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Rehabilitation of Concrete Structures - A Review

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Highlights

- This paper focuses on the rehabilitation of concrete structures.
- Several design equations are included in the study.
- A review about different rehabilitation techniques is performed.

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Abstract

Concrete is considered as the most used material in the construction industry. Concrete structures need to be checked and maintained periodically in order to avoid the progression of any cracks to the concrete elements. However, there are some circumstances and problems that causes the deterioration of the concrete structure either totally or partially. In such cases, the repairing techniques, methods and materials cannot serve as a good solution to stop and solve the deterioration. The progression and initiation of damages into the concrete sections may cause a reduction in the durability and strength of the system. Rehabilitation techniques are used to stop the damages and enhance the performance of deteriorated concrete structures where they can restore their strength and durability. These damages may occur due to: the ingress of harmful ions such as chloride and sulfate, freeze and thaw cycles, fire attack, environmental and thermal changes. Several factors and measures can be taken into account while choosing the rehabilitation technique such as the environment surrounding, the section type, the properties of the section and the location of the concrete members that need rehabilitation. Several design equations based on selected standards are reported in order to calculate the properties of rehabilitated structural element. These mainly included the capacity of rehabilitated elements, shear and axial strength.

1. INTRODUCTION

In the last few decades, concrete structures become the most commonly used structures all over the whole world [1]. Concrete is considered as the most abundant material used in construction field [2]. This can be due to the excellent properties concrete has such as high strength, excellent mechanical properties, good durability properties, ability to be shaped and formed in several dimensions, size and shapes and many other properties [3]. However, due to several causes, concrete structures are facing hazardous problems related to the ingression of cracks and deterioration of the concrete elements. These cracks may be classified into several types such as active cracks, passive, also known as dead cracks, and dormant cracks where they occur due to several problems and circumstances [4,5]. They may be present due to inadequacy in design details, corrosion of steel reinforcing bars due to the environment surrounding the concrete structure, fatigue, settlements, handling and transportation problems while casting the concrete elements, chemical attacks such as sulfate attack and penetration of chloride, temperature and weathering conditions, fire attack, shrinkage, freezing and thawing, creep, and unforeseen accidents such as explosions and tsunamis [5-15]. These cracks may expand to deteriorate the concrete element where the section will lose its strength

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and durability properties. Thus, rehabilitation is required in order to restore the properties of the concrete elements that are deteriorated. There is a major difference between repair, rehabilitation and retrofitting techniques and methods [16-18]. Mainly, repair is considered as a process where the behavior of the concrete element after being repaired does not change too much from the original behavior. It is main purpose is to restore the architectural shape of the concrete structure and its function but without increasing its performance too much. Repair techniques can be classified as follows: epoxy resin injection, routing and sealing of cracks, stitching the concrete cracks, drilling and plugging, additional of reinforcement either by traditional reinforcement or by prestressing steel technique, gravity filling, dry packing, chemical grouting, surface treatments and arrays, crack arrest, autogenous crack healing [6]. However, retrofitting technique is a method used to increase the behavior and performance of the concrete structure such as increasing the flexural strength, shear, ductility, fatigue resistance, service life, tensile strength, and many others … Mainly, its purpose is to increase and upgrade the seismic resistance of existing concrete structures [16-18]. Moving on to the rehabilitation technique, it is a process where a restoration and restitution of behavior, performance and strength of concrete elements and structures is performed. Its purpose is to restore the concrete member or element to its original state after being deteriorated due to several problems [16,17]. There are several techniques for rehabilitation including steel jacketing, concrete jacketing, ferrocement jacketing, fiber reinforced polymer (FRP) jacketing, stitching, plate bonding, adding swimmers to a damaged reinforced concrete member… Regarding the need for rehabilitation, it may be needed in special cases where the design of the structure is incorrect (errors in detailing and calculations), incorrect handling and execution, environmental conditions and weathering problems, attacks due to chemical surroundings, old structures known as ageing structures, overloading process due to several causes such as changing the structure from one aspect to another, extreme stresses, and corrosion due to severe conditions surround the concrete structures [18]. Also, recently, the inclusion of supplementary cementitious materials [19-25], aggregates replacement materials [26,27] and fibers [28,29] in concrete mixes become wide. This also may affect the progression of cracks and the technique of rehabilitation that must be chosen. This paper reviews the several techniques of rehabilitation with way of performing, advantages and disadvantages, types and design equations used to calculate capacity and parameters after rehabilitation is applied.

2. REHABILITATION TECHNIQUES AND METHODS

There are several rehabilitation techniques used to increase the performance of already existing concrete structures, elements and members. These techniques are studied and explained including their types, advantages and disadvantages, steps and procedure applied.

2.1. Steel Jacketing Technique

It is a rehabilitation and strengthening method where steel plates or steel sections are added around an existing concrete section, mostly a concrete column and a beam column joint as shown in Figure 1 [30,31]. It is considered as one of the most efficient techniques that enhance the ductility of the damaged sections [32,33]. It is mainly applied in order to enhance the load carrying capacity, increase the ductility, enhance the shear strength and improve the seismic forces resistance [30,34,35]. Moreover, it is considered to be so beneficial in avoiding the local buckling [36,37]. There are several pros for steel jacketing related to economy, time consuming and efficiency [38,39] such as no additional weight is added to the structure, no curing time is needed, no increase in the cross sectional area of the section, no much time is needed, and it can be considered as costless. Despite all the advantages steel jacketing technique has, there are some disadvantages including: heavy equipment is needed to handle the steel plates or steel sections; maintenance is very difficult to be applied for steel jackets, degrade under fire and corrosive environments [38,39].

