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DEVELOPING A DECISION-MAKING MODEL FOR REINFORCED CONCRETE COLUMNS STRENGTHENING

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ABSTRACT: Steel tubes (ST) have long been used to strengthen RC columns, while the application of CFRP for this purpose is a recent practice. Both techniques have many advantages and shortcomings. In this paper, a multi-criteria decision-making model is introduced to quantify the selection of one of the two techniques. Four criteria and 28 factors affecting them are identified to develop the model. The selected criteria are cost, strengthening efficiency, durability, and project scope achievement. The model is fed by data collected from execution activities, field surveys and previous laboratory test results. The model has been validated and applied to a real case study. The detailed discussion and analysis indicated that many features support the use of CFRP in the investigated case study. Furthermore, the analysis emphasised that the strengthening efficiency and durability decide the selection while project scope achievement criterion is insignificant compared to other criteria. Ultimately, the obtained results from the case study provide the construction market with a decision that supports the use of the CFRP by 56 %, while the use of ST is only supported in 44 %.

Keywords: Decision making; AHP; RC Columns strengthening; CFRP, Steel Tubes

1. INTRODUCTION

RC structures need to be strengthened for many reasons, such as poor design, the degradation of the materials over time and the amplification of the load capacity due to a new utilization of the building. New design codes may also increase the specifications, such as seismic action recommendations. The strengthening should be based on the structural assessment and achievement of objectives to minimise the intervention to the building for economic reasons and reduce the consequences of the strengthening work on the non-structural elements and normal use of the building. The best strengthening technique for the axial force capacity is jacketing. The external addition of steel and carbon fiber reinforced plastics (CFRP) is more suitable in cases that present reinforcement insufficiency or columnar defects. RC columns fail via several modes, as shown in Fig. 1 [1]-[2]. The confinement can be increased to improve the ductility, seismic behaviour of the structure and axial capacity load, which prevents these failure modes. If the concrete is weak, its Young's modulus is low and creep strain is high. In this case, more axial loads would be transferred from the concrete core to the steel bars. Because the bond stress is low, de-bonding may occur, which may result in internal voids. The main bars, which experience more stress, may buckle and cause column bulging. Some links may also be overstressed, as shown in Fig. 2[1]-[2]. If the links are opened and the main bars buckle, explosive axial failure would occur.

		
Alkali-silica reactivity	Rebar corrosion	Overloading

Fig.1 modes of RC columns failure [1]-[2]

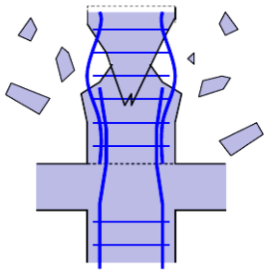

Fig. 2 Mechanism for mode of failure of RC column [1]-[2]

This led to the search for an established, reliable, economical, and easy to apply strengthening technique. Section enlargement, steel jacketing, steel encasing, or wrapping with FRP can be used to strengthen, retrofit and repair RC columns to increase the load carrying capacity. Losing additional loads due to strength deterioration or material deficiency after strengthening the carrying capacity in the column may lead to the catastrophic failure of structures. The selection of suitable material options can be a very complex process that is influenced and determined by numerous preconditions, decisions, and considerations [3]. Because several methods are available to strengthen the RC columns and each technique features many advantages and disadvantages, specialists in the field of RC strengthening must make a decision to select the appropriate strengthening method. Therefore, this paper introduces a decision-making model to support these experts in their selection. The model addresses two common strengthening techniques for RC columns, confinement using ST or CFRP. Specifically, this study focuses on four criteria and associated factors to build the proposed model. These criteria include the cost, strengthening efficiency, durability and project scope achievement. The main research objectives of this study are (1) identifying multiple criteria, including the sources, activities, and all factors, that control the selection of RC Column strengthening techniques, i.e., ST or CFRP; (2) designing a multi-criteria decision support model to ease the material selection process; (3) testing the designated model using data from an actual case study; and (4) discussing the factors and reasons that affect the two techniques for RC column strengthening in detail based on the results of the model application.

