Review on Strengthening Reinforced Concrete Columns Using Reinforced Concrete Jackets

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Abstract. This paper highlights the review of the effects of concrete surface treatment and loading on the structural behavior of reinforced concrete (RC) columns retrofitted with RC jackets. The concrete surface treatment aspect is assessed based on the surface roughness, use of dowel bars, use of shear connectors, and applying bonding agent between the column core and the jacket. However, the loading aspect is evaluated based on preloading history and the applied loading pattern. The latest researches and recommendations for concrete jacketing are presented. It is found that sand-blasting with the use of dowel bars or shear connectors helps the retrofitted column to behave monolithically. Preloading does not have a significant effect on the retrofitted column. However, it is recommended to apply the load on the full retrofitted cross-section.

1. Introduction

In buildings, columns are the vital structural elements that transfer the load of the upper floors to the ground or foundations. In general, columns can sustain two main kinds of loads, the axial–flexural load and the lateral shear load. Columns have a high axial load capacity compared to their lateral load capacity. Buildings and columns are designed to withstand internal and lateral loads such as an earthquake. In some cases, where buildings are designed as per the old seismic requirements, columns are more vulnerable and weak. Under lateral loads, weak columns can exhibit severe damages or collapse and fail drastically. In other cases, columns are deteriorated due to environmental effects, aging of concrete, or adding new floors. In all cases, weak or damaged columns require structural intervention to retrofit and strengthen the affected columns. The removal or replacement of the damaged columns can be costly and unpractical as the structural integrity is altered. There are several jacketing techniques used to strengthen and repair the reinforced concrete (RC) columns before or after being damaged such as concrete jackets, steel jackets, and fiber reinforced polymer (FRP) jackets. Each technique has its advantages and limitations.

In this paper, reinforced concrete jacketing intervention is evaluated. RC jacketing is considered as a highly valuable retrofitting technique in terms of cost and efficiency [1]. The RC column retrofitting is a common research field in seismic studies. It is mainly because the induced seismic energy stress in a building frame structure is dissipated by the displacement of the columns resulting in minor to serious damages based on the magnitude of the earthquake. Therefore, the necessity for repairing arises to ensure the facility's smooth post-earthquake recovery. The concrete jacketing method works as an active or passive measure since it is used to strengthen the column before or after being damaged. It depends on increasing the original column cross-section by adding a new confining layer of
unreinforced or reinforced concrete with longitudinal and transversal reinforcement as shown in Figure 1. Moreover, the RC jacket can be a local or global jacket based on its height. The global jacket confines the full height of the column while the local jacket is applied for a partial column height commonly for the quarter, one third, half, two thirds, or three-quarters of the column’s full height.

The first step for RC jacket retrofitting starts with preparing the concrete interface surface. This can be achieved by several methods such as hand-chiseling, electrical scarifying, or sandblasting. Besides, dowel bars or bent down bars (shear connectors) can be connected in the contact surface to facilitate the load transfer mechanism between the original concrete core and the new concrete layer. Moreover, the bonding agent can be applied between the two concrete layers for enhancing the interface bond strength.

In the second step, the additional longitudinal and transversal reinforcement are installed. The last step consists of casting the jacket with the respective concrete thickness, grade, and type. Due to the high cost and the need for specialist workmanship in non-shrinkage grout or shotcrete application, the conventional concrete jacket is commonly practiced especially for the case of thick jackets.

The objective of this paper is to review concrete jacketing considering two main aspects: concrete surface treatment and loading. The previous experimental researches and studies are evaluated to provide engineers with valuable recommendations on this kind of structural interventions.

2. Interface Surface Treatment

The shear transfer mechanism at the contact area between the original core and the added jacket depends mainly on three factors. The first factor is concrete-to-concrete cohesion. It depends on the kind of interface preparation either smooth or rough contact surface which defines interface cohesion stress. The surface preparation could be carried out by several tools such as mechanical scarifying, chipping, electric hammering, and sandblasting. Cohesion strength depends on the tensile strength of the weakest concrete (column or jacket) of the interface area. The second factor in the shear transfer mechanism is the friction caused by the aggregate interlock. It depends on the friction coefficient between the two concrete surfaces as it depends on the normal stress at the interface. The friction coefficient depends on the smooth or rough interaction surface. However, the normal interface stress depends on the clumping action of the stirrups. The clumping action is activated when the concrete expands transversally under loading known as Poisson’s effect. The third factor is the dowel action at the interface surface. They are steel bars connecting the jacket and the column concrete contact areas. They depend on the angle they form with the concrete (vertical or inclined) as well as their yield and...
tensile stress. Recently, shear connectors formed by welding the corner bars of the column and the jacket using bent down bars have been used instead of dowels [3].

