STRENGTHENING OF REINFORCED CONCRETE COLUMNS BY REINFORCED CONCRETE JACKET

PROJECT RECOMMENDATIONS

ANDRÉ FILIPE DA SILVA HENRIQUES
andre.f.s.henriques@tecnico.ulisboa.pt

INSTITUTO SUPERIOR TÉCNICO
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ABSTRACT

Reinforced concrete jacketing is a current strengthening method of reinforced concrete columns. It shows advantages particularly in seismic retrofitting, since it enhances strength, ductility and consequently the energy dissipation of the strengthened column. However, there are not any guidelines, only published research on different parameters related with this method. In the present work, after processing all the information resulting from a technical-scientific literature review, project recommendations are presented and discussed. These have as target-readers designers, contractors, and other technicians involved in structural rehabilitation of reinforced concrete structures and they take into account the conception, design, detailing, execution and quality control of this technique. It is concluded that there are relevant aspects in the execution of this method that can influence the behavior of the strengthened column. In particular, the preparation of the surface of the original column, the use of steel connectors, the use of a concrete in the jacket with higher strength than the concrete of the original column, and the anchoring of the steel longitudinal reinforcing rebars of the jacket to the slab/footing.

Keywords: strengthening of reinforced concrete columns, reinforced concrete jacket, concrete-to-concrete connection, interface resistance.

1 Introduction

Nowadays, there is an increasing need in structural rehabilitation. This need can occur from the beginning of the construction phase of a building until the end of its service life. Júlio [22] refers some reasons that can lead to structural rehabilitation:

- development of more demanding code requirements;
- design errors;
- execution errors;
- errors in the concrete composition;
- occurrence of earthquakes and other accidents;
- changes in the structure functionality for more demanding conditions;
- changes in service requirements of the structure;

In the specific case of reinforced concrete (RC) columns, Kaliyaperumal and Sengupta [30] refer that the most errors/deficiencies that can be found are: (i) disproportionate dimensions and inadequate sections of columns leading to an inadequate flexure and shear capacities of framed structures; (ii) inadequate stirrups spacing especially in the plastic hinge regions; (iii) inadequate flexure capacity, specially near the beam-column joints; (iv) insufficient stirrups detailing (e.g. lack of adequate end hooks), leading to a shear fail of the column; (v) inadequate location and short splice lengths of the longitudinal reinforcement, leading to a poor transfer of the load between the steel bars; (vi) short columns due the presence of partial-height infill walls leading to an increase of the shear force and (vii) lower concrete strength or poorer quality than the design concrete.

There are a lot of strengthening methods to retrofit columns, and this work focuses on structural rehabilitation of columns by RC jacketing.

This method is characterized by the increase of the column section over the total height of the column by adding a new layer of concrete (jacket) with longitudinal reinforcement and stirrups (Fig. 1). The RC jacket increases the axial, flexure and shear strength and also the stiffness, ductility and energy dissipation of the retrofit column, being an advantageous method in seismic retrofit operations. If a column is correctly detailed, RC jacketing can also guarantee a more ductile behavior of the structure, by ensuring that failure occurs in beams and not in columns. Therefore, a brittle failure in columns is avoided [47].

The great variety of advantages of this method is what differentiates it from other methods. The following advantages are highlighted: (i) the low cost of workmanship and materials, since the construction processes are current; (ii) the suitability of RC jacket for the repair of serious damages due to an earthquake [41]; (iii) the absence of need to protect against corrosion or fire, unlike other retrofit methods [22] and (iv) when used to strengthen columns in buildings, since the stiffness increase is uniformly distributed, foundation strengthening might be avoided [40].

This method also presents some disadvantages, including: (i) the increase of the section may collide with the architecture; (ii) when executing the jacketing method the space needs to be clear, being a problem in an office, for example, where the space is always occupied; (iii) produces a lot of dust and
small fragments, depending on the technique used to remove the deteriorated concrete, the equipment used to create a roughness in the column surface and the technique used for placing the concrete; (iv) it produces a lot of noise pollution, leading to workers’ health problems [7]; (v) in case that continuity is required it is needed to drill holes in the slab/beam and in the foundation to insert the longitudinal reinforcement, and in this cases the position of the longitudinal reinforcement can be conditioned leading to a column bundle reinforcement located in the corners [22].

