A Comparative Analysis on the Methods of Strengthening Isolated Reinforced Concrete Columns

Mungur Ved Vritesh, Seeboo Asish

Civil Engineering Dept., Faculty of Engineering, University of Mauritius, Reduit, Mauritius
vmungur15@gmail.com

Abstract. In the construction industry, there are several methods which have been used to improve the capacity and effectiveness of structural concrete structures. Engineers can extend the life of the structures by implementing strengthening techniques. One of the techniques to strengthen columns and beams is the use of jacketing. The strength of the structural members is enhanced through the surface structural bonding of materials such as Carbon-Fibre Reinforced Polymer (CFRP), Glass-Fibre Reinforced Polymer (GFRP), ferrocement, steel angles, steel plates, wire mesh and so on. In this study, 18 reinforced concrete short columns of cross-sectional size 60 mm × 60 mm and 500 mm height were cast using concrete grade 30 MPa. The columns were subjected to compressive axial loads till failure. Moreover, the damaged columns were strengthened using three structural strengthening techniques namely, Reinforced Concrete Jacketing (RCJ), Reinforced Concrete Wire Mesh Jacketing (RCWJ) and, Steel Jacketing (SJ). The columns strengthened using RCJ and RCWJ had a cross section of 120 mm × 120 mm while SJ had a cross section of 66 mm × 66 mm. Six different configurations were used for each technique. The experimental investigations showed a minimum increase of 48.0%, 48.7% and 35.2% in the axial compressive strength when strengthened using RCJ, RCWJ and SJ respectively. Among the three strengthening techniques, SJ was determined to be the effective technique on considering structural design, time production and costs.

1. Introduction
Reinforced Concrete (RC) is one of the most used materials in the construction sector in both developing countries and the remotest area in the world [1]. The main RC structures are slabs, beams, columns, foundation, and staircase and each of them plays an important role in the durability and stability of a building structure. Likewise, column is the skeletal backbone of a structure and is usually designed in compression to transmit the loads sustained from beams and slabs to the foundation [2].

However, during the service life of the column, the design performance of the structure may be affected. The reasons arose due to environmental degradation (change in temperature and high humidity), poor workmanship, inadequacy in the structural design, deficiency in the materials used [3], and the exceedance of the design load of the column due to the construction of additional floors to a building.

There are several buildings which consist of cracked column or even failed column. As a result, it is costly and difficult for the owner to pull down the damaged column and build another column to expect it to work as per the new design. Additionally, during the process of pull-down, the adjacent structural members may be affected in terms of strength and may cause disturbance to the whole structure. Therefore, to restore the structural integrity of the column, it is worthy to consider strengthening works. Moreover, with the world aiming at sustainable design it can be said that strengthening work is a more sustainable solution over demolishing and constructing another structure; as the latter involves the
conservation of existing resources and reducing the overall carbon footprint [4]. Additionally, the strengthening works need to be effective, economical and require a design method to assess the actual features of the concerned building.

When a damaged column is being strengthened, the strengthened column must have the following objectives [5]:

i. The column must re-establish its structural integrity by gaining an increase in the compressive strength, durability, and stiffness;
ii. The aesthetic of the column must be maintained;
iii. There should be proper bonding with parent surface of the existing column, and;
iv. The method used must be easy to apply.

The intent of this study was to determine the effective method of strengthening isolated reinforced concrete columns on considering structural designs, production, and costs. The main objectives of the research were to:

a) Design and cast sample columns using a concrete mix design of grade 30 MPa;
b) Subject the sample columns with axial compressive forces till failure and apply the methods of strengthening to the damaged columns;
c) Perform a comparative analysis in terms of structural designs, production, and costs of the strengthened columns.

2. Literature Review

2.1. Reinforced Concrete Jacketing

In this method, existing RC column is strengthened with the addition of concrete, longitudinal and transverse reinforcement. As a result, the cross section of the column is increased over a part or the entire length of the column. Additionally, the transverse reinforcement (stirrups) must be placed and positioned around the existing column while the longitudinal reinforcement must be continuous through the slabs [6]. Moreover, the spacing between the stirrups must not exceed 300mm and the addition of cast-in place concrete must have a thickness of at least 50mm [7]. This technique improved the structural performance of the column that is the compressive axial load carrying capacity, stiffness, and ductility. However, this technique is time consuming due to the installation of formworks and props [4].

