Key Parameters for Building Reinforcement with an UHPFRC Overlay

Raphaël Fabbri (corresponding author) – Architect – Maître de Conférence des Ecoles d'Architecture, ENSA Paris-Belleville, 60 boulevard de la Villette, 75019 Paris, FRANCE – Partner and General Director of ATELIER MASSE, 14 rue des Jeûneurs, 75002 Paris, FRANCE Email: r.fabbri@atelier-masse.fr

Jenine Principe – Ph.D. student, University of Naples Federico II, Department of Architecture, Via Toledo 402, Naples, NA 80132 Italy, Phone: +39 347 89 72 048; Email: jenine.principe@unina.it

Julien Derimay – Ductal® Project Manager – LafargeHolcim – 61 rue des Belles Feuilles, BP40 75782 Paris Cedex 16, FRANCE – Email: julien.derimay@lafargeholcim.com

Sebastien Bernardi – Ductal® Technical Head – LafargeHolcim – 61 rue des Belles Feuilles, BP40 75782 Paris Cedex 16, FRANCE – Email: sebastien.bernardi@lafargeholcim.com

Abstract: Among the various kinds of building materials, since the 20th century the reinforced concrete is certainly the most common. However, many concrete structures present risks linked to technical obsolescence and degradation phenomena which often require a refurbishment necessary to increase the structure load-bearing capacity. It has been already proven that the addition of an UHPFRC overlayer on a concrete existing section can improve the resistance and the durability of the whole structure, as long as a strong bond between the new layer and the concrete is provided.
Starting from the experience gained from bridge and viaduct repair, this paper presents the key parameters to design an UHPFRC reinforcement cast on an existing concrete slab. The method consists in using a calculation tool for preliminary design developed by Atelier Masse and LafargeHolcim, that compute the gain of the bending moment capacity of a slab with and without an UHPFRC overlay. After having fixed a set of preliminary assumptions, the paper will describe the behaviour of the cross-section and the influence of the different parameters (existing reinforcement percentage, UHPFRC type, fiber content, thickness of the overlayer etc. etc.) on the bending moment capacity gain. The aim is to help the designer choosing the right project strategies in case of a concrete structure refurbishment.

Keywords: Design criteria, Refurbishment, UHPFRC overlay

1. Introduction

The spread use of reinforced concrete structure in the building market is probably due to its low implementation cost, to its ease of execution and to the flexibility of the material, which can be utilized in different application, from complex infrastructures to simple dwellings.
Many constructors and designers have put their trust in a material which was believed to be eternal. However, almost 100 years have passed since the concrete had started its path in the history of construction, demonstrating, at the contrary, as its durability is a very relevant issue.
In fact, it is often necessary a refurbishment intervention in order to increase the load-bearing capacity of the structure, which is no more able to satisfy law and security requirements because of the damage caused by technical obsolescence and degradation phenomena.
Among the various technique utilized for repairing existing concrete structure, in the last couple of years, the use of an UHPFRC layer of on the harmed element, such as a column, a slab or a deck, has been proved to be successful.
Starting from these experiences, it has been set a preliminary design calculation tool able to estimate the gain of positive bending moment capacity – at Service Limit State (SLS) and Ultimate Limit State (ULS) – of a reinforced concrete slab or beam strengthened with an UHPFRC overlayer. In fact, while in civil engineering applications, the scientific literature considers mainly the negative bending moment on supports (Brühwiler and Denarié, 2008), which makes the uniaxial tensile behaviour of UHPRFC a fundamental element giving importance also to fibres and reinforcements content, in architectural engineering, in particular in the case of floor slab retrofitting, the gain of the load-bearing capacity in terms of positive bending moment can be extremely significative. Considering that the main objective is to give decision-making tools, this paper will identify the key parameters for the preliminary design. Although today, the calculation tool takes in charge both SLS and ULS bending moment, and different kind of cross-section, this paper will focus only on rectangular cross-section under positive bending moment ULS.
This study is based on the French standards (NF P 18-470 and NF P 18-710) and the Eurocodes.

2. Background

In the last years, the research in the UHPFRC field has explored the opportunities offered by the cast-in-site applications. In the United States, the Federal Highway Administration has launched a major redevelopment campaign for the road infrastructures, using the UHPFRC or as a widespread reinforcement on existing road surfaces or as a ductile joint between prefabricated elements in traditional or innovative concretes (Graybel, 2017).
At the same time in Switzerland a massive experimentation program (Noshiravani and Brühwiler, 2013) has proven that through an addition of an UHPFRC overlayer on a reinforced concrete existing section, it is possible to improve the resistance and the durability of the whole structure, as long as a strong bond between UHPFRC and concrete is provided through an adequate surface preparation. These experimentations have led to the drafting of a technical standard (SIA 2052, 2016) for the calculation of RC-UHPFRC composite elements, significantly contributing to the spread of ultra-performance concretes as reinforcement materials, providing a reference methodology for structural design, which has been an important starting point for the definition the calculation tool here presented.

