# (S)FRC IN EC2 AND IN MODEL CODE 2020

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Dedicated to Prof. György L. Balázs
for his 65th birthday

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*The current Eurocodes are under revision and estimated to be available in 2025. For the first time in the European history, Eurocode 2: "Design of concrete structures" will be extended with a European-wide harmonized annex, covering steel fibre reinforced concrete. The work on Annex L – Steel Fibre Reinforced Concrete has already started in 2012 and significantly benefitted from the work carried out for the fib Model Code of Concrete Structures 2010. The use of performance classes of Model Code 2010 as well as parts of the design approach were the basis for the new steel fibre reinforced concrete annex. In addition, the latest state of science has been used to prepare a powerful but, in the same way, easy-to-use design document for structural engineers, covering both ultimate and serviceability limit states for steel fibre reinforced structures, with or without reinforcement. At the same time the new Model Code 2020, mainly concentrated on existing structures and sustainability, extended to all types of fibres as the previous Model Code, has tried to look at FRC as to a generalized concrete, able to exhibit a significant toughness in uniaxial tension, integrating its resistance equations to those of conventional concrete, guaranteeing in many structural cases a sustainable choice for the reinforcement and paying more attention to high- and Ultra-high performance materials and at the same time to hybrid solutions for the reinforcement.*

**Keywords:** Fibre Reinforced Concrete, classification, sustainability, constitutive laws, design equations

## 1. INTRODUCTION

Fibre reinforced concrete is introduced in the codes as a composite material. After several decades of research work and some years of pioneer applications, Fibre Reinforced Concrete (FRC) is nowadays a material ready for the construction world community, also considering that design rules are already available in several Countries and fib Model Code 2010 included specific sections for design of FRC elements. FRC can be a suitable solution especially for statically indeterminate structures, where stress redistribution occurs. In addition to the structural bearing capacity, FRC is particularly useful for better controlling crack opening in service conditions, which has a particular influence on structural durability, especially in aggressive environments. Furthermore, structural robustness is nowadays a major concern among structural engineers. Even in this perspective, FRC could improve structural behaviour since it provides structural resistance both in compression and in tension in all the regions of the structural element.

The reasons why FRC is regarded more sustainable than plain concrete can be resumed in the following items: reduction of the global volume of composite and of steel reinforcement, smaller crack widths, stiffer response at SLS, durability increase in relation to fatigue loads, ductility increase, larger specific toughness, robustness increase with reference to unexpected load conditions (resilience increase), lower amount of human workmanship with the only disadvantage of higher costs in recycling if steel has to be separated by concrete.

The performance usually adopted to evaluate a sustainability index is compressive strength for concrete and tensile strength for steel bars, but, as it is well known, the role of fibres in the composite is played mainly on toughness guaranteed by the bond with cementitious matrix, strongly affected by the shape and the material of the fibre itself. So, if we consider in a sustainability index the performance, we have to specify that if we look to uniaxial compressive behaviour, compressive strength $f_c$ weakly improves, but it is not the only interesting parameter to be considered. The post-cracking behaviour can be significantly modified by fibre pull-out and this performance becomes essential all the times we have a failure in compression especially if the failure mechanism is due to cyclic behaviour (as in seismic events) or if the resistant mechanism is conceived in a redundant structure, where the failed mechanism can conserve a certain ductility and the corresponding bearing capacity can be added to the resistance of other mechanisms. Therefore, in uniaxial compression, looking to the performance, we should consider toughness up to a certain strain: with this proposal we could refer to the post-peak branch proposed by Gonzalo Ruiz et al. (2018, 2019). By considering at the denominator of the sustainability index the embodied energy or the energy required to store the $CO_2$ emitted in the production, subtracting it from the atmosphere, or the addition of both terms, we could obtain a dimensionless term. To consider the dissipated energy means to look at the Ultimate Limit State (ULS), but also the service life could be considered by evaluating the allowable number of cycles between a minimum and a maximum serviceability stress that could be correlated to about 60% of the peak strength $f_c$; the minimum stress could be set equal to the percentage of the maximum stress related to the dead weight contribution with respect to the total loads acting in rare condition at SLS. The cycle number up to failure could become a significant measure of the service life expectation, giving to the engineer an idea of

