Performance of reinforced concrete columns strengthened with carbon fiber reinforced polymer (CFRP) - case study of an abandoned school project

N M Amin¹ and N A Ahmad¹

¹ Faculty of Civil Engineering, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia

Corresponding E-mail: norli830@uitm.edu.my

Abstract. This research presented a case study of an abandoned three-storey school building focusing on strengthening of Reinforced Concrete (RC) column with Carbon Fiber Reinforced Polymer (CFRP) jacketing. The constructed structural element of the building was assessed and evaluated by visual observation, destructive tests and non-destructive tests include carbonation tests, ferro scan tests, steel reinforcement verification, Ultrasonic Pulse Velocity (UPV), coring tests and rebound hammer tests. The modeling of the whole building was carried out using Orion 18, a structural analysis program based on the site test results in order to assess the structural integrity of the building. Based on the structural analysis conducted in Orion 18, a column at ground floor level was chosen to be strengthened with multilayer CFRP jacketing. This column has cross-section of 300mm x 300mm with 3600mm in height. Results were obtained through non-linear Finite Element simulation. The behavior of the column with and without CFRP jacketing was studied to observe its axial stress and strain behavior in ABAQUS Finite Element software. The result shows that increasing in number of CFRP layers has a significant effect on the behavior of such columns which was expected due to confinement effect.

1. Introduction

An abandoned school project consists of multiple building of classroom and administration building was chosen for the case study. The construction of this building has been started seen 2012 and due to delay in construction, the first appointed contractor was terminated in 2014 with almost all the RC structural members had been constructed. In 2016 a new contractor was appointed to continue the remaining work. Hence, there is a need for structural assessment and evaluation to be conducted in order to assess the structural integrity of the building. This research will only focus on Block B which has three-storey classroom building.

Block B which is a three-storey building was model using a computer program Orion 18 Software based on the result obtained from the destructive and non-destructive testing results. There are four carbonation tests, three ferro scan tests verified with one steel reinforcement verification test were conducted to identify the reinforcement arrangement, concrete cover, and concrete behavior when reacting with phenolphthalein. In order to identify the concrete strength of the structural members, there are 15 coring tests, 18 UPV tests and 32 rebound hammer tests were conducted. Reinforced concrete structural members and loads for the building analysis were assigned according to BS8110.

This research also analyzed and observed the behavior of the column strengthening technique using the new technologies that are less time consuming and have an easy installation method which is CFRP jacketing. A column with cross-sectional area of 300mm x 300mm at the ground floor level was...
randomly chosen to be modeled with and without CFRP sheets jacketing using nonlinear analysis in ABAQUS Finite Element Software.

1.1. Carbon fiber reinforced polymer (FRP) jacketing

Carbon Fiber Reinforced Polymer (CFRP) jacketing is widely used in construction industry in recent years. FRP is a composite material made of a combination of reinforced fibers and polymer matrix. The function of reinforced fiber is to provide strength and stiffness. There are three types of fibers alignment which are aligned fibers; the fibers are woven parallel to each other, random fibers; the fibers are woven randomly according to a specific density and woven fibers; the fibers are woven in the shape of a net and this is the strongest among the three. CFRP fiber fabrics are available in different fabric weights. Thousands of individual fiber filaments approximately 6 micro diameters are bonded as tows and formed into fabrics by gluing or weaving onto a plastic supporting mesh which does not contribute to the strengthening properties of the fabric.

It is necessary to consider the effect of the confinement provided by the CFRP in designing the strengthened column. As shown in figure 1 concrete in square column confined by hoop FRP displays an approximately bilinear stress-strain response. The stress-strain curve shows that the initial behavior of the unconfined column and confined column with CFRP is almost the same since the FRP wrap exerts a limited confining pressure on the concrete. The lateral deformation continues to increase as the axial stress increase which reduces the concrete stiffness. The FRP wrap is fully activated in transition zone once unconfined concrete reached its peak strength. At this stage, the stress-strain response becomes approximately linear with a slope dependent upon the stiffness of the hoop FRP.

