Possibilities and challenges of NSM for the flexural strengthening of RC structures

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ABSTRACT: Near surface mounted (NSM) is a technique that has been used to increase the flexural and the shear resistance of reinforced concrete (RC) structures. The performance of the NSM for the flexural strengthening of RC beams and slabs was already well proved, from research to case-studies. However, the influence of some variables that govern the effectiveness of the NSM, such is the case of the distance between consecutive bars, the reinforcement ratio of existing longitudinal steel bars, the relative position between longitudinal steel and FRP bars, the concrete strength class, and the type and layer thickness of the adhesive is still not well understood. Strengthening procedures need also some improvements in order to increase the effectiveness of this technique. These topics are discussed in the present work, based on the research already done. Specific issues that need extra and deep research are addressed.

1 INSTRUCTION

Gluing fibre reinforced polymer (FRP) strips by a structural adhesive into thin slits cut in the cover of reinforced concrete (RC) beams' faces is a strengthening technique that is gaining increasing attention of the FRP community. A considerable number of research projects has shown the effectiveness of this near surface mounted (NSM) technique to increase the flexural resistance of RC beams and slabs (Blaschko & Zilch 1999; El-Hacha & Rizkalla 2004; Barros & Fortes 2005; Barros et al. 2007; Bonaldo et al. in press; Kotynia 2005). However, the number of strengthening interventions in which this technique was used is still scarce, due to the inexistence of well accepted design equations, able to evaluate the contribution of the NSM FRP-strips with enough accuracy in order to provide the necessary confidence for the designer (Nanni et al. 2004). Furthermore, several improvements need to be done in the procedures of the technique in order to increase its effectiveness, not only in terms of the time to execute these procedures, but also on the exploitation of the high tensile strength of FRP materials. The available research indicates that the material properties of the FRP strips and adhesives have a considerable influence on the NSM strengthening effectiveness, but a comprehensive study in this context does not exist. Contradictory tendencies still exist in the results from distinct provenience (Haskett el al. 2007; Bonaldo et al. in press). The detrimental interference, in terms of strengthening effectiveness, of existing steel reinforcements, which is as pronounced as high is its percentage, is well documented from experimental research, but it is not yet well treated from the available analytical models. A decrease tendency of the NSM strengthening effectiveness with the decrease of the spacing between strips, mainly in RC beams, has also been observed in several experimental programs, but this phenomenon is still not well simulated by the available analytical models.

The available experimental research shows that, at the load corresponding to the deflection for the serviceability limit state, the stresses installed in the CFRP strips are much lower than their tensile strength. For the externally bonded reinforced (EBR) technique there are some prestressing techniques able of installing the laminates with a pre-stress level that increases significantly the effectiveness of this strengthening technique (Meier 2007). The high tensile strength of FRP strips used in the NSM technique can be effectively exploited only if the strips are applied with a certain pre-stress and if the premature failure modes are avoided. However, according to the authors' knowledge few research programs with the active NSM technique have been carried out (Nordin et al. 2001; Jung et al. 2007).

The production of monitored FRP strips, without adding extra sophisticated operations in the pultrusion manufacture process, is also an important contribution for a larger use of the NSM technique, since these FRP strips have the reinforcing and the monitoring capabilities, being the sensors (optical fibre sensors) well protected. In the pullout tests carried out to assess the FRP-concrete bond behaviour, these monitored FRP strips can be used, with notable advantages, since the presence of the sensors does not disturb the FRP-concrete bond properties, which is not possible with conventional strain gages.

The present work analyzes the possibilities of the NSM technique for flexural strengthening of RC structures and discusses the topics that deserve more research and attention of the FRP community in order to have well sustained strengthening practice, design guidelines that allow the engineers to assume this technique as a valid alternative to other strengthening techniques.