2.2. Reinforced Concrete Wire Mesh Jacketing

The use of wire mesh as a strengthening material is a technique applied to enhance the structural properties of RC columns. This technique consists of increasing the cross-section of the column with the addition of concrete or cement mortar and wire mesh being wrapped around the newly added reinforcement of the damaged column. A study using wire mesh concrete jacketing led to an increase of 33% in the load carrying capacity [8]. Also, the strengthened column exhibited a failure in a ductile manner as compared to a brittle failure of the non-strengthened control column specimens.

2.3. Steel Jacketing

In this strengthening technique, four steel angles are fixed at the corners of the existing column while steel strips are spaced and welded to the steel angle to form a steel cage. The steel plates are encased through the column and a non-shrink grout is used to fill the gap between the column and the steel. Such method is effective in enhancing the loading capacity and stiffness of the RC column; however, there is an issue where an antirust work must be faced during the strengthening works [9]. This technique involves an elasto-plastic confinement where maximum confined pressure is achieved through the yielding of steel bars [10].

3. Experimental Programme

3.1. Sample Columns

An actual isolated column of a building of cross-sectional size 350 mm × 350 mm was scaled down for laboratory testing. The scaled column was termed as sample column. The size of the sample columns
was 60 mm × 60 mm and height 500 mm. Moreover, the dimension of the sample column was respected as per Clause 3.8.1 of BS 8110-1:1997.

The main reinforcement of the columns consisted of four Ø6 mm steel bars (f_y = 250 MPa) while Ø6 mm steel bars (f_y = 250 MPa) were used as links with spacing of 72 mm. The detailed reinforcement of the sample column is illustrated using Figure 1.

![Figure 1. Detailed Reinforcement of Sample Columns](image)

3.2. Experimental Investigation

The experimental investigation consisted of two phases:

Phase 1: Production of Sample Columns and Damage till Failure
- To cast 18 sample columns having characteristics strength of 30 MPa;
- To subject the sample columns to compressive axial forces until failure;
- To record the failure load and the corresponding compressive deflection.

Phase 2: Application of Strengthening Techniques and Determination of the Gain in Compressive Axial Strength
- To strengthen the damaged columns by applying the techniques of Reinforced concrete jacketing, Reinforced concrete wire mesh jacketing and Steel jacketing;
- To subject the strengthened columns to compressive axial loads;
- To record the failure load and the corresponding compressive deflection;
- To compare the maximum compressive loads of the sample and strengthened columns to determine whether there is an improvement or not in the properties of the strengthened columns.

3.3. Test on Hardened Concrete

   a) Standard concrete cubes were used for compressive strength test.
   b) The sample columns were cured for 28 days as compared to the cubes which were removed from the curing tank on 7 and 28 days respectively for compressive strength test.

3.4. Testing Setup and Instrumentation to Fail the Sample Columns

This stage involved the failure of the 18-sample columns to subsequently strengthen the sample columns using the three selected techniques. The compression testing was performed using the setup as shown in Figure 2.
Figure 2. Schematic Diagram of the Testing Setup

The sample column was subjected to vertical compressive loads which was provided by the bottle hydraulic jack. Steel plates were provided at top and bottom ends of the column such that spalling of the concrete is restricted during loading. Loading was increased incrementally. Moreover, the instrumentation consisted of a dial gauge which was fixed to the loading setup to measure the compressive displacement of the sample column when loaded. The loading was stopped when the sample column was failed.

