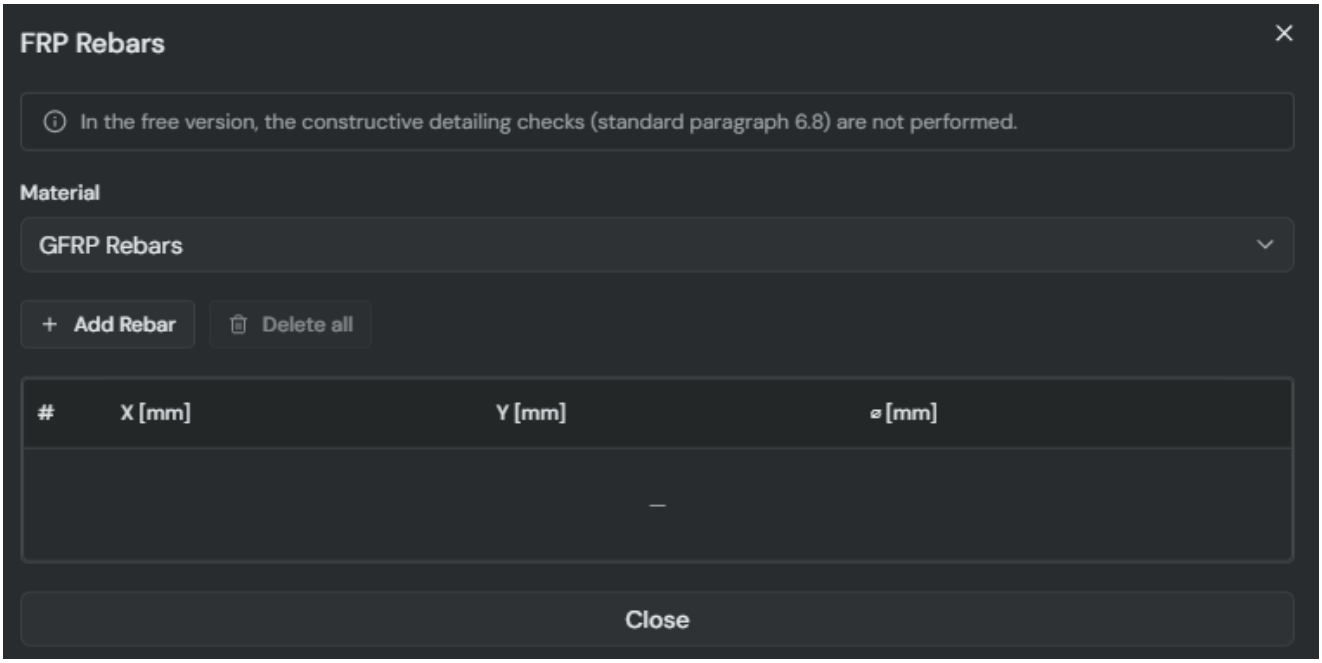


Figure 5 *— «Add FRP Rebars» window*

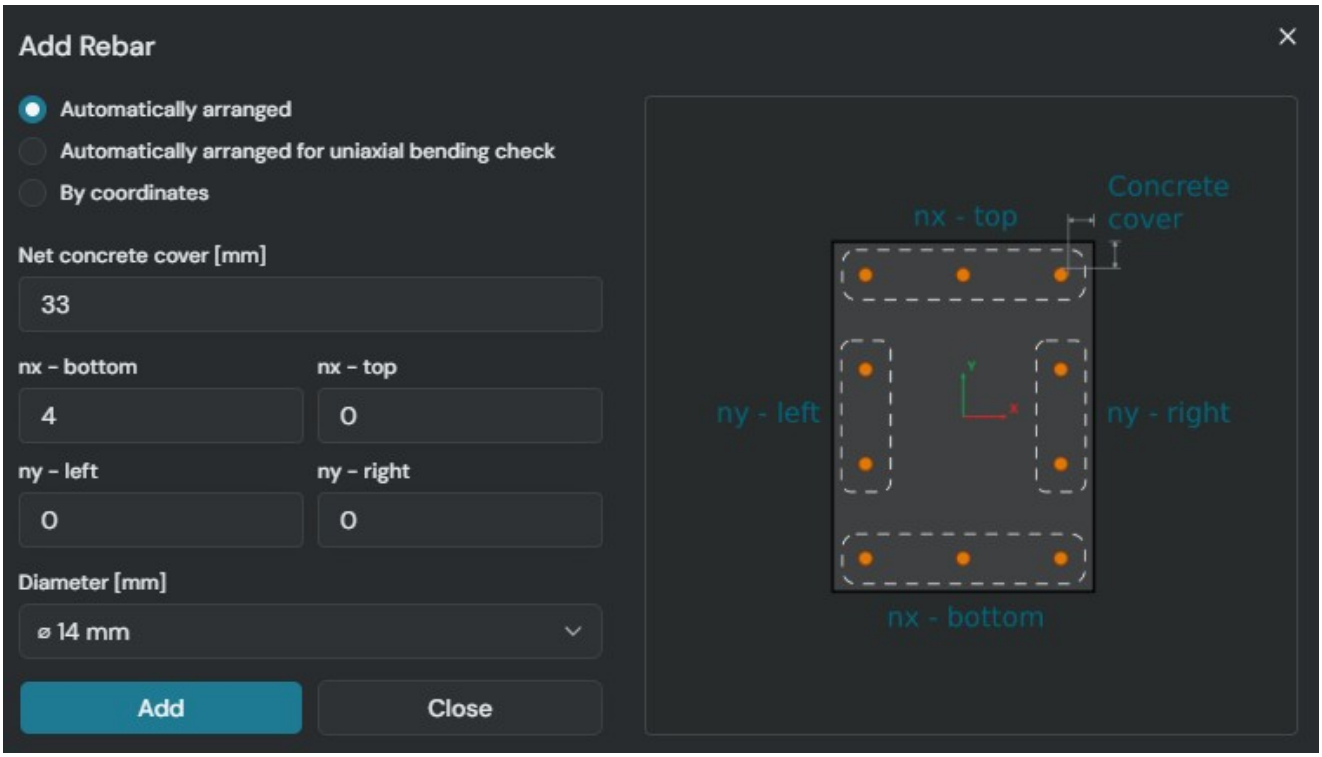