3. Methodology for setting the calculation tool

3.1. Material definition and cross-section parametrization

The main characteristics of the materials involved in the tool have been set in order to let the designer chose as many features as possible. The concrete classes go from C12/15 to C55/67, always utilizing the parabola-rectangle diagram for describing the behavior at ULS and a linear elastic one at SLS. In both cases, no tensile stress has been considered in concrete.

In the Existing Reinforced Concrete section (ERC) SLS calculation, it has been used the instantaneous Young's modulus (E_{cm}) and so the creep has not been considered. However, since the overlaying happens after a long time, in the new UHPFRC-Reinforced Concrete cross-section (U-RC) the creep must be inevitably evaluated. In fact, the concrete could have accumulated a certain amount of strain during its service period. For this reason, it has been used the effective modulus of elasticity ($E_{c,eff} = E_{cm}/(1+\varphi_{\infty,t})$) instead of E_{cm} for the U-RC beam.

Where great accuracy is not required, provided that the concrete is not subjected to a compressive stress greater than $0{,}45 * f_{ck}$, which is the characteristic compressive strength, the creep coefficient can be considered equal to 2, which is a value commonly used in practice. $E_{c,eff}$ is so given by $E_{cm}/(1+2)$, which means that $E_{c,eff}=E_{cm}/3$. Therefore, in the U-RC cross-section, the concrete SLS behavior law is represented as shown below (figure 1, on the right).

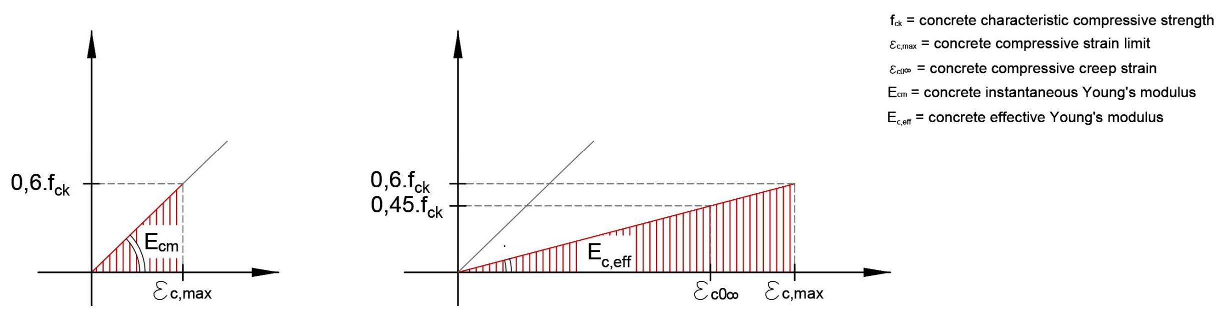


Figure 1. Concrete SLS behavior law without and with the creep effect.

With regards to the steel, which can be of B500A, B500B, B450B and B450C type, the ULS behavior law is linear until the elastic elongation limit, after which the stress is equal to the limit of elasticity used for calculation (f_{yd}), limited in traction at ε_{su} (rupture limit elongation used for calculation).

The UHPFRC chosen can be of four types, depending on the percentage and typology of metallic fibers present in the mix. First of all, it is important to underline that the modulus of elasticity of UHPFRC in tension and compression is never superior to 56 GPa, which is not significantly higher than the concrete one. For composite U-RC elements, this is advantageous with respect to deformation induced stresses due to temperature scatters. However, the UHPFRC is used only in compression while calculating the positive bending moment capacity of the examined U-RC beam.

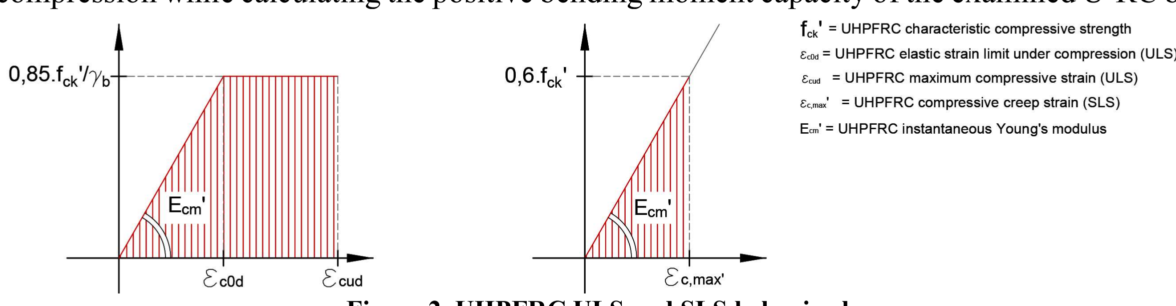


Figure 2. UHPFRC ULS and SLS behavior laws

With regard to the definition of the parametric cross-section, it is possible, for the moment, to calculate rectangular and t-shaped beams, which are after subdivided in 100 horizontal layers, for each of which the compression and tensile resultant forces and the moment with respect to the neutral axis are obtained.

