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Identifying the Factors Affecting the Ranking of Reinforced Concrete Beams Using Multi-Criteria Decision-Making Approaches under Conditions of Uncertainty

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Abstract

This research was carried out with the aim of identifying the effective factors in the construction of Reinforced Concrete (RC) beams. The current research was applied from the point of view of the objective and descriptive survey from the point of view. The statistical population of the research included all experts in the construction industry, from which 10 experts were selected for weighting and choosing the best strategy. In this research, data analysis was done using the Swaraphazi method to determine the weight of criteria, and the Electra method was used to choose the best strategy for reinforcing RC beams. The findings of the research showed that the order of importance of the criteria in the selection of reinforcement strategies for RC beams is as follows: time (C1) with a weight of 0.33 ranks first, cost with a weight of 0.22 (C4), high volume of operations (C5) with a weight of 0.15 ranks third, compatibility with climate (C2) with a weight of 0.1 in the fourth rank is the information of the employer, consultants and contractors (C3) with a weight of 0.062 in the fifth rank, the effectiveness of quality (C10) with a weight of 0.043 in the sixth rank, separation of the reinforcing page (C6) with a weight of 0.028 in the rank seventh, expert people (C7) with a weight of 0.019 in the eighth place, access to material C12 with a weight of 0.012 in the ninth place, the possibility of creating the required coverage C11 with a weight of 0.008 in the tenth place, the complexity of calculations C9 in the eleventh place and C8 transport were ranked 12th. Also, the results of Electra analysis showed that the best strategy for strengthening concrete beams was to use Glass Fiber Reinforced Polymer (GFRP) composites and to use Sisal Fiber Reinforced Polymer (SFRP)composite.

Keywords: Retrofitting, Reinforced concrete beams, Uncertainty.

1 | Introduction

Crack progression in Reinforced Concrete (RC) elements leads to significant additional stress, which is observed in tensile reinforcing steel bars. The risk of failure of these elements must be considered and carefully managed to increase the safety and stability of the building and avoid the creation of secondary risks

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that can cause construction failure. This research considers the risk of failure of defective beams with insufficient connections. The severity of this risk can be reduced by analyzing its impact based on experimental and numerical research. To minimize damage in elements that bend, adequate edge bond length for steel reinforcement is recommended by all RC design codes.

If the length of the edge connection is implemented according to the RC design requirements, there is minimal deficiency in terms of total load capacity and deformation under applied loads. However, the ductility and strength of structural members may be reduced by insufficient edge joint length. In addition, insufficient edge joint length may prevent the transfer of tensile stresses between the two partner steel bars. Such problems may be evident in the transfer of stresses that are created in columns during horizontal loads.

Huge damages due to runway failure were reported in field inspections after the earthquake. Premature bond collapse of RC elements can significantly compromise their design capacity. Yield failure and gap failure were considered two common types of joint failure observed in the reinforcing steel bars under tension. Compared the bond behavior of conventional vibrating concrete and self-compacting concrete in areas of weak bond and highlighted key differences. It was found that increasing the bond length increases energy absorption and facilitates a more ductile failure mode, even under weak bond conditions.

When there is sufficient concrete cover of the enclosure, direct collapse of the outlet occurs. Conversely, insufficient concrete confinement leads to split failure, where the concrete splits near the bar. Several main factors affect the resistance to the crack failure mode, including the diameter of the reinforcing bars, the arrangement of the bars, and the presence of transverse reinforcement.

In the case of flanged bars, the force is transferred from one bar to the host concrete, which then transfers the force to the other bar. Fissure cracks that initiate at the loaded end and propagate along the cladding steel bars are caused by force transfer that creates radially outward stresses. The failure modes of a single bar and lapped bars share similarities, which makes current design regulations specify similar or longer development lengths for lapped bars compared to single anchor bars [1].

This deficiency can potentially lead to the collapse of a building, especially under horizontal loads. To prevent such damage, the structural elements of a building are reinforced using the necessary techniques, and as a result, the problems caused by the insufficient length of the edge connection are solved.

2 | Methodology

RC structures are widely used in construction. However, their performance is influenced by several factors, including the properties of the materials used and the prevailing conditions. RC elements lose their strength due to aging, exposure to natural disasters, or defects in concrete manufacturing and construction. Accordingly, the necessity of strengthening RC elements before loading becomes an important aspect so that the existing structures can withstand additional loads during their useful life and avoid any sudden failure, especially shear failure.