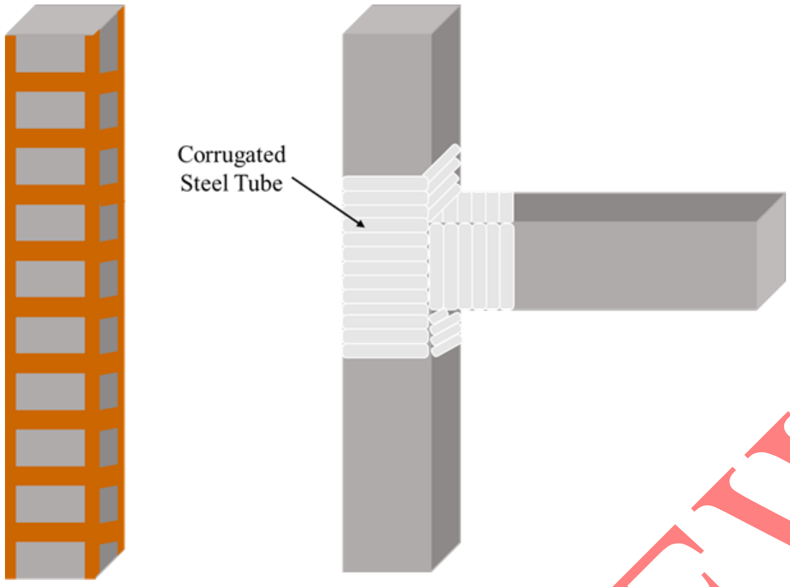

Figure 1. *Steel jacketing of concrete columns and beam column joints [30,31]*

There are several steps applied in order to perform the steel jacketing rehabilitation and strengthening technique [40-42]. First, the concrete cover must be removed totally from the section. Second, using either a wire brush or a sand compressor, the reinforcement steel bars must be cleaned very well. Third, the reinforcement steel bars shall be coated with a material in order to protect it from the prevention of corrosion. This material used can be an epoxy material. Forth, according to the design performed, the steel jackets, steel plates or sections, are installed in their required dimension, size and thickness. Fifth, small openings are performed in order to pour epoxy material inside these pores. Sixth, the epoxy material is poured in order to guarantee the bond between the concrete section and the steel jacket used. Figure 2 shows the different steps that must be applied while performing the steel jacketing method.

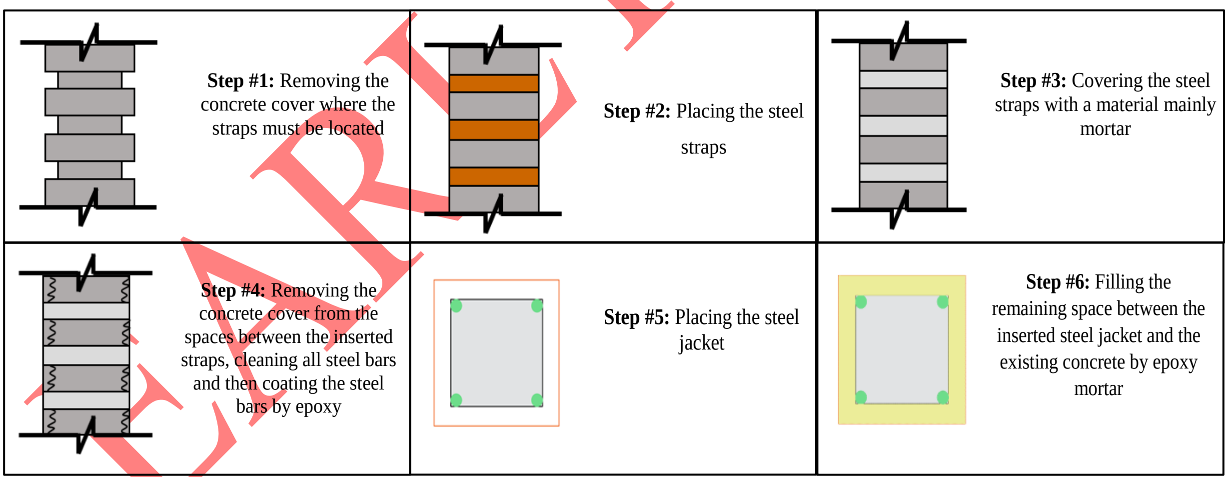

Figure 2. *Steel jacketing of concrete columns procedure [41]*

There are different options for performing steel jacketing technique [43]. The first option is to totally encase the concrete column by thin steel plates. These plates are placed at small distances from the surface of the column and the gaps are filled with non-shrinking grout. However, if no total encasement is needed, there is an alternative for the steel cage [43]. The steel angles are inserted on the corners of the already existing cross section of the column. Then, welding is applied between either transversal straps or continuous steel plates with the steel angles. Concerning the space between the existing concrete and the steel cage, it is usually filled with non-shrinking grout or mortar. Regarding areas subjected to corrosion and fire, a shotcrete or grout concrete cover shall be provided.