The first slope of the curve is known as the initial elastic zone with the initial rigidity equal to EI and the second slope as the final plastic zone with a rigidity $E_f$. The slope in the plastic zone increase in accordance with the strengthening stiffness and the slope is closely connected with the strengthening stiffness $E_f$ and is not influenced by the kind of FRP sheet [1]. Hence that the strengthened column confinement governed by the failure of the FRP rather than the concrete itself. Based on [2] there are two factors contributing to the confined behavior which are confinement stiffness and confinement rupture strain capacity.

![Figure 1. Idealized stress-strain curves for FRP-confined concrete [3].](image_url)

1.2. Confined concrete for square column

The confinement action exerted by the FRP on the concrete core is a passive type and will be activated by lateral expansion of concrete under axial load. Lateral strain increase as the axial stress increases and the confining device develops a tensile hoop stress balanced by a uniform radial pressure which reacts against concrete lateral expansion. [4] When column strengthened with FRP subjected to axial compression, the concrete will expand laterally, and expansion is restrained by the FRP.

Based on [5] research, FRP confinement for the square and rectangular column not as effective in increasing the axial strength compared to the circular column and the effectiveness of FRP confinement in increasing the axial strength decrease as the unconfined concrete compressive strength increases. This is because the confining action for square and rectangular columns is mostly concentrated at the corners rather than around the entire parameter and thus level of confinement varies throughout the cross-
section. Research conducted by [6] and [7] shown the confined square columns with reasonable levels of rounding at corners increase 50% maximum in compressive stress while for circular column increase 200% in compressive stress. The efficiency decreases further with columns of rectangular cross-section. Figure 2 shows the effective confinement areas in circular, square, and rectangular columns.

![Effective Confinement Areas](image)

**Figure 2** Effective confinement areas in circular, square, and rectangular columns [8].

2. Methodology

2.1. Structural assessment and evaluation

Based on visual observation, the overall condition for the beam and column are still in good contact despite being abandoned for about two years. Both column and beam do show a little significant quality of deterioration. There is honeycomb problem at both beam and column but it is not very serious and can still be repaired. However, there is present of crack on the slab and it can result in structural failure.

There are four carbonation tests conducted for the Block B which is at the first floor level for beam GH/1, column J/1 and D3 and at the corridor Column K/0. The carbonation test result was tabulated in table 1 shows that there is inconsistency in concrete structural members when reacting to phenolphthalein as a pH indicator. There is some part of the concrete structures turns to purple and there is some part of it does not change to purple. When concrete turns to purple shows that the concrete not carbonated with the carbon dioxide in the air and this concrete can still protect the reinforcement from corrosion and vice versa. This shows that there is problem with the preparation of the concrete mixture.

| Point | Structure | Location | Carbonation Depth | Note |
|-------|-----------|----------|-------------------|------|
| 1     | Beam GH/1 | First floor | < 5mm             | Concrete not carbonated |
| 2     | Column J/1| First floor | < 2mm             | Concrete not carbonated |
| 3     | Column K/0| Corridor   | > 20mm            | Carbonated Concrete    |
| 4     | Column D3 | Ground floor | < 5mm             | Concrete not carbonated |

Ferro scan testing was conducted at three different locations at the Block B which are one at ground floor level for staircase column and another two at the first-floor slab. Result shows that the steel reinforcement was installed according to the construction drawing. However, verification of steel reinforcement was conducted to double confirm the Ferro Scan result and identified the type and size of steel reinforcement.