![Jacketing of a RC column](image)

Fig. 1 - Jacketing of a RC column [23].

Being an up growing method in structural retrofit and in the absence of any design recommendations but only numerical and experimental published research about parameters related with this method, it is necessary to define some guidelines to support designers, contractors, and other technicians involved in the structural rehabilitation of RC structures when using this method. For this purpose, it was first necessary to analyze all the documents available and then process all the information and understand the influence of all parameters related to this method, namely the interface resistance (including the surface roughness, the application of bonding agents and the use of steel connectors), concrete jacket and curing conditions, installed load in the original column, inadequate detailing and damages in the original column, reinforcement corrosion of the original column and detailing of the jacket reinforcement. Some methodologies for the design of RC jacketing, with particular incidence in the monolithic coefficients, which are used in EC8-1 [13] were also discussed. In this article only the relevant conclusions obtained from all information are presented.

2 Project Recommendations

2.1 Characterization of the element

Before the strengthening operation it is necessary to inspect the structure, collect all the available information and analyze the safety conditions in order to obtain an accurate characterization of the structure, as well as to characterize the existing pathologies [9].

Firstly, if there is any project available, an analysis must be conducted. The strengthening element must be characterized geometrically and the reinforcement must be analyzed in terms of location and quantities, using a scan radar detection system (pachometer test). The state of preservation of the substrate, namely the concrete and the reinforcement, should be observed and diagnosed using appropriate techniques (e.g. corrosion measure, carbonation depth, chloride penetration, cracking, among others), in order to analyze its pathologies. The strength and other materials’ mechanical properties should be determined using in situ tests and/or lab tests (e.g. pull-off tests, and pull-out tests, among others). It is convenient to measure the surface hardness using a Schmidt sclerometer and ultra-sounds propagation to define different concrete quality areas in order not to use destructive tests. If there aren’t any correspondence between the project and the reality or if the project doesn’t even exist, a more comprehensive data collection should be carried out.

Based on this information, the retrofit solution must be design in order to minimize not only the cost of the intervention but also its impact in the normal operation of the building during the execution of the strengthening works [18].

2.2 Jacketing type

The strengthening of RC columns by RC jacket usually involves the complete cross-section (total jacket). However, if there are architectural constraints RC jacket can be applied only in some sides of the column (partial jacket). This is the typical case of edge or corner columns in buildings. In this case, the interface resistance plays an important role in ensuring a monolithic behavior of the strengthened column and, for this reason, special attention must be paid in the design, detail and execution of this method.

The jacketing can be divided into two groups, regarding the load demands:

(1) if the jacket is used to increase column’s flexure, shear and axial strength, it is executed along all its height and the longitudinal steel rebars must cross the slab/beam and anchor the footing to ensure continuity between floors (Fig. 2a));
Fig. 2 – Jacket types. a) directly loaded; b) indirectly loaded [8].

(2) if the jacket is used to increase only the axial strength of the column it is not necessary to execute it along all its height and the longitudinal steel rebars don’t need to cross the slab/beam nor anchor the footing. In these cases the jacket will only confine the original column and will only resist to an increase of the axial load (Fig. 2b);

2.3 Temporary shoring of the structure

An important aspect to mention in this method is how it’s made. When strengthening a column with RC jacket, the column is already subjected to loads including self-weight, masonry walls, etc. Depending on the situations, the corresponding stresses/strains may be relevant and, in these cases, a temporary shoring of the column must be taken into account in order to prevent deformations or even the collapse during the repair. If an active shoring is considered, then the original column and the jacket, i.e. the composite element, will work together and resist to the total load. If a temporary shoring is not used, the jacket will only resist to load increments.

The temporary shoring is usually an expensive solution that can be performed by means of hydraulic jacks and a temporary reaction structure (Fig. 3), which may not be always practicable, since it may not be easy to adopt a suitable support for its positioning (e.g. case of some bridges).

For RC columns with a current reduced axial force \( \nu \leq 0.7 \), it is not necessary to use any temporary shoring since the load won’t lead to a negative effect in the strengthened column [16,25,28,38,49].

It should be noted that the greater the jacket’s thickness and longitudinal reinforcement, for current reduced axial forces \( \nu \leq 0.7 \), the lower the influence of the original column’s loads, since the jacket will become more dominant in the strengthened column [38].