In some special cases where the concrete section, specifically column, needs to carry bending moment and then transfers it to the floors, a steel collar shall be installed at the neck of the concrete column either by bolts or by a specific and suitable bonding material as shown in Figure 3 [44].

Figure 3. *Steel collar at the columns [44]*

In some cases, steel jacketing can be performed in different ways depending on the section that needs rehabilitation [45]. For example, Figure 4 shows different ways for strengthening of a concrete member where metallic anchors can be used or not.

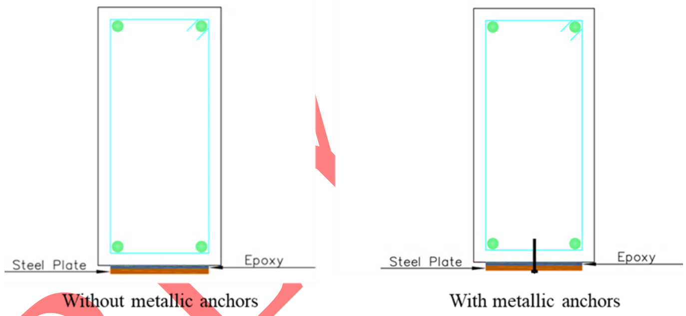

Figure 4. *Strengthening of concrete member [45]*

Regarding the steel jacketing by steel plates, a general concept was adopted by Waghmare [46]. The thickness of steel plate must be at least 6 mm, the height of jacket shall be 1.2 to 1.5 times the length of splice in flexural columns and full height in shear columns, and the space between existing concrete and steel jacketing was filled by a cementitious grout of thickness 25 mm.

However, there are some adopted equations to check the design of the new sections [47].

The axial strength design equation for an existing column is stated as follows:

$$\Phi P_{n1} = 0.75 \times \Phi \times [0.85 \times f_c' \times (A_g - A_{st}) + f_{yt} \times A_{st}]. \quad (1)$$

In Equation (1), Φ is the strength reduction factor, P_{n1} the is axial strength, f_c' is the compressive strength of concrete, A_g is the gross area of the concrete member, A_{st} is the total steel area of the longitudinal bars and f_{yt} is the yield strength of bars.

Regarding the capacity of the new column, it is calculated according to the following equations:
In case where $P_e \geq 0.44\ P_{no}$:

$$\Phi P_{n2} = \Phi P_{no} [0.658^{\frac{P_{no}}{P_e}}] \quad (2)$$

$$P_{no} = f_y \times A_s + f_{yt} \times A_{st} + 0.85 f_c' \times A_c \quad (3)$$

$$P_e = \pi^2 \frac{EI_{eff}}{L_c^{\,2}} \quad (4)$$

$$L_c = K\,L \quad (5)$$

$$EI_{eff} = E_s \times I_s + E_s \times I_{sr} + C_1 \times E_c \times I_c \quad (6)$$

$$E_c = 0.043 \times \gamma_c \times \sqrt{f_c'} \quad (7)$$

$$C_1 = 0.25 + 3 \times (\frac{A_s + A_{st}}{A_g}) \leq 0.7 . \quad (8)$$

In Equation (2), P_{no} is a variable, P_e is elastic critical buckling load. However, in Equation (3), f_y is the minimum yield strength of steel section. In Equation (4), EI_{eff} is the stiffness of composite section and L_c is the effective length of the member and in Equation (5), K is the effective length factor and L is the length of the member. In Equation (6), E_s is the modulus of elasticity of steel and E_c is the modulus of elasticity of concrete. In Equation (7), γ_c is the unit weight of concrete, I_s is the moment of inertia of the steel section, I_{sr} is the moment of inertia of steel bars, I_c is the moment of inertia of the concrete section and C_1 is the coefficient used to calculate effective rigidity of encased composite member.

Concerning the design for the rehabilitation and strengthening of a column beam joint, the following equations are adopted [31,32]:

Design of anchored bolts: $A_{vij} \times \frac{f_{yj}}{n}$ (9)

$$A_{vij} = 2 \times t_j \times d . \quad (10)$$

In Equation (9), A_{vij} is the area for the jacket resisting the shear in the joint, f_{yj} is the yield strength of steel jacket and n is the number of bolts used in steel angles. In Equation (10), t_j is the thickness of steel jacket and d is the depth of the beam.

However, the shear strength enhancement is calculated by the following rule:

$$V_{sj} = 2\, f_{yj} \times h \times t_j . \quad (11)$$

In Equation (11), h is the largest member dimension.

2.2. Concrete Jacketing Technique

Concrete jacketing is considered as a technique used to improve, increase and restore the capacity of concrete sections mainly columns and beams where it is also used to improve the load carrying capacity and the ductility of beams [36,48-51]. There are several methods to perform concrete jacketing technique [52,53]. The first method is performed by using dowel connectors and micro concrete where dowel connectors are attached to the surface of concrete as shown in Figure 5. The second method is carried out using bonding agent and micro concrete. Regarding the bonding agent, it is applied on the surface of the section using a brush. Then, the jacketing is applied. However, the third method is fulfilled by a combination between bonding agent, dowel connectors and micro concrete. The dowel connectors are placed on the surface of the beam and the bonding agent is then applied. However, the fourth method is applied using micro concrete only without the interference of bonding agents and dowel connectors. Mainly, the use of dowel connectors to connect the old concrete with the new concrete improves the bond strength and stiffness in section [54]. There are several pros and cons for the concrete jacketing technique [39,55,56]. Regarding the advantages, concrete jacketing enhances the stiffness of the structure, improves the performance of seismic, increases the shear and flexural capacities and improves the ductility. However, regarding the drawbacks, the size of concrete members rehabilitated is increased leading to an increase in the weight of the section, it is considered as time consuming technique, it needs skilled labors to be accomplished and is expensive.