2.1. Increasing Surface Roughness

In the research of Julio et al. (2004) [4], several surface preparation techniques were applied on concrete cubes and prisms to investigate their effect on the bond strength between the two concrete layers. Sand-blasting, chipping, pre-wetting the surface before roughening was applied for the contact surface. In the next stage, specimens were subjected to a pull-off test and slant shear test to measure the bond strength in tension and shear respectively. It is stated that pre-wetting the surface before treatment was insignificant. However, sand-blasting the substrate surface showed the largest bond strength values under both tension and shear tests. In the study of Vandoros and Dritsos (2006b) [5], the jacketed columns tested under cyclic load showed that the mechanical roughening of the concrete surface produced higher strength than using the dowel bars. In the research of Elbakry and Tarabia (2016) [6], the direct shear test revealed that hand-chiseling roughening of the concrete surface provides a bond strength 3.19 times greater than grinding the interface surface.

2.2. Dowel Bars and Shear Connectors

Vandoros and Dritsos (2006b) [5] investigated the effectiveness of the interface treatment on columns strengthened with reinforced shotcrete jackets. The interface treatment constituted of roughening the surface by a mechanical scrabble, embedding steel dowels (Figure 2), and a combination of the two mentioned techniques. Specimens were tested under cyclic load. The columns were a half-height full scale of ground floor designed as per the old Greek Code. Interface treatment techniques were proved to affect the failure mechanism and crack patterns. Regardless of the surface treatment technique, all the strengthened specimens acquired a larger lateral strength, stiffness, and energy dissipation than the original column. Even though the retrofitted specimens had slightly lower strength and stiffness than the monolithic one, they had higher energy dissipation and drift ratios through all loading stages. The superiority of energy dissipation in the strengthened specimens is due to the additional friction at the interface resulting from surface preparation. The specimen treated with both surface roughening and dowel bars produced the best retrofitting outcomes as it behaved similarly to the monolithic specimen through all loading history.

In the study and Vandoros and Dritsos (2008) [7], it is reported that the energy dissipation of the specimen with bent down bars (welded between the longitudinal reinforcement of the column and the jacket and known as shear connectors, Figure 3) exceeded that of the monolithic specimen. Moreover, using dowel bars and welding the jacket stirrup ends resulted in the nearest behavior to the monolithic specimen.

In a similar study, Achillopoulou et al. (2013a) [8] tested the dowel bars and shear connectors under axial load test to determine their effect on the shear transfer mechanism. Results revealed that the welded bars (shear connectors) accounted for the maximum load capacity of the retrofitted specimen. However, when the diameter of the welded bar was greater than the diameter of the longitudinal reinforcement of the column and jacket, early buckling phenomena occurred. Consequently, for larger welded bar diameter the axial load capacity and stiffness of the strengthened column decreased. On the other hand, the use of dowel bars at the interface surface resulted in plastic regions around the dowel bars. Even though the plastic region is formed but the load strength increased, Achillopoulou et al. [3] reported that when the dowel bar diameter increases, the maximum axial load capacity increases, and the slip between the column and jacket decreases significantly. Whilst the use of dowel bars at the interface surface had a great effect on the slip resistance, its effect on the load capacity is minimal. Even though shear connectors increased the initial stiffness of the retrofitted columns tested under axial load, the secant stiffness is reduced due to buckling of longitudinal bars [9].

In a recent study, Tayeh et al. (2019) [10] reported that using dowel bars at the concrete surface produced the highest axial load capacity compared to preparing the surface with mechanical wire brushing or mechanical scarification. In a different study, Murugan and Sengupta (2020) [11]
investigated surface roughening, surface roughening with dowel bars, and surface roughening with shear connectors on RC rectangular column with full RC jacket. The three different interfaces showed a similar lateral strength capacity under both monotonic and cyclic tests. However, specimens with shear connectors showed the highest stiffness under both monotonic and cyclic loadings. According to Julio et al. (2005) [12] and Julio and Branco (2008) [13], for columns with jacket thickness less than 17.5% the column thickness, the jacketed columns can attain monolithic behavior without surface treatment when self-consolidating grout is used under monotonic and cyclic tests. The use of dowel bars between the old and new concrete increased the bond strength of the RC jacketed specimen by 4.61 times under the direct shear test [6]. Bousias et al. (2007a) [2] reported that the absence of surface preparation or connections between the column core and the jacket results in interface slippage without affecting the lateral load capacity, energy dissipation, or deformation of the jacketed column.