Figure 6 *— Bar insertion — automatic arrangement*

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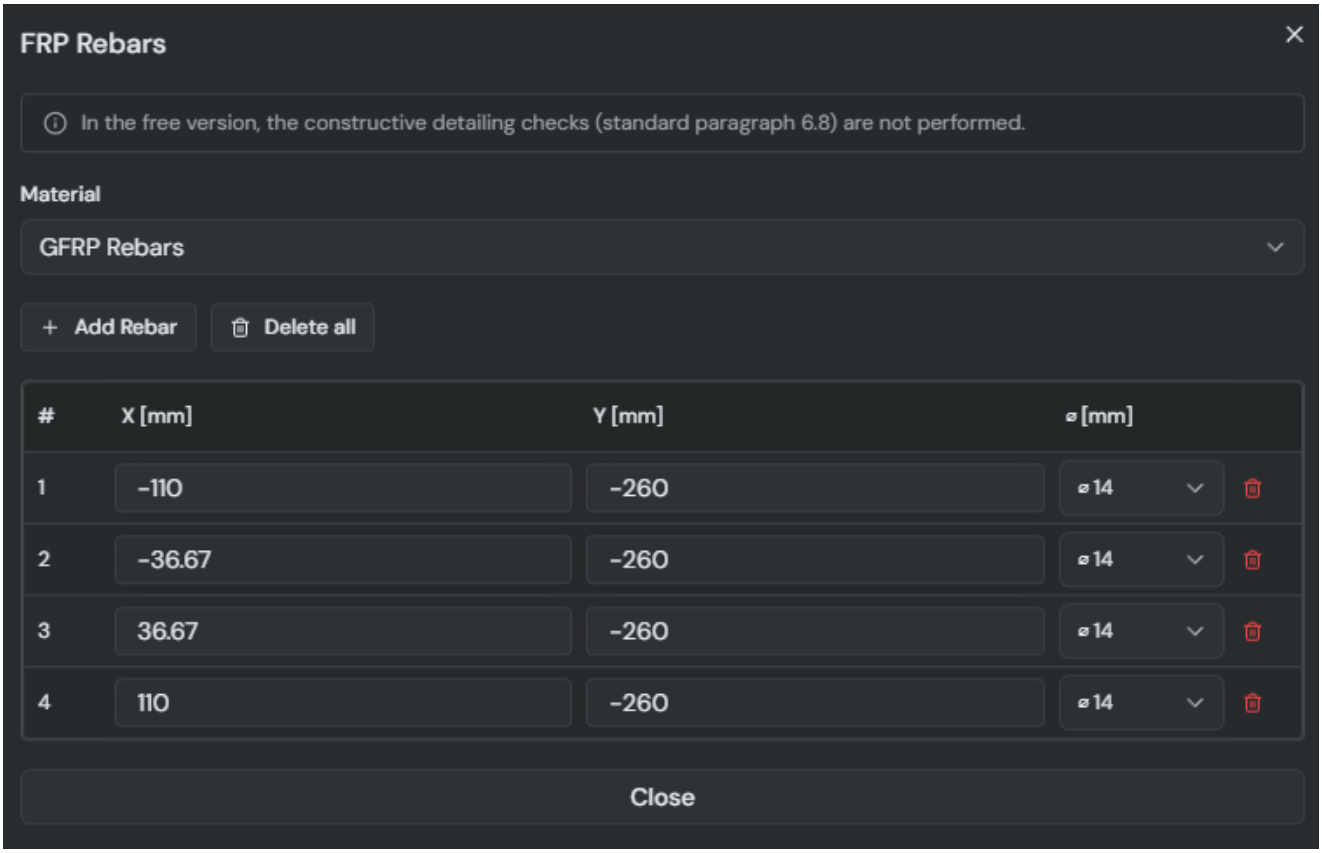