Fiber-reinforced polymer (FRP) materials have received attention in recent years for use in strengthening and reconstructing RC elements. FRP is a material consisting of polymers reinforced with different types of fibers. This combination has several advantages over other common building materials such as steel and wood. FRP is known for its high strength, lightweight, non-corrosiveness, ease of handling and installation, and wide availability and versatility in all sizes, geometries, and dimensions. There are different types of fibers. However, carbon, glass, and aramid are the most widely used types of FRPs [2].

Two main techniques can be used to strengthen RC elements with FRPs: External Bonding (EB) techniques and near-surface installation. The EB technique is applied by bonding FRP sheets or sheets to the external surfaces of the RC element using high-strength adhesives (epoxy resin or cement grout).

Several studies were conducted on the strengthening of RC elements with EB Carbon Fiber Reinforced Polymers (CFRP) in compression, bending, and shear. The main conclusion proved that the use of CFRP in the strengthening process increases the capacity of all elements. However, premature failure has occurred widely due to CFRP absorption and debonding. In shear strengthening, the EB technique was effective in increasing the capacity using all designs of sheets and laminates (horizontal, vertical, and inclined with different angles). However, inclined CFRP sheets recorded better improvement than other designs. In addition, the greater the effective depth of the beam, the greater the probability of CFRP separation and propagation of shear cracks before failure [3].

The NSM technique was considered as a solution to delay the separation of CFRP due to the increase of the bonding surface between the concrete and CFRP surfaces. This technique is applied by installing FRP bars, ropes, or strips into pre-cut open grooves in the concrete cover using epoxy or cementitious adhesives. This technique does not require any surface treatment or preparation other than grooving and reduces fire damage, aging effects, and mechanical damage. In 2023, Zignago and Barbato [3] studied the behavior and capacity of RC beams strengthened with NSM CFRP.

Round bars and strips were used with spacing, slope, and groove-filling epoxy resin. They concluded that the use of NSM-CFRP increases the shear capacity. However, debonding of the lateral concrete cover of the inner stirrup was observed without debonding of the CFRP. In addition, the stiffer the epoxy resin used, the lower the contribution of CFRP to the shear capacity. In 2020, Al Ajarmeh et al. [4] investigated the effect of strengthening RC beams with NSM-CFRP in shear. The depth of lateral concrete cover, NSM-CFRP inclination angle, and strip length were tested.

This research proved that longer and sloping strips are better than short and horizontal strips. In addition, the separation of the concrete cover can be delayed or prevented by increasing the depth of the concrete cover. Ahaieva et al. [5] conducted a study to investigate the behavior of RC beams reinforced with CFRP strips and ropes. Different distances, slopes, and designs were considered.

The results showed that ropes and inclined strips have the highest capacity depending on the distance. The smaller the distance used, the greater the increase in capacity. In addition, the use of NSM-CFRP ropes and strips changed the failure mode from brittle shear to flexural shear failure [6].

Deep RC beams transfer the load to the support as a simply supported beam through a compression mechanism. A beam that has a greater height (h) compared to the length of the span (l) is called a deep beam. The ratio of length to height (l/h) should be less than a certain value compared to the deep beam. According to the American Concrete Institute (ACI) 318-14 [5], deep beam is defined in two aspects. First, the beam has a clear span-to-depth ratio less than or equal to four times the depth of the beam. Second, the concentrated load area is located at twice the depth of the member from the surface of the support. The deep beam is considered a complex phenomenon, as various experimental investigations have already been carried out, but its structural behavior is still not reliable. Many researchers concluded that failure is largely influenced by its shear capacity.

Therefore, the transformation of shear behavior into one of the key factors in analyzing the behavior and safety of deep beam structure includes nonlinear deformation strains and non-bending behavior. The elastic theory is not applicable to the analysis of the behavior of deep beams because the plate sections do not remain flat after the concrete cracks. Considering the structural behavior, the load transfer mechanism of deep beams occurs through concrete footings, with supports forming an arch effect and further leading to higher shear strength [7]. Deep beams as transfer elements The load and support of gravity structures act on the offshore foundation. Grid openings are often used in such beams to provide access to doors, windows, and other facilities, such as ventilation units and air conditioning ducts, or to accommodate critical facilities. The expansion of such openings due to mechanical requirements or changes in building performance reduces the shear capacity of the element and thus creates a serious safety hazard.