3.5. Strengthening of Damaged Columns

3.5.1. Reinforced Concrete Jacketing. Six of the damaged sample columns were strengthened using this technique. The process was executed with the addition of horizontal steel connectors in the sample columns. Steel connectors of diameter 6 mm were added to the sample by drilling a 10 mm diameter hole. The details of the jacketing are given in Table 1.

| Diameter of Horizontal Steel Connector | 6 mm |
|----------------------------------------|------|
| Length of Horizontal Steel Connector   | 90 mm|
| Diameter of Holes to be Drilled        | 10 mm|
| Thickness of New Concrete              | 30 mm on each side |
| Diameter of Vertical (Main) Bar        | 6 mm |
| Length of Vertical (Main) Bar          | 470 mm|

Epidermix 372 was used to bond the steel connectors to the concrete and fill the void between the hole and the steel bar. Additionally, the main bars were welded to the horizontal steel connectors. Different combinations were used for the strengthening works and the details of the combinations are given in Table 2.
Table 2. Combinations Used for Concrete Jacketing Columns.

| Strengthened Column | Number of Vertical Bar | Number of Steel Connector | Spacing between Steel Connectors (mm) |
|---------------------|------------------------|---------------------------|--------------------------------------|
| RCJ                 | RCWJ                   |                           |                                      |
| RCJ1                | 2                      | 2                         | 300                                  |
| RCJ2                | 2                      | 3                         | 150                                  |
| RCJ3                | 2                      | 4                         | 100                                  |
| RCJ4                | 4                      | 4                         | 300                                  |
| RCJ5                | 4                      | 6                         | 150                                  |
| RCJ6                | 4                      | 8                         | 100                                  |

Figure 3 showed the reinforcement of the strengthened jacket with the exposed surfaces of the sample columns being hacked to provide good bonding between the old and new concrete.

![Figure 3. Reinforcement of the RC Jackets](image)

3.5.2. Reinforced Concrete Wire Mesh Jacketing. Six of the damaged sample columns were used for strengthening through the technique of reinforced concrete wire mesh jacketing. The process was implemented in a similar way as the technique of RCJ except that in RCWJ, galvanised steel wire mesh was used. The details of the reinforcement are given in Table 3.

Table 3. Details of Reinforced Concrete Wire Mesh Jacketing.

| Diameter of Horizontal Steel Connector | 6 mm       |
| Length of Horizontal Steel Connector  | 90 mm      |
| Diameter of Holes to be Drilled       | 10 mm      |
| Thickness of New Concrete              | 30 mm on each side |
| Diameter of Vertical (Main) Bar        | 6 mm       |
| Length of Vertical (Main) Bar          | 470 mm     |
| Size of Galvanised Steel Wire Mesh     | 25 mm x 25 mm x 1.15 mm |
| Number of Wrapping of Wire Mesh        | 1 wrap around the damaged sample column |

The combinations used for this strengthening technique are given in Table 2.

Casting of Concrete

New column moulds using marine board were prepared and had internal dimensions of 120x120x500 mm. Concrete grade of 30 MPa was used to fill the moulds containing the sample columns strengthened using RCJ and RCWJ. The moulds of the reinforced concrete jackets are illustrated using Figure 4.
Steel Jacketing (SJ). Six of the damaged sample columns were used for strengthening through the technique of steel jacketing. Cement grout was used to fill the spalled concrete such that the column regains its original shape. The cement grout was prepared using a ratio of 1:3 for cement: fine aggregate. The RC columns were then cured for 7 days to apply the required reinforcement. The process was implemented by using steel angle bars and steel strips. The details of the steel jackets are given in Table 4.

Table 4. Details of Steel Jacketing.

| Property                        | Value                        |
|---------------------------------|------------------------------|
| Size of Equal Angle Bar         | 25 mm × 25 mm × 3 mm         |
| Size of Steel Strips            | 25 mm × 3 mm                 |
| Steel Grade                     | S235                         |
| Properties of Steel Used        | Hot Rolled and Non-Galvanised|
| Connection between Angle Bar and Steel Strips | Welding                    |
| Length of Equal Angle Bar to Use | 490 mm                      |
| Length of Flat Steel Strips to Use | 10 mm                      |

The different combinations used for steel jacketing is given in Table 5.