Figure 7 *— Coordinates of the inserted FRP bars*

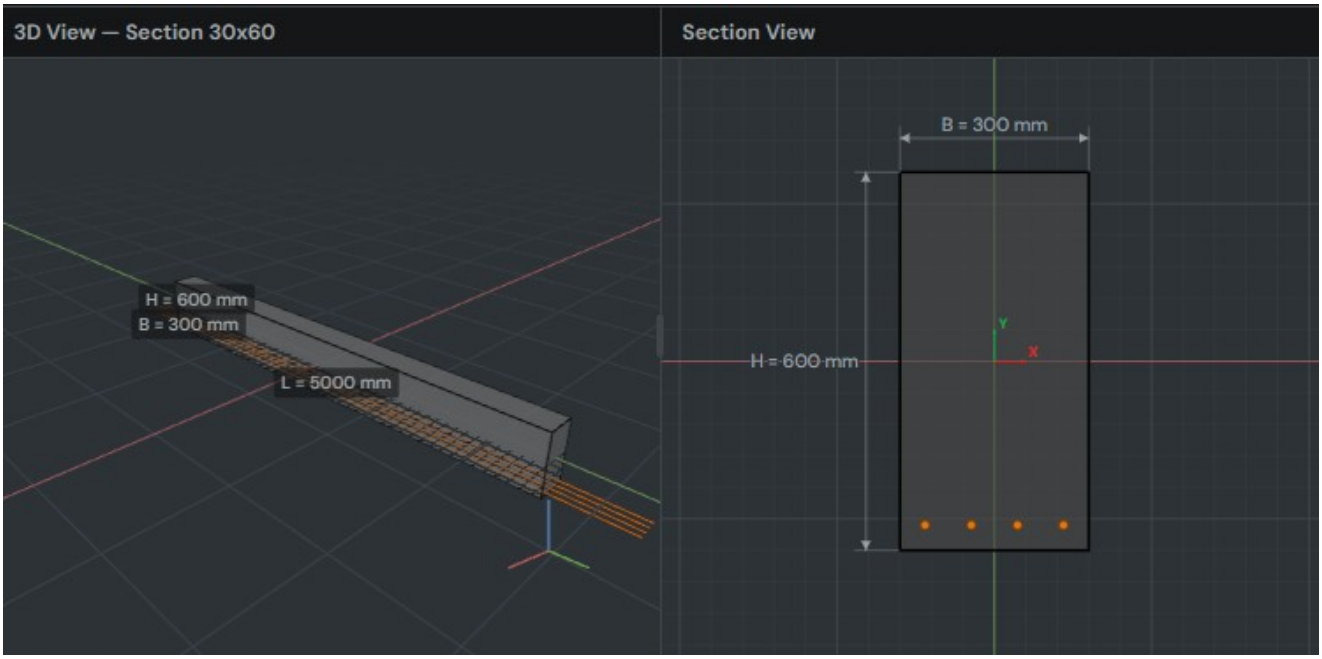


Figure 8 *— Section rendering: 3D view and cross-section*

The defined loads are reported:

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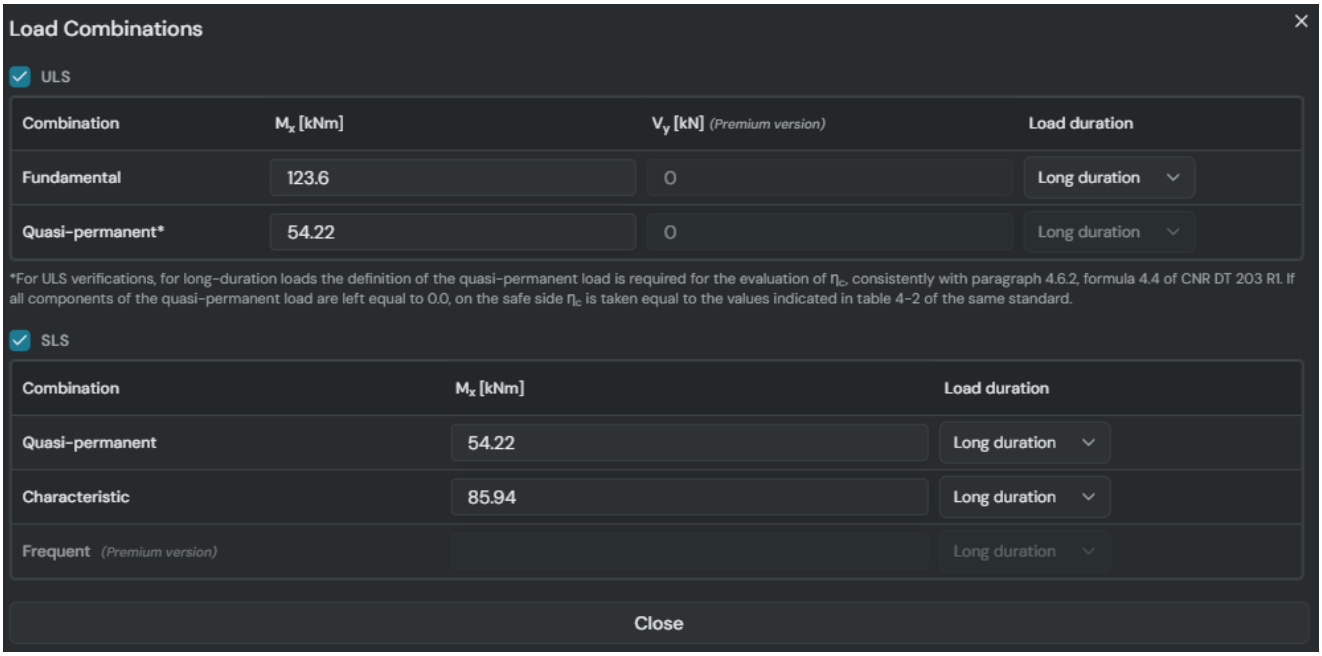


Figure 9 — *Loads and ULS/SLS combinations*

3.3 Comparison of the results

The results obtained from the FRP RC Studio platform are reported below.