3 | Deep Beams

Deep RC beams transfer the load to the support as a simply supported beam through a compression mechanism. A beam that has a greater height (h) compared to the length of the span (l) is called a deep beam. The ratio of length to height (l/h) should be less than a certain value compared to the deep beam. According to the ACI 318-14, deep beam is defined in two aspects. First, the beam has a clear span-to-depth ratio less than or equal to four times the depth of the beam. Second, the concentrated load area is located at twice the depth of the member from the surface of the support.

The deep beam is considered a complex phenomenon because various experimental investigations have already been carried out, but its structural behavior is still not reliable. Many researchers concluded that failure is largely influenced by its shear capacity. Therefore, the transformation of shear behavior is one of the key factors in analyzing the behavior and safety of the structure. Deep beam includes non-linear deformation strains and non-bending behavior [8]. The elastic theory is not applicable to the analysis of the behavior of deep beams because the plate sections do not remain flat after the concrete cracks [9]. Considering the structural behavior, the load transfer mechanism of deep beams occurs through concrete footings, with supports forming an arch effect and further leading to higher shear strength [10].

Deep beams act as load transfer and support elements for gravity structures based on offshore foundations. Grid openings are often used in such beams to provide access to doors, windows, and other facilities, such as ventilation units and air conditioning ducts, or to accommodate critical facilities. The expansion of such openings due to mechanical requirements or changes in building performance reduces the shear ability of the element and thus creates a serious safety risk [11]. In the construction of high-rise buildings, the pipes and ducts of the utilities contain essential services such as water, gas, and electricity supply, which require a significant number of pipes or tubes. In the past, such pipes or ducts were usually suspended under a concrete slab covered by a suspended ceiling, forming a dead chamber [12]. With dead space, the building is said to be higher than the required head space, hence increasing the cost of construction. With the growth of the construction industry, openings of various shapes are created through the floor joists for the flow of pipes and conduits of the facilities. It has become a relevant practice in avoiding the problematic issue of headspace caused by the suspension of pipes and ducts. It is, therefore, important that these pipes and ducts are routed through an opening in a floor beam to reduce headroom and provide a more compact and economical structure. The shape of the openings is different in the shape of a circle, square, or rectangle. Round openings are commonly used in electrical wiring, telephone lines, and computer networks, while air conditioning services use square or rectangular openings. Such gaps in RC beams raise many concerns about the structural performance of the members. This action makes the simple beam more complicated. As the cross-sectional dimensions of the beams change abruptly, the opening angles are exposed to high levels of stress, which can lead to extensive cracks that are not aesthetically and sustainably permissible. In addition, the openings on the RC beam in the cross-section of the network reduce its rigidity.

This can lead to multiple cracks and distortions that severely damage the strength and stability of the beam. The reduced area in the total cross-sectional dimension of a beam changes the behavior of a simple beam to a more complex behavior. To restore the load-carrying capacity of the deep RC beam, strengthening the vicinity of such a span is very important. Therefore, RC beams, including spans, should be properly constructed and inspected for strength and stability to minimize losses. Shear behavior is the main factor that can disturb the internal stresses of the deep beam structure. In shear behavior, compression grows in one direction, while tension grows in the vertical direction. As the beam depth increases, shear behavior leads to sudden failure. Because of their brittle nature, crack propagation is much greater in larger size deep beams than in smaller size deep beams. The failure of deep beams occurs due to the crushing of concrete in the compressive zone of the adjacent supports or directly along the shear crack formation [13].

Fig. 1. Deep beams.

Reinforcement of beams with openings depends especially on its categories. In the construction industry, openings in deep beams are primarily classified as pre-planned or post-planned openings. Factors such as location, size and shape are already identified during the construction phase in pre-planned openings. Hence, it is beneficial to provide adequate reinforcement and serviceability of spandrel beams during construction. This factor improves the reinforcement behavior of a deep beam with openings. Considering the case of post-planning openings, the existing beam element is drilled for openings that affect the performance of the structure. However, specific guidelines or standards regarding structural element openings are not currently available in any of the major codes. During the process of loading the pipes and conduits of the installation, problems may occur. Opening positions in the deep beam are provided or relocated by mechanical and electrical engineers [14].