The steel reinforcement verification was conducted at first-floor slab F1-G/2-3. Based on the steel reinforcement verification result it is found out that the type and spacing of the reinforcement used do not comply with the construction drawing. The type of the reinforcement used is BRC mesh reinforcement instead of high tensile strength reinforcement. Although the size of the reinforcement is the same but the spacing provided differ from the construction drawing. The comparison of steel verification with construction drawing is tabulated in table 2.
Table 2 Comparison between steel verification result with construction drawing.

| Construction Drawing Steel reinforcement verification | Main Reinforcement (mm) | Link (mm) | Concrete Cover (mm) | Result |
|-------------------------------------------------------|-------------------------|-----------|---------------------|--------|
| T10-200                                               | T10-200                 | 25        | Not comply the construction drawing |
| BRC-10 (200 x 220)                                   | BRC-10 (200 x 220)     | 20        |                     |
|                                                       |                         |           | (Bottom Cover)      |

MS 1242:1991 (Clause 6.5.3) specified that the compression strength of in-situ concrete when tested should be 80% of the design strength. In order to determine the reinforced concrete strength, there are fifteen (15) coring test, eighteen (18) Ultrasonic Pulse Velocity (UPV) test and thirty-two (32) rebound hammer test is conducted. From the results obtained it is shown that there is concrete structure member does not achieve 80% of the design concrete (compression strength, $f_{cu}=35\text{N/mm}^2$). The reinforced concrete strength for slab range between $17.6\text{N/mm}^2$ to $47\text{N/mm}^2$ with almost half of the test specimens do not achieve the design compressive strength. For column structural there are about 27 testings conducted and about 20 percent of the specimen failed to achieve the minimum design compressive strength with range of $10.68\text{N/mm}^2$ to $54.09\text{N/mm}^2$. Even though the compressive strength for the beam achieved the minimum design compressive strength but it has raised question since there are only two tests conducted for the beam.

2.2. Structural analysis using Orion Software

Three-dimensional linear elastic behavior models of the reinforced concrete building were analyzed using Orion 18. The height of the building is 10.8m with length 50.3m and width of 11.9 m. Typical floor height is 3.6 m. In this research, the RC building will be simplified in the Orion 18 where only bare frame with slabs is constructed. Some assumptions and approximation modeling were made when creating a reinforced concrete in Orion 18.

The structural properties of the bare frame building were assigned in accordance with BS8110 design code consideration. The beams, columns, and slab thickness cross-section are tabulated in table 3 as described in as-built drawing.

Table 3 Material properties details for the structure model.

| No. | Design Parameters                              | Values of Parameters |
|-----|-----------------------------------------------|----------------------|
| 1   | Compressive strength concrete, $f_{cu}$ for Beam and Column | Minimum $20\text{N/mm}^2$ |
| 2   | Characteristics strength of high yield strength, $f_y$ for longitudinal reinforcement | $460\text{ N/mm}^2$ |
| 3   | Characteristics strength of high yield strength, $f_s$ for shear link reinforcement | $250\text{ N/mm}^2$ |
| 4   | Nominal concrete cover ground slab, ground beam, stump and column | 40mm |
| 5   | Nominal concrete cover upper slab and upper beam | 25mm |
| 6   | Density of concrete, $\rho_c$ | $24\text{kNm}^3$ |

2.3. Finite element modelling for column strengthening

The nonlinear analysis is developed by means of ABAQUS Finite Element Software to simulate the nonlinear behavior of confined column. A three-dimensional deformable solid analysis is conducted to have realistic model. The model general configuration is a vertical column fixed to bottom which is restrained in all directions. For this study, a column at the Ground Floor area in grid line 2/D was chosen for the column strengthening with CFRP jacketing. This column has cross-sectional dimension of 300mm x 300mm with 3600mm in height with main reinforcement and shear reinforcement as shown in figure 3.
Each corner of the column was rounded with 30mm radius to avoid premature failure of CFRP due to shearing at sharp corner and to improve the RC column behavior. There are four (4) models of column with different number of CFRP layers was modeled and each modeled was named as tabulated in table 4. In all cases, the principal fibers were oriented perpendicular to the column axis, in a so-called 0º orientation. Based on [9], the epoxy-based bonding agent can be ignored due to its lower stiffness and for the simplicity of the model.