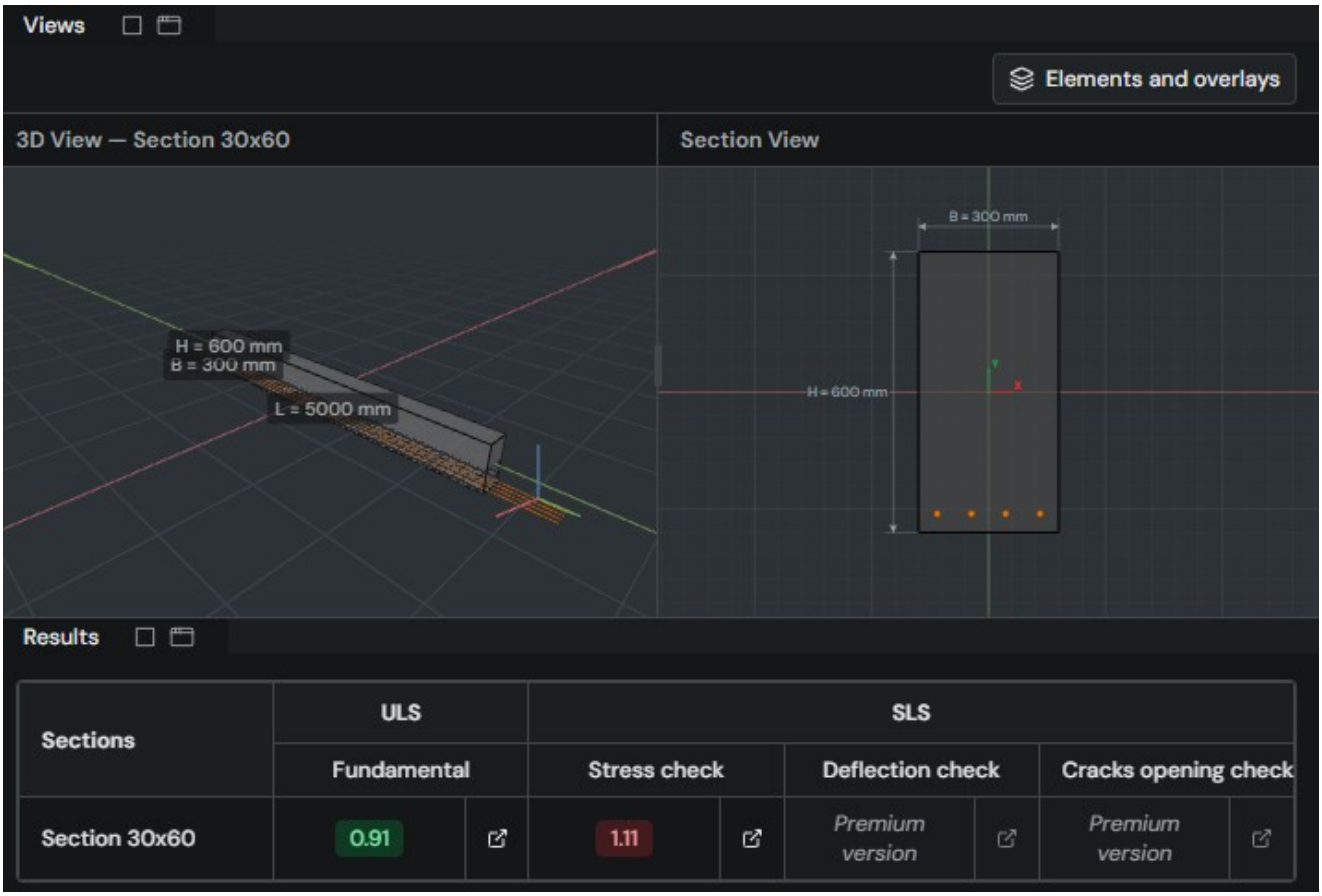


Figure 10 — *Section verification summary*

3.3.1 ULS results

By viewing the detail of the ULS verification, one obtains:

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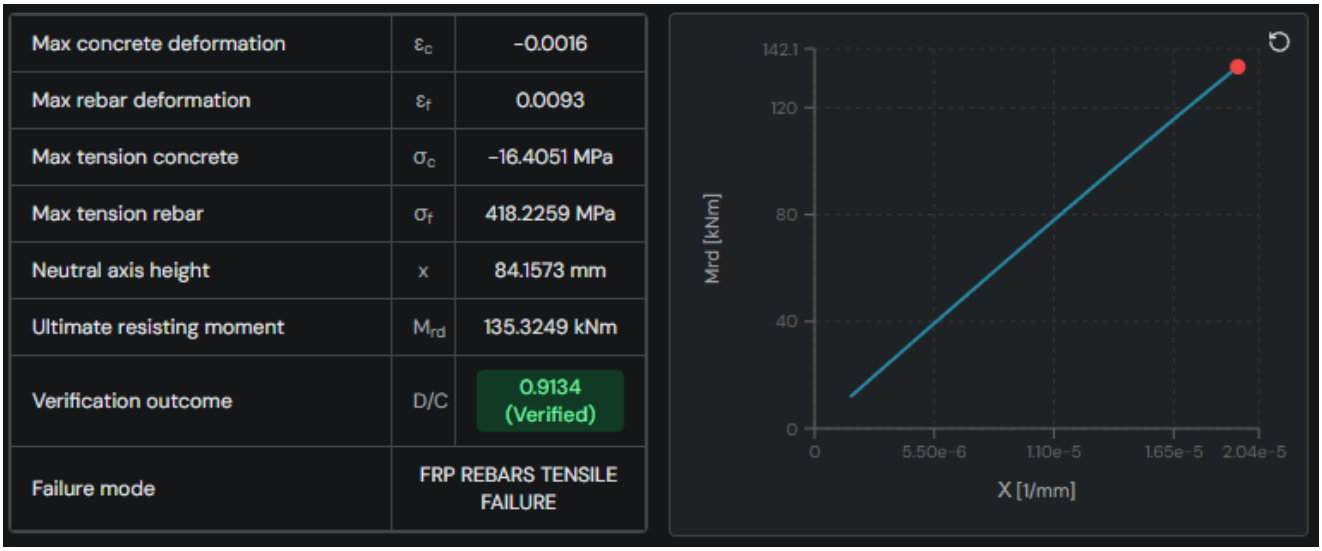


Figure 11 — *ULS verification detail*

These can then be compared with those reported in CNR-DT 203 R1.