![Figure 2. Dowel bars anchored to the original column](image1)

![Figure 3. Bent down steel connectors](image2)

2.3. Bonding Agents
According to Julio et al. (2003) [15], the bonding agent did not show a significant effect on the bond strength between the column core and jacket. The interface tension and shear capacities were reduced
when the bonding agent was applied on a sand-blasted surface. The use of a bonding agent between the column and jacket is insignificant [6, 16]. The adhesion of the bonding agent with the jacket concrete was weaker than its adhesion with the original concrete substrate.

3. Loading History and Patterns
The loading effect in the case of RC jacketed columns depends on two main factors. The first factor is based on the service loads carried by the column during retrofitting. Full preloading is the actual state since RC columns are usually retrofitted while they are under service loads. However during retrofitting, columns can be fully preloaded, partially preloaded, or unloaded based on the adopted shoring system. Even in the unloaded case, the column will still bear its self-weight. The second factor is the loading pattern whether the load is applied on the original column cross-section only or the entire retrofitted cross-section. When the load is applied at the column core, the load is resisted initially by the column before being transferred to the jacket section through the confinement mechanism activation. This case applies to the partially jacketed column or a total jacketed column after concrete shrinkage. However, for a full-height jacket, if special non-shrinking concrete is used, the axial load is transferred immediately to the entire retrofitted cross-section.

3.1. Loading History
Ersoy et al. (1993) [17] reported that even though unloading the column before jacketing is recommended, the jacketed preloaded column behaved similarly to the unloaded jacketed column. Moreover, the cyclic or monotonic load pattern had a minor effect on strength capacity. On the other hand, the load pattern was more influential on the stiffness since the columns under monotonic load attained 40 % higher stiffness than the columns under cyclic load. Preloading damage before jacketing does not have a significant impact on the retrofitted column [18]. For damaged columns subjected to cyclic post-peak load before jacketing, the jacket effectiveness did not have a significant difference compared to the non-damaged jacketed specimen [2]. According to Vandoros and Dritsos (2006a) [19], preloading the column before jacketing reduces the jacket compressive stresses and therefore increases the dissipated energy. Even though preloading reduced the initial stiffness, it maintains the stiffness during loading.

In the research of Takeuti et al. (2008) [20], square and circular columns were axially preloaded between 44 % and 87 % of their ultimate capacity. After jacketing, the ratio of the maximum axial load capacity of the preloaded to non-preloaded columns was between 0.98 and 1.08. Therefore, preloading did not have a remarkable impact on the load capacity of the jacketed column. For non-preloaded columns, the reinforcement stress in the jacket and the core column were similar before the peak load. On the other hand, for both square and circular sections, the preloaded columns had an apparent difference in the reinforcement stress of the column core and the jacket. This is contributed to the preloading large stresses developed in the original column before jacketing. Consequently, the preloaded columns exhibited larger ductility than the non-preloaded columns. Sengottian and Jagadeesan (2013) [21] had the same findings for the ductility increase as the preloading level before jacketing increases. Julio et al. (2005) [12] and Julio and Branco (2008) [13] stated that preloading the columns before jacketing did not influence the lateral load capacity of the retrofitted columns under monotonic and cyclic loadings.

Mourad and Shannag (2012) [22] preloaded the columns to various percentages of their ultimate load before jacketing with ferrocement jacket. For the column preloaded up to 100 % of its failure load, the ferrocement jacket restored its capacity and stiffness to the values of the original non-strengthened column. For original columns with no preloading, the ferrocement jacket increased the axial load carrying capacity and stiffness by 33 % and 26 % respectively. Furthermore, the ferrocement jacket changed the failure from a brittle manner in the original non-preloaded column to a ductile failure in the preloaded jacketed column. Similar findings were reported by Tarkhan (2015) [23] on columns preloaded and jacketed with ferrocement jackets. As the preloading ratio increased from 50 % to 75 %
of the ultimate load, the columns exhibited a lower load-carrying capacity and energy absorption while their ductility increased.