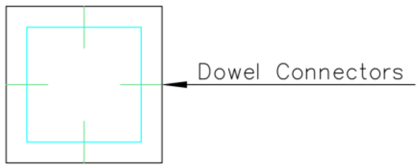

Figure 5. *Dowel connectors on the surface of a beam [52]*

There are several steps that shall be applied in order to perform the concrete jacketing technique [57,58]. First, the load on the section, for example column, must be eliminated or reduced using mechanical jacks. Second, the concrete cover must be removed and the reinforcing bars must be cleaned by a compressor or a wire brush. Third, the steel reinforcement must be coated by epoxy in order to protect and prevent corrosion. Fourth, steel connectors, also known as dowel connectors, must be added into the surface of the concrete section after digging small holes. These holes must be filled by an epoxy material. Fifth, vertical steel connectors shall be added. Sixth, an epoxy material must be used to coat the existing concrete section in order to ensure that the bond between the existing concrete and new concrete is accomplished. Finally, the new concrete shall be poured before the epoxy material used for bonding purposes dry. The concrete poured shall be with low shrinkage and aggregates used must be of small sizes with sand and cement. In some cases, an admixture is used to prevent shrinkage. Different steps are illustrated in Figure 6.

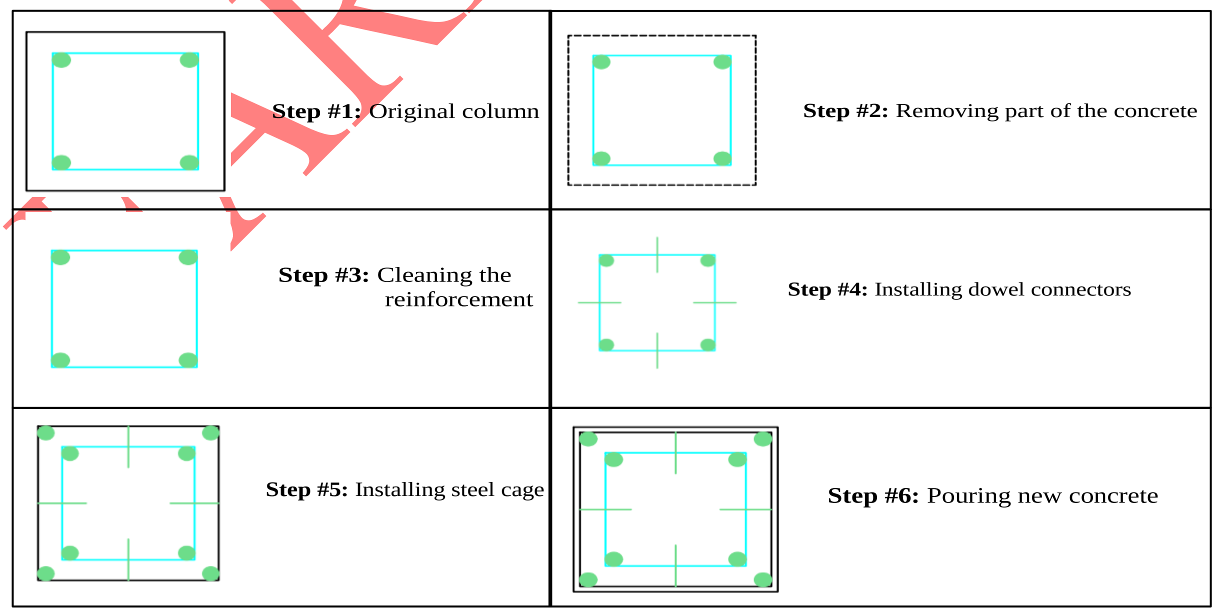

Figure 6. *Steps of concrete jacketing process [58]*

Waghmare [46] adopted a general concept for the design of concrete jacketing technique. The minimum width of the concrete jacket must be 10 cm if the concrete is cast in place and 4 cm if it is shotcrete. The ties used shall have a 135 degrees hook and the diameter of bars used must be not less than 1/3 of the diameter of already embedded longitudinal bars.

However, there are some equations used to design the concrete jacket stated as follows [59]:

$$A_g\,(\text{jacket}) = \frac{P_u}{0.6375 \times [(0.85 \times f_c') + \rho \times (f_y - 0.85 \times f_c')]}. \tag{12}$$

In Equation (12), A_g (jacket) is the jacket cross sectional area, P_u is the ultimate load on the concrete section, ρ is the steel ratio and mainly taken as 0.5% and f_y is the steel yield strength.