2. SIGNIFICANCE OF RESEARCH

The selection of a method to strengthen RC columns faces many problems, the most important of which is the lack of a scientific method or model to select a suitable technique. This process is fundamental and has always been considered one of the critical problems for consultants and contractors. Each technique features many advantages and disadvantages in the four selected criteria (cost, strengthening efficiency, durability and achievement scope during construction). Combining these advantages and disadvantages to compare and quantify the two techniques for the purpose of decision-making is exceedingly difficult. Therefore, a multi criteria decision-making model to support the decision makers who handle the application RC column strengthening is proposed. The proposed model embraces the broader sense and many factors of the four criteria for RC column strengthening. Improving the performance of this method not only increases benefits the consultants or contractors but also reduces risk and prevents cost or time overruns of the project.

3. MULTI-CRITERIA DECISION MAKING IN CONSTRUCTION PROJECTS

Many construction projects require important decisions before starting due to many reasons, such as multiple available construction techniques, several material alternatives, and the comparison and selection of various projects, contractors, bids and planning alternatives. The decision makers face many problems because several factors affect more than one criterion with many advantages and disadvantages. A decision is an irrevocable allocation of resources [4]. The criteria may be incompatible due to the overlapping of advantages and disadvantages. Dikmen et al. [5] presented project selection model that was based on quantitative and qualitative criteria. Ravanshadnia et al.[6] proposed a construction project selection model that used a fuzzy multi-attribute decision making method to identify whether a tender should be offered and to select a project by considering probable policies. Other studies have used decision-making systems in construction projects, such as Ning et al. [7], who used a decision-making system to plan a dynamic multi-objective and unequal-area construction site layout. Nieto-Morote and Ruz-Vila [8] presented a multi-criteria decision problem based on Fuzzy Set Theory, which uses a linguistic assessment or exact assessment of the performance of contractors based on qualitative or quantitative criterion. Ebrahimnejad et al. [9] used a decision-making system for a construction project problem subject to multiple criteria in a fuzzy environment. Yao-Chen and Shih-Tong[10]employed a fuzzy multiple criteria decision-making approach to systematically assess the risk of a metropolitan construction project. Scherer and Schapke [11] introduced a management information system to support decision-making for construction projects across all management levels within the owner and the contractor organizations. Issa et al. [12] introduced a multi-criteria decision-making model to support decision makers who work in ground improvement projects, such as embankment construction that utilizes stabilizer materials. Van Kesteren et al. [13] presented a material selection consideration model in which product personality, use, function, material characteristics, shape, and manufacturing processes comprise the elements that are considered by the designer during the material selection process. Rahman et al. [14] developed a multi criteria decision-making model to solve combinational problems associated with the material selection process by considering the life cycle of the cheapest materials and technologies. Knoeri et al. [15] analysed the behaviour and decision-making regarding recycled mineral construction materials of construction stakeholders in the construction material market in Switzerland.

4. DATA COLLECTION FOR MODEL DEVELOPMENT

Semi-structured interviews to be executed by professionals regarding strengthening RC elements in construction projects are introduced in this study. The interviews were conducted with a fairly open framework that allows for conversational and two-way communications. They can be used to both give and receive information. The objective of these interviews is to identify the main criteria and the factors affecting them. These criteria and factors will be used as a basis for the development of the proposed model. The interviews included many Egyptian university researchers, employees at research centers, and consultant engineers in addition to contractors that routinely strengthen RC elements. The interviews identified four criteria and twenty-eight factors affecting them that theoretically impacted decision-making. These criteria and factors served as the theoretical foundation of the proposed model. The results of this section are summarised in Table 1.