**Table 4** Summary of column strengthening with CFRP jacketing modelled.

| Column   | Longitudinal steel | Lateral steel | No. of CFRP layers |
|----------|--------------------|---------------|-------------------|
| RColumn0W | 10T25             | R10 – 225mm   | -                 |
| RColumn1W | 10T25             | R10 – 225mm   | 1 layer           |
| RColumn3W | 10T25             | R10 – 225mm   | 3 layers          |
| RColumn5W | 10T25             | R10 – 225mm   | 5 layers          |

Concrete grade for the column was set to compressive strength 20N/mm² since the column compressive strength result tested with the destructive and non-destructive test varied from 54.09N/mm² to 10.68N/mm² and that is the lowest compressive strength can be set in Orion 18 Software. Concrete column was modeled using a solid eight-node element (C3D8R) due to the concrete core deformation characteristics when subjected to axial compression. The material properties for concrete column was set as elastic behavior and by taking into consideration of concrete damaged plasticity as suggested in ABAQUS software manuals. Young’s Modulus of concrete, \( E_c \), and stress-strain curves for compressive behavior was calculated by using equation (1), equations (2), and equation (3) respectively. Poisson’s ratio, \( v \), and concrete damage plasticity are inputted as shown in table 5 based on simplified concrete damage plasticity (SCDP) by [10]

\[
E_c = 4700\sqrt{f'_c} \tag{1}
\]

where \( f'_c \) is compressive strength of concrete at 28 days in MPa.

\[
\varepsilon_0 = \frac{2f_c}{E_c} \tag{2}
\]

\[
f = \frac{E_c \varepsilon}{1 + \left( \frac{E_c}{f'_c} \right) \varepsilon} \tag{3}
\]

where \( \varepsilon_0 \) is the strain at ultimate compressive strength, \( \varepsilon \) is the strain at stress \( f'_c \), and \( f \) is the stress for a value in the stress-strain relationship of concrete.

**Table 5** Material properties for concrete with concrete damage properties [10].

| Concrete Elasticity | Youngs Modulus, \( E_c \) 21019 MPa |  
|---------------------|----------------------------------|
| Poisson Ratio, \( v \) | 0.2                              |

| Concrete Plasticity |  
|---------------------|----------------------------------|
| Dilation angle | 31  |
| Eccentricity | 0.1 |
| \( f_{so}/f_{co} \) | 1.16 |
| \( K \) | 0.67 |
| Viscosity parameter | 0 |
Concrete Compressive Behavior

| Stress (MPa) | Strain |
|-------------|--------|
| 6.00        | 0.00000 |
| 11.25       | 0.00030 |
| 15.32       | 0.00060 |
| 17.99       | 0.00090 |
| 19.45       | 0.00120 |
| 20.03       | 0.00150 |
| 19.99       | 0.00180 |
| 19.59       | 0.00210 |
| 18.97       | 0.00240 |
| 18.23       | 0.00270 |
| 17.46       | 0.00299 |
| 16.68       | 0.00329 |
| 15.92       | 0.00359 |
| 15.19       | 0.00389 |
| 14.51       | 0.00419 |

Concrete Tensile Behavior

| 2 | 0 |
|---|---|

The steel reinforcement was modeled using three-dimensional truss element (T3D2). The material properties for steel reinforcement was set as elastic perfectly plastic behavior with Young’s Modulus and Poisson's ratio of 200GPa and 0.3 respectively. Steel reinforcement was embedded in the concrete column.

CFRP sheet is modeled with deformable three-dimensional shells obtained by extrusion elements (S4R). The CFRP was modeled with linear elastic behavior up to rupture as it has elastic brittle behavior. In this study, CFRP is considered as orthotropic element. Hence, it is necessary to consider the properties of the element in each direction separately. The details properties of the CFRP sheet are taken from [11] studies as modeled in validation modeling. The Young’s Modulus in the main direction is set to 230GPa and the thickness of CFRP is 0.129mm. While for the orthotropic material model, in engineering constant in the ABAQUS software are as shown in table 6. Interaction of CFRP sheets and RC column was model with surface-to-surface contact elements. The surface of CFRP sheets was defined as a master surface whereas the concrete surface was defined as slave surfaces.