The gross sectional area for circular columns after being concrete jacketed is stated as follows [59]:

$$A_{gt} = \frac{\pi \times D_0^2}{4} + A_g\,(\text{jacket}). \tag{13}$$

In Equation (13), A_{gt} is the total area of the circular column after applying concrete jacketing and D_0 is the initial diameter of the already existing concrete column.

Also, Al-Afandy and Bakry [59] stated another equation that can be used to calculate the total area for the circular column after being concrete jacketed

$$A_{gt} = \frac{\pi \times (2\,t_{jacket} + D_0^2)^2}{4}. \tag{14}$$

In Equation (14), t_{jacket} is the thickness of the concrete jacket.

However, the vertical steel area reinforcement is calculated as follows [59]:

$$A_s\,(\text{jacket}) = 0.5\% \times A_g\,(\text{jacket}) = 0.005\,A_g\,(\text{jacket}) \tag{15}$$

In Equation (15), A_s (jacket) is the area of vertical steel reinforcement.

The axial loading after jacketing the concrete section can be calculated according to the following equation [60]:

$$P_j = \frac{P_i}{(A_c \times f_c) + (A_j \times f_j)}. \tag{16}$$

In Equation (16), P_j is the axial load after jacketing, P_i is the axial load existing on the old concrete section, A_c is the cross sectional area of the old concrete section, f_c is the concrete strength of the old concrete section, A_j is the cross sectional area of the concrete section after being strengthened by concrete jacketing And f_j is the concrete strength of the concrete section after being strengthened using concrete jacketing.

2.3. Ferrocement Laminate Jacketing Technique

Ferrocement jacketing is applied by a combination between a cement mortar with a wire mesh described as a thin layered mesh as shown in Figure 7 [36,61,62]. The percentage of cement mortar in ferrocement jacketing process is around 95%, however; the wire mesh percentage is 5% [63]. The mesh used have no specific type, it can be made of steel, metallic or fibers. Regarding the thickness of the jacketing technique, it must be very thin, mostly below 25 mm thick [64,65]. However, the sections used can range between 20 - 40 mm thick. Concerning the wire meshes, the number of layers and the size of openings can highly affect the section properties [39,66]. Regarding the diameter of the wire mesh used, it ranges between 0.55 mm - 3 mm with openings of sizes ranging between 6 mm - 25 mm. Wire meshes can be formed with different types and shapes such as square, hexagonal, expanded, welded, diagonal or diamond meshes [67-69]. Figure 8 shows the different shapes of meshes that can be used [68].

There are various pros for the use of ferrocement jacketing [36,70-72]. These advantages are enhancement in strength, ductility, durability, resistance of fatigue, elongation and crack in addition for being light, its weight is low and it improves the toughness. It can be quickly applied without the interference of any bonding material [73]. In addition to that, the raw materials used in this technique are available and the cost to perform and fulfill it is low [74-76]. A higher shear capacity and tensile strength is gained after rehabilitation technique [77,78]. Regarding the disadvantages, they lie under the need for very skilled and intensive labors in order to prepare the mesh and model it and enlargement in the area of section [36].

There are several steps applied in order to apply the ferrocement laminate jacketing technique [36]. The first step is to place the skeletal frame. Second, the meshes must be prepared and modeled. Third, plastering is applied on the section. Fourth, the curing process followed by hydration process is applied.

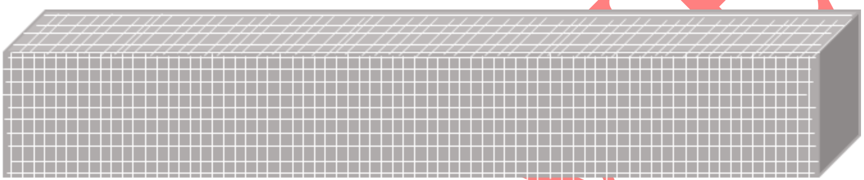

Figure 7. *Ferrocement laminate jacketing technique [61]*

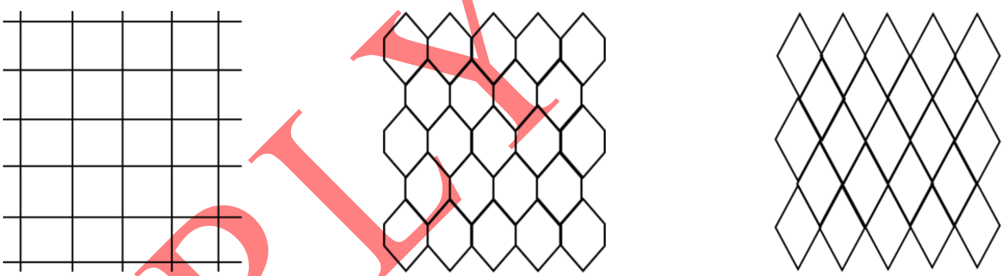

Figure 8. *Wire mesh shapes [68]*

However, regarding the design equations adopted in the ferrocement jacketing technique, they are stated as follows:

The ultimate load carrying capacity, designated by P_u, and the pressure confined, designated by f, after jacketing a concrete column can be expressed as follows [79,80]:

$$P_u = f_{cc} \times A_c + f_y \times A_s \tag{17}$$

$$f_{cc} = k\,f + f_{c0} \tag{18}$$

$$f = \frac{2\,N\,A_w \times (H_j + b_w)}{D_c \times H_j \times b_w} \times f_{yw}. \tag{19}$$

In Equation (17), P_u is the ultimate load carrying capacity, f_{cc} is the strength of concrete (confined), A_c is the area of concrete section, f_y is the yield strength of reinforced bars and A_s is the area of reinforced steel bars. However, in Equation (18), f_{c0} is the strength of concrete (unconfined), k is the coefficient used to represent the confinement effectiveness and f is the pressure confined. In Equation (19), N is the number of wire mesh layers, A_w is the wire cross sectional area (individual), H_j is the jacketing height, b_w is the wire mesh opening size, D_c is the perimeter of column divided by 2 and f_{yw} is the wire mesh tensile strength (single).