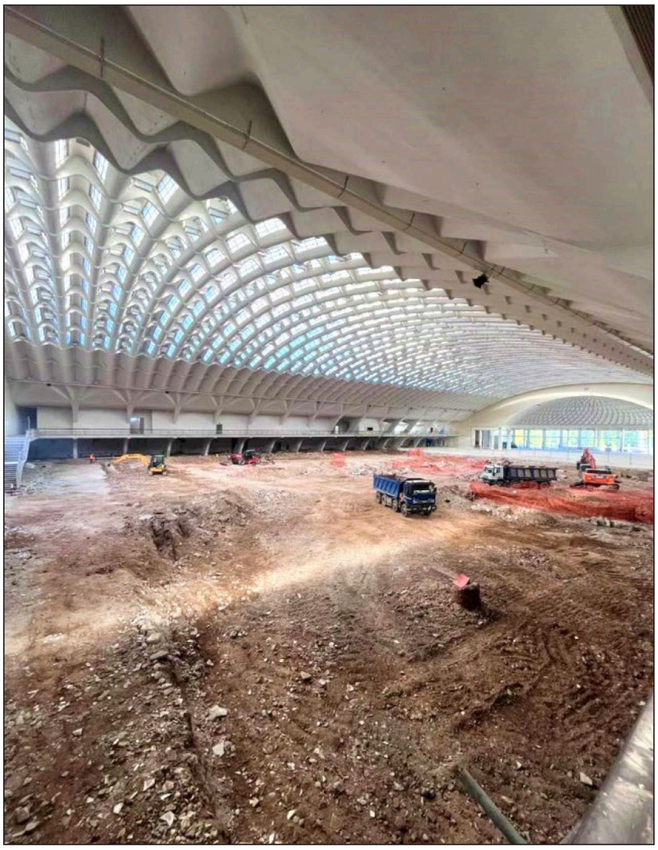


**Fig. 1:** *P.L. Nervi: Pavillon B – Torino. Picture taken in the occasion of the visit organized in the Regenerate workshop carried out in Lecco (2023), in the framework of Recube project financed by EEC*


**Fig. 2:** *Recube Erasmus Plus project financed by EEC: partners and BME contributions*

damage and irreversible strain evolution in the service life. This measure could be determined on a virgin material from a mechanical point of view or on a material subjected, at least one in his life, to an ULS condition.

An impressive comparison based mainly on the volume reduction was proposed by Voo & Foster (2010) looking to a retaining wall or a simple precast overpass.

P.L. Nervi thinking to ferrocement, but in a certain way anticipating the introduction of FRC, in 1940 wrote: "*We wondered if, increasing significantly the diffusion of the steel and its percentage (i.e. reinforcement ratio), it could not be possible to create a new material characterized by a higher strength and especially a larger elasticity and elongation ...*". The wonderful execution of his light and optimized large-span vaulted ceilings can easily demonstrate the powerful of ferrocement material (*Fig. 1*): in the figure the vault span is equal to 94 m, without any pre-stressing and with 38 mm of thickness of the bottom chords!

For this reason, the research on optimized and challenging solutions to be performed with FRC material has to be inspired by the examples of the great Masters of Engineering as Pier Luigi Nervi. This important cultural European heritage of R/C structures needs to be taken care for and kept integrated in our evolving and changing contemporary life. To this aim, I would like to remember that Prof. Balazs is participating to Recube project (*Fig. 2*), cooperating with other eleven universities, P.L. Nervi foundation and other partners cited in the figure. The purpose of this project is to offer the cultural and technical tools required for a respectful and viable approach to a correct architectural conservation and repurposing of the Modern Heritage and to show it can be structured in an overall European shareable knowledge. Establishing and promoting unified best practices in the field of Modern architectural preservation is one way to strengthen our common European identity, while opening up new creative possibilities for young designers, builders and city planners.