2.4 Design

The retrofit is classified according to the increment of the original column’s section (initial section). If the area of the jacket section is less than twice the area of the initial section, then the strengthened method is considered to be slight, otherwise it is considered to be significant. In the latter case, the contribution of the original column to the strength of the strengthened column can be neglected [18]. Depending on the conservation state of the original column and the mechanical properties of the materials, it is up to the designer to decide whether to consider a total, partial or null contribution of the original column.

The design of this method can be accomplished assuming a monolithic behavior of the strengthened column and considering a correction factor, \( K_{NJ} \leq 1 \), called monolithic coefficient, to take into account the non-monolithic behavior of the strengthened column. The strength is initially calculated with the bases of the constitutive...
relationships of the new materials, assuming that there is a perfect bond between the old concrete and the added one, as if it was an RC section considering two layers of reinforcement. The EC8-3 [14] states in section A.4.2.2 that the design can also be made assuming that the properties of the jacket's concrete can be applied to the whole section.

In order to take into account the increase in the compressive strength of the original concrete due to confinement, the following equations, presented in section 3.1.9 of EC2 [12] and 5.4.3.2.2 of EC8-1 [13], should be used:

\[
\begin{align*}
 f_{ck,c} &= f_{ck}(1,000 + 5,0 \frac{\sigma_2}{f_{ck}}), \quad \text{for } \sigma_2 \leq 0,05f_{ck} \quad (1) \\
 f_{ck,c} &= f_{ck}(1,125 + 2,5 \frac{\sigma_2}{f_{ck}}), \quad \text{for } \sigma_2 \geq 0,05f_{ck} \quad (2) \\
 \epsilon_{c,cc} &= \epsilon_{c}(f_{ck,c}/f_{ck})^2 \quad (3) \\
 \epsilon_{cu,cc} &= \epsilon_{cu} + (0,2 \sigma_2/f_{ck}) \quad (4) \\
 \frac{\sigma_2}{f_{ck}} &= \frac{\sigma_3}{f_{ck}} = 0,5\alpha\omega_{n} \quad (5)
\end{align*}
\]

where:
- \( f_{ck,c} \) represents the characteristic compressive cylinder strength of confined concrete at 28 days;
- \( f_{ck} \) represents the characteristic compressive cylinder strength of concrete at 28 days;
- \( \sigma_2,\sigma_3 \) represents the effective lateral compressive stress at the ultimate limited state (ULS) due to confinement;
- \( \epsilon_{c,cc} \) represents the compressive strain in the confined concrete at the peak stress \( f_c \);
- \( \epsilon_{cu,cc} \) represents the ultimate compressive strain in the confined concrete;
- \( \epsilon_{cu} \) represents the ultimate compressive strain in the concrete;
- \( \alpha \) represents the confinement effectiveness factor;
- \( \omega_{n} \) represents the mechanical volumetric ratio of confining reinforcement.

It is stated that when only four longitudinal rebars are used in the jacket, one in each corner, the concrete of the jacket can be considered as unconfined, since in these cases the stirrups will not have a significant influence in the increase of the concrete jacket's compressive strength [8].

It should be considered jackets with less thicknesses, by using high-strength concretes (HSC), with a compressive strength greater than the concrete of the original column. Thereby, it will reduce not only the concern with the surface treatment of the original column but also the cost of the strengthened operation [27,35,44]. A smaller thickness will also lead to a less significant change in the structure mass and, therefore, the dynamic behavior of the structure will not be affected [31]. However, the jacket's thickness must be adequate for placing the longitudinal and transverse reinforcement of the jacket with the correct cover, and a minimum thickness of 50 mm should be adopted [18].

It should be noted that for an undamaged column with a bending moment/shear force ratio (M/V) equal or greater than 1.5, and a total jacket with a thickness less than 30% of the original column width (\( \delta/l \leq 0,30 \)), a monolithic behavior can be obtained without increasing the roughness of the surface and/or applying steel connectors [34].