However, the shear strength for reinforced concrete column (confined) after being jacketed using ferrocement jacketing technique can be expressed using the following equation [71]:

$$V_j = \frac{0.125 \times \pi^2 \times n \times d_w^2 \times f_{yj} \times D'}{g_w} \quad (20)$$

In Equation (20), V_j is the shear strength of column after applying ferrocement jacketing method, n is the number of layers of wire mesh, d_w is the wire mesh diameter, g_w is the wire mesh spacing, D' is the strengthening jacket core diameter and f_{yj} is the wire mesh allowable stress.

Mabrok et al. [68] proposed a design equation to calculate the reinforced column ultimate capacity, the model used is stated as follows:

$$P_n = 0.35 \times f_{cu} \times A_c + 0.67 \times A_s \times f_y + C_1 \times f_{cm} \times A_{cf} + C_2 \times A_{sf} \times f_{sf} \quad (21)$$

In Equation (21), P_n is the reinforced column ultimate capacity, f_{cu} is the compressive strength of concrete, f_{cm} is the compressive strength of mortar, f_{sf} is the yielding strength of wire mesh, f_y is the yielding strength of reinforced steel bars, C_1 is the mortar constant factor, C_2 is the wire mesh constant factor, A_c is the cross sectional area of concrete, A_{cf} is the area of mortar used and A_{sf} is the area of wire mesh used.

2.4. Fiber Reinforced Polymer (FRP) Jacketing Technique

FRP can be used in different types and forms. They can be either rods or fibers or laminates or sheets [81-83]. It can be used as jacketing technique to rehabilitate beams, columns, girders, etc [84,85].

There are different FRP types, they may be made of glass, carbon, natural and aramid fibers [81,86].

Carbon fiber reinforced polymer (CFRP) is considered as a light weight material [39]. It is composed of carbon fibers with a polymer matrix. The most effective way to perform CFRP jacketing technique is to be installed with the help of some epoxy resins or any other resin like polyurethane. The role of epoxy resins is mainly to attach the CFRP with the structural element and saturate the carbon fibers used.

However, glass fiber reinforced polymer (GFRP) can also be used as jacketing technique for concrete members [39]. There are several types of glass such as high strength glass (S-glass), chemical glass (C-glass), and electrical glass (E-glass). The GFPR are considered as the most suitable fiber to be used in jacketing since it has a very high tensile strength, a strong resistance to chemical attacks and can be used in corrosive environments. Despite all these advantages, GFRP are brittle and cannot resist fatigue.

Moving on to the aramid fiber reinforced polymer (AFRP), it is also knowns as one of the FRP jacketing techniques used for concrete structures and members [87]. This type is considered as organic type that is made of some aromatic polyamides. The main property of such type is being highly tough. However, their tensile strength and young's modulus of elasticity are considered to be intermediate. Also, AFRP are known by high heat resistant, high strength, toughness, and abrasion. AFRP increases the ductility, shear capacity, flexural strength, and serviceability. However, there are some disadvantages related to the long term behavior and performance of the concrete member after being jacketed by AFRP and also since AFRP is light by weight, it may cause an instability in the concrete element or structure. So, when AFRP is used to rehabilitate a concrete element or structure, it shall be monitored and checked periodically.

Concerning the use of basalt fiber reinforced polymer (BFRP) as a jacketing technique, it can be wisely used to rehabilitate concrete members and elements. This method is considered as environmentally friendly method, green and cheap since it is made up of natural materials [88,89]. Their manufacturing process does not cause a lot of hazardous emissions to the atmosphere and can perform greatly when used to rehabilitate reinforced concrete members and elements. Results have shown that this type of FRP has an excellent mechanical property, good electrical properties, can insulate sound, non-conductive, have high permeability, and can resist acid alkali attack. Also, it can be so beneficial in fire attacks [90].

FRP jacketing method has several advantages and disadvantages [91-95]. Regarding the pros, FRP is considered to be easily handled and transported. The strengthening composite materials used are so light and can be transported in an easy way. Also, FRP are known by their good fatigue and durability properties where they do not need continuous maintenance. Since FRP are made of thin layers, the cross sectional area and dimensions of the existing concrete sections will not be affected or enlarged. In addition to that, FRP strengthening technique can be applied during a very short period of time where a little period is needed for the hardening process. They are considered to be non- corrosive elements, have high tensile strength and stiffness, also they can resist chemical attacks. Moving on to the cost needed to accomplish FRP strengthening and rehabilitating process, the overall cost is considered to be low as compared to other rehabilitation techniques and processes. In addition to that, FRP are flexible where they can be shaped and formed to any needed shape. Moreover, they can behave in a good way at elevated temperatures [96]. However, concerning the cons, mainly FRP materials are considered to be so brittle, so they can be destroyed or damaged directly by any attack. The temperature, moisture and environment surrounding the section can highly affect the materials used for bonding process.