Looking to design standards, it is worth to note that FRC in Eurocode 2 Annex L is made of steel fibres only, while Model Code 2020 is open also to synthetic fibres. Moreover, even if several countries fought to introduce Annex L as a normative Annex, the majority voted to keep it as an informative one. Several National Standards have been developed in the last 10 years in Europe: a weak form of Annex L could favour the risk to hamper the European market of fibres and diverging criteria in FRC structure design. Only a shared and large scientific community operating in the next years in the fib framework (TG4.1) could prevent this risk.

In the paper the main assumptions introduced in the Eurocode 2 - Annex L and in the Model Code 2020 final drafts are resumed and commented to show the progress and the present research borders at which Prof. Balazs greatly contributed.

## 2. PERFORMANCE CLASSES

The performance classes introduced in the Model Code 2010 based on the third point loading tests carried out on a notched prismatic specimen, defined in EN 14651, represent the basic identification of the composite to be correctly compared with different solutions offered in the market. It has been conserved both in the Eurocode 2 Annex L and in the Model Code 2020. It should be highlighted that in the Annex L the range accepted is only 1-8 MPa on $f_{R1k}$, while in Model Code 2020 also classes 10, 12 and 14 MPa are added. This clearly shows the aim in Model Code 2020 to include the mechanical performance of Ultra High Performance FRC. In fact, even if small cross section specimens made of high performance SFRC can show nominal bending strength values up to 20-30 MPa for a crack opening displacement of 0.5 mm, when testing the material according to EN 14651 standard, the performance class is around 10÷14 b÷c. For common use, it should be underlined that, even if maximum aggregate size, water/cement ratio and compressive strength usually qualify concrete matrixes, often they are not enough for fully qualifying the interaction between fibres and concrete mix. Fibre type, as well as aspect ratio, steel mechanical performance and its shape combined with grading curve, w/c ratio and filler type can significantly contribute to the final SFRC performance. The knowledge on this topic requires further research efforts, because it could allow the producer to dynamically recalibrate the final performance of the composite without facing with a new qualification procedure every time that one of the parameters has to be changed. Several experimental results have confirmed how SFRC performance can be predicted by considering the change of the fibre content (with the same concrete matrix) assuming a linear relationship (between material properties and fibre content) in favour of safety.

It is worth to note that the determination of $f_{R1k}$ and $f_{R3k}$ shall be based on a log-normal distribution according to EN 1990 (5% quantile, 75% confidence level). Unless explicitly agreed otherwise, the coefficient of variation shall be assumed unknown. Only in Annex L a factor $\kappa_{k,max}$ defined in EN 206 shall be taken as 0,6 and the characteristic values $f_{Rik}$ cannot be greater than $\kappa_{k,max} f_{Rim}$. Only in the case the COV on the material extracted by the structure should be also checked, a higher value equal to 0,7 could be used if the COV is lower than 0,15. This condition finds a justification in the difference between the on-site empirical evaluations as compared with the lab-measured strengths.

## 3. CONSTITUTIVE LAWS

The constitutive law in uniaxial tension introduced in both the standards is rather close to that proposed by Model Code 2010 (*Fig. 3*). Besides the stress-bock models, in the linear models the correlation between the nominal residual strengths $f_{Rik}$ identified in bending by means of EN 14651 and the uniaxial tension strength assumed in the pull-out regime is that proposed by di Prisco et al. (2013). In particular, the $f_{Fts}$ is regarded as a fixed point at a crack width $w_1 = 0.5$ mm, and the two points of the linear pull-out branch are referred to as follows:

$$f_{Ft1} = 0.37\, f_{R1k} = f_{Fts} \tag{1}$$

$$f_{Ft3} = 0.57\, f_{R3k} - 0.26\, f_{R1k} \tag{2}$$

with:

$$\varepsilon_{Ftu} = 2.5 mm/l_{cs};\ l_{cs} = \min\{h;\ s_{rm}\} \tag{3a,b}$$

where $l_{cs}$ is the structural characteristic length and depends on the kinematic model. If a plane-section model is assumed, it can be defined by Eq. (3); $s_{rm}$ represents in this case the minimum crack distance. In case a F.E. approach is used, $l_{cs}$ is correlated to the element size and needs a careful calibration. The dashed linear piecewise branches are introduced to favour localization in case of F.E. use. If plane-section model is adopted, the pull-out branch can intersect directly the initial elastic branch, without any peak, because the