2 STRENGTHENING TECHNIQUE PROCEDURES

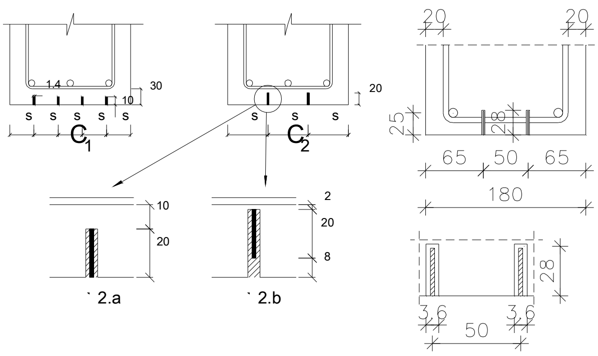
Since the available experimental research shows that carbon FRP (CFRP) elements of rectangular cross section are more effective than elements of round and square cross section (El-Hacha & Rizkalla 2004), only CFRP strips are considered in the present work. The procedures of the NSM strengthening technique are the following: 1) using a diamond blade cutter, slits of a width higher than, in general, 3 to 5 mm the thickness of the CFRP strip (that ranges from 1.4 to 3 mm) and a depth larger than 2 to 5 mm the width of the CFRP strip (that ranges from 10 to 30 mm, being the maximum value limited by the thickness of the concrete cover) are cut on the concrete surface of the element to strengthen; 2) slits are cleaned by compressed air and strips are cleaned by acetone; 3) adhesive is mixed according to the supplier recommendations; 4) slits are filled with the adhesive; 5) adhesive is applied on the faces of the strips; and 6) strips are introduced into the slits and adhesive in excess is removed. The adhesive curing period should be the one recommended by the supplier. To reduce the application time of the strengthening technique and to assure the desired quality on the strengthening intervention, it is indispensable the development of equipments able to: i) open, with high accuracy, the slit with the pre-defined geometry and up to the desired end point (the possibility of introducing some roughness on the concrete faces of the slit should be also a capability of this equipment); ii) inject the adhesive according to the void volume between strip and the surrounding concrete (the adhesive should be applied under pressure control in order to minimize the possibility of forming voids in the micro-structure of the adhesive). To assure uniform thickness for the adhesive layers, the equipment for the injection of the adhesive should have a guide that maintains the strip in the required position. A simpler alternative is the application of micro-separators on the lateral faces of the laminates, orthogonally to the fibres' direction, made with polymeric material and applied during the manufacturing process of the strips.

3 MATERIALS

3.1 Strips

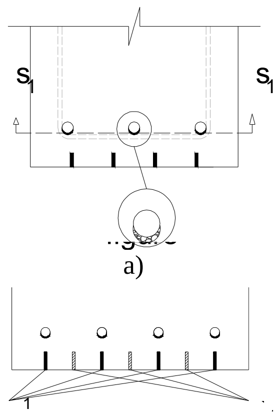
Bond tests and analytical models have shown that the pullout load increases with the increase of the width of the strip (Bianco et al. 2007). Haskett el al. (2007) have also verified that strips installed as deepest as possible into the slits have provided the largest pullout load and energy dissipation. Both conclusions indicate that the slip should have the maximum possible depth (limited by the thickness of the concrete cover) and the strip should have the largest possible width. For instance, for the same FRP strengthening ratio, C2 configuration might be preferable than C1 configuration (Figure 1). Between C2.a and C2.b configurations, the last one might provide the best bond performance, due to the high level of confinement that concrete applies to the strip. In this context, a recent experimental program (Kotynia 2006) explored the possibility of cutting the bottom horizontal arm of the steel stirrups in order to apply CFRP strips of an width larger than the concrete cover (Figure 1b). The results were well promising, but extra research needs to be carried out in order to evaluate the influence of this strategy in terms of the shear resistance of this type of beams.

Due to concrete casting conditions, under the tensile longitudinal bars exist a concentration of voids and defects on the microstructure of the material (S1-S1 plane in Figure 2a). Therefore, the NSM flexural strengthening effectiveness has a tendency to reduce with the increase of the number of longitudinal of steel bars. Furthermore, the relative positioning of strips and existing longitudinal tensile bars might have some interference in terms of strengthening effectiveness, since as smaller is the distance between these elements as lower might be this effectiveness, due to the detrimental effect of the interaction between these elements, as well as the presence of a concrete layer of reduced stiffness under the longitudinal steel bars, as already pointed-out, Figure 2b (C2 configuration seems to be more effective than C1). Research should be carried out to quantify the influence of these effects in terms of NSM strengthening effectiveness.



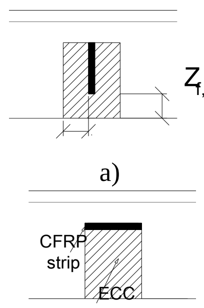
a) b)

Figure 1. NSM flexural strengthening configurations (dimensions in mm).



b)

Figure 2. a) Critical surface; b) Possible configurations for the relative position of strips and steel bar.



b)

Figure 3. Configurations to assure higher protection against fire.

3.2 Adhesives

Experimental and analytical research (Sena-Cruz & Barros 2004; Bianco et al. 2007) show that as high is the elasticity modulus of an adhesive as smaller is the bond length to transfer the stress from the FRP to the concrete, but the larger is the tensile stress in the surrounding concrete. Therefore, in case of structures with concrete cover of reduced tensile strength, the adhesive should have a relatively low elasticity modulus, able to distribute the bond stresses for a long bond length, decreasing, in this way, the maximum tensile stress transferred to the surrounding concrete.

