Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-4-8

CRITICAL COMPARISON BETWEEN TWO STRENGTHENING TECHNIQUES OF REINFORCED CONCRETE COLUMNS

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In last years, in order to better understand the behavior of confined reinforced concrete, a lot of studies have been made. In addition, also a lot of experimental test have been conducted. In particular the attention has been devoted to the columns strengthened with FRP, while other old techniques have been completely forgotten. Herein a comparison between different methodologies for the strengthening of concrete columns is presented. In addition to columns confined with FRP the concrete confined with angles and battens is considered. The comparing between these two methodologies shows that some advantages arise when battens and angles are used. In fact, they can be effectively used, also when the ratio between the two sides of the column section is greater than 2, by means of steel bar passing through the section. In such a case the confining action due to FRP is negligible. In addition, angles can provide strengthening both in tension and in compression, depending on the structural detail adopted at the concrete floor slab.

Keywords: Angles and battens, FRP, SFRC, Confined concrete, Column repair.

1 INTRODUCTION

The need to improve the seismic performances of existing buildings or to retrofit them according to the new-seismic regulations is a more and more pressing need in areas subjected to high seismic risk. Among the new available technologies, great attention has received the confinement of structural members by applying one or more layers of fiber-reinforced materials in a polymeric matrix (FRP) bonded to the element's surface. It is important to underline that the idea is not completely new. In fact, several centuries ago the retrofitting of columns by means of steel rings in critical sections of the pier with the aim of stabilize damaged material or improve the compressive resistance, stiffness and ductility has been made. Generally, the confinement has one or more of the following advantages: increase of the compressive strength of the columns, increase of the rotational ductility of critical sections, repair of elements damaged due to past seismic events or degraded due to the lack of maintenance, improvement of the confining and constraining action for compressed bars when there are no appropriate stirrups. With reference to the problem of retrofitting existing buildings, there is the need to provide designers with a valid calculation model accounting for all the parameters affecting the ultimate behaviour of reinforced concrete columns. For what concerns the strengthening with FRP, it has been widely analyzed, both from an analytical and experimental point of view, and a lot of constitutive model have been proposed (Montuori *et al*. 2012, Montuori *et al.* 2013). In fact, many researchers have developed and proposed different constitutive laws. Some of them require an iterative procedure, some require, as collapse condition, the attainment of the ultimate value of concrete axial strain, while others refer to the ultimate strain of FRP; finally, some of them consider only the maximum value of the lateral confining pressure, while others its whole development as a function of the concrete axial strain. On the contrary for what concerns the strengthening with angles and battens only few analytical model have been proposed and only few experimental test have been performed (Campione 2012, Campione *et al*. 2015, Garzón-Roca *et al*. 2011, Garzón-Roca *et al*. 2012, Montuori and Piluso 2009). Regarding this last strengthening technic it is important to underline that it has been described in a lot of engineering manuals for several decades, but the problem is often dealt from a qualitative point of view with only rough suggestions devoted to the evaluation of the load carrying capacity of the strengthened member. In particular, depending on the structural detail adopted at the concrete floor slab location or for the column-to-foundation connection, the angles can be considered as acting both in tension and in compression, only in compression or, finally, they can be considered as providing a confining action only. In addition, it should be noted that for a given stress-strain constitutive law, the effectiveness of confinement is strongly affected not only by the characteristics and the numbers of layers of the used FRP material (or by the dimensions of angles and battens used), but also by the shape of the section. In particular, square and rectangular sections show a performance improvement, both in terms of strength and ductility, less than that occurring in the case of circular sections. This is due because in circular sections the whole area is laterally confined, while in case of square and rectangular sections, according to the well-known "arch effect", only a part of the section area is effectively confined.

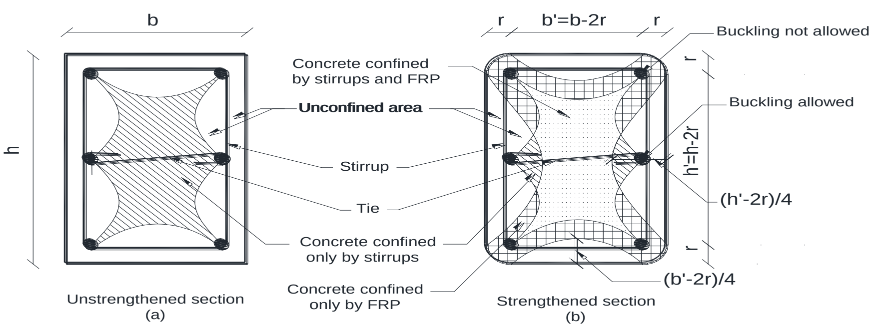

Figure 1. Different confined zones of rectangular sections.