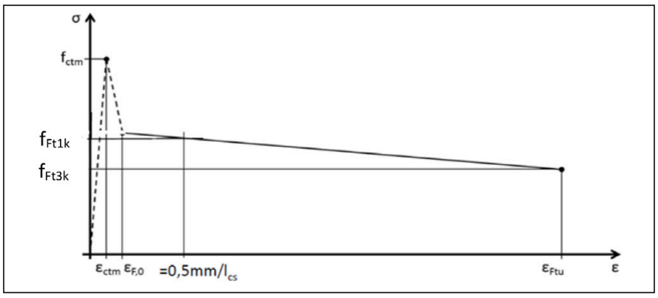


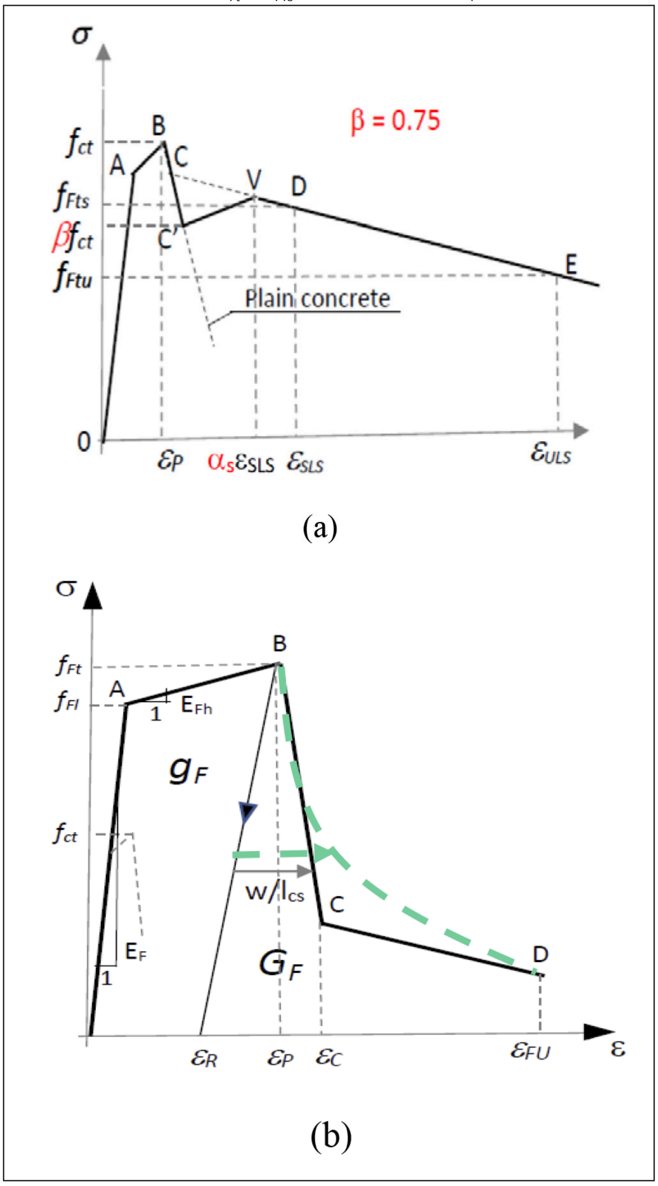
**Fig. 3:** Constitutive law in uniaxial tension according to Annex L