3.2. Solver implementation

In the case of floor slabs, it results more significative to study the positive bending moment at the mid-span, because is not always possible to work in correspondence of the structure supports which often continue along the following levels of the building. Hence, the following assumptions have been fixed: the Navier-Bernouilli hypothesis which assumes that during the deflection of the beam, the cross-sections remain flat and normal to the deformed longitudinal fibres (except for the creep effect, see below); it is assumed that there is a perfect adherence between all the different materials; it is not been done the shear check on the supports; it has not been considered the auto-stress due to shrinkage in UHPFRC in compression.

The shrinkage has not been taken into account because it induces tensile auto-stresses which can be favourable in the case of a positive bending moment, so determining an increase in the compressive resistance of the beam. The compressive strain in U-RC section is obtained using iterative calculation which starts from 0 arriving maximum to the fixed compressive strain limit ($\varepsilon_{c,lim}$), with the objective of reaching forces equilibrium within the cross-section. If the calculated compressive strain become equal to $\varepsilon_{c,lim}$ and the equilibrium is still not reached, the tensile strain ε_{su}, initially fixed, starts diminishing using the same 'incremental step'. The process continues until the equilibrium is reached, as shown in the flow-chart below.

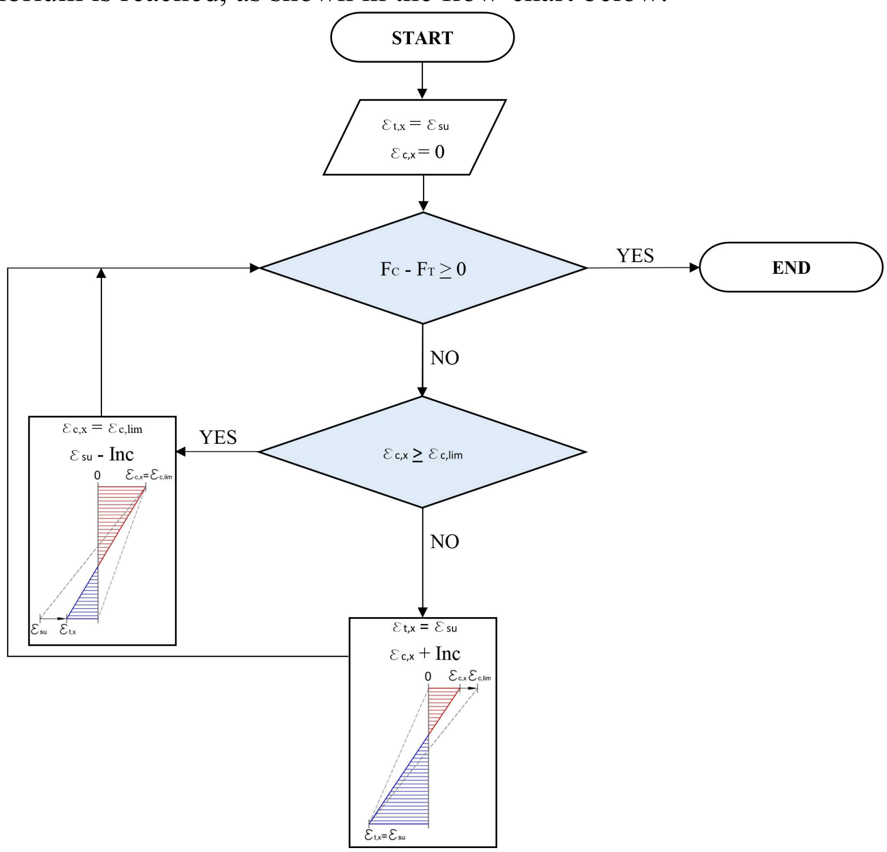


Figure 3. Iterative solver flow chart

In order to correclty define the strain limits, we have to consider all the steps of the implementation of the U-RC section. In fact, in the ERC cross-section, according to Eurocode, under a quasi-permanent instantaneous load, the strain is equal to $0{,}45*f_{ck}/E_{cm}$ (after this value is not possible to use a fixed creep coefficient), while, under a quasi-permanent long-term load, the strain is given by $0{,}45*f_{ck}/E_{c,eff}$ (figure 4).