There are several FRP techniques that are used to rehabilitate and strengthen concrete sections depending on the property that needs to be enhanced as shown in Figure 9 [97-104]. The location, shape, orientation, length, width and dimensions of FRP used depends on the property and type of section that need to be rehabilitated and can be considered as factors that affect the performance and behavior of concrete sections after being jacketed [105,106].

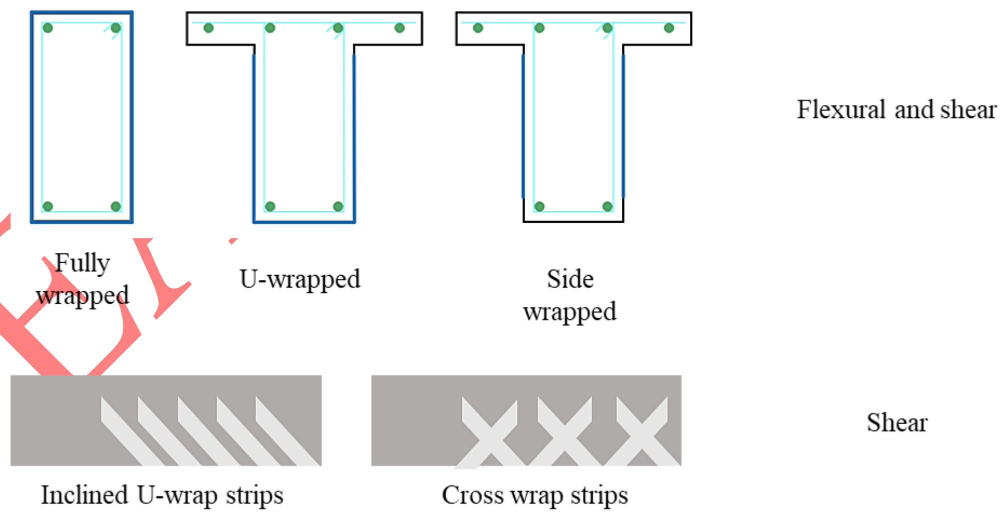

Figure 9. *Fiber reinforced polymer techniques [104]*

In addition to that, there is a further development for FRP, mainly plate bonding [91]. This development is well known as near surface mounted reinforcement (NSMR). Mainly, CFRP rods are bonded into the concrete cover using sawn grooves. One of the advantages of this method is preventing from freeze-thaw problems. But, this technique cannot be applied in places where the concrete cover is not sufficient.

Moving on to the design equations used for fiber reinforced polymer jacketing technique, the shear strength of a reinforced concrete beam jacketed using CFRP is calculated as follows [107,108]:

$$V_d = V_c + V_s + V_f \tag{22}$$

$$V_f = f_{uf} \times t_f \times d. \tag{23}$$

In Equation (22), V_d is the shear strength including concrete and steel (design shear strength), V_c is the shear strength including only concrete, V_s is the shear strength including only steel and V_f is the shear strength including the composite (CFRP). However, in Equation (23), f_{uf} is the CFRP tensile strength in a way where they are parallel to the steel stirrups, t_f is the CFRP thickness and d is the measured distance from the centroid of the tension steel up to the compression flange.

However, the above equation can be only used and applied in cases where there exists a mode of rupture and where the beams are considered to be narrow in comparison to the length of the section.

Another equation is suggested where it is applicable in other cases where the length is taken into consideration and is stated as follows [107,109,110]:

$$V_f = \frac{A_f \times \sigma_{eff}}{S} \times L_{eff}. \tag{24}$$

In Equation (24), A_f is the CFRP cross sectional area, σ_{eff} is the design stress, L_{eff} is the effective length of the laminates and S is the stirrups spacing.

Concerning the variation in the equation of axial strength, it is stated as follows [111]:

$$\Phi P_n = \Phi \times [0.85 \times 0.95 \times f_{cc}' \times (A_g - A_{st}) + f_y \times A_{st}] \tag{25}$$

$$f_{cc}' = f_c' \times [2.25 \times \sqrt{1 + 7.9 \times \frac{f_1}{f_c'}} - 2 \times \frac{f_1}{f_c'} - 1.25] \tag{26}$$

$$f_1 = \frac{K_a \times \rho_f \times f_{fe}}{2} = \frac{K_a \times \rho_f \times \varepsilon_{fe} \times E_f}{2}. \tag{27}$$

In Equation (25), Φ is the strength reduction factor, P_n is the nominal axial strength, f_{cc}' is the compressive strength of concrete (confined), A_g is the gross area of the concrete member, A_{st} is the total steel area of the longitudinal bars and f_y is the yield strength. In Equation (26), f_c' is the compressive strength of concrete and f_1 is the FRP confining pressure. However, in Equation (27), ρ_f is the reinforcement ratio for FRP, K_a is the efficiency factor (equals to 1 for circular sections), ε_{fe} is the effective strain and E_f is the tensile modulus of elasticity.