If it is needed to increase the surface roughness and/or apply steel connectors, then the shear resistance at the interface must be evaluated using the following equation, presented in section 6.2.5 of EC2 [12]. This resistance must be compared with the shear stress in the interface in order to guarantee a monolithic behavior of the strengthened column.

\[
v_{rdi} = c f_{ctd} + m \sigma_n + \rho f_{yd}(\mu \sin \alpha + \cos \alpha) \leq 0,5v f_{cd}
\]

Where:
- \( v_{rdi} \): represents the design shear resistance at the interface;
- \( c \): represents the coefficient of adhesion;
- \( f_{ctd} \): represents the value of the design tensile strength of concrete;
- \( \mu \): represents the coefficient of friction;
- \( \sigma_n \): represents the stress per unit area caused by the minimum external normal force across the interface;
- \( \rho \): represents the reinforcement ratio for the steel connectors;
- \( f_{yd} \): represents the design yield strength of reinforcement;
- \( \alpha \): represents the angle between the steel connectors and the surface and should be limited so that 45° ≤ \( \alpha \) ≤ 90°;
- \( v \): represents a strength reduction factor;
- \( f_{cd} \): represents the design value of concrete compressive strength.

Once all the characteristics of the materials have been defined, the resistance of the RC columns jacketed with RC must be calculated, as if it was a monolithic section. Finally, the monolithic coefficients provided in the section A.4.2.2 of EC8-3 [14] should be applied:

- \( K_{\psi} \): monolithic coefficient for shear strength;
- \( K_{My} \): monolithic coefficient for yield moment;
- \( K_{\delta,\theta} \): monolithic coefficient for deflection/rotation angle at failure;
- \( K_{\delta,\mu} \): monolithic coefficient for deflection/rotation at yielding.

In Table 1, other monolithic coefficients are presented. These coefficients are more realistic.
than those proposed by EC8-3 [14], since there are coefficients for different jacket's thickness and for two types of jackets, in particular, total jacketing and partial jacketing of 3 sides [35]. These coefficients are valid for a surface with both friction and adhesion coefficients equal to or greater than 1 and 0, respectively.

Table 1 – Proposed monolithic coefficients by Lampropoulos et al. [36].

<table>
<thead>
<tr>
<th>Jacket's type</th>
<th>(\delta/l)</th>
<th>Monolithic coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K_F)</td>
<td>(K_k)</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Where:
- \(K_F\) represents the monolithic coefficient of strength;
- \(K_k\) represents the monolithic coefficient of stiffness;

A more detailed design can be obtained by using numerical models that simulate the behavior of the interface between the old concrete and the added one. This method is more complex and involves greater computational effort, since the load transfer mechanisms in the surface are difficult to analyze and they must be quantified with precision in order to achieve a correct behavior of the strengthened column.

If the column is designed to resist a seismic load, then the reduction of both adhesion and friction coefficients of the interface must be taken into account. From a practical point of view, a lower coefficient of friction and adhesion can be adopted from the beginning, avoiding the consideration of the interface degradation [33]. The coefficients of friction and adhesion can be estimated, in a preliminary way, through section 6.2.5 (2) of EC2-3 [12]. Later on, the adoption of these coefficients must be checked with the 2D Laser Roughness Analyzer Method (2D LRAM) referred in section 2.7.

In the development of this numerical method, the second order effects, related to longitudinal reinforcement buckling, can be neglected when the relation between the stirrups spacing and the diameter of the longitudinal reinforcement is smaller than 4,5 [8]. The stresses/strains present in the original column should be considered, in order to obtain a more accurate model.

Two other important parameters that must be considered in the numerical model are the differential shrinkage and differential stiffness due to differences both in the age and strength capacity of the original concrete and the jacket concrete [32,33,44]. In case of bridge columns it may be also important to consider the effect of temperature variations.

The design can also be made with simplified models, in which it is not necessary to take into consideration the roughness of the surface. Unlike the monolithic coefficients, these methodologies give the response of the reinforced column when it is subjected to a monotonic loading [8,36,37].

2.5 Detailing

The detailing of the longitudinal and transverse reinforcement is very important to ensure a good performance of the strengthened column. There are several reinforcement detailing prescriptions, depending on the jacket’s type (Fig. 4).

If it is a total jacket, the detailing must be similar to the presented in Fig. 4a), using steel connectors only if needed. If the jacket is partial, there are many ways to detail this type of jacketing, presented in Fig. 4b-f): (i) jacket stirrup welded to a steel bar placed externally to the column (Fig. 4b); (ii) jacket stirrup embedded within the original column through a hole (Fig. 4c); (iii) jacket stirrup placed in a hole in the original column (Fig. 4d); (iv) jacket stirrup connected by welding to angle joints joined through a steel bar (Fig. 4e) and (v) jacket stirrup connected by welding to angle joints fixed at the two ends of the original column by means of metal wall plugs (Fig. 4f).