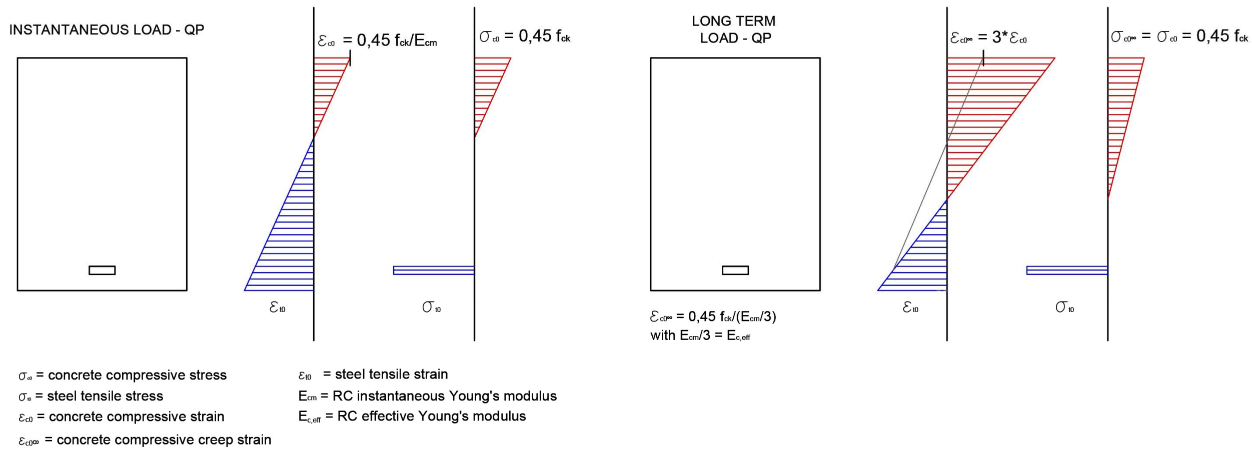


Figure 4. Strain under instantaneous and long term quasi-permanent load in the ERC cross-section

When the liquid UHPFRC is cast on the ERC section, while the reinforced concrete beam has already developed a creep strain $\varepsilon_{c0\infty}$, the UHPFRC strain will be equal to 0 (figure 5, left). Then, when a load is applied, the maximum possible compression strain before the rupture of the whole beam can be no more than $\varepsilon_{c0\infty} + \varepsilon_{cud}$, which is the maximum UHPFRC compression strain. However, considering $\varepsilon_{c0\infty} + \varepsilon_{cud}$ and a generic steel tensile strain, the so obtained strain represents a "virtual" U-RC section behaviour, which is the behaviour that the composite beam would have had if it was all realized at the same time. In this case, there should be also the shrinkage induced strain which, as anticipated, can cause tensile auto-stresses which can be favourable and so, it is treated as negligible. Though, the virtual strain does not show the real behaviour of the UHPFRC because it has not developed any creep strain yet. Hence, to not overestimate the UHPFRC stress response, in each point (eventual reinforcements included) of the added part, the stress is calculated subtracting to the virtual strain the creep strain $\varepsilon_{c0\infty}$ (figure 5, right).

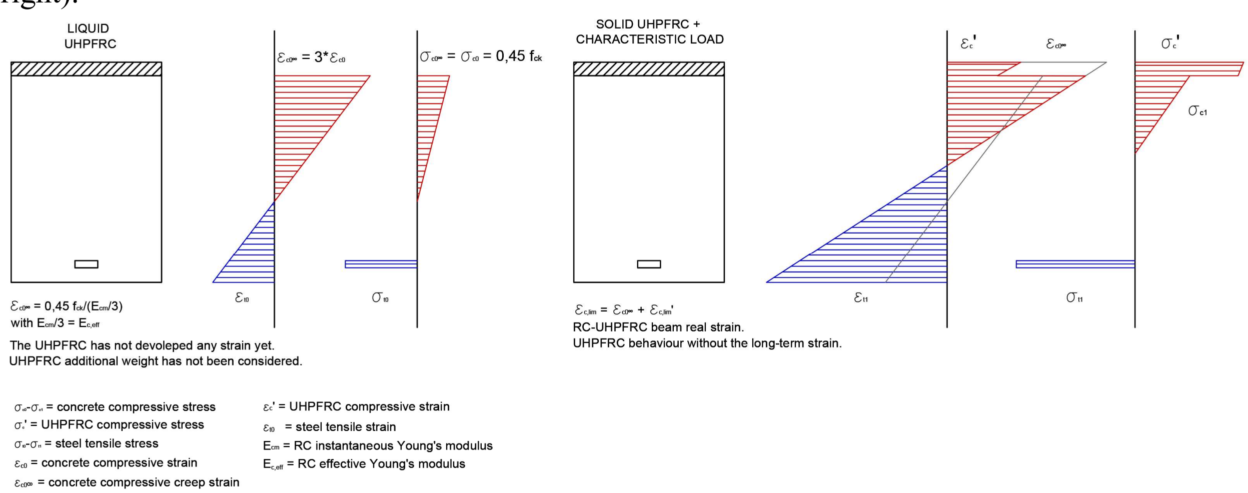


Figure 5. Strain immediately after the UHPFRC casting (left) and after the setting of the UHPFRC and the

application of the characteristic load (right).

