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PERFORMANCE OF STEEL JACKETED RC COLUMNS USING VARIOUS CEMENTITIOUS FILLING MATERIALS

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ABSTRACT

Repair and strengthening techniques of RC elements are considered to be challenging due to time, cost, and space constraints. Conventionally, several techniques have been used in the retrofitting of RC element. Recently a new technique has been introduced in some cases which is concrete filled steel jackets. Little research has been found in this area. Consequently, more data is required for a safe and economic design of this technique. This technique comprises a steel cage consisting of four steel angles with steel strips at fixed spacing to prevent the buckling of the angles. The space between the RC column and the steel cage is filled with different cementitious materials. The experimental program consisted of ten RC columns, two of them are unstrengthened columns. Eight steel cages were used with the same length of the column to confine the RC columns. Three different concrete mixes along with grout were prepared with different grades to be used as the filling concrete. LVDTs and strain gages were mounted on the specimens to record the load displacement and stress strain curves of the specimens. The specimens were then uniaxially loaded till failure. The Results of this study reveal that the proposed technique have significant effects on the load carrying capacity, ductility and stiffness of the strengthened columns for different types of filling mixes. Moreover, the Eurocode 4 design equations for composite sections tends to be overestimating the capacities of the columns and Regalado's equation provide reasonable design values.

Keywords**:** (**Repair, Strengthening, RC Columns, Steel Jacket, Concrete Class**)

1. INTRODUCTION

Repair and retrofitting works are considered to be very challenging as most of the times the reasons which lead to the damage of concrete are vague. Since there is no clear guidelines or codes for the design of the repair works, so it is mainly dependent on the experience, judgement and inspection of the responsible engineer. Time and cost represent additional constraints to the repair works. In many cases the damaged structures have to be repaired while they are in service. Also, the performance and lifetime of the repaired or strengthened structure is mainly dependent on the repair process. That is why the choice of the appropriate repair or strengthening technique is thought to be very crucial. The following can be considered as a summary for the deterioration and damage that the concrete is subject to: Poor quality concrete, corrosion of reinforcement steel, carbonation, freeze-thaw damage, earthquake damage, underestimated design and environmentally related problems.

Various techniques are used in the repair of reinforced concrete elements. These techniques are epoxy repair, concrete and steel jackets, and FRP. The choice of the technique depends on the nature of the problem, cost, and the skilled labor. Moreover, the external strengthening is used whenever there is a need to increase the capacity of the building (Papanikolaou et al., 2012) (Karayannis et al.). The research in this area covered various variables that affect the process of repair and strengthening. These factors include the preloading of old concrete, spacing of transverse reinforcement, interface between concrete and repair material, type of confinement, the type of member, shape and size effects, and concrete class. The main design assumption that the concrete core is unloaded. This can be referred to as conventional design methods. As shown in figure 1, the design using the conventional method assumes that the behavior of the concrete follows the path ABC in loading without confinement. It is well known that the repair can significantly increase the post peak strength of concrete elements and hence follows the path ADE after retrofitting. For repaired elements, the behavior exhibits a totally different path which is RST due to permanent deformations from the loading stage before damage. The totally different mechanical behavior of concrete is the reason that hinders the effectiveness of the conventional design method. The design of confining methods for repair of concrete members should involve the load capacity, restorability and deformability of the concrete member. (Ma et al, 2017)