Table 1 Criteria and factors of the proposed model

Criterion 1 (C1) : Cost
C1-1: Material price
C1-2: Cost difference due activities execution. (Not due to materials or manufacturing)
C1-3: Design Cost
C1-4: Maintenance cost
Criterion 2 (C2): Strengthening Efficiency
C2-1: Failure mode (ultimate limit)
C2-2: Cracking load (service limit)
C2-3: Ductility
C2-4: Deformation (service limit)
C2-5: Additional loads due to material weight
C2-6: Effect of column shape (square-circular)
Criterion 3 (C3): Durability
C3-1: Effect of Fire
C3-2: Effect of chemicals
C3-3: Humidity effect
C3-4: Seismic effect
C3-5:Effect of weather conditions on the durability
C3-6:The durability on the long run
Criterion 4 (C4): Project scope achievement
C4-1: Column finishing
C4-2: Geometry (final dimensions)
C4-3: Function with other construction elements
C4-4: Availability of materials in the market
C4-5: Limits for the use of materials in the two cases
C4-6: Need for administrative approval for the use of materials
C4-7: Difficulties to achieve the Geo-environmental properties during execution
C4-8: Need special equipments or method of construction technology for activities execution
C4-9: Need for special workers or crews
C4-10: Need more efforts for supervising during execution
C4-11: Time difference for completing activities
C4-12: Rework for some activities

5. AHP MODEL FRAMEWORK

The Analytic Hierarchy Process (AHP) is an approach that can be used to address complex systems and select from several alternatives. This approach provides a comparison of the considered options. The (AHP) was developed by Saaty [15] and has been implemented in construction projects, decision-making and risk assessment to solve many problems [5]-[16]. The decision-making framework of AHP models assumes a unidirectional hierarchical relationship among decision levels [17]. The hierarchical approach allows AHP to investigate the interrelationships among sustainability criteria. This feature is important, as the various aspects and criteria pertaining to sustainable development are often linked [18].

This work utilizes an AHP model because this approach offers a logical and representative method to structure the decision problem and deriving priorities. This model primarily aims to support the selection of a construction method for RC columns strengthening, i.e., CFRP or ST. After arranging the problem in hierarchical terms, the relative importance of each identified criterion was calculated using a pair wise comparison technique, as suggested by Saaty [19], and applied to the four identified criteria. For example, the decision makers can be asked many questions, such as “How important is (criterion 1) compared to (criterion 2)?". The second level of questions interchangeably combines the four criteria and the selection of ST or CFRP. An example of a question at this level is "How important is (criterion 1) compared to the use of ST or the use of CFRP?" The model consists of one matrix in the first level and 4 matrices in the second level. The comparisons are based on preference scale introduced by Saaty [15]. The pairwise comparisons from each branch at each level of the hierarchy are entered into a matrix and used to determine a vector of priority weights. The decision maker should select a defined number from 1 to 9 to perform pairwise comparisons of the elements. The nine-point scale can be defined as follows: 1 refers to "equal importance", 3 refers to "somewhat more important", 5 refers to "much more important", 7 refers to "very much more important", and 9 refers to "absolutely more important". The consistency ratio (CR) is calculated as a measure of cognitive effort for the decision as follows:

$$CR=CI\backslash RI \quad (1)$$

Where (CI) is the consistency index and (RI) is the relative importance or eigenvector. These values are calculated according to the procedure presented in previous study [15].

6. CASE STUDY DESCRIPTION

The proposed model was applied to a building renovation project in Cairo, Egypt. The project intended to renovate the Nile Ritz Carlton Hotel to modernise the facility and meet the modified design and more stringent specifications. This hotel has been operating since 1959 and consists of a 13-story building on 64,000 square meters. The project aims to replace and renovate all of the hotel operating systems of the rooms, ballroom, meetings and conference rooms and elevators. Moreover, the renovation aims to update the telephones systems, alarms and fire-fighting equipment to ensure that the hotel meets the highest international standards and specifications. The major structural problems of the hotel renovation are the need for architectural changes and new uses for different areas of each floor. Due to the new design, many columns are needed to strengthen the structure. CFRP was selected to strengthen the RC columns. The proposed model was applied during this phase to confirm this selection.

7. MODEL APPLICATION AND VALIDATION

The brainstorming is one of the most common identification techniques for data collection in the construction industry. A brainstorming session was conducted at the contracting company that is to carry out the strengthening procedure in the presence of a consultant, owner and representative. This brainstorming session consisted of a question and answer session to obtain the data to feed the model and ensure that everyone fully understood each response. All attendees were informed of the objective of the session to enhance its efficiency. Several comparison matrices were introduced. The four identified criteria and 28 factors were explained to the attendees. Table 2 shows the resultant comparison matrix for the four criteria. Each number refers to a certain importance as explained in details in section 5.