![Fig. 4 – Reinforcement arrangement depending the jacket’s type (total or partial) [18].](image-url)
There are several rules presented in the section 9.5 of EC2-1 [12] that must be followed, related to diameters and spacing of longitudinal and transverse reinforcement. The most relevant are the following:

\[ \varnothing_{\text{min}} = 8 \text{ mm}; \]  
\[ A_{x,\text{min}} = \max \left[ \frac{0.10 N_{\text{ed}}}{f_{yd}}; 0.002 A_{c} \right] \]  
\[ A_{x,\text{max}} = 0.04 A_{c}, \text{ outside the overlap splice zones} \]  
\[ A_{x,\text{max}} = 0.08 A_{c}, \text{ in the overlap splice zones} \]  
\[ s_{cl,\text{max}} = \min \left[ \frac{20 \times \text{the small diameter of the reinforcement}}{\text{smallest column width}} \times \frac{400 \text{ mm}}{} \right] \]  

- in a circular section the number of longitudinal rebars must be greater than four and in a polygonal section at least one rebar must be placed at each angle;  
- the stirrups’ diameter must be greater than 6 mm or 1/4 of the maximum diameter of the longitudinal rebar;

where:
\[ \varnothing_{\text{min}} \] represents the minimal diameter of the longitudinal reinforcement;  
\[ A_{x,\text{min}} \] represents the total area of minimum longitudinal reinforcement;  
\[ N_{\text{ed}} \] represents the design value of the compressive axial load;  
\[ A_{c} \] represents the concrete area;  
\[ A_{x,\text{max}} \] represents the total area of maximum longitudinal reinforcement;  
\[ s_{cl,\text{max}} \] represents the maximum space between the stirrups.

There are also other rules that must be considered if the columns are primary elements of resistance to seismic action. These are presented in sections 5.4 and 5.5 of EC8-1 [13].

With regard to longitudinal reinforcement, several authors also recommend:  
- use of rebars with larger diameter but in less quantity to avoid damaging the concrete when the slab is drilled [30];  
- use of at least four rebars, one at each corner, with a minimum diameter of 12 mm [17,19];  
- longitudinal reinforcement ideally distributed along the perimeter of the column. However, if it’s necessary to increase the flexure resistance and longitudinal rebars can’t be distributed along the column’s perimeter due to the presence of beam reinforcement, the longitudinal reinforcement of the jacket can be grouped in the corners without any disadvantage as long as codes’ requirements are satisfied [2-4,41].

Regarding the jacket’s stirrups, some authors also recommend:  
- a diameter equal or greater than 8 mm and 1/3 of the longitudinal reinforcement diameter [39];  
- 200 mm of maximum stirrup’s spacing and, near the beam-column connections, spacing must not exceed 100 mm [19,39];  
- jacket’s stirrups should have half spacing or less of the original column’s stirrups and should be placed out of phase in relation to these [17];  
- the ties’ ends of the stirrups must have a length greater than 100 mm and an angle equal or greater than 135° [19,30];  
- if it is not possible to bend the ties’ ends to form an angle of 135° as referred in the EC2-1 [12] they can be welded with a welding length of 50 mm [50].

2.6 Jacketing procedure

2.6.1 Surface preparation

After the design and detailing of the jacketed column, a correct execution of this method is very important to guarantee a good behavior of the strengthened column.

If it is necessary to increase the surface roughness of the original column, several techniques can be adopted, namely the sand blast (Fig. 5), a water demolition technique or other techniques that creates a similar roughness [24,39]. It is recommended to use one of these techniques for:  
- columns with \( \delta / l > 0.30 \);  
- columns with a M/V relation greater than 1,5 and/or  
- damaged columns. If it’s not possible to use these techniques, or when it’s only necessary to increase slightly the surface roughness, it is recommended to use a steel brush, although this technique causes a lower surface resistance [24,30]. No demolition equipment that can have a major impact on the structure should be used (e.g. a jack hammer), once it causes micro-cracking of the substrate, leading to a decrease in strength of the strengthened column [1].