Table 6 Orthotropic material properties in each direction [11].

| Young’s Modulus | Shear Modulus | Poisson ratio |
|-----------------|---------------|---------------|
| E₁₁              | 230GPa        | G₁₂           | 7GPa          | v₁₂   | 0.3 |
| E₂₂              | 12GPa         | G₁₃           | 7GPa          | v₁₃   | 0.3 |
| E₃₃              | 12GPa         | G₂₃           | 7GPa          | v₂₃   | 0.45 |

3. Result and discussion

3.1. Structural assessment and evaluation results

The summary of testing results is tabulated in table 7. From the structural assessment and evaluation, it is shown that there is inconsistency in the RC structure construction. Therefore, structural strengthening is required in order to increase structural strength and preserve structural stability. Before structural strengthening is conducted, an analysis of the whole building is required in order to check the structural integrity of the building. In this case, the concrete strength of 20N/mm² was adopted in structural analysis. All structures members of the building were set to the worst case of 20N/mm² since the column compressive strength result tested with the destructive and non-destructive test was varies from 54.09N/mm² to 10.68N/mm² and 20N/mm² is the lowest compressive strength that can be set in Orion 18 Software.
Table 7 Summary of the destructive and non-destructive testing results.

| Method of testing                  | Number of test | Results                                                                                                                                 |
|-----------------------------------|----------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Visual Observation                | -              | - honeycomb problem at both beam and column                                                                                           |
|                                   |                | - present of crack on the slab                                                                                                         |
| Carbonation Test                  | 4 tests        | There is inconsistency in concrete structural member when react to phenolphthalein as a pH indicator                                  |
| Ferro Scan                        | 3 tests        | Steel reinforcement was installed according to the construction drawing                                                              |
| Steel Reinforcement Verification  | 1 test         | Type and spacing of the reinforcement used do not comply with the construction drawing                                                |
| Coring Test                       | 15 tests       | 36 testing for slab shows concrete strength from $17.6 \text{N/mm}^2$ to $47 \text{N/mm}^2$ with almost half of the test specimen are not achieve the design compressive strength. |
| Ultrasonic Pulse Velocity         | 18 tests       | 27 testing for column shows concrete strength from $10.68 \text{N/mm}^2$ to $54.09 \text{N/mm}^2$ with 20 percent of the test specimen are not achieve the design compressive strength. |
| Rebound Hammer Test               | 32 tests       | Beam shows that it is achieved the minimum design compressive strength. Only two tests conducted for the beam.                         |

3.2. Structural integrity of the building

From the analysis conducted in Orion 18, it was found that there is one line of the continuous beam (beam 2/A-L1) and seven columns (column 2/D, 2/E, 2/F, 2/G, 3/D, 3/E, and 3/F) fail the building analysis. This shown that these columns and beam need to be strengthened in order to restore the structure integrity and to ensure the safety of the building. The results obtained from the analysis also explained the column 2/D selection for the FEA as it carries the highest loading compared to the other fail column. The fail structure element was shown in figure 4.

Figure 4 Result from the Orion 18 shows failure in columns and beam in block B.
3.3. Results for column 2/D in ABAQUS FEA

Nonlinear analysis in ABAQUS Finite Element software was used to study the behavior of the column with and without CFRP jacketing. Column RColumn0W was modeled without CFRP as the control model and the other three model RColumn1W, RColumn3W, and RColumn5W were modeled with one layer, three layers and five layers of CFRP respectively. Strain at the upper parts of the column were measured and plotted against stress for each model. The stress-strain curve was plotted and tabulated as in figure 5 and table 8.