Table 2 The comparison matrix for the four criteria

Items	C1	C2	C3	C4
C1	1.00	0.20	0.33	1.00
C2	5.00	1.00	3.00	7.00
C3	3.00	0.33	1.00	3.00
C4	1.00	0.143	0.33	1.00

C: Criterion

The results from the brainstorming session were designed to address the decision-making process for materials selection to stabilize the RC columns. The consistency ratio was 1.90 %, which is less than 10% and indicates that the matrix is consistent. For the second level, 4 matrices were filled out as explained above. The collected data for this case study indicated that the ST is somewhat more important for criterion 1, while the CFRP is somewhat more important for criterions 3 and 4. For criterion 2, both methods are assumed to be equally important. Ultimately, the model supported the use of CFRP by 56 % versus only 44 % support for the use of ST. Therefore, CFRP is preferable by approximately 27%.

8. DISCUSSION AND ANALYSIS

As mentioned previously, four main criteria that influence the selection of ST or CFRP as a strengthening material were identified in the investigated case study. The coefficient of preference (CP) is defined as a coefficient that measures the percentage of preference for each technique related to a specified factor. The sum of all coefficients of preference of all techniques in a certain project should be equal to 1. Thus, our model features two coefficients of preference, namely CP for ST (CP¬ST) and CP for CFRP (CP¬CFRP), and

$$CP_{ST}+CP_{CFRP}=1 \quad (2)$$

The first criterion aims to compare the cost incurred when using both materials. The cost of strengthening RC columns includes the price of raw materials, the cost of executing activities, and design and maintenance costs. In fact, CFRP material is more expensive than steel. Based on the data available for the construction market in Egypt during the execution time, the cost of strengthening one layer of a 40 * 40 cm RC column using a steel tube is lower than using CFRP by approximately 35% according to the case study. Fig. 3 clearly shows a difference in the CP values for Factor (C1-2), which is the cost difference due to the execution of activities. This difference is due to the difference in routine work, such as the preparation of a column and in-situ tests that use either ST or CFRP. The CP values for factor C1-3 are almost the same. As shown in the figure, the CP values for factor C1-4 significantly differ (Maintenance cost). The low CPST value is due to the high sensitivity of steel to environmental factors, such as corrosion.

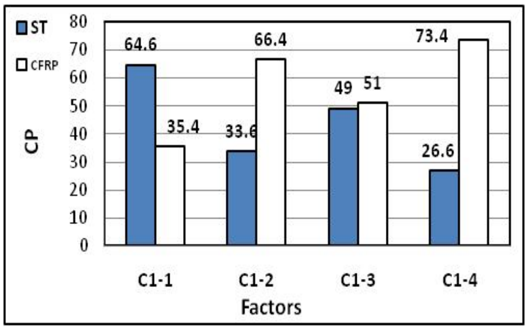

Fig. 3 CP values for ST and CFRP in Criterion (1)

The second criterion addresses the strengthening efficiency impacts of the two techniques. The strengthening efficiency is a general term that refers to many parameters, such as the ultimate and service limit. These criteria depend on the case. The failure load of specimens should be constant to ensure the reliability of other items. Abdelhafez et al. [20] experimentally observed that local buckling failure of the plate panels occurred before the maximum load is reached. The steel panels buckled at the central part of the specimens. As the two opposite faces of the columns buckled inward, the other two perpendicular faces buckled outwards. A steel tube column demonstrated a very symmetric buckling mode about the axes of the cross section [21]. Composite wrapping can enhance the structural performance of square RC columns in terms of both the maximum strength and ductility [22]. All CFRP-wrapped specimens failed suddenly and explosively, and this failure was preceded by typical creeping sounds. For short specimens (L/a =2), the fiber rupture starts mainly in the central zone and then propagates towards both ends. Slender specimens mainly collapsed in their upper or lower regions [23]. Figures 4 and 5 show the failure modes in both cases from an experimental work by Abdelhafez et al [20].