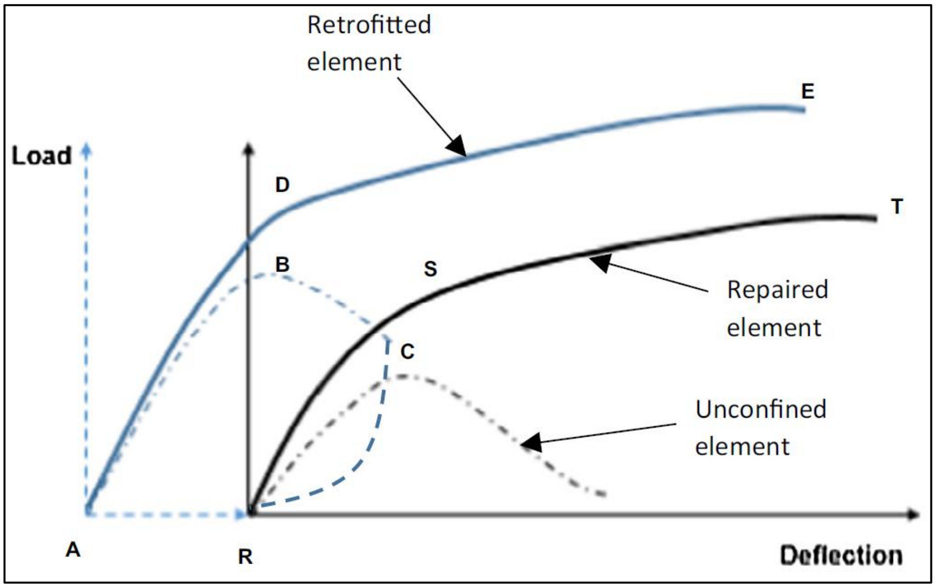

Figure 1: Load Deflection Curve of Repaired Elements (Ma et al., 2017)

1.1. RC Columns Strengthened with Angles and Battens

Four angles are used at the corners of the columns and steel battens are welded at a fixed spacing to prevent the buckling of the angles. The gap between the steel cage and the concrete column is filled with epoxy or cement to guarantee the bonding between them. (Tarabia, 2014). The steel battens are used to prevent the bulging of the concrete i.e. increase the confinement.
The advantages of this system is that it does not enlarge the area of RC column. Also, it has adequate durability and ease of application. This system is also known to be protective against fire and corrosion. (Adam, 2008) (Campione, 2013). (Tarabia, 2014) proved that the ductility of the columns increased by about 50% in the strengthened columns.

Several Design Equations were proposed for the design using the above mentioned technique. According to the Eurocode 4, the section is assumed to be a composite section and could be designed according to the following Eq.1

[1] $P_{EC4} = 0.85 * A_c * F_c + A_L * F_{yL} + A_s * F_{ys}$

where; where A_c is the cross-section area of the RC column to be strengthened, f_c the compressive strength of the concrete, As the cross-section area of the longitudinal reinforcement of the column, f_{ys} the yield stress of the longitudinal reinforcement, A_L the cross-section area of the angles forming the cage, and f_{yL} the yield stress of the steel used in the angles.

(Regalado, 1999) reduces the ultimate load obtained by EC4 to account for the slippage between the steel cage and the mortar and that the column does not behave as a composite section. Eq.2 was proposed

[2] $P_{Reg} = 0.6 * (0.85 * A_c * F_{c} + A_L * F_{yL} + A_s * F_{ys})$

Regalado's assumption was found to be very conservative which induces more costs for design using this method. On the other side, it is non conservative to assume that the section acts as a composite section (EC no.4 assumption) due to the incompatibility in the deformation between the steel and reinforced concrete. (Calderon, 2009)

2. RESEARCH MOTIVATION

This study is of crucial importance particularly in these days in Egypt. The buildings in Egypt are in dire need of repair works and strengthening due to the large number of buildings constructed after Jan, 2011. These buildings subject the life of civilians to danger. Also many governmental buildings were exposed to major damages due to explosions during the recent terroristic attacks. Moreover, the current status of Egypt's infrastructure shows that a lot of them in a questionable state. As the demolition of these buildings, in such circumstances, is neither practical nor accepted option, so rapid and economic repair and strengthening techniques have to be implemented. 3 main aspects have the major contribution behind this study: 1) Egypt's need for widely accepted rapid and economic repair and strengthening techniques. 2) The influence of endangered of buildings and infrastructure on the Egyptian economy. 3) The effectiveness of the proposed repair and strengthening technique that is already used in some repair projects.