The structural engineer analyzes the identified drilling position so that it may not be in the critical zone. This simplifies opening positions in the structural element for the arrangement of pipes and ducts that may not be considered during the construction phase. Simplifying the installation of longer pipes and ducts results in time savings, less manpower, and cost-effectiveness, especially in multi-story construction. The construction of these openings greatly interrupts the load transfer mechanism, which can lead to the failure of the structure. According to previous studies, the failure of a deep beam is controlled by its shear capacity [15].

In order to increase the shear capacity and regain the strength of the affected deep beam, it is treated with external reinforcing materials, namely FRP. FRP composites consist of fiber, resin, binder, fillers, and additives. Due to the increased deformation modulus, the fiber contributes to the mechanical strength of the FRP, while the resin helps to transfer or distribute stress from one fiber to another to protect the fibers from environmental and mechanical damage. The fiber-matrix interface significantly affects the performance of FRP composites. In addition, fillers are useful for reducing cost and shrinkage, while additives help improve mechanical and physical properties as well as the performance of composites. The FRP reinforced the deep girder externally and strengthened other such structural members affected during the drilling process. Beg said Toptancı et al. [16] different types of FRP sheets that are used in industries include CFRP, Glass Fiber Reinforced Polymer (GFRP), Aramid Fiber Reinforced Polymer (AFRP), and reinforcement polymer. It is made with Basalt Fiber Reinforced Polymer (BFRP).

Compared to other FRPs, glass FRPs are relatively inexpensive. This material is the most widely used material in the construction sector. However, the primary disadvantages of GFRP include reduced deformation modulus, reduced moisture and alkali resistance, as well as reduced durability due to tensile failure. Polymers with more static and impact behavior are called AFRP. However, their use is limited due to both reduced durability and UV sensitivity. Another disadvantage of aramid fibers is the difficulty of the cutting technique and its process [17].

On the other hand, BFRP is a very durable material with high-temperature resistance and strong tensile strength. Additional benefits include high acid resistance, superior electromagnetic properties, corrosion resistance, UV and radiation resistance, and excellent vibration resistance.

Finally, CFRP has a large deformation modulus and greater fatigue resistance, as well as no water absorption [18]. Therefore, CFRP is the most widely used external reinforcement material and is widely recommended by industries and researchers due to its outstanding properties, i.e., higher tensile strength, lighter weight, corrosion resistance, flexural strength, and recovery of overall structural strength. And its ease of use in the field of construction.

Based on past research, various researchers have investigated the structural behavior of deep-RC beams and their strengthening performance using foreign materials. However, due to the complex behavior and deformed geometry, limited research is available on the structural behavior of openings in deep beams. Opening flow in the web of an RC beam contributes to several beam performance issues, for example, reduced beam stiffness, excessive cracking, excessive deflection, and reduced beam strength. In addition, a sudden change in beam cross-sectional dimensions resulted in high-stress concentration at the corners of the span, which may contribute to cracks that are intolerable from an aesthetic and durability point of view. The short stiffness of the deep beam may also cause excessive deflection under service load, causing significant redistribution of internal forces and moments in an RC deep beam. Fibrous materials, such as CFRP sheets, can increase the structural integrity of deep RC beams [19].

These fibers of CFRP layers are generally uniformly distributed and randomly oriented. CFRP sheets can increase structural strength, reduce the need for steel reinforcement, improve ductility, reduce crack width, tightly control crack width, improve durability, and increase frost resistance. Due to the uniform distribution of CFRP fibers, it acts as a three-dimensional reinforcement.

4 | Determining the Weight of Each Criterion Using the Fuzzy Swara Method

4.1 | The Results of Prioritizing Indicators Using the Fuzzy Method

The results of the first step: in this step, each of the indicators for identifying the position of RC beams was coded from C1 to C12, and then each of the indicators was sorted in descending order using the opinions of experts, the results of which are given in *Table 1*.

Table 1. Ranking of RC beams ranking indicators.