Table 5. Combinations Used for SJ.

| SJ Strengthened Column | Number of Angle Bars | Number of Flat Steel Strips on Each Side | Spacing between Steel Strips (mm) |
|------------------------|----------------------|-----------------------------------------|-----------------------------------|
| SJ1                    | 4                    | None                                    | None                              |
| SJ2                    | 4                    | 2                                       | 465.0                             |
| SJ3                    | 4                    | 3                                       | 232.5                             |
| SJ4                    | 4                    | 4                                       | 155.0                             |
| SJ5                    | 4                    | 5                                       | 116.3                             |
| SJ6                    | 4                    | 6                                       | 93.0                              |

The angle bars were fixed to the RC column using Epidermix 372. It should be noted that rawl bolts were not used as a method of fixation because the corners of the RC column would have been damaged when drilling the holes. The steel strips were welded to the angle bars. Also, a gap of 5 mm was kept at both ends of the column to prevent direct compressive loading of the steel angle bars during testing. The combinations used for steel jacketing are shown in Figure 5.
3.6. Testing of Strengthened Sample Columns
This stage formed part of Phase 2 with the purpose of determining the gain in compressive axial strength of the 18 damaged sample columns which were strengthened. The procedures of the testing were carried in the same way as described for failing the sample columns.

3.7. Precautions Taken During Experimental Investigations
- The steel bars were cleaned using a wired brush.
- The surfaces for welding were cleaned and dried. After welding, the welds were cleaned and all loose materials in the surrounding areas were removed.
- The surfaces of sample and strengthened columns were painted with white cement to allow the visibility of cracks when subjected to compressive loading.

4. Test Results and Discussion

4.1. Compressive Strength Test
The concrete was designed to have a characteristics strength of 30 MPa. The obtained compressive strength was validated since the strength gained by the concrete had met the minimum requirement of 67 % and 99 % on 7 and 28 days respectively [11].

4.2. Failure of Sample Columns
On compressive loading, the sample column was failed when the concrete was spalled-off due to the buckling of the main reinforcement bars. The failure load was obtained from the Load-Displacement graphs. The failure of the sample column is illustrated using Figure 6.
Figure 6. Failed Column

Graphs of load-displacement of the damaged sample columns were plotted to extrapolate the failure load. This is because the loading was increased incrementally and often, the sample column failed between the two consecutive readings, thus, it was difficult to obtain the failure load due to the drastic change in the meter reading during the experimental testing. The load at failure and deflection at failure are given in Table 6.

Table 6. Summary of the Failed Sample Columns.

| Column Ref. | Compressive Strength (MPa) | Load at Failure (kN) | Deflection at Failure Load (mm) | Maximum Deflection (mm) |
|-------------|-----------------------------|----------------------|---------------------------------|-------------------------|
| RC 1        | 39.8                        | 81.4                 | 3.79                            | 4.91                    |
| RC 2        | 39.8                        | 103.4                | 5.56                            | 8.77                    |
| RC 3        | 39.8                        | 92.5                 | 3.53                            | 3.86                    |
| RC 4        | 39.8                        | 78.1                 | 7.09                            | 9.51                    |
| RC 5        | 39.8                        | 112.1                | 4.36                            | 4.91                    |
| RC 6        | 39.8                        | 141.8                | 5.59                            | 6.59                    |
| RC 7        | 40.2                        | 126.0                | 7.50                            | 8.45                    |
| RC 8        | 40.2                        | 112.3                | 5.98                            | 6.79                    |
| RC 9        | 40.2                        | 129.1                | 5.76                            | 6.97                    |
| RC 10       | 40.2                        | 98.9                 | 3.67                            | 12.35                   |
| RC 11       | 40.2                        | 106.2                | 4.80                            | 7.87                    |
| RC 12       | 40.2                        | 84.7                 | 4.73                            | 7.72                    |
| RC 13       | 40.2                        | 80.6                 | 4.65                            | 6.22                    |
| RC 14       | 40.2                        | 92.3                 | 3.61                            | 4.37                    |
| RC 15       | 40.2                        | 109.2                | 5.55                            | 9.47                    |
| RC 16       | 40.2                        | 119.2                | 5.28                            | 8.34                    |
| RC 17       | 40.2                        | 100.2                | 4.94                            | 5.78                    |
| RC 18       | 40.2                        | 104.8                | 2.42                            | 3.36                    |

Figure 7 displayed a sample graph, and it was observed that on compressive loading of the column, there existed a non-linear relationship between the load and deflection which conformed with previous research. The failure load was obtained at the maximum point of the curve and after failure, no load was taken by the column. However, the deflection increased because the concrete in contact with the steel plate of the setup was being spalled-out of the column.
4.3. Testing of Strengthened Columns

Load-Displacement graphs of the loaded strengthened columns were plotted as shown in Figure 8 and a comparison of the graph for both damaged and strengthened columns was done.