Fig. 4 Failure mode of ST strengthen columns [20]

Fig.5 Failure mode of CFRP strengthen columns [20]

Fig.6 shows that factor (C2-3), which concerns the ductility, indicated that both the strength and ductility increased when columns were wrapped in steel and fiber jacketing. The wrapping with CFRP sheets prevented the early buckling of the longitudinal bars [24]. No distinct post-behaviour was observed as the slenderness ratio increased. Increasing the amount of CFRP sheets increased the compressive strength of the confined column, but the rate of this increase was less than that of the deformation capacity [24]. Ostensibly, ST is more ductile than CFRP, which fails suddenly. The deformations, which are represented by factor (C2-4), were proportional to the strengthening method.

The effect of CFRP confinement on the deformation capacities decreased compared to ST, which exhibited ductile behavior [24]-[25]. The weight of CFRP is negligible compared to that of steel. The additional weight, which is represented by factor (C2-5), increased the stresses in the column section and required more strengthening than CFRP.

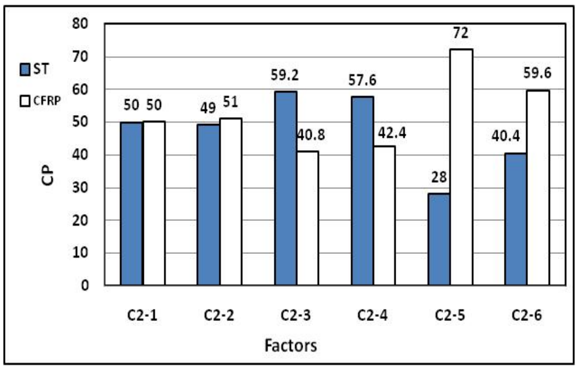

Fig. 6 CP values for ST and CFRP in Criterion (2)

The effect of increasing the column shape, as represented by factor (C2-6), is a decrease in the strength and ductility. The rate of decrease is more important for normal strength concrete specimens. The CFRP confinement is more efficient for circular than for square sections, as the composite wrap was greatly affected by its premature damage at the sharp column corner. Increasing the strengthened columns with a slenderness ratio (0.3) exerted an overall small effect on its load carrying and deformation capacities [24]. The third criterion, which refers to durability, is one of the important issues, especially when ST or CFRP materials are used to strengthen RC columns. Several parameters affect the durability of materials used in strengthening, such as fire, chemicals, humidity, seismic events, weather conditions and durability in the long run.

Building fires are nearly always man-made. In a fire, the main problem is the combustibility of the contents and failure of the structure. The extent of the ensuing damage depends primarily on the structural performance of the building both during and after the fire. With the development of habitations, attitudes to fire protection and fire precautions also developed [26], sometimes subtly, but mostly from better experience. Increasing the fire level deteriorates material [27]-[28]-[29]. Above 600 Co, the strength of concrete is reduced by more than 60 % [28]-[29], as shown in figure (7). For steel structures at high temperatures, the relationship between stress and strain changes considerably. At increased temperatures, the material's properties degrade and its capacity to deform increases, which is indicated by the reduction in Young's modulus [30], as reported in Fig 8. Identical material behaviour is assumed for both tension and compression.

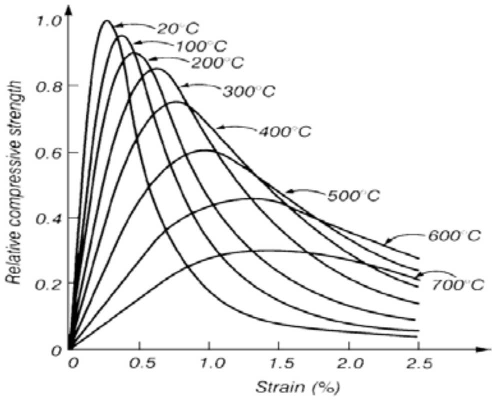

Fig. 7 Concrete stress-strain relationship at high temperature [30]