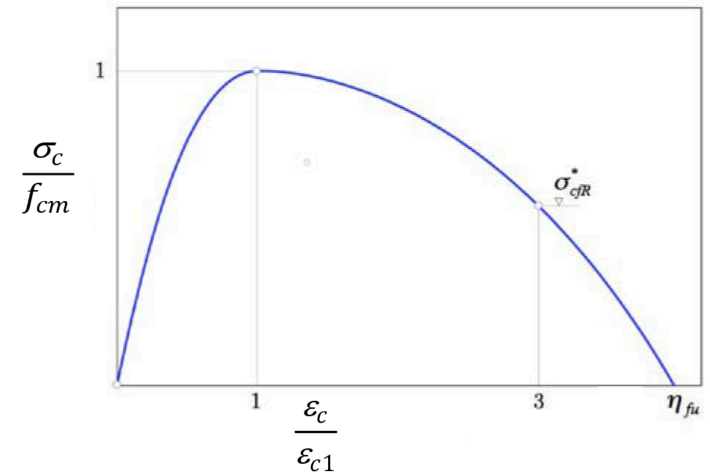
peak contribution is negligible and is not considered in R/C structures.

The Model Code 2020 introduces the same softening related to fibre pull-out in terms of σ–w and transforms it in σ–ε by using the same $l_{cs}$, but in case of design suggests a model that is elasto-softening or rigid-softening. When the model is used to check a serviceability condition of an uncracked element, the pre-peak is two-piecewise and the first post-peak softening branch is the same suggested for plain concrete.

It is worth to note that in Model Code 2020 also specialized models valid for high performance concrete are suggested, like those indicated in *Fig. 4*, which are able to appreciate the

**Fig. 4:** Constitutive laws in uniaxial tension for high performance materials, not fully hardening: (a) quasi-plastic materials ($f_{Fts} > 0.8\, f_{ctm}$); (b) hardening materials ($f_{Ft} > f_{FTS}$) with peak strain ($\varepsilon_P$) < 0.01.






$$\varepsilon_{c1}(‰) = 0.7 f_{cm}^{1/3}(1 + 0.03 f_{R,1k})$$

and, for $\varepsilon_{c1} \le \varepsilon \le \varepsilon_{cu1}$:

$$k = 1 + \frac{20}{\sqrt{82 - 2{,}2 f_{R1,k}}}$$

and $\varepsilon_{cu1} = k\,\varepsilon_{c1}$

**Fig. 5:** Constitutive law in uniaxial compression for FRCs

stabilizing contribution of fibres to the pre-peak behaviour, associated to the stable crack propagation occurring with the multi-cracking, before localization.

More details on the last model *(Fig.4b)* can be searched in Zani and di Prisco (2023). Of course, the constitutive law in uniaxial tension can be identified also via uniaxial tension test.

Finally, in both the codes, Annex L and Model Code 2020, a novel uniaxial compression law affected by $f_{R1k}$ is also introduced (*Fig. 5*; Gonzalo Ruiz et al., 2018, 2019).

The proposed model becomes very significant every time failure is caused by the reaching of the ultimate strain in compression: fibre reinforcement guarantees a passive confinement to the loaded volume, amplifying the stable crack propagation, accompanied by a weak increase of the compressive strength, and favouring the dissipation in the unstable crack propagation.

# 4. EFFECTIVE STRENGTHS: ORIENTATION AND SIZE EFFECT COEFFICIENTS

Random distribution of fibres can be regarded as a strength as well as a weakness. It is a strength because the single fibre randomly oriented can work for a very wide range of directions.

In fact, if we consider scantly effective the fibre contribution out of a double cone characterized by an angle $\alpha = 30°$ astride its axis, the solid angle covered by a single fibre corresponds to a solid angle $\omega = 3.86\pi$. This peculiarity is also a weakness, because the designer cannot know precisely its distribution and orientation that is affected by casting procedure and its boundary conditions.