![Stress-strain curve for column with and without CFRP Jacketing.](image)

**Figure 5** Comparison of stress-strain curve for column with and without CFRP Jacketing.

| Column     | Stress (MPa) | Strain (%) |
|------------|--------------|------------|
| RColumn0W  | 16.51        | 1.41       |
| RColumn1W  | 23.82        | 1.20       |
| RColumn3W  | 31.12        | 1.36       |
| RColumn5W  | 30.69        | 0.90       |

**Table 8** Stress-strain value from ABAQUS FEM.

4. Conclusion

Based on the results obtained it shows that it is important to conduct structural assessment and evaluation towards the abandoned structure before the new appointed contractor continues the remaining works. Due to the inconsistency of the structural performance, a structural strengthening needs to be done.

The analysis result of the CFRP jacketing shows good performance in the strengthened column. It is shown that the CFRP jacketing can improve the behavior of the RC column when subject to axial load. It can be concluded that the axial capacity of the column increases as the number of layers CFRP sheets increase with almost the same deformation level of the column.

Nowadays CFRP structural jacketing have high potential in construction industry. This study only focuses on column strengthening using full-length wrap with one direction CFRP orientation only. It is not necessary to wrap the whole length of the column with CFRP. Further study on partially wrap CFRP jacketing can be made to save the construction cost. On the other hand, the degree of fiber orientation of CFRP sheets also would give different results in structural strengthening. Another recommendation can be made is to combine the CFRP sheets and plate application in column strengthening technique. The combination of these two different materials might increase the column performance in axial stress.
and deformation. There are a few types of CFRP plate available in the market as compared to the CFRP sheet.

Acknowledgments
The authors gratefully acknowledge the financial support of the Faculty of Civil Engineering, Universiti Teknologi MARA, Selangor MALAYSIA.

References
[1] De Lorenzis L and Tepfers R 2004 Applicability of FRP confinement to strengthen concrete columns Nordic Concrete Research Publication (Oslo: The Nordic Concrete Federation 1/200) 31 4 64-72A
[2] Teng J G, Jiang T, Lam L and Luo Y Z 2009 Refinement of a design-oriented stress-strain model for FRP-confined concrete ASCE J. of Comp. for Constr. 13 4 269-78
[3] Technical Report No. 55 2012 Design Guideline for Strengthening Concrete Structures Using Fibre Composite Materials 3rd Edition
[4] Lorenzis L D and Tepfers R 2003 A comparative study of models on confinement of concrete cylinders with fiber-reinforced polymer composites ASCE J. of Comp. for Constr. 7 3 219-37
[5] Harajli M 2006 Axial stress-strain relationship for FRP confined circular and rectangular concrete columns Cement and Concr. Comp. 10.1016/j.cemconcomp.2006.07.005 28 938-48
[6] Darby A P, Coonan R M, Ibell T J and Evernden M 2011 FRP confined square and rectangular columns under concentric and eccentric loading Proc. of Adv. Comp. in Constr. (ACIC) (Warwick)
[7] Toutanji H, Han M, Gilbert J and Matthys S 2010 Behaviour of large scale rectangular columns confined with FRP composites ASCE J of Comp. for Constr. 14 1 62–71
[8] Parvin A and Brighton D 2014 FRP Composites strengthening of concrete columns under various loading conditions 1040-1056. 10.3390/polym6041040 6
[9] Matias J V, Julio E and Silvestre N 2016 Numerical modelling of circular concrete columns strengthened with hybrid FRP jackets Available from file:///C:/Users/user/Downloads/ExtendedAbstract_Jorge_Matias_final.pdf
[10] Esfahani M R, Kianoush R and Tajari A R 2007 Flexural behavior of reinforced concrete beams strengthened by CFRP sheets Eng. Str. 10.1016/j.engstruct.2006.12.008 29: 2428-44
[11] Ayyad J 2016 Finite Element Modelling of Reinforced Concrete Columns StrengthenedExternally With CFRP Sheets (Palestine: The Islamic University of Gaza, Unpublished Master Thesis)