Rank	The Ranking Indicators of RC Beams	Code
1	Time	C1
4	Adaptability to the weather	C2
5	Notification of the employer, consultants, and contractors	C3
2	Cost	C4
3	The high volume of operations	C5
7	Detachment around the amplifier page	C6
8	Expert people	C7
12	Transportation	C8
11	Complexity of calculations	C9
6	Quality effectiveness	C10
10	The possibility of creating the required coverage	C11
9	Access to material	C12

The results of the second step: in this step, the importance of each index compared to the previous index was determined by each expert using fuzzy verbal expressions, and the results are shown in *Table 2*.

Table 2. The relative importance of each index compared to the previous more important index according to experts and the range of verbal expressions and corresponding fuzzy numbers.

connoisseur 5	connoisseur 4	connoisseur 2	connoisseur 1	Code
-	-	-	-	C1
(0.28, 0.33, 00.4)	(0.28, 0.33, 00.4)	(0.28, 0.33, 00.4)	(28, 0.33, 00.4)	C4
(0.4, 0.5, 0.66)	(0.28, 0.33, 00.4)	(0.22, 0.25, 0.28)	(0.4, 0.5, 0.66)	C5
(0.4, 0.5, 0.66)	(0.22, 0.25, 0.28)	(1, 1, 1)	(0.28, 0.33, 00.4)	C2
(0.4, 0.5, 0.66)	(1, 1, 1)	(0.28, 0.33, 00.4)	(0.22, 0.25, 0.28)	C3
(0.28, 0.33, 00.4)	(0.4, 0.5, 0.66)	(0.28, 0.33, 00.4)	(0.66, 0.5, 1.5)	C10
(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	C6
(0.22, 0.25, 0.28)	(0.22, 0.25, 0.28)	(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	C7
(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(28, 0.33, 00.4)	C12
(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(0.22, 0.25, 0.28)	C11
(28, 0.33, 00.4)	(28, 0.33, 00.4)	(28, 0.33, 00.4)	(1, 1, 1)	C9
(0.4, 0.5, 0.66)	(0.22, 0.25, 0.28)	(0.22, 0.25, 0.28)	(0.28, 0.33, 00.4)	C8

5 | Choosing the Best Strategy Using the Electra Method

At this stage, using the weights obtained from the fuzzy method, the best strategy for reinforcing RC beams is chosen. Et choice in translating to reality means an elimination choice in translating to reality. In this method, instead of ranking the options, the non-ranking concept is used. In this method, all options are evaluated using non-ranked comparisons, and in this way, ineffective options are removed. All the steps of the Electra technique are based on a coordinated set and a non-coordinated set, which is why it is known as coordination analysis. In the Electra method, quantitative and qualitative indicators are used, and two-way comparisons between options obtain their ranking.

Multi-indicator problems are expressed contractually with a set of options, indicators, and superior values. In these problems, a set of options must be evaluated, and the desired evaluation is done with a set of indicators. The steps of doing the work are as

I. Calculation of the normal decision matrix of the scale-free matrix.

II. Calculation of the weighted normal decision matrix.

III. Specifying coordinated and inconsistent sets.

IV. Calculation of coordination matrix.

V. Calculation of the inconsistency matrix.

VI. Determining the effective coordination matrix.

VII. Determining the effective inconsistent matrix.

VIII. Calculation of the effective overall matrix.

7 | Conclusions

7.1 | The Results of the Fuzzy Swara Analysis to Weight the Criteria

According to the findings of the research, time (C1) is ranked first with a weight of 0.33; cost is ranked with a weight of 0.22 (C4); high volume of operations (C5) is ranked third with a weight of 0.15, compatibility with climate (C2) is ranked with a weight of 1/0 in the fourth place, Information of the employer, consultants and contractors (C3) with a weight of 0.062 in the fifth place, the effectiveness of quality (C10) with a weight of 0.043 in the sixth place, separation of the reinforcing page (C6) with a weight of 0.028 in the seventh place, people Expert (C7) with a weight of 0.019 in the eighth place. Access to material C12, with a weight of 0.012, ranked ninth; the possibility of creating the required coverage C11, with a weight of 0.008, ranked tenth; the complexity of calculations C9, ranked eleventh; and transportation C8, ranked 12th.

7.2 | The Results of Electra's Analysis to Choose The Best Strategy

I. Use of GFRP composites.

II. Use of polymer composite reinforced with SFRP.

III. Using rebars made of GFRP.

IV. Polymer sheets reinforced with external FRP.

V. Use of GFRP reinforcement.

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