From Figure 8, the following comments were made:
- The displacement of the strengthened column was greater than that of the damaged column which showed that the strengthened column was loaded in a ductile manner while the damaged column failed in a brittle manner.
- The stiffness of the strengthened column was increased since the latter could resist more deflection before failure.
- Also, the compressive loading of the strengthened column was increased.
The same behaviour was observed for columns strengthened using RCJ, RCWJ and SJ.

4.4. Load-Carrying Capacity of Strengthened Columns
The increase in percentage in the load-carrying capacity of the strengthened columns is illustrated in Figure 9.

![Figure 9. Percentage Increase in the Load-Carrying Capacity of Strengthened Columns](image)

From Figure 9, the following were enumerated:

**Reinforced Concrete Jacketing**
- Columns RCJ1, RCJ2, RCJ3 and RCJ4 gained over 100% of its initial strength;
- A similar percentage could have been obtained for RCJ5 and RCJ6 if the column were loaded till failure. Failure was not attained because of the limited capacity of 220 kN of the load cell.

**Reinforced Concrete Wire Mesh Jacketing**
- Columns RCWJ1 to RCWJ6 gained over 45% of its initial strength.

**Steel Jacketing**
- The SJ columns gained over 35% of its initial strength.

4.5. Comparative Analysis of the Three Strengthening Techniques
A comparative analysis of the methods was performed to determine the efficient techniques among the three selected techniques. The analysis was based on the structural designs, production, and cost.

4.5.1. *Structural Design and Production*. From the experimental investigation, the structural designs were performed successfully as the three methods used gained a minimum increase in strength of 48.0
%, 48.7% and 35.2% when strengthened using RCJ, RCWJ and SJ respectively. Production is the time required to execute the strengthening works till the proper operational work of the isolated column. Therefore, the duration to implement the techniques was determined and given in Table 7.

Table 7. Duration to Implement the Strengthening Methods.

| Strengthening Technique                        | Time Duration (Days) |
|-----------------------------------------------|----------------------|
| Reinforced Concrete Jacketing (RCJ)           | 17                   |
| Reinforced Concrete Wire Mesh Jacketing (RCWJ)| 17                   |
| Steel Jacketing (SJ)                          | 7                    |

From the above, steel jacketing required less time to implement the strengthening method; this is because, for the process of steel jacketing, there is no need to install formworks, cast concrete, dismantle the formworks and to cure the column. Likewise, RCJ and RCWJ had the same time duration since they carry the same procedures for implementation. In this sense, SJ is a method which will suit a client and contractor in the shortest time delay.

4.5.2. Costing. A cost analysis was performed to determine the cost estimate to strengthen isolated columns. Prices from a hardware shop were used for the analysis. The total cost estimate is given in Table 8.

Table 8. Cost Estimate.

| Bill No. | Description          | RCJ  | RCWJ  | SJ   |
|----------|----------------------|------|-------|------|
| Bill No. 1 | Materials          | 244.89 | 246.39 | 224.35 |
| Bill No. 2 | Labour and Equipment | 200.00 | 200.00 | 200.00 |
| Sub Total      |                    | 444.89 | 446.39 | 424.35 |
| Add 15% VAT    |                    | 66.73  | 66.96  | 63.65  |
| Total Amount Inclusive of VAT |            | **$511.62** | **$513.35** | **$488.00** |

From Table 8, the following were observed:

a. SJ is the cheapest among the three strengthening techniques.

b. RCJ and RCWJ differs by USD 1.73.
   This difference arises due to the use of different diameter of steel bars and the wire mesh which is used solely for the RCWJ method.

c. RCJ and SJ differs by USD 23.62 while RCWJ and SJ differs by USD 25.35.
   This difference can be explained due to installation of formworks and casting of concrete for both RCJ and RCWJ whereas, SJ involves the fixation of the angle bars and welding of the steel plates.