2 STRENGTHENING WITH FRP

In last years, among the different technological solutions for the retrofitting and the strengthening of reinforced concrete structural elements (Montuori *et al.* 2012a), the technique of confinement by means of FRP has gained more and more interest of researchers and practitioners. As showed in Figure 1, within a reinforced concrete section strengthened by means of FRP wraps, four differently confined parts can be identified so that four different concrete stress-strain constitutive laws need to be considered: 1) unconfined concrete; 2) concrete effectively confined by stirrups; 3) concrete effectively confined by FRP; 4) concrete effectively confined by FRP and stirrups. Therefore, the first step to be made is the delimitation of confined and not confined parts of the original pre-existing section. To this aim, the longitudinal “confining bars” or “restraining bars”, which are those located in the corners and the intermediate ones provided that they are restrained by steel ties, have to be identified. Starting from these restraining points, it is possible to determine the parabola arches dividing zones of effectively confined concrete from zones of unconfined concrete, as it is shown in Figure 1a for the unstrengthened original section. It is well known that wrapping by means of FRP sheets needs preliminarily the rounding of the corners of the existing section. Therefore, in the models generally adopted, it is assumed that the confining effect is exerted along the whole rounded corner, so that the final points of the rounding radius can be considered as "restraining point" (Figure 1a). Similarly to the parabola between the longitudinal bars of the unstrengthened section, the span-to-depth ratio of the parabola between two corners, separating confined and unconfined concrete, can be considered equal to 4. By means of such parabolas the four zones of differently confined concrete can be identified (Figure. 1b). As soon as the different stress-strain constitutive laws for all the different concrete zones constituting the cross section are known and the steel stress-strain behavior has been defined, a fiber model can be easily developed by assigning to each fiber the corresponding σ - ε law according to the fiber location. It is important to underline that the effect of the strengthening is constituted only by the confining effect which is able to provide an increase in the axial resistance but a very poor increase in the flexural resistance. In addition a very significant increase in ductility is obtained as well described in (Montuori *et al.* 2013).

3 STRENGTHENING WITH ANGLES AND BATTENS

The strengthening of reinforced concrete columns with angles and battens has been described in a lot of engineering manuals since several decades ago, but the problem is often treated in a qualitative way rather than in a quantitative one, with only rough indications devoted to the evaluation of the load carrying capacity of the strengthened member. Only in the last years the researchers provided designers with a valid calculation methodology which accounts for many parameters often neglected in current design practice.

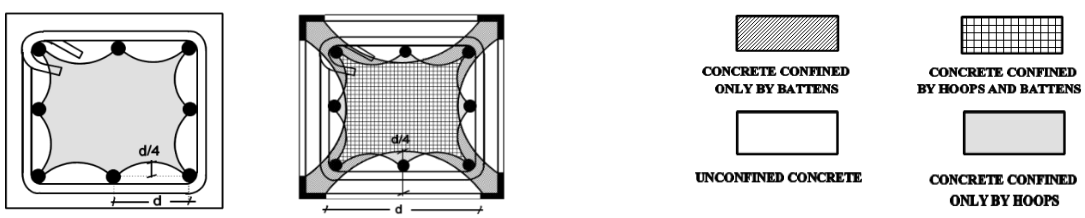

Figure 2. Different confined zones of rectangular sections when angles and battens are used.