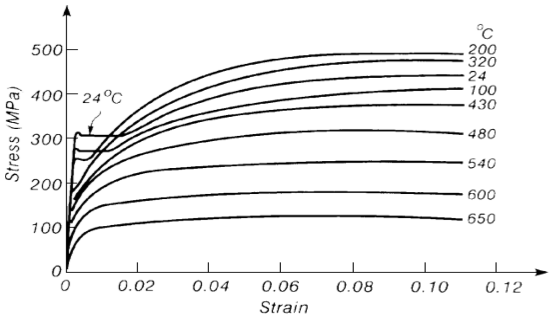

Fig. 8 Steel-strain relationship at high temperature [30]

Heating significantly affects the strength, physical properties and stiffness of both CFRP and steel, and some of these changes are not reversible by subsequent cooling [31]-[32]-[33]. CFRP confinement is more sensitive to fire than steel jacketing. The coefficients of thermal expansion of the fibers and resin differ; fluctuations in the temperature may weaken the material and result in debonding. At high temperatures, the laminate may discolour [34]-[35]. Adhesive materials are sensitive to fire at 100Co due to bond degradation. Above 270 Co, CFRP will completely separate[26].

The CP values of ST or CFRP for this criterion are shown in Fig 9. Factors (C3-2), (C3-5) and (C3-6), which refer to chemicals, weather conditions and the long-term durability, respectively, clearly result in the mechanical corrosion of the steel jacketing. Solar radiation can cause discoloration, and the action of ultra-violet rays will cause chemical reactions that break the molecular chains of the polymer in the CFRP jacketing. For fibers, this weathering is responsible for a flexural strength loss of 12-20% over 15 years [36]. The steel jacketing may be less efficient for strengthening after weathering and chemical degradation, and this decrease may be faster in steel than CFRP. At the strengthening stage, humidity (C3-3) exerts a plasticizing effect on the material and causes swelling and warping. In addition, water can fill any voids in a lamina and cause blisters to appear at fiber-resin interfaces. As a result, the bond between the constituents is weakened. After strengthening, moisture did not affect the CFRP system. The steel tubes are affected by humidity and are sensitive to moisture and riddled with corrosion.

As indicated by factor (C3-4), rectangular steel jacketing with adhesive anchor bolts significantly improved the seismic response of columns with inadequate lab splices [37]. The best results were achieved when at least two adhesive anchor bolts were used at the top and at the bottom of the steel jacket. Columns with inadequate shear strength flexed and sustained large cyclic deformation when strengthened with steel jackets [37].

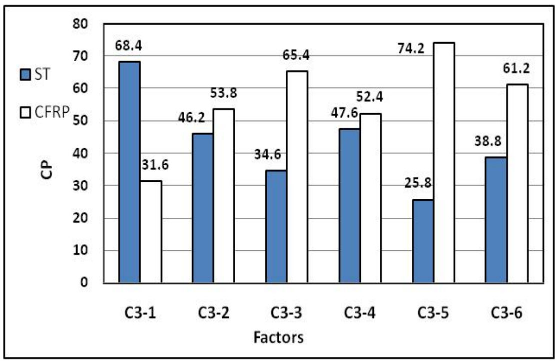

Fig. 9 CP values for ST and CFRP in Criterion (3)

The fourth criterion highlights the factors associated with the execution stage for the purpose of project scope achievement. The execution activities differed between ST and CFRP. Figure (10) summarises the relationship between CP values for both techniques in the fourth criterion. Finishing columns strengthened with ST is easier than with CFRP, as indicated by the CP values for factor (C4-1). The column cross section increased more in ST than CFRP after strengthening. ST utilizes functions other than confinement to strengthen the column, unlike CFRP. Recently, CFRP has been abundant on the market, unlike steel, which is a common material. Limits for the use of materials in the two cases seem to be the same, although steel cannot be used in adverse atmospheric conditions or marine structures. The geo-environmental properties during execution affect ST to result in more efficient strengthening than CFRP. ST requires special equipment, special workers or crews and more supervising efforts during execution than CFRP. CFRP is very simple in its application and can be executed in a shorter time than ST. In addition, CFRP is non-reusable.