3. EXPERIMENTAL WORK

The experimental work consists of ten cast in place concrete columns. Eight of the ten columns were jacketed using concrete filled steel jackets. The steel jackets were formed from four vertical angles with steel battens at a suitable spacing to prevent the buckling of the steel angles. The mechanical properties of the filling concrete is expected to have a direct effect on the efficiency of the concrete jacketing. Thus, the concrete grade of the filling concrete was changed for different specimens to evaluate the overall performance of the jacket. Different water-cement ratios were used as well as cement content. The values of the cement content adopted were chosen to simulate the commonly used range in the concrete columns. The w/c ratio ranged between 0.35 to 0.55, while the cement content was between 350 to 430 kg/m^3. This variation was to be able to evaluate the performance of the jacketing under different strengths of filling concrete.

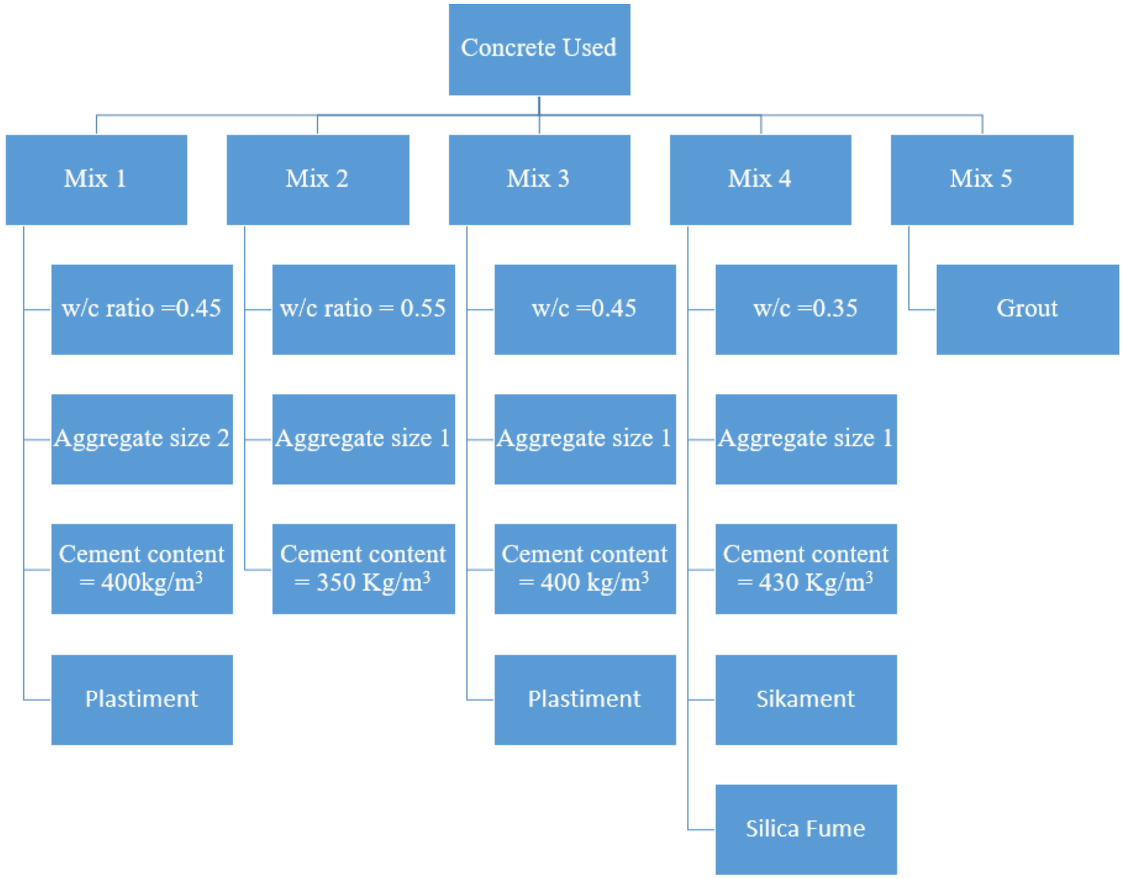

Figure 2: Diagram illustrates the mixes used in this study

3.1. Specimen Preparation

Ten columns were prepared with the following dimensions (150 x 150 x 1250 mm) to simulate the core concrete that need repair/strengthening. The core concrete columns were casted using concrete mix 1. The concrete was reinforced with four steel bars 8mm at the corners and stirrups 6 mm each 20 cm. Eight out of the ten specimens were jacketed using concrete filled steel jackets with dimensions (240 x 240 x 1250mm), while two columns were left as control specimens. The jackets were filled with concrete mixes 2-5; two columns from each mix as shown in table 1. The steel cages consisted of four steel angles (30 x 3mm) and steel strips with dimensions (40 x 3mm). The clear spacing between the strips was 265 mm. Two standard cubes complying with BS 1881 (150 x 150 x 150 mm) for testing at 28 days were prepared from each mix.

Table 1: Filling Materials for different specimens