Fibre distribution is assumed usually homogeneous in the cast, even if this property has to be checked in the real conditions; on the contrary orientation factor can be significantly affected by cast direction, flowability of the mix, boundary conditions imposed by the formwork and its filling strategy. In both the codes a coefficient $\kappa_0$ is introduced ranging between 0.5 and 1.7. It expresses the ratio between the orientation factor of the cast in a specific location and that computable for the EN14651 specimen, equal to about 0.54÷0.58 according to Dupont and Vandewalle (2005) depending on the fibre length. It may be helpful to remember that a value of 0.5 corresponds to a perfect 3D random orientation, while the unity corresponds to the perfect alignment at right angle with the cracked plane. This value can be predicted by means of suitable numerical models (Ferrara et al., 2017) or can be measured on-site in case of a real construction by means of a magnetic device applied to a cylindrical specimen cored in the specific point of interest, or testing the same cylinder by means of Double Edge Wedge Splitting test (Martinelli et al., 2021; Laranjeira et al., 2011).

To simplify the computation of the bearing resistance of a hybrid structure, where conventional reinforcement is coupled to FRC, the effective strength in uniaxial tension considers a second coefficient, taking into account the reduction of the standard deviation identified by means of bending tests (EN14651; *Fig. 6a*) with the size of the volume involved in the failure process and the increase of redistribution capacity of the structure (Fig.4b; di Prisco et al., 2016; Pourzarabi et al., 2018, Colombo et al., 2017). This coefficient denominated $k_G$ corresponds conceptually to the coefficient $K_{Rd}$ already introduced in the Model Code 2010.

The coefficient $\kappa_G$ is evaluated in the Annex L according to a simplified expression firstly introduced in the Austrian guidelines:

$$\kappa_G = 1.0 + 0.5 \times A_{ct} \le 1.5 \tag{4}$$

where $A_{ct}$ is the area of the tension zone (in m²) of the cross section involved in the failure of an equilibrated system. In the Model Code 2020 the same expression is suggested, but also a more complex and precise evaluation is indicated.

By introducing the safety coefficient $\gamma_F = 1.5$, as in the previous Model Code 2010, the uniaxial tension design strength becomes:

$$f_{Ft1d} = \kappa_O \cdot k_G\, f_{Ft1}/\gamma_F \tag{5a}$$

$$f_{Ft3d} = \kappa_O \cdot k_G \cdot f_{Ft3}/\gamma_F \tag{5b}$$

A similar approach has to be followed also for stress-block constitutive models or any kind of law deduced according to a more complex identification procedure or directly by a uniaxial tension test.

To complete the identification of the σ–ε law, the computation of the crack distance $s_{rm}$ has to be computed by adopting the equation based on the equilibrium of a tie portion as described in *Fig. 7*.

$$s_{rm} = \left(k_c c + k_{\phi/\rho} k_{fl} k_b \frac{(f_{ctm} - f_{Fts,ef})\phi}{\tau_{bms}\rho_{s,ef}}\right) \tag{6}$$