Experimental research has shown that concrete elements strengthened according to the NSM technique, after have been subjected to high temperatures presented higher residual strength than concrete elements strengthened according to EBR technique (Fortes 2004). In these tests epoxy adhesives were used to bond CFRP materials to concrete. If engineering cement composites (ECC, Lee 2003), designed to have enhanced fire resistance, are used to bond NSM strips to concrete, a much higher residual strength might be achieved, which is a topic of high relevance (Porter & Harries 2005), not yet investigated. Furthermore, since experimental research on the influence of the thickness of the adhesive layer on the flexural capacity of RC slabs revealed that the load carrying capacity of these structures are marginally affected when the thickness of the adhesive layer varies between 1.3 mm to 6.3 mm (Bonaldo et al. in press), it seems that the highest performance in terms of fire resistance is attained when the thickness of the layer of the ECC material (t_a) is equal to the largest possible depth of the most exterior edge of the strip (Z_{fe}, see Figure 3a). However, this should be proved by experimental research, as well as the effectiveness of the strengthening configuration represented in Figure 3b, since in this last case the strip has higher protection against fire action. It seems that the benefits of adopting the above strategies to provide higher fire protection to CFRP materials exceed the detrimental effect of having a smaller internal arm for the strips. However, the costs for executing slits of 10 to 15 mm width should also be taken into account in this analysis.

4 PARAMETERS THAT INFLUENCE THE FLEXURAL STRENGTHENING EFFECTIVENESS

The available research indicates that NSM is more effective than EBR for the flexural strengthening of RC beams and slabs (El-Hacha & Rizkalla 2004; Kotynia 2005; Barros & Fortes 2005; Barros et al. 2007). The increase in the load carrying capacity can exceed 300% in case of RC slabs strengthened with a CFRP ratio (ρ_f) of 0.5%, a steel ratio (ρ_s) of 0.9% and A_f/A_s=0.74, where A_f and A_s are the cross sectional area of the strips and longitudinal steel bars (Bonaldo et al. 2007). In beams the effectiveness of the NSM flexural strengthening is not so pronounced, since experimental research has provided values for the increase of the maximum load ranging from 35% (ρ_f=0.21%, ρ_s=0.57%, A_f/A_s=0.42, Barros et al. 2007) to 221% (ρ_f=0.2%, ρ_s=0.27%, A_f/A_s=0.74, Kotynia 2005). The distinct effectiveness of the NSM technique in beams and slabs (that happens also with the EBR technique) is caused by the different crack pattern occurred in these two types of structures. In beams, the formation of critical diagonal cracks (CDC) introduces not only axial tensile forces in the CFRP laminates, but also shear force components due to the relative slip of the faces of these cracks, which promotes the occurrence of premature failure modes due to the detachment of the concrete cover (Figure 4a). This effect is so pronounced as high is the percentage of CFRP reinforcement and as high is the percentage and number of longitudinal tensile steel bars.

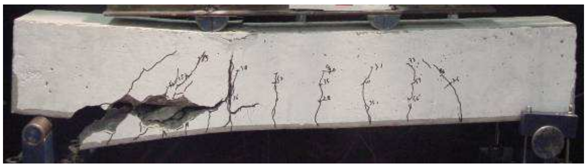
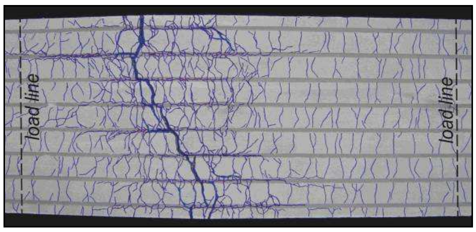
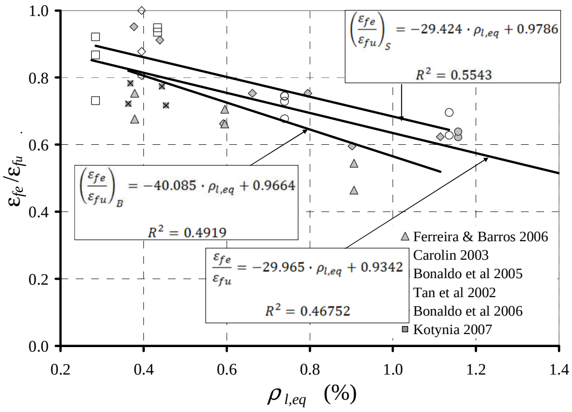
a) 
b) 

Figure 4. Typical failure modes in: a) beams and b) slabs.