Specimen	Dimensions (mm)	Core Concrete	Filling Concrete
C11-C12	150 x 150 x1250	Mix 1	No jacket
C21-C22	240 x 240 x1250	Mix 1	Mix 2
C31-C32	240 x 240 x1250	Mix 1	Mix 3
C41-C42	240 x 240 x1250	Mix 1	Mix 4
C51-C52	240 x 240 x1250	Mix 1	Mix 5

Figure 3: Test setup and specimen tested

4. RESULTS AND DISCUSSIONS

The experimental tests started at 28 days and were completed after 120 days. A concrete time dependent strength has been adopted (Montouri et al., 2009) to evaluate the strength of concrete at the time of testing the specimens.

[3] $Fcu(t) = Fcu(28) \times \exp(0.38 \times (1 - (28/t)^{0.5}))$

The strength of the filling concrete and grout is shown in table 2.

Table 2: Cubic strength of concrete specimens

Concrete Mix	Day of test	Fcu (t) (MPa)
Mix 1 (No jacket)	28	37
Mix 2	56	23.7
Mix 3	56	44
Mix 4	90	49.2
Mix 5 (Grout)	120	65.4

4.1. Load Carrying Capacity

Generally, the loads of the strengthened columns are much higher than those of the reference columns. Of course, this cannot be attributed only to section enlargement but also to the confinement provided by steel angles and jackets. Figure 4 shows the ratio of the failure load of the specimens with compared to the reference columns. It is clear that group number 5 yielded the highest capacity (about 20% higher than other groups) due to the high strength of grout. While the other groups produced comparably equal capacities despite using different classes of concrete jacketing. These analogous results shows that the confinement effects is more effective and functional for lower strength concrete. The strengthening effects might be a exaggerating as the cross section after enlargement is 2.5 times the old cross section. The reason behind these dimensions is to leave a suitable space for the concrete jacketing for compaction.

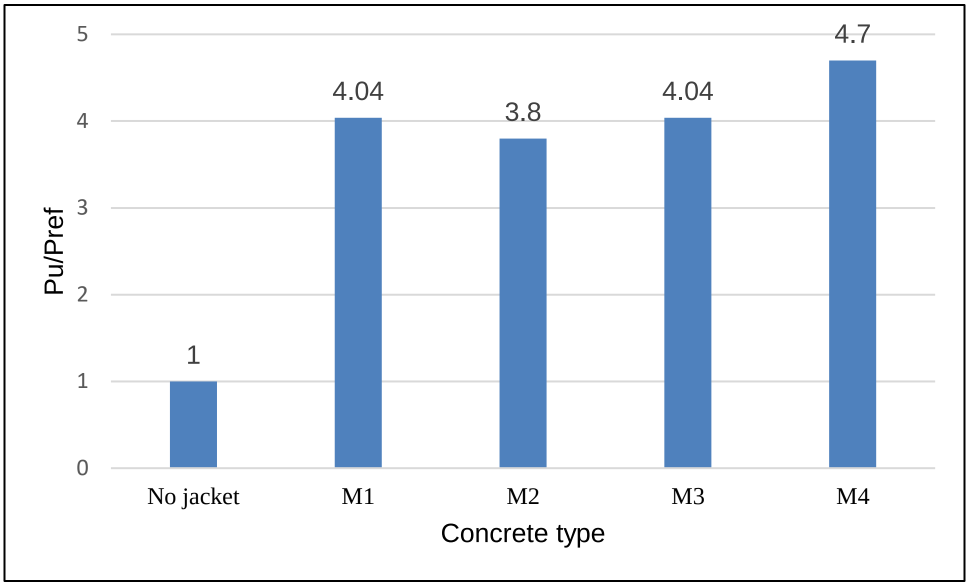

Figure 4: Ratio of load bearing capacity of strengthened columns to reference columns