As a consequence of these considerations, which have to be done in order to be coherent with the perfect adherence of the plain section hypothesis and with the experimental results, the UHPFRC virtual behavior law is shifted along the strain axes of $\varepsilon_{c0\infty}$ (figure 6).

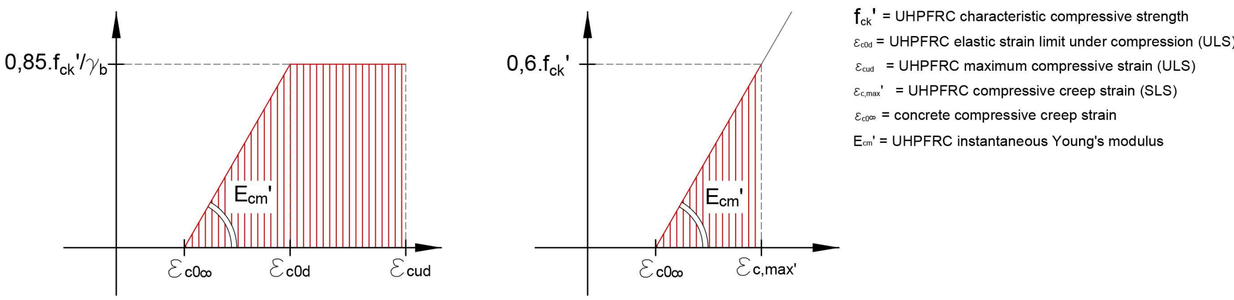


Figure 6. UHPFRC behavior law shift

4. Analysis and results

After the solver implementation, more than 400 tests have been carried out to establish the effectiveness of the tool, to outline the relation between the parameters involved and, above all, to understand their impact on the definition of the bending moment capacity gain. The principal tested variables are the type of UHPFRC, the thickness of the overlay and the reinforcement area.

Variables	**Range**
Type of UHPFRC (DUCTAL from LAFARGEHOLCIM)	G2 FM 200 STT G2 FM 325 STT G2 FM AF STT NaG3 FM STT
Thickness of the overlay	25 mm (i.e. 0.98 in.) 30 mm (i.e. 1.18 in.) 35 mm (i.e. 1.38 in.) 40 mm (i.e. 1.57 in.)
Reinforcement area	From 0,5% to 5,0% (with a step 0,5%)

Although different kinds of rectangular cross-section (from slabs to beams) have been tested, the behavior is similar. The values presented below are those for a one-meter slab with a height of 150 mm (5.91 in.) and with the inferior reinforcements positioned at 110 mm (4.33 in.) from the upper limit of the section, but they can be generalized.

The data obtained show which are the significative material parameters influencing the calculation. In fact, the G2 FM 200 STT and G2 FM AF STT types present exactly the same results, having the Young's modulus E_{cm}', the characteristic compressive strength f_{ck}', the mean compressive strength f_{cm}' and the mean value of post-cracking strength f_{ctfm}' matching. Furthermore, the gain values for FM 200, FM AF and 325 FM for low reinforcement areas are equals (figure 7). It happens because the UHPFRC is not using its maximum capacity, which means that ε_{cud} has not been reached. Hence, for low reinforcement areas, the fiber content (which determines the differences between FM 200, FM AF and 325 FM) does not affect the bending moment capacity gain.

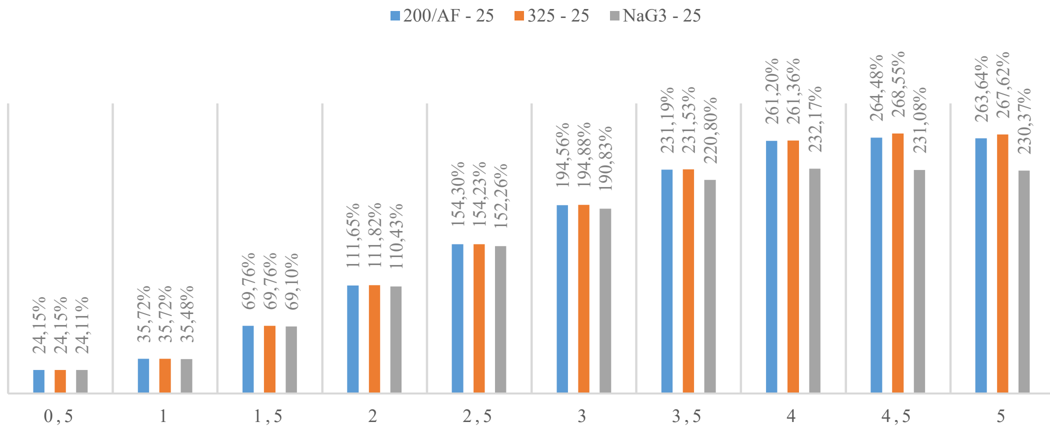


Figure 7. Different UHPFRC type ULS bending moment gain (vertical axis) with respect to the reinforcement percentage (horizontal axis). In this graph the 25 mm (0.91 in.) UHPFRC layer is considered