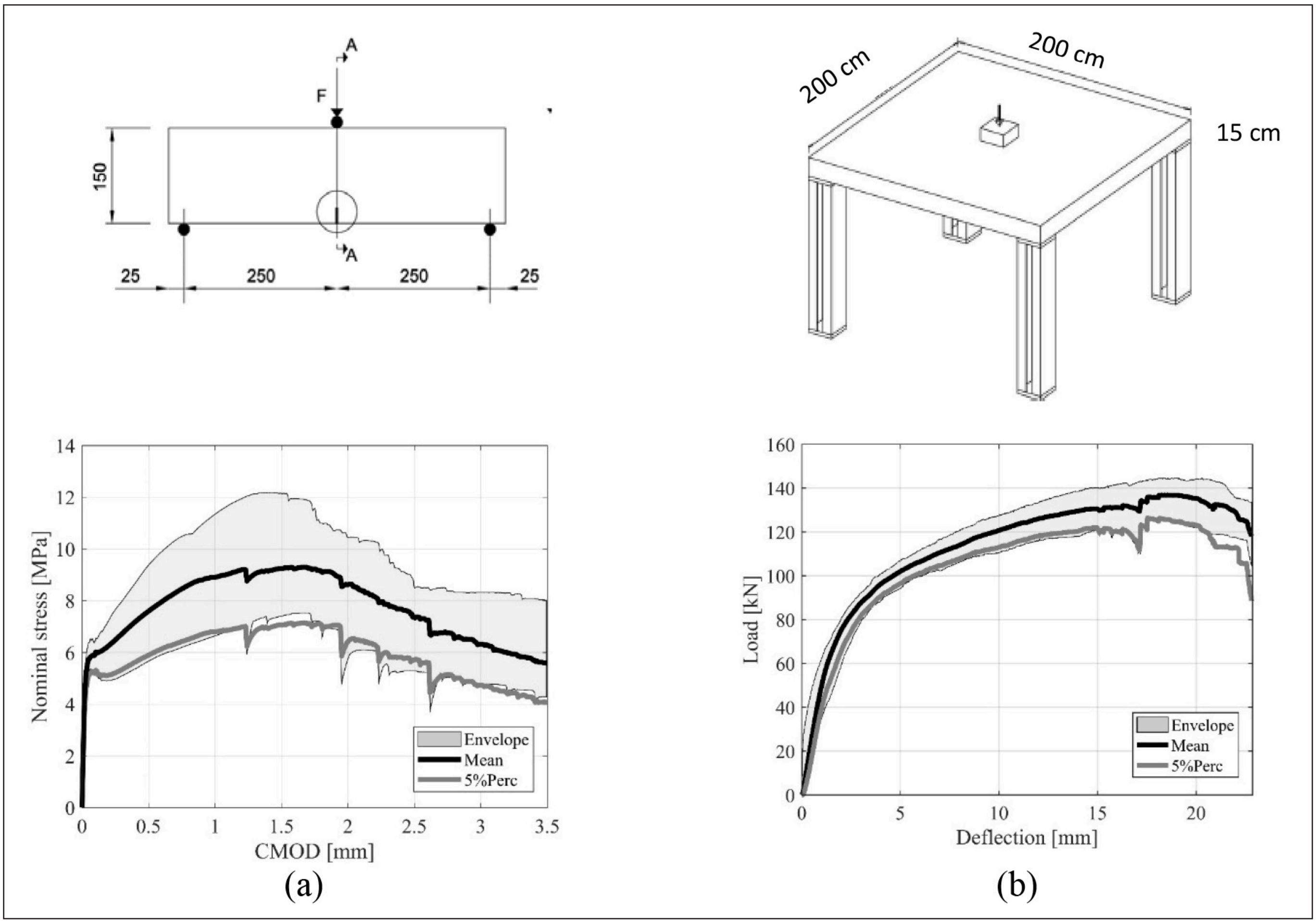



**Fig. 6:** Reduction of standard deviation passing from the test specimen (a) and the structural response of a plate supported in the corners (b) made of the same FRC

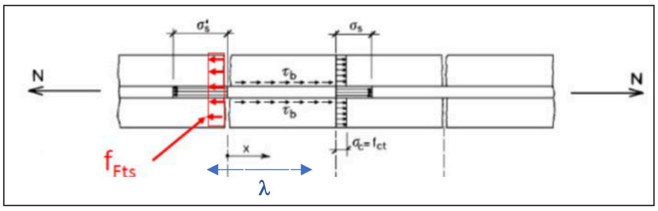



**Fig. 7:** Equilibrium of a tie portion to compute the distance between a crack and a cross section where the concrete stresses are at the onset of cracking.

where $k_c$ is a coefficient to account the effect of the cover,often simplified with the value 1.5, c is the cover, ϕ is the bar diameter, $\rho_{(s,ef)}$ is the reinforcement ratio, $k_{\phi/\rho}$ is a coefficient that accounts for the bond $\tau_{bms}$ (if the bond $\tau_{bms}$ is constant $k_{\phi/\rho}$=0.25), $k_{fl}$ is a factor to account the stress distribution before cracking and finally $k_b$ is a factor to accounts the casting position ranging between 0.9 and 1.2 and $f_{Fts,ef} = \kappa_O f_{Fts}$. The term $f_{Fts,ef}$ represents the stresses applied on the cracked plane which are usually considered negligible in case of plain concrete. It is worth to note that in the equation no increase of $\tau_{bms}$ is suggested, even if several experimental tests have proven a growth of $\tau_{bms}$ strength with fibre contribution (Tiberti et al, 2015). The crack opening is therefore reduced by the decrease of crack spacing, but also by the reduction of the steel stress due to contribution of fibre in tension.