Later, the surface must be cleaned using a water blast or compressed air in order to remove all the dust and thus allowing a better adhesion to the new concrete [18].

Concerning the use of bonding agents to increase the interface resistance, they should not be used if the surface is prepared with a sand blast, a water demolition technique or another technique that creates a similar roughness, once it will lead to a lower resistance of the strengthened column [10,26,30]. If the surface has no roughness at all, it is recommended to create it rather than using bonding agents in order to improve the behavior of the strengthened column.
2.6.2 Addition of steel connectors

Adding steel connectors can be very important in some situations, namely: (i) damaged columns; (ii) columns with a partial jacket and (iii) short columns. The use of steel connectors in this situations improves the behavior of the strengthened column, approaching them to a monolithic one [25, 28]. It is pointed that the connectors don’t significantly influence the load at which interface slip occurs but will increase slip resistance.

There are several types of steel connectors used in current practice. It is recommended to use Hilti connectors and chemical anchorages suitable for cracked and uncracked concrete, such as Hilti HCC-B with the chemical anchor HIT-RE 500 [20]. It should be noted that these connectors are usually used to strengthening concrete overlays. The connectors must be placed perpendicular to the column’s surface (Fig. 6) and sealed with a chemical anchorage.

2.6.3 Column damages

If there are any physical damages in the original column, for example induced by a seismic load like an earthquake, the column must be treated first. This operation may be more or less difficult depending on the degradation state of the column:

1) if the column is heavily damaged, all the deteriorated concrete has to be removed and the reinforcement should be left exposed to ensure a better connection between the old concrete and the added one (Fig. 7a);

2) if the column doesn’t present a significant degradation, i.e. if only the concrete cover is damaged, only the concrete cover layer should be removed, exposing some of the reinforcement of the original column (Fig. 7b).

After that, all the column’s reinforcement that is deteriorated must be repaired, the surface must be treated using a sand blast, a water demolition technique or another technique that creates similar roughness and then it should be cleaned using a water blast to remove all the existent dust. If the column doesn’t present a significant degradation (second case) steel connectors must be applied to improve the behavior of the strengthened column [6, 41].

2.6.4 Corrosion of steel rebars

The steel rebars corrosion of the original column is particularly important in structures subjected to aggressive environments, namely coastal areas, due to the presence of marine salts. In these situations, the following procedures must be followed [46]:

1) removal of all the contaminated and damaged concrete;

2) cleaning of corroded reinforcement using a sand blast;

3) application of a cementitious anti-corrosive coating if the reinforcement is composed by plain rebars.

If the reinforcement is composed by ribbed rebars it’s not necessary to apply any anti-corrosive coating [21]. In this cases, it’s only recommended to clean these rebars using a sand blast.

For RC columns with a degree of corrosion of the reinforcement up to 10%, if the surface of the

Fig. 5 - Increase of surface roughness using a sand blast [22].

Fig. 6 - Connector’s scheme.

Fig. 7 – Surface preparation types. Adapted from Gomes e Appleton [18].
original column was treated with a sand blast or any other technique that creates similar roughness, the strengthened column has a $\delta/l$ ratio smaller than 0.30, and the jacket is used to increase only the axial strength of the column, then it's not necessary to clean the corroded rebars in order to obtain a monolithic behavior of the strengthened column [51].

2.6.5 Added reinforcement

After repairing the original column (if necessary) and the surface preparation, the jacket's reinforcement, including the stirrups and the longitudinal rebars, are placed. Regarding this step in the jacket's execution, the following important details must be taken into account:

- during the execution of the drills in the slab for placing the jacket's longitudinal reinforcement, the holes should be made according to the arrangement showed in Fig. 8. The longitudinal rebar must be centered in the hole with a distance ($d_{min}$) between the rebar's face and the edge of the hole larger than the rebar diameter and greater than 10 mm [12], to ensure a good connection between the longitudinal reinforcement and the jacket's concrete [3,4];
- the overlapping of the longitudinal reinforcement of the jacket must be made at half of the floor level [30];
- when anchoring the jacket's reinforcement to the foundation, the following procedures must be followed [23]:
  1. drilling the holes with dimension and depth adopted according to the manufacture's chemical anchorage specification;
  2. careful cleaning of the holes (to prevent slipping of the reinforcement), using a vacuum cleaner or a water blast. In the latter the holes must be completely dry before the application of the chemical anchorage;
  3. placing and anchorage of the longitudinal reinforcement according to the manufacture.