However, the main parameter affecting the bending moment capacity gain is the percentage of reinforcement. The relation between the two parameters is mainly linear and can be approximated to a broken line, which is subdivided in three different parts.

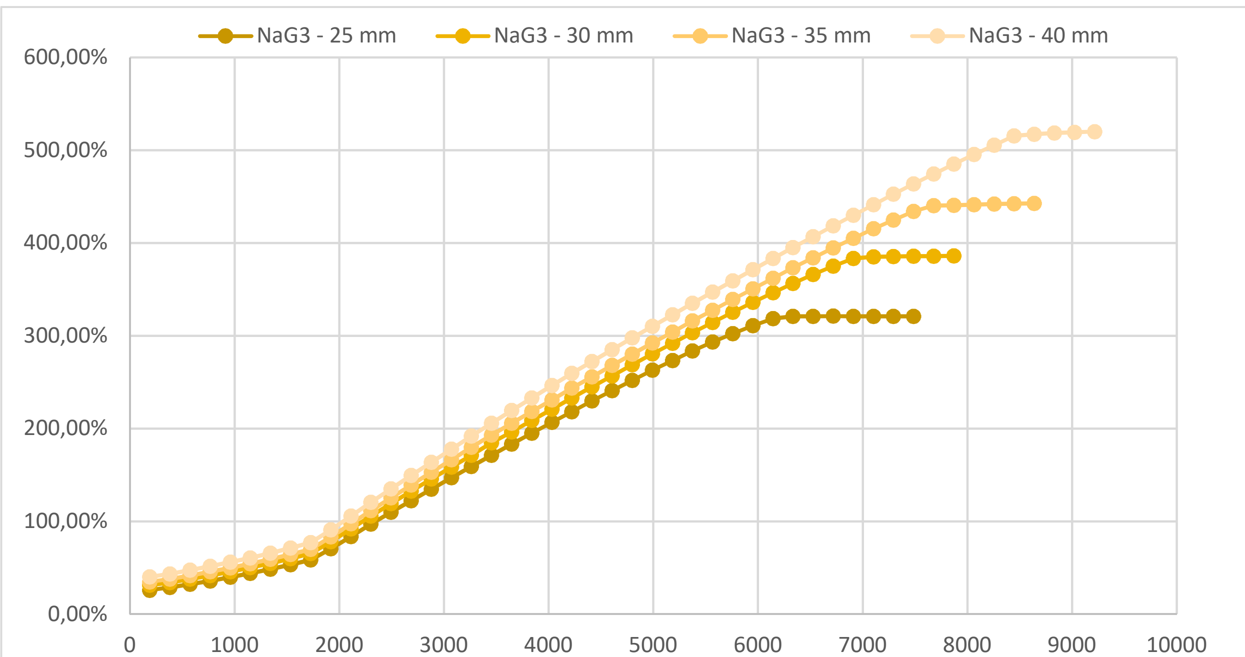
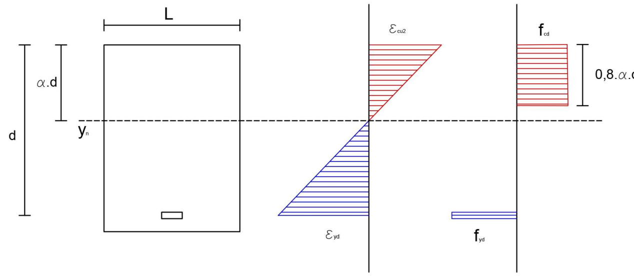


Figure 8. Different ULS bending moment gain (vertical axis) with respect to the reinforcements area (horizontal axis) for each thickness considered. In this graph the NaG3 UHPFRC type is considered