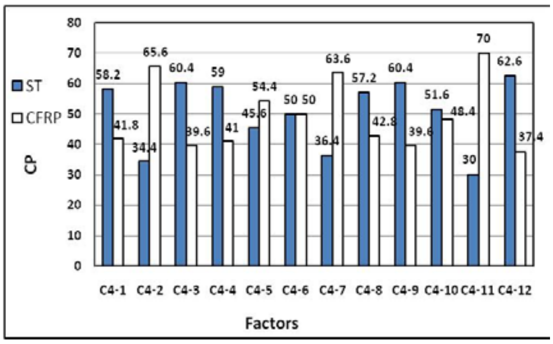

Fig.10 CP values for ST and CFRP in Criterion (4)

9. BOXPLOT ANALYSIS

The boxplot invented by Tukey [38]is an efficient way to present data. It can provide a quick visual summary that easily shows the centre, spread, range and any outliers. The box contains 50% of the data, the upper edge of the box represents the 75th percentile, the lower edge represents the 25th percentile, and the median is represented by a line drawn in the middle of the box. The ends of the lines (called whiskers) represent the minimum and maximum values of the data set, unless the data contain outliers. In this research, a boxplot analysis was introduced to summarise and compare the sets of data for the CP values of factors that affect RC strengthening via the two techniques. The boxplot was drawn for CP values and constructed side-by-side for the four criteria of both techniques, strengthening by ST or CFRP. These plots are presented in Fig 11. Notably, the range is widest for criterion (1), which concerns the cost. This wide range for CP values refers to the high differences among the CP values for factors that affect this criterion, especially in the case of CFRP (35.4 to 73.4) and (26.6 to 64.6) in ST. The ranges in boxes in criterion 2 are closer to other criteria, which indicate that the factors that affect the strengthening efficiency have similar CP values. Criterion (3) includes the highest CP value for factor (C3-5), which is the Effect of weather conditions on the durability for CFRP. This gives CFRP an important advantage in resisting the weather conditions. One factor in Criterion 3 is an outlier. Factor (C1-3), which represents the “Effect of Fire”, is an outlier with a small value for CFRP and ST. This finding proves that this factor has a small effect on CFRP and strong effect on ST compared to other factors in the same criterion. Although criterion 4, which concerns the execution activities, faces the largest number of factors, it does not have the largest range on the boxplot. This finding reflects that the CP values in this criterion are similar and that the values are low for most factors, which proves that the investigated factors for this criterion are not significant compared to other investigated criteria. The figure shows the importance of criterion 2 and 3 if compared with other criteria.

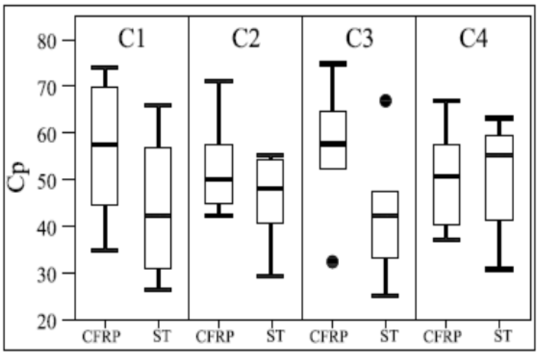

Fig. 11 Boxplot analysis for the four criteria

10. CONCLUSIONS

This work develops a multi-criteria decision-making model to quantify the selection of ST or CFRP technique to strengthen RC columns. The obtained results recommended the use of CFRP technique to strengthen RC columns. Based on the obtained results, specific conclusions can be drawn as follows:

•The developed model in this study can be used sufficiently flexible in other study cases related to the strengthening of RC elements after some modification.

• The use of CFRP as a strengthening material in the case study is better compared to ST technique. Specifically, the model supports the use of CFRP 56% versus a support of 44 % for the use of ST.

• The implementation of CFRP in RC columns is more efficient in circular sections compared to that in triangular sections.

• In spite of the investigated factors that affect the project scope achievement criterion are important, strengthening efficiency and durability are more important compared to other criteria and control the selection.

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