![Fig. 8 – Scheme of a hole in the slab for placing the longitudinal reinforcement.](image1)

2.6.6 Added concrete

After placing the jacket's reinforcement, the jacket's concrete is placed.

In order to increase the adhesion between the original concrete and the new one it is recommended that the surface of the original concrete is dried but the concrete substrate is saturated [5,15].

In general, due to the reduced thickness of the jacket and the existence of longitudinal reinforcement and stirrups, it's difficult to guarantee a proper vibration of the added concrete. For this reason, it's recommended the use of a self-compacting concrete (SCC) avoiding concrete segregation [23,27,30]. When using SCC, special care must be taken regarding the formwork, since its water tightness must be ensured. Also, this concrete, being a HSC, has often silica fume additions in its composition. For this reason they are also high-durability concretes (HDC) and therefore called high-performance concretes (HPC). The use of HSC (Fig. 9) allows a higher capacity to be obtained for a lower thickness but will lead to a smaller ductility when compared to the one associated to normal concrete [8].

It must be used a non-shrinkage concrete since the concrete of the original column is much older than the new one and therefor it can introduce stresses in the interface due to differential shrinkage. This issue is more important for rectangular columns and for columns with higher jacket thickness [32,33].

It can also be used shotcrete with similar characteristics than the referred HPC, with the disadvantage of requiring specialized workmanship and therefore increasing the method’s cost [48]. Depending on each structure's particularities it is up to the designer to decide which solution is most appropriated to the strengthened column.

![Fig. 9 – Adding the jacket's concrete [23].](image2)

If it’s necessary to ensure the jacket’s continuity along the building's height, holes must be executed in the slab to place the jacket's longitudinal reinforcement (as referred in the chapter 2.6.5) and the concrete must be placed through these holes to guarantee a good involvement of the reinforcement by the added concrete.

The type of concrete to be used, including the mixing composure, fresh and hardened requirements as well as specification of the concrete process including moisture requirements,
must be specified in order to ensure a good performance of the strengthened column [29].

After adding the jacket’s concrete, a controlled cure must be followed, through successive wetting cycles in order to achieve a greater interface resistance and consequently a better behavior of the strengthened column [44].

2.7 Quality control and monitoring

The quality control in a structure retrofit operation is very important, once it allows the assessment of the performance of the adopted solution. Different parameters must be checked, including:

- characteristics of the concrete jacket in the fresh and hardened states;
- surface roughness;
- steel connectors anchorage (if used);
- interface resistance.

If it is important to monitor the behavior of the strengthened column, strain gauges must be applied.

The characterization of the added concrete must be performed by using standard tests such as the spreading test (Fig. 10a)). The surface roughness can be measured indirectly using the 2D LRAM, correlating the following parameters: (i) maximum peak-to-valley height ($R_{\text{max}}$); (ii) total roughness height ($R_t$) and (iii) maximum valley depth ($R_v$) with the friction and cohesion coefficients [42,31]. If a numerical model has been made, the roughness measured by the LRAM must be compared with the one used in the model in order to validate it. The interface resistance can be evaluated by using pull-off tests (Fig. 10b)) and then correlated with the slant shear strength [24]. Finally the connectors’ anchorage can be evaluated using pull-out tests before adding the new concrete (Fig. 10c)).

3 Conclusions and further developments

3.1 Conclusions

This paper presents some design recommendations to support the design and execution of the strengthening of RC columns by RC jacket. These recommendations were created by gathering and processing as much information as possible about this method. The following main conclusions may be drawn from those studies and the project recommendations:

- The interface surface preparation is an important factor to guarantee a good connection between the original column and the jacket and, consequently, a monolithic behavior of the strengthened column. If it is necessary, the surface should be prepared using a sandblast or a water demolition technique. If it is not necessary to create such a rough surface, an iron brush can be used, even if this technique presents worse results when compared to the techniques previously mentioned;
- No demolition equipment should be used which would have a major impact on the structure (e.g. a jack hammer), once it causes micro-cracking of the substrate leading to a decrease of the strength of the strengthened column;
- For an undamaged column with a bending moment/shear force ratio equal or greater than 1,5, with a total jacket with a thickness less than 30% of the original column width, a monolithic behavior can be obtained without increasing the roughness of the surface and/or applying steel connectors. This result allows both cost and time reduction in the strengthening method;
- If the surface is prepared with a sand blast or a water demolition technique, or other technique that produces similar roughness, bonding agents should not be used to increase the adhesion of the substrate and consequently the interface resistance;
• For RC columns strengthened with partial jacket, short columns and/or damaged columns, it’s crucial to apply steel connectors together with a surface preparation with sand blast or a water demolition technique, to improve the behavior of the strengthened column;

• Before placing the concrete jacket, the substrate must be saturated and the surface must be dry to get a better interface resistance;

• It is important to use high strength concrete (HSC) in the jacket, with a resistance greater than the original concrete to increase the interface resistance and, consequently, the resistance of the strengthened column;

• It should be used a non-shrinkage concrete to reduce the shrink effects and a self-compacting concrete (SCC) due to the lower thicknesses;

• Successive wetting cycles should be applied during the concrete cure to improve the behavior of the strengthened column and minimize the negative effects of the concrete shrinkage. Shrinkage can significantly affect the strength of the strengthened column in case of greater jacket’s thickness and if the concrete jacket doesn’t have a shrinkage reduction in its composition;

• Pre-installed loading with a reduced axial force (ν ≤ 0,7) doesn’t affect significantly the strength of the strengthened column, although it affects its stiffness. For this values this effect can be ignored and it’s not necessary to use a temporary shoring;

• The effect of the reinforcement’s corrosion can be ignored in case that the reinforcement of the original column is made by ribbed rebars. However, if the rebars are plain then, a cementitious anti-corrosive coating must be adopted in order to improve the adhesion between the steel and concrete;

• The use of longitudinal reinforcement bundle, generally in the jacket corners to avoid drilling beams, has no significant influence on the behavior of the strengthened column;

• The number of holes to be drilled in the slab for placing the longitudinal reinforcement must be minimized, i.e. it is recommended to use longitudinal reinforcement with a larger diameter but in less quantity to avoid damaging the existing concrete;

• The jacket’s stirrups must be placed offset from the stirrups of the original column and with a space equal to half of them, in order to obtain a better behavior of the strengthened column;

• The surface roughness of the original column must be evaluated with a quantitative method (e.g. 2D LRAM) and the parameters $R_{\text{max}}$, $R_y$ and $R_v$ should be used to predict, by a linear correlation, the friction and adhesion coefficients;

• There is a linear correlation between the slant shear tests and the pull-off tests, and for this reason, the evaluation of the shear strength of the interface can be measured indirectly through pull-off tests, in situ;

• If a numerical model is used to predict the behavior of RC columns strengthened with RC jacket, then the degradation of the interface strength, namely the coefficients of adhesion and friction, should be considered due to the cyclic loading. In practice, it is equivalent to replace the interface degradation by the estimation of a coefficient of friction and adhesion lower than the one actually existing;

• Since only four longitudinal rebars are often used in the jacket, the concrete jacket can be considered as unconfined;

• For a relation between the stirrups’ spacing and the diameter of the longitudinal reinforcement lower than 4,5, the second order effects related with the buckling of the longitudinal rebars can be neglected.

3.2 Further developments

Since this retrofit technique is an up growing method in structural retrofit, some suggestions for future developments are presented in order to continue the present work.

It’s proposed the execution of experimental models of corroded RC columns subjected to a cyclic loading in order to understand the relevance of the corrosion of the original RC column’s reinforcement. It’s suggested that several experimental models with different $\delta/l$ ratios and different surface roughness’s are conducted to understand the effect of corrosion with the variation of these parameters.

It’s also advisable to carry numerical models to study the influence of the ‘I’ shape connectors for short RC columns and with partial jacket (two and three sides) since there aren’t documents about this subject.

It’s proposed to carry experimental models to understand the effects of fire on the behavior and strength of RC columns strengthened with RC jacket, since there aren’t works that evaluate the influence of this action.

Finally, EC8-3 [14] improvements are proposed relatively to the strengthening of RC columns with RC jacket, since this code doesn’t provide any indications regarding the surface preparation of the original column, the use of steel connectors and the added concrete strength, these being important parameters for the correct execution of this method.

References