It is easy to individuate two different significative points (A_{smin} and A_{smax}), which represents a particular disruption of the behavior of the tested slab. The lower limit represents the last point in which the concrete has a linear behavior. This means that for very low content of reinforcement (about 1.5% of the cross-section), both the concrete and the UHPFRC do not reach their maximum compressive strength and so in the ERC and U-RC section the values of the moment are quite similar and, as a consequence, the gain is little. This implies that if the existing reinforcement is low, it is sufficient to utilize small thickness of UHPFRC to obtain good results. In fact, in the case of high thickness it is very unusual that the UHPFRC reaches its maximum compressive strength in all its points, thus nullifying the use of large quantity of material. A formula to obtain the reinforcement area for which the concrete has still a linear behavior is defined as follows:

$$A_{smin} = \frac{0{,}8.\alpha.d.b.f_{cd}}{f_{yd}} \qquad [1]$$

$$\text{with } \alpha = \frac{\varepsilon_{cu2}}{\varepsilon_{yd}+\varepsilon_{cu2}} \qquad [2]$$



$$M_{u,min} = 0{,}8.\alpha.(d+e).f_{cd}.(1-0{,}4.\alpha).(d+e) \qquad [3]$$

where $\alpha.d.b$ is the concrete compressive area, f_{cd} is the design compressive strength of concrete. The formula of $M_{u,min}$ is simplified (the gain is due only to the lever arm)

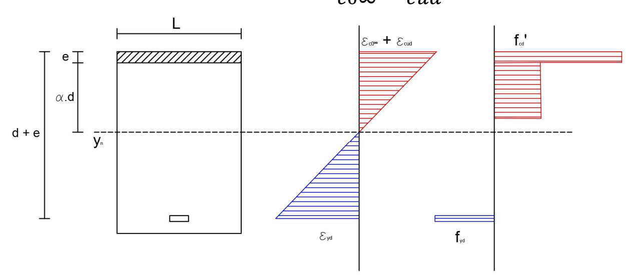
In the upper part of the graph, there is a "plateau" where the bending moment capacity gain remains the same even increasing the reinforcement area (to better understand the behavior of the U-RC beam very high value of reinforcement have been studied). The starting point of the plateau rises with the increase of the UHPFRC thickness. This happens because, while increasing the reinforcement, in order to balance the tensile forces, the UHPFRC gradually reaches its maximum compressive strength. When all the UHPFRC parts have reached it, the bending moment capacity gain starts to be constant, even because the reinforcements area is so high that the steel does not work using its capacity. In fact, the starting point of the plateau represent the last reinforcement area value for which the steel uses his full tensile strength. This value can be obtained with the following formula:

$$\alpha = \left(1+\frac{e}{d}\right)\frac{\varepsilon_{c0\infty}+\varepsilon_{cud}}{\varepsilon_{yd}+\varepsilon_{c0\infty}+\varepsilon_{cud}} - \frac{e}{d} \qquad [4]$$

$$\mathrm{H}'_{Pl} = (\mathrm{e}+\alpha.\mathrm{d}).(1-\frac{\varepsilon_{c0\infty}+\varepsilon_{c0d}}{\varepsilon_{c0\infty}+\varepsilon_{cud}}) \qquad [5]$$

If $\mathrm{H}'_{Pl} \geq \mathrm{e}$

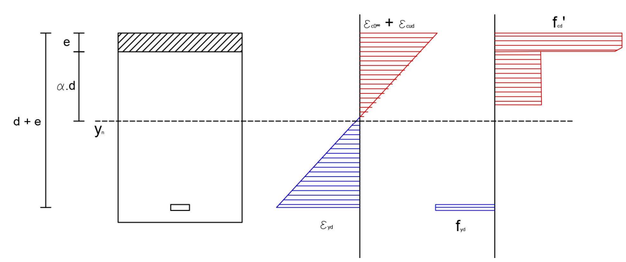
$$A_{smax} = \frac{b}{f_{yd}} \times (\mathrm{e}.f'_{cd} + 0{,}8.\alpha.d.f_{cd}) \qquad [6]$$



$$M_{u,max} = \mathrm{b.e.}f'_{cd}.\left(\mathrm{d}+\frac{\mathrm{e}}{2}\right) + 0{,}8.\alpha.d.f_{cd}.(1-0{,}4.\alpha).d \qquad [7]$$

If $\mathrm{H}'_{Pl} < \mathrm{e}$

$$\varepsilon_{c1} = \frac{(\varepsilon_{c0\infty}+\varepsilon_{cud}).\alpha.d}{e+\alpha.d} - \varepsilon_{c0\infty} \qquad [8]$$



$$A_{smax} = \frac{b}{f_{yd}} \times \left(\left(\mathrm{H}'_{Pl} + \frac{\varepsilon_{c1}+\varepsilon_{c0d}}{2.\varepsilon_{c0d}}.(e-\mathrm{H}'_{Pl})\right).f'_{cd} + 0{,}8.\alpha.d.f_{cd}\right) \qquad [9]$$

$$M_{u,max} = \left(\mathrm{H}'_{Pl} + \frac{\varepsilon_{c1}+\varepsilon_{c0d}}{2.\varepsilon_{c0d}}.(e-\mathrm{H}'_{Pl})\right).b.f'_{cd}.\left(\mathrm{d}+\frac{\mathrm{e}}{2}\right) + 0{,}8.\alpha.\mathrm{b}.d.f_{cd}.(1-0{,}4.\alpha).\mathrm{d} \qquad [10]$$