In the research demonstrated by Achillopoulou et al. (2013a) [8], the RC square columns were fully retrofitted with RC jackets and the effect of preloading on the axial capacity of the retrofitted specimens was observed. Preloading the columns to their maximum bearing load before jacketing did not influence the maximum bearing load and deformation capacities of the retrofitted columns. Preloaded and non-preloaded columns had almost the same peak load and deformation. However, after the peak load, the preloaded specimens had a 15% lower load capacity at the same deformation of the retrofitted non-preloaded specimen. In the post-peak behavior, preloading increased the strength degradation and consequently reduced the ductility of the columns. When the column was preloaded to its maximum bearing load it was capable to behave monolithically after being jacketed even if no repair was applied before jacketing [3].

Krainskyi et al. (2015) [24] studied rectangular columns retrofitted by rectangular RC jackets under a uniaxial compression test with a 150mm eccentricity. For the columns preloaded up to 30%, 50%, 70%, and 90% of their limit strength, the RC jacket increased the strengthened column capacity by 278%, 266%, 272%, and 243%, respectively. Therefore, it is recommended to unload the column before jacketing as it increases the confinement efficiency for the concrete jacket.

Mohamed Sayed et al. (2020) [25] studied the effects of columns cracks on the jacketing outcomes. Square, rectangular, and circular RC columns were fully jacketed withRC jackets and tested under concentric axial loads. A group of columns was subjected to axial load until the appearance of the first crack. Then, the axial load was ceased and the columns were repaired and jacketed. Compared to columns jacketed without initial cracks, columns jacketed after initial cracks showed a 15.7%, 14.1%, and 13.5% lower axial capacity for squared, rectangular, and circular columns respectively. When the initial damage level increases, the maximum load capacity of the retrofitted column is reduced [9].

3.2. Loading Patterns

In the study conducted by Sezen and Miller (2011) [26], two load patterns were investigated on circular columns jacketed with RC jackets under axial load. In the first load pattern, the axial load was applied to the column cross-section (load pattern B), while in the second load pattern column and jacket cross-sections were axially loaded (load pattern D) as shown in Figure 4. When the jacket is not applied to the entire column height, it will not bear any axial load in the vertical direction. The axial load is resisted by the original column but the jacket still can provide the transverse confinement for the original column. When the axial load was applied to the column and jacket (LPD), the axial load capacity was larger than loading the column solely (LPB).

In a different study conducted by Achillopoulou et al. (2013b) [3], the square RC columns were initially preloaded before being strengthened with full height RC jackets. The effect of the axial load pattern was analyzed through two different axial load conditions. In load pattern A (LPA), the axial load was applied directly on the top of the column (core) while at the bottom the load was supported by the jacket section solely (Figure 4). The target of LPA was to study the load transfer mechanism from the column to the jacket depending on the interface surface resistance. Due to the longitudinal concrete shrinkage during the hardening period, a small area or gap not fully jacketed is formed at the column edge. However, the concrete shrinkage in the transversal direction is assumed to be eliminated by the lateral expansion of the old concrete. On the other hand, the load pattern B (LPB) has the same top-loading condition where the axial load is applied to the column only. At the bottom, the load was supported by the full cross-section of the column and jacket. This pattern simulates the real status and function of the retrofitted column where the axial load is transferred by column and supported by both the column and the jacket. Results demonstrated that the load transfer from the column to the jacket was the same in both load patterns. Whether the jacket or the total column-jacket cross section absorbs the axial load, they had the same axial load capacity.

In similar research, Achillopoulou et al. (2014) [9] tested RC columns initially preloaded and then strengthened by a full RC jacket under two different load patterns. The maximum axial load was
greater in LPD when the full cross-section at top and bottom was loaded than for the case of LPB when the column section was loaded at the top. This is contributed to the effect of the direct loading on the jacketed area resulting in direct activation of its capacity in LPD. In the LPB case, the jacket confining mechanism is not activated until the entire distribution of the load from the column to the jacket. Therefore, its axial load capacity was smaller than the LPD case.

4. Conclusions
The review of the previous experimental studies led to the following conclusions:
(1) The sand-blasting surface roughening produces the largest concrete bond strength.
(2) The use of dowel bars or shear connectors are the most appropriate to achieve a monolithic behavior and increase the lateral load capacity. The appropriate size of shear connectors and the potential of plastic hinge formation around the dowel bars need to be considered when dowel bars or shear connectors are used.
(3) The use of a bonding agent between the column core and concrete jacket is insignificant.
(4) Even though unloading the column before jacketing is recommended, most studies agreed that preloading doesn’t have a significant effect on the retrofitted load capacity. Preloading reduces the jacket compressive stresses and therefore increases the ductility and dissipated energy.
(5) It is recommended to extend the jacket to the top and bottom faces of the column with non-shrinkage material when full jacket height is applied.

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