4.5.3. Comment on Analysis. The criteria of structural designs were satisfied by the three selected strengthening methods and thus, the latter cannot be used to differentiate between the best strengthening method. It implied that the production and costing were the demarcating factors. Therefore, from the above analysis, steel jacketing is the technique which required less time and was more cost effective. As a result, the technique of steel jacketing was deemed to be the best strengthening method of Reinforced Concrete Isolated Columns.

Besides this, though steel jacketing is selected to be the best technique, the client/contractor may not stick to steel jacketing for a strengthening work. For such reason, a decision table is proposed. The decision table consists of the main aspects which the client/contractor may wish to have upon strengthening the column. The decision table is illustrated using Table 9, 10.
Table 9. Legend to Use Table 10.

| Likely to Use |
|---------------|
| High          |
| Medium        |
| Low           |

Table 10. Aspects to Consider before Strengthening an Isolated Column

| Aspects to Consider before Strengthening the Isolated Column | Strengthening Techniques |
|------------------------------------------------------------|--------------------------|
|                                                            | Reinforced Concrete Jacketing | Reinforced Concrete Wire Mesh Jacketing | Steel Jacketing |
| 1. Restoration of Structural Strength                        |                          |                                         |                |
| 2. Ease of Construction                                     |                          |                                         |                |
| 3. Aesthetic                                               |                          |                                         |                |
| 4. Cost of Implementation                                  | USD 511.62               | USD 513.35                              | USD 488.00 |
| 5. Duration of Strengthening Work                          | 17 days                  | 17 days                                 | 7 days       |
| 6. Increase in Space around the Isolated Column             | High Increase in Space   | High Increase in Space                  | Low Increase in Space |
| 7. Dead Load                                               | High Increase in Dead Load| High Increase in Dead Load              | Low Increase in Dead Load |

The above table is used to guide the client/contractor on the strengthening technique to be selected based on the site condition and the specification of the column to be strengthened.

5. Conclusions

In a nutshell, in this research work, the effective method of strengthening isolated damaged reinforced concrete columns on considering structural designs, production and costs was determined through an experimental analysis.

In this study, the experimental investigation was based on casting sample columns which were subjected to compressive loading and damaged till failure. The damaged columns were then strengthened using the three techniques; Reinforced Concrete Jacketing (RCJ), Reinforced Concrete Wire Mesh Jacketing (RCWJ) and, Steel Jacketing (SJ). The strengthened columns were then subjected to compressive loadings. Based on the experimental results, the following conclusions are made:

1. The sample columns were failed due to the buckling of the reinforced steel bars followed by spalling of the concrete.
2. The confinement of the isolated reinforced concrete column using RCJ, RCWJ and SJ improved the compressive axial load-carrying capacity of the column since they achieved a minimum increase in strength of 48.0 %, 48.7 % and 35.2 % respectively. As a result, the strengthened columns minimised the early failure of the column when loaded.
3. During the compressive testing of the strengthened columns, cracks appeared after a loading of 200 kN which gave rise to an enhancement in the durability and stiffness of the column.
4. RCJ and RCWJ provided a good bonding with the old hacked concrete surfaces since no debonding of the new concrete from the old concrete was observed.
5. The strength improvement for both RCJ and RCWJ was accounted due to the shear friction provided by the addition of the steel connector in the column.
6. A spacing less than 300 mm of the steel connectors for both RCJ and RCWJ methods proved to be more effective in improving both the axial compressive strength and maximum deflection of the column.
7. The steel strips used in SJ methods enhanced the confinement to the concrete and provide lateral supports to the angle bars.
8. The advantage of SJ over RCJ and RCWJ was the insignificant increase in the cross-section of the column.
From the above, the results of this research work were in accordance with the previous studies from the literature, thus, the experimental investigations were successfully carried out.

Finally, to determine the effective strengthening techniques among the three methods, three main factors were considered namely, structural design, production, and cost. However, only production and cost were the factors which were able to differentiate in selecting the best technique. From the comparative analysis, the three methods were economical and long-lasting strengthened techniques, but steel jacketing was the one to be deemed the efficient technique since it required less time to strengthen the column and was more economical.

Acknowledgement(s)
The authors would like to acknowledge the support received from the University of Mauritius, and the assistance of the technicians at the concrete laboratory of the civil engineering department. Also, I thank my parents, friends and above all the god almighty for making this work complete.

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