where f'_{cd} is the design value of UHPFRC compressive strength, e is the UHPFRC thickness. In this case all the UHPFRC has a plastic behavior, so the formula considers its maximum compressive strength. However, for large thickness, it can be possible than a part of the UHPFRC has still an elastic behavior. To verify this, the plastic height H'_{Pl}, which is the height of the plastic UHPFRC, must be considered. Some design codes are considering a maximum reinforcement percentage, usually inferior to A_{smax}. For example, the maximum reinforcement percentage considered by the Eurocodes (4%), is equal to 6000mm² in figure 8.
The both formula of A_{smin} and A_{smax}have been check with the calculation tools.

5. Conclusions and Future works

Compared to other solutions, casting UHPFRC overlay on existing concrete structure is very efficient for refurbishing or for increasing the bending moment capacity: rapidity, no access under the structure, finishing, fire resistance … The principle disadvantage is the weight overload due to UHPFRC thickness. To spread this reinforcement system, it is important to be able to quickly identify and size the relevant parameters. This is the topic of this research.
For the design of the overlay, it is crucial to know the existing steel reinforcement A_s inside. The gain capacity depends to this value. If $A_s < A_{smin}$ [1], the minimum thickness of UHPFRC overlay can be cast (commonly 25mm), because it has been demonstrated that for low values of rebar area the overlay cannot work properly so nullyfing the effort of utilizing this material. If $A_s > A_{smax}$ [6] or [9], the maximum thickness of UHPFRC overlay can be cast, even with reinforcement inside, considering that the material will work at its maximum strength. Other way, the thickness of UHPFRC overlay can be designed, by interpolating the gain between A_{smin} and A_{smax}. The bending moment capacity can be linearly interpolated in-between.
Now our work is focusing on the other situations (SLS, negative bending moment, T-beam …). The calculation solver is already set up for. In future, the results presented here will be compared to case study. Some simplified assumptions (stress of existing concrete, creep, shrinkage …) are very unfavorable for the design, and they must be evaluated.

6. References

Brühwiler, E., and Denarié, E., “Rehabilitation of Concrete Structures Using Ultra-High Performance Fibre Reinforced Concrete”, *Proceedings of The Second International Symposium on Ultra High Performance Concrete*, Eds., Fehling, E., Schmidt, M., and Stürwald, S., Kassel University Press, Kassel, Germany, 2008, pp. 895–902.

Graybeal, B. A., “Emerging UHPC-based bridge construction and preservation solutions”, *Proceedings of AFGC-ACI-fib-RILEM Int. Symposium on Ultra-High Performance Fibre-Reinforced Concrete*, Eds. Toutlemonde, F., and Resplendino, J., RILEM Publications S.A.R.L., Paris, France, 2017, pp. 965-974.

Makita T., and Brühwiler, E., “Fatigue behaviour of bridge deck slab elements strengthened with reinforced UHPFRC”, Proceedings, *IABMAS: Bridge Maintenance, Safety and Management*, Stresa, June 2012, pp. 1974-1980.

Noshiravani, T. and Brühwiler, E., "Experimental Investigation on Reinforced Ultra-High-Performance Fiber-Reinforced Concrete Composite Beams Subjected to Combined Bending and Shear", *ACI Structural Journal*, Vol. 110, No. 2, March/April 2013, pp. 251-262.

Oesterlee, C., *Structural Response of Reinforced UHPFRC and RC Composite Members*, Doctoral Thesis, N. 4848, Ecole Polytechnique Fédérale de Lausanne, Switzerland, 2010

Tayeh, B.A. *et alii*, "Utilization of Ultra-High Performance Fibre Concrete (UHPFC) for Rehabilitation. A Review", *Proceedings of the 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering*, Solo, Jawa Tengah, Indonesia, March 2012, pp. 525-538.

Béton fibré ultra-performant (BFUP) - Matériaux, dimensionnement et exécution, Technical Leaflet SIA 2052, 2016.

NF P18-710 - Complément national à l'Eurocode 2 – Calcul des structures en béton : règles spécifiques pour les Bétons Fibrés à Ultra-Hautes Performances (BFUP) (16/04/2016)

NF P18-470 - Bétons – Bétons Fibrés à Ultra-Hautes Performances – Spécification, performance, production et conformité (29/07/2016)

NF P 18-711-1 - NF EN 1992-1-1 - Eurocode 2 Calcul des structures en béton – Partie 1-1 : Règles générales et règles pour les bâtiments (10/2005)

7. Acknowledgements

We would like to express our gratitude to the Doctorate School of the Department of Architecture of the University of Naples Federico II and to Ductal Team for their support.