4.2. Strength Index

To reduce the exaggeration and focus on the beneficial effects of the concrete filled steel jackets, non-dimensional curves are plotted in which the capacity of each column is compared with the nominal strength of each column. The nominal strength represents the sum of the strength of the material of the column. So, P_{nom} = (As*Fys + Ar + Fyr + 0.8 * Ac * Fcu + C) where, As is the area of the steel angles, Fys is the yield stress of the steel angles, Ar is the area of the longitudinal bars reinforcement, Fyr is the yield stress of the longitudinal bars, Ac is the area of the concrete jacket, Fcu is the cubic strength of the concrete jacket and C is the capacity of the inner concrete column. As shown in figure 5, the beneficial effects of steel jacket are clear. The strength index values range increased by 140% to 210% compared to the reference columns. The confinement is advantageous in case of lower strength concrete as it makes full use of the composite action between steel and concrete jackets. As the strength of the concrete jacket increases, the confinement effects becomes almost constant. Although, using grout as a filling material between the inner column and the steel jacket gives the highest capacity, yet it does not make use of the full capacity of the section compared to lower strength concrete.

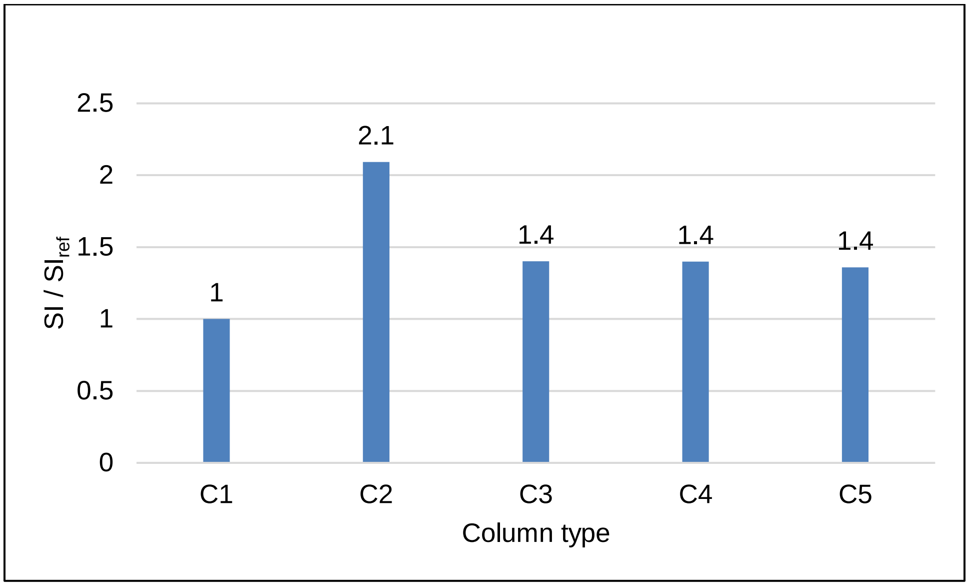

Figure 5: Ratio of strength index of strengthened specimens to reference columns

4.3. Stress-Strain Behavior

The ductility of the strengthened columns is significantly greater than that of the reference column. The results reveal also that ductility increase with increasing the compressive strength of then concrete jacket except for group 3. This can be explained due to breaking of the weld between the angle and the steel strips of specimen C31. Correspondingly, the values of the secant modulus at failure are decreasing as the concrete strength increase. The secant modulus better represents the behavior of the specimens at failure than the tangent modulus. The results are listed in table 4-5. The table also shows that all the strengthened columns can bear higher stresses than the reference columns, up to 80% increase in the maximum stress.