It is also interesting to observe that in some structural situations we can define several $l_{cs}$ depending on the bending we are examining even if the material is only one FRC. In fib bull. 105 the case of a U channel made of FRC and reinforced with few bars located just in the corners is shown and commented (*Fig. 8*). The longitudinal bending of the whole profile can show 3 different structural characteristic length: one associated to the reinforced bottom chord, one associated to the two webs and one associated to the bottom slab that is subjected mainly to uniaxial tension, but is reinforced only at the two side borders. The fourth structural characteristic length is that correlated to the crack distance introduced by the transversal bending of the profile.

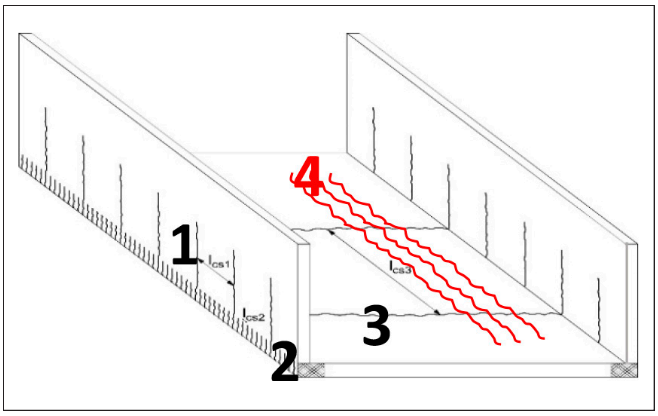



**Fig. 8:** The case of U channel, where 4 characteristic structural lengths can be defined.

## 5. *STRUCTURAL DUCTILITY*

The topic that adsorbed the largest effort in the debate of TG2 committee devoted to the preparation of Annex L was the evaluation of the structural ductility. Dancygier and Karinsky (2019) have highlighted as R/C beams characterized by a minimal reinforcement showing a ductile behaviour can become brittle if concrete is substituted by a FRC. The physical reason is associated to the degree of heterogeneity introduced by fibre distribution. If the amount of reinforcement associated to the level of hardening of steel is able to prevent localization, ductility is preserved and brittleness does not appear (Gebreyesus et al. 2023). This experimental observation pushed the committee to exclude the possibility to use hybrid solution to obtain a minimum reinforcement: minimum reinforcement in longitudinal bending of beams cannot be reduced by fibre addition. Looking to the elevated plates, they can be helped by internal structural redundancy, but they cannot be advantaged by soil interaction as ground slabs: for these elements it is important to understand if they can be computed by means of yield lines, that implies to respect the assumptions of limit analysis, even if in some points the specific bending behaviour could be softening. By testing a series of elevated plates in two laboratories at Politecnico di Milano and at the University of Brescia, (di Prisco et al., 2019; Colombo et al., 2023), it has been shown that the limit analysis can be always adopted and the design rules indicated in the two codes implies a design value of the bearing capacity which remains always on the safe side. At the same time hybrid solution appears as the most effective solution both in terms of serviceability behaviour and ultimate bearing capacity.

## 6. CONCLUDING REMARKS

The results obtained in many experimental campaigns have confirmed the effectiveness of fibre reinforced concrete as a construction material. It allows a significant increase of durability, an optimization of the construction process both in terms of economics and in terms of building speed.

Even if some topics like multi-axial behaviour, fatigue, shear, punching, torsion, structural creep, fire resistance and high-strain rate behaviour require further research efforts, the applications carried out all over the world justify its powerful growth in the market and the introduction in the future Eurocode 2 will promote it furthermore in the civil engineering application fields. At the same time the future work that will start next year in the *fib* TG4.1 will try to collect the novelties on the knowledge border, trying to clarify the aspects that are not yet fully understood.

## 7. ACKNOWLEDGMENTS

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