2.5. Swimmers

Swimmers is considered as an advanced rehabilitation process used mainly to rehabilitate reinforced concrete slabs after being damaged due to impact loading or any other problem. Swimmers are steel shaped bars, they are inserted to the concrete slab between the existing reinforcing steel bars [112]. The size of these swimmers, way of shaping and tying, dimensions, spacing and angles used while shaping them, all are factors that affect the performance of the member or element being rehabilitated. Figure 10 shows the shape of swimmers used to rehabilitate concrete slabs [112].

Figure 10. *Swimmers used to rehabilitate a damaged concrete slab [112]*

2.6. Stitching

Typically, stitching method can be performed in two different ways. Mainly, slot stitching method is used to rehabilitate concrete pavements that are damaged [113]. The first and the most commonly used way is by cross stitching displayed in Figure 11. Deformed tie bars are drilled at specific angles into the holes embedded in the crack and then tie bars are grouted or epoxy materials are placed to bond the bars into the existing concrete pavement. However, the second way is performed by slot stitching presented in Figure 12. Slots are performed and tie bars are inserted into these slots across the crack or joint. There are several steps that must be applied in order to accomplish cross stitching technique. First, a hole shall be drilled along the crack using drill rigs. Second, using the drill rig, the exact location for the hole that must be drilled in order to insert tie bars shall be located. Third, monitoring and checking the hole location if drilled in the exact place shall be performed. Fourth, epoxy material or any grouting material shall be inserted to the already drilled holes by injection process in order to get a good bind between the tie bars used and the existing concrete pavement. Fifth, tie bars shall be inserted into the holes drilled that are containing the grouting material.

Also, there are several steps to accomplish slot stitching method [113]. First, the slots shall be cut in a way perpendicular to the joint or crack with the help of a slot cutting machine. Second, the cut slots must be cleaned and concrete must be removed from the slots. Third, the deformed steel bars are inserted and embedded inside the slots of the concrete section. Fourth, a backfill material is inserted in the slot and then vibration takes place to make sure the backfill material goes around all deformed bars. A low shrinkage backfill material is a must in such places. Finally, flush and curing the surface process took place.

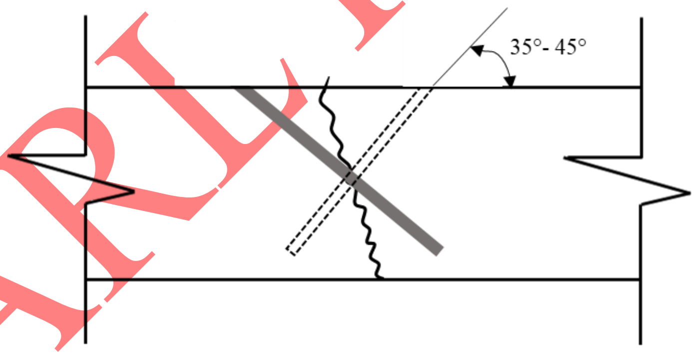

Figure 11. *Cross stitching method [113]*

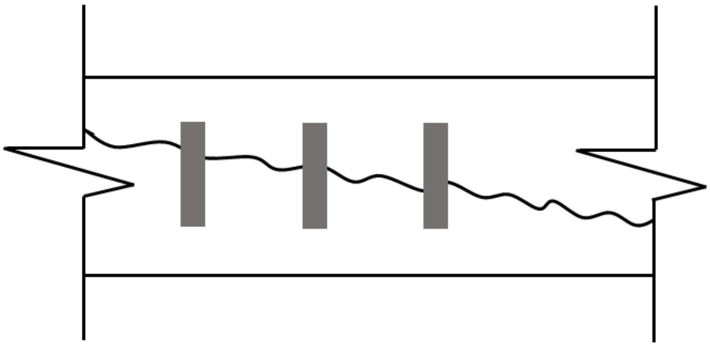

Figure 12. *Slot stitching method [113]*

3. CASE STUDY OF THE STRENGTHENING AND REHABILITATION OF A SCHOOL BUILDING

This case study deals with the strengthening and rehabilitation of a school building located in Mauritius due to poor construction quality [114]. After inspecting and assessing the existing building using destructive and non-destructive testing methods, results show the importance of applying strengthening and rehabilitation of some concrete elements. Columns, beams and bases were rehabilitated by jacketing the existing elements according to specific standards and calculations. Reinforcements are doweled into the existing elements and concrete is used for casting. However, slabs are strengthened and rehabilitated using steel channels. After finalizing the execution period, only hairline cracks were detected revealing the adequacy of the rehabilitation method chosen.

4. CONCLUSION

As a conclusion, concrete is considered as the most abundant material, however; it must be checked periodically in order to avoid any severe cracks that cannot be solved by repairing materials and methods. The rehabilitation techniques are used in places where repair cannot anymore solve the problem. These techniques differ in type, shape, uses, and properties. Each jacketing technique can be used in special cases depending on the property that need to be strengthened. There are several techniques that cannot be performed where the environment surrounding contains severe attacks and moistures. Choosing the technique for rehabilitation shall be performed according to several standards and properties in order to avoid any problems after rehabilitation process. Several design equations are used in order to calculate the new properties and capacities of the damaged concrete elements and members after being rehabilitated using any of the rehabilitation techniques. These equations included the calculation of capacities of the rehabilitated elements, shear and axial strength.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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