Table 3: Maximum stress and strain values

Specimen	Max. Stress (KN/m^2)	Corresponding strain (□strain)	Secant Modulus (GPa)
C11	1670	1213	1.37
C21	2450	1641	1.49
C31	2272	1192	1.9
C41	2450	2028	1.2
C51	3023	3206	0.94

4.4. Load – Axial Deformation Behavior

Generally, the vertical axial deformations are greater in the strengthened columns than the reference columns. Neglecting the seating deformations, the load-deformation curves exhibited a linear behavior for almost all the strengthened specimens. The stiffness of the columns was determined using the linear portion of the load deformation curve to avoid the influence of the flat part at the beginning of the curve associated with the seating of the specimen. As clear in figure, the stiffness of the strengthened columns is much higher than the reference column. It reaches up to twice the value of the reference columns. This is not surprising due to the effects of the section enlargement. The axial shortening of the strengthened columns increased by 240 up to 345% despite the increase in the columns stiffness. The results reveals the role of concrete filled steel jackets in increasing the deformability of concrete columns. Group 5 recorded the highest axial shortening values compared to other specimens. It confirms that the ductility of the concrete filled steel jacketed columns increases with the increase of the concrete jacket class. On the other side, the stiffness of the columns increases with the increase of the concrete strength as expected however, the stiffness of group 5 showed a reduction by almost 10%. The increase in the elastic stiffness leads to less deformation at working loads. So, for the working load stage, using concrete with silica fume and can yield better results than using grout.