Figure 5 shows that there is a tendency for a decrease of $\varepsilon_{fe}/\varepsilon_{fu}$ with the increase of $\rho_{l,eq}$, where ε_{fe} and ε_{fu} are the maximum strain possible to apply to the strips (also designated by effective strain, ACI 440 2002) and the strain at tensile strength of the strips, respectively, while $\rho_{l,eq} = A_s/(b\, d_s) + (A_f\, E_f / E_s) / (b\, d_f)$ is the equivalent reinforcement ratio, where b is the beam width and d_s and d_f are the effective depth of the longitudinal steel bars and CFRP strips, respectively, and E_s and E_f are the Young's Modulus of the longitudinal tensile steel bars and CFRP strips, respectively. This effect is not taken into account by the most recognized guidelines (ACI 440 2002; fib 2001; CNR-DT 200 2006; CIDAR 2006). Figure 7 shows that regardless the value of $\rho_{l,eq}$, $\varepsilon_{fe}/\varepsilon_{fu}$ is higher in slabs (subscript S) than in beams (subscript B). Furthermore, the decrease of $\varepsilon_{fe}/\varepsilon_{fu}$ with the increase of $\rho_{l,eq}$ is more pronounced in beams than in slabs.

Another aspect not taken into account in the available guidelines is the increase tendency of the $\varepsilon_{fe}/\varepsilon_{fu}$ with the increase of a_f/b ratio on the NSM flexural strengthened RC beams (see Figure 6), where a_f is the spacing between strips. In RC slabs, the distance between longitudinal bars is, in general, larger than the distance in beams, and the occurrence of CDC has reduced tendency to occur. In consequence, the tensile strength of the CFRP strips was attained in RC slabs, even for a short distance of 38 mm between CFRP strips (Bonaldo et al. 2007). The flexural cracks formed in slabs failing in bending only introduce axial tensile forces in the CFRP strips (the shear force components applied to the strips at the cracks, due to slip of crack's faces are negligible).



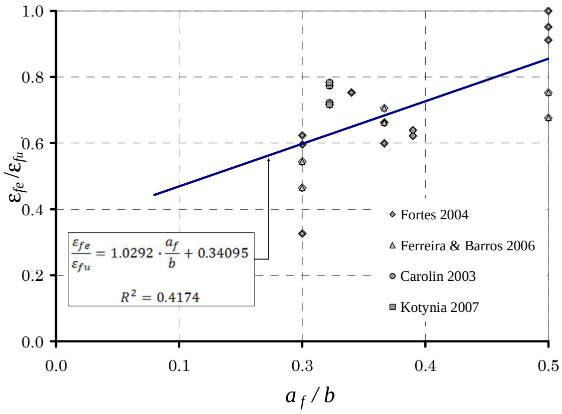


Figure 7 - Strengthening efficacy index vs. longitudinal equivalent reinforcement ratio for the NSM.

Figure 8 - Influence of the a_f/b ratio on the $\varepsilon_{fe}/\varepsilon_{fu}$.

Experimental research showed that the thickness of the adhesive layer has marginal influence on the flexural behavior of RC slabs strengthened according to the NSM technique (Kotynia 2006; Bonaldo et al. in press), which indicates that the use of cement based adhesives of enhanced fire resistance and a thickness layer that guarantees the desired protection to the strips against fire is an idea that should be investigated.

Due to the characteristics of the application of NSM technique, it is specially adjusted to increase the negative bending moments of continuous RC beams and slabs. In fact, the opening process of the slits can be executed by conventional equipment used to open the crack control joints in the slabs. However, the linear-elastic behaviour of the CFRP strips up to its brittle failure puts some concerning about the moment redistribution capacity, which is intimately related to the level of ductility of the behaviour of the strengthened structure. Preliminary tests indicates the possibility of assuring high levels of moment redistribution with the formation of the plastic hinges at the centre support and below the point loads, without the occurrence of CFRP-premature failure modes (Bonaldo in prep.).

5 CONCLUSIONS

The paper points out the main achievements found in the NSM technique for the flexural strengthening of RC beams and slabs. A focus was put on the influence that certain parameters have on the effectiveness of the NSM flexural technique, namely: reinforcement ratio of existing longitudinal steel bars and NSM strips; the relative position of steel and strips; distance between consecutive strips; type of strips and adhesives; layer thickness of the adhesive. Several topics that deserve more and deeper research, as well as new ideas were also referred.

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