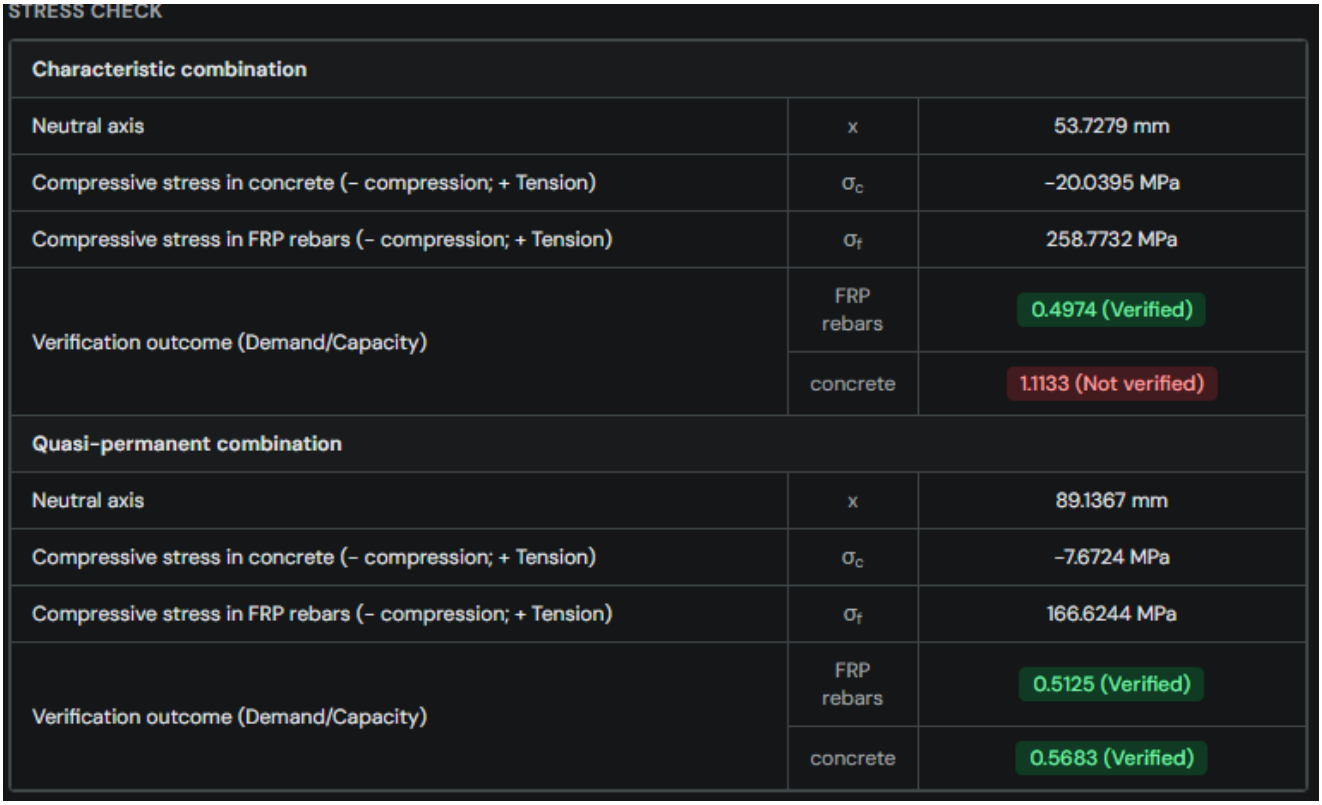
Quantity	FRP RC Studio	CNR-DT 203 R1	DP	Rating
σf [MPa]	418	413	1.2%	**excellent**
Neutral axis [mm]	84.15	84	0.18%	**excellent**
Mrd [kNm]	135.3	134.7	0.44%	**excellent**

The difference in σf is due to the simplification adopted by the code in evaluating the stress state of the bars for the quasi-permanent combination.

3.3.2 SLS results

By viewing the detail of the SLS verification, one obtains:

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STRESS CHECK

Characteristic combination		
Neutral axis	x	53.7279 mm
Compressive stress in concrete (– compression; + Tension)	σ_c	-20.0395 MPa
Compressive stress in FRP rebars (– compression; + Tension)	σ_f	258.7732 MPa
Verification outcome (Demand/Capacity)	FRP rebars	0.4974 (Verified)
	concrete	1.1133 (Not verified)
Quasi-permanent combination		
Neutral axis	x	89.1367 mm
Compressive stress in concrete (– compression; + Tension)	σ_c	-7.6724 MPa
Compressive stress in FRP rebars (– compression; + Tension)	σ_f	166.6244 MPa
Verification outcome (Demand/Capacity)	FRP rebars	0.5125 (Verified)
	concrete	0.5683 (Verified)

Figure 12 *— SLS verification detail (stress check)*

These can then be compared with those reported in CNR-DT 203 R1.

Quantity	FRP RC Studio	CNR-DT 203 R1	DP	Rating
σf [MPa] (quasi-permanent)	166.62	166	0.37%	**excellent**
σc [MPa] (quasi-permanent)	7.67	7.6	0.92%	**excellent**
Neutral axis [mm] (quasi-permanent)	89.14	89.1	0.44%	**excellent**
σf [MPa] (characteristic)	258.77	257.5	0.49%	**excellent**
σc [MPa] (characteristic)	20.04	19.8	1.2%	**excellent**
Neutral axis [mm] (characteristic)	53.7	53.4	0.56%	**excellent**

The minimal differences are due to the different calculation model used: the platform, as explained, adopts a fibre model, whereas CNR-DT 203 R1 applies the closed-form formulas provided for rectangular sections without axial force and with a single layer of GFRP reinforcement. The advantage of the fibre model is that it allows the study of generic geometries, reinforcement configurations and load conditions, with a minimal percentage error.

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