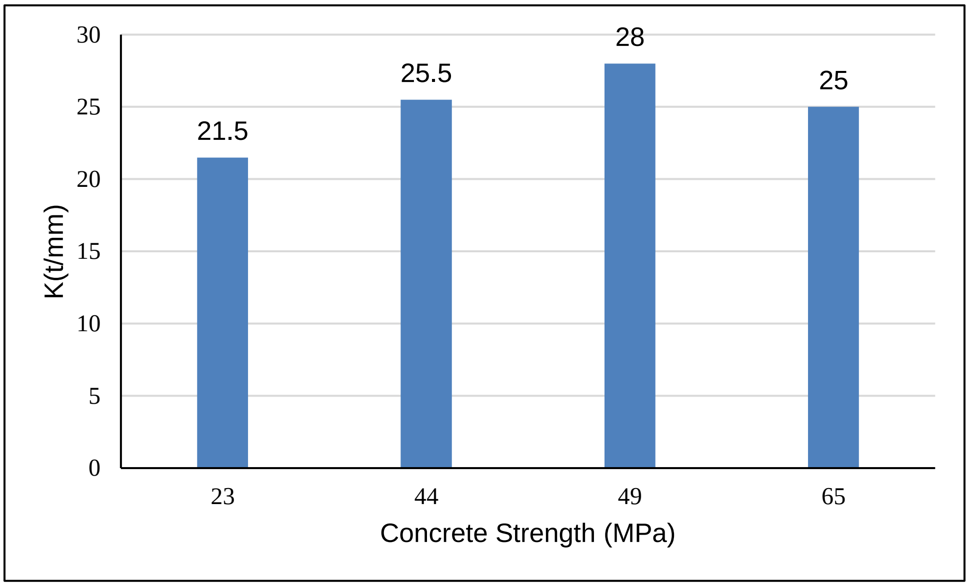

Figure 6: Linear stiffness for different concrete strengths

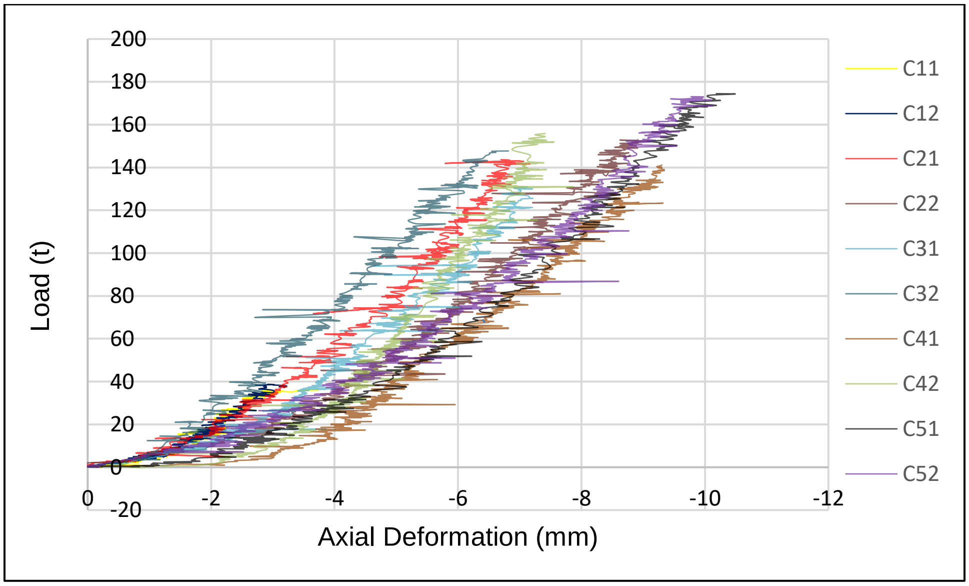

Figure 7: Load Deformation Curves of different specimens

4.5. Design Proposals

As highlighted in the literature, there are several methods for the design of the steel jacketed columns. The ultimate loads of the jacketed columns were compared with the design loads of the EC4 and

Regalado equations as they represent the upper and lower bounds of the design proposals. The EC4 equation considers the jacketed column to act as a composite section. While, Regalado reduces the capacity by a constant factor taking into consideration the incompatibility in the deformations between the steel jacket and concrete. The results are summarized in table 4-7.

Table 4: Comparison of ultimate loads with EC4 and Regalado

Column	Pu (Ton)	EC4 (Ton)	Regalado (Ton)	Pu/PEC4	Pu/PReg
C21	143.7	142.9	85.7	1.01	1.68
C22	153	142.9	85.7	1.07	1.79
C31	130.9	199.7	119.9	0.65	1.09
C32	147.7	199.7	119.9	0.74	1.23
C41	141.2	213.7	128.2	0.66	1.10
C42	155.8	213.7	128.2	0.73	1.22
C51	174.5	258.6	155.1	0.67	1.13
C52	173.1	258.6	155.1	0.67	1.12

From the above table it is clear, that generally the EC4 method is overestimating the capacity of the jacketed columns. On the other hand, Regalado equation underestimates it. However, for the lower strength filling concrete the EC4 equation yields better results and the columns behave almost as a composite section and . While, for higher strength concrete there is a noticeable reduction in the capacities of the composite section. Hence, design using the EC4 equation is non conservative and Regalado's equation represents a better and safer solution.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In light of scope, material, equipment and other parameters and variables associated with this study, the following can be considered as the most important findings:

a. The results reveal that ductility is clearly affected by the compressive strength of the filling concrete jacket. This was shown as it increases with the increase of the compressive strength.
b. All the strengthened columns can bear higher stresses than the reference columns, up to 80% increase in the maximum stress.
c. The results reveal that stiffness of the jacketed columns is noticeably impacted by the compressive strength of the filling concrete jacket. It increases with the increase in the compressive strength of the filling concrete. This conclusion is not valid for the grout.
d. For the working load stage, using concrete with silica fume and can yield better results than using grout as it had the highest stiffness.
e. For the ultimate load stage, grout can bear higher stresses accompanied with higher ductility.
f. Design using the EC4 equation is non conservative and Regalado's equation represents a better and safer solution.
g. When using lower strength filling concrete, the jacketed column behaves as a composite section with its maximum capacity.

5.2. Recommendations

Similar to other research work, further investigations need to be conducted to cover the following:

a. Other types of concrete classes need to be examined to confirm the findings of this study.
b. The influence of preload on the behavior of the concrete filled steel jackets needs to be further examined.
c. The bond between concrete and steel should be thoroughly studied such as using epoxy or dowels and observe the change in the confinement action of the RC columns.

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