The methodologies which are now available (Montuori and Piluso 2009, Montuori and Piluso 2015) account for the following issues which are relevant to an accurate evaluation of the ultimate resistance of the strengthened column: the deformations resulting from the loads acting on the original pre-existing section; the effect of the different behavior of effectively confined concrete with respect to the unconfined one; the variation of effectively confined concrete area as a consequence of the strengthening intervention (Figure 2); the variation of the σ–ε law for the effectively confined concrete considering the difference between the concrete effectively confined only by the battens, the concrete effectively confined only by the existing hoops, and the concrete effectively confined both by the battens and by the existing hoops; the possibility of buckling of longitudinal bars. In addition, depending on the kind of structural detail adopted at the beam-to-column joint location, the angles can be considered as acting both in tension and in compression, only in tension or, finally, they can be considered as providing a confining effect only. In particular, with reference to an intermediate story, the angles can be considered acting both in tension and in compression provided that the angles strengthening the column are effectively connected to those strengthening the columns of the adjacent stories (Figure 3). As, it is almost impossible to create such a connection through the floor slabs without producing significant damage to the non-structural elements, the designers could provide the angles with an end plate to be connected to the floor slabs aiming to ensure the transmission of the compression forces only. Obviously, in this case the model has to account just for the angles acting in compression. Finally, when no attention is devoted to the structural detail regarding the connection between the angles and the floor slabs, the angles have to be considered as confining elements only, because the confinement is due to the batten action which is restrained by the angles. In addition, if the section has a ratio between the sides greater that 2 than the confining effect can be obtained by inserting an horizontal bars connected with the battens as showed in Figure. 3b. It is important to underline that present codes, generally, do not provide design rules for the dimensioning of retrofitting system represented in Figure 3a and 3b. As an example, in Eurocodes no information is provided for the design of the angles, even if, a very simple criterion can be adopted. In fact, if angles are used also in compression, then they should be able to avoid buckling. According to this request the slenderness λ of the angles is given by S_b/ρ_{min} where S_b represents the spacing between the angles (Figure 3a) and ρ_{min} is the minimum radius of gyration of the adopted angle. According to EC3 the design buckling $N_{b,Rd}$ of a compression member having area A and yield strength f_y is given by $\chi A f_y/\gamma_{M1}$ where γ_{M1} is the safety partial factor and χ is the reduction factor for the relevant buckling mode. As reported in EC3, if the non-dimensional slenderness $\bar{\lambda}$ is lower than 0.2 then χ is equal to 1 and so the buckling phenomenon is avoided. The non-dimensional slenderness is given by: $\lambda/93.9\varepsilon$ where $\varepsilon = \sqrt{235/f_y}$ with f_y in N/mm^2. So it can be concluded that the buckling is avoided if the following relation is satisfied:

$$\bar{\lambda} \leq 0.2 \;\; \Rightarrow \;\; \frac{\lambda}{93.9\varepsilon} \leq 0.2 \;\; \Rightarrow \;\; \frac{S_b}{\rho_{min}} \leq 0.2 * 93.9\varepsilon \;\;\; \Rightarrow \;\; S_b \leq 18.78\,\varepsilon\,\rho_{min} \tag{1}$$

As an example, if we consider a section of 60 x 60 x 6 with f_y = 275 Mpa for the angle of the reinforcement, then, in order to avoid the buckling, the spacing between the battens must be lower than 18.78 ε ρ_{min}= 18.78 * 0.924 * 1.37 = 23.78cm.

4 COMPARISON BETWEEN THE TWO TECHNIQUES

As it obvious from Figures 1, 2, 3a and 3b there are some important differences between the two considered techniques. In particular, when the ratio between the base and the height of the section is greater than 2, the use of FRP is not able to provide any confining effect. While in the case of section strengthened with angles and battens, the insertion of a horizontal bar connected with the battens, can lead to an effective confining action as showed in Figure 3b. In addition, the second technique can provide also resistance in tension and in compression because the angles, if the structural detail is appropriately realized, can be behave as an additional vertical reinforcement. Furthermore, the application of FRP requires an appropriate moisture degree when it is applied and the corners of the existing section are to be rounded. These two problems in the case of angles and battens are not present, in fact they can be applied without mortar and in any condition. Another problem that cannot be forgotten is the low value of the transition temperature (*Tg*) of FRP. In fact, is generally in the range 50-100 Celsius degree, depending on the resin type, which is the adhesive between the strengthening and the concrete. When the temperature exceeds this limit value the performance of FRP drops dramatically because the thermal energy absorbed when temperature is greater than *Tg* leads the resin chains to move and become more flexible with a consequent reduced bond capacity. In addition, it is well known that

FRP composite materials are particularly sensitive to cuts and incision produced by cutting tools, so that also vandalism could be a problem as mentioned in several codes regarding the strengthening with FRP. Last but not least the lack of understanding and confidence in the long-term performance of externally bonded (FRP) is still in progress. In fact, it is now generally accepted that a very important issue with externally bonded FRP composites is their susceptibility to degradation when exposed to moisture. Some recent studies state that a reduction of effectiveness greater than 50% can be achieved due to moisture effect. So it can be concluded that the use of "classic" technique is simpler that the use of FRP. Notwithstanding, the amount of works regarding the strengthening with FRP in last decades is enormously greater than the works devoted to the strengthening with angles and battens. The reason is probably due to the fact that angles and battens are considered "old", while FRP is considered "new". But, after years of research, it is now clear enough that the "old" technique could be better and economically convenient with respect to the "new" one. As an example, if there is the need to improve the seismic resistance of a concrete moment resisting frame, the use of angles and battens can provide an amount of ductility and resistance which is able to promote the development of a more dissipative collapse mechanism (Montuori and Muscati 2015, Montuori and Muscati 2016). In the last years, the use of SFCW (Steel Fiber Composite Wraps) as an alternative to the FRP has been proposed and several experimental programs have been developed. These "very new" fibers, generally, are applied by means of little angles located at the four corners of the section, so that a sort of modern angles and battens is realized. Notwithstanding in some cases the use of a resin, instead of a cement mortar, is still proposed. In this case all the problems regarding the FRP remain.

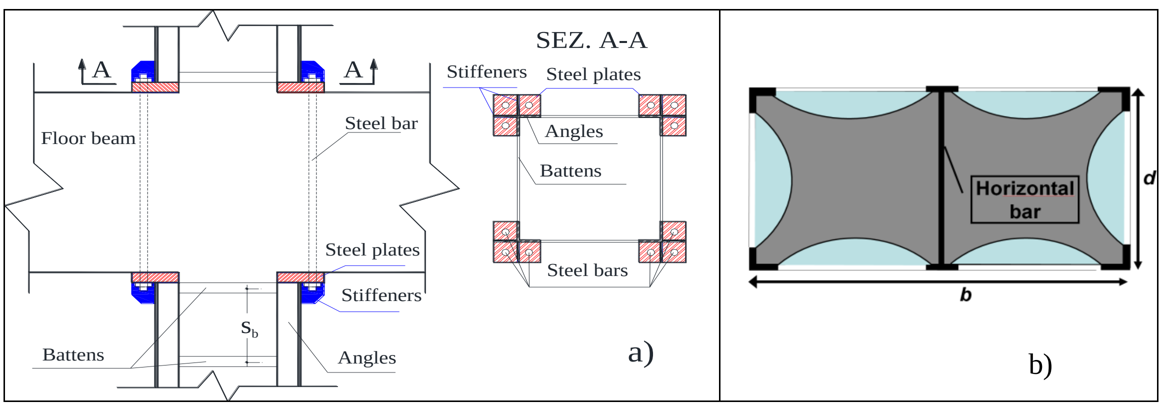

Figure 3. Structural detail for angles acting both in tension and in compression a) and confining effect in case of b/d >2 b).

5 CONCLUSIONS

In this paper two different techniques for the strengthening of reinforced concrete columns have been analyzed: a "new" one and an "old" one. The new one has been widely analyzed both from a theoretical and experimental point of view, while for the old one the data available in present literature is rather poor, even if the presence of angles can constitute an effective increase of longitudinal reinforcement depending on the adopted structural detail. If the angles can be located assuring continuity through the concrete floor slab, or if the structural detail of the joint is able to transfer the angle action from one story to the following one, they can be considered acting both in tension and in compression. Several critical aspects regarding the reinforcement with FRP have been analyzed and discussed showing that not always the new is better than the old. In addition it is important to underline that there are also different methodology that can be used as alternative or together with the analyzed ones to protect old and new structures. In particular the use of special devices that can be added to the structure should be always considered as a complementary strategy when columns are reinforced with FRP or angles and battens (Castaldo 2014, Castaldo and De Iuliis 2014, Castaldo and Tubaldi 2015, Castaldo *et al.* 2015, Palazzo *et al.* 2014, Latour *et al.* 2014, Latour *et al.* 2015, De Iuliis and Castaldo 2012, Montuori *et al.* 2014, Piluso *et al*. 2014).

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