Simulation Nonlinear of Structural Behavior of Hollow Reinforced Concrete Deep Beams Strengthened By CFRP.

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Abstract  
Deep beam is adopted in many structural buildings and especially in high rise buildings and bridges in the form of transfer girders. Deep beam is primarily loaded in the plane of the member, such a beam is a two-dimensional member in a state of plate stresses whose dominant feature is shear. The beam theory is not applied on this type of beam. In the current paper, five models that represent reinforced concrete deep beam are simulated using finite elements approach by ANSYS to evaluate the full performance under the effect of four-point load. Controls with four models contain longitudinal perforations amending by carbon fiber reinforced polymer CFRP to restore the strength of deep beam without openings. Different parameters are considered such as openings geometry, CFRP layers and CFRP ordination. The result of the analysis indicates that the finite element approach that is applied for analyzing is close to the experimental test. The presence of CFRP restores the strength capacity of deep beam and the failure mode of the deep beam for all models is shear failure.  

KEYWORDS: Deep beam, CFRP, Finite elements, ANSYS, Perforations, Re-strengthening.  

NOMENCLATURE  
| Symbol | Description |
|--------|-------------|
| Af     | CFRP external reinforcement, (mm²) |
| Av     | CFRP shear reinforcement with spacing s, (mm²) |
| As     | Area of steel reinforcement, (mm²) |
| c      | Distance from extreme compression fiber to the neutral axis, (mm) |
| d      | Distance from extreme compression fiber to the neutral axis, (mm) |
| df     | Depth of FRP shear reinforcement, (mm) |
| Ef     | Tensile modulus of elasticity of CFRP, (MPa) |
| fc     | Specified compressive strength of concrete, (MPa) |
| fe     | Effective stress in the CFRP; stress level attained at section failure, (MPa) |
| h      | Overall thickness of a member, (mm) |
\( k_1 \) Modification factor applied to \( k_2 \) to account for the concrete strength
\( k_2 \) Modification factor applied to \( k_3 \) to account for the wrapping scheme
\( L_e \) Active bond length of CFRP laminate, in. (mm)
\( M_n \) Nominal moment strength, (N-mm)
\( s_f \) Spacing FRP shear reinforcing as described in, (mm)
\( t_f \) Nominal thickness of one ply of the CFRP reinforcement, (mm)
\( V_c \) Nominal shear strength provided by concrete with steel flexural reinforcement, (N)
\( V_n \) Nominal shear strength, (N)
\( V_s \) Nominal shear strength provided by steel stirrups, (N)
\( V_f \) Nominal shear strength provided by CFRP stirrups, (N)
\( w_f \) Width of the FRP reinforcing plies, (mm)
\( \alpha \) Angle of inclination of stirrups, degrees
\( \beta \) Ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis
\( \varepsilon_{ef} \) Effective strain level in CFRP reinforcement; strain level attained at section failure, (mm/mm)
\( \varepsilon_{fr} \) Design rupture strain of FRP reinforcement, (mm/mm)
\( \kappa_\psi \) Bond-dependent coefficient for shear
\( \psi_f \) Additional CFRP strength-reduction factor

1. Introduction

A deep beam is classified as the structural element fails to shear due to the rigidity that resulted from a large section for the beam span. A deep beam also shows a less shear span depth ratio for both concentrated and uniformly distributed load. The behavior and strength of deep beam shows a difference as compared with the slender beam in which the deep beam analysis and design for positive, negative and side reinforcements. Carbon fiber reinforced polymer (CFRP) widely adopted to strengthen or re-strengthen the structural members. Advantages of CFRP such as higher strength, lightweight and lower density as compared with steel lead the structural engineering to be adopted in many projects. Cracking of deep beam makes redistributions of stresses that is later developed due to post cracks so that the deep beam capacity predicate as inelastic analysis [1]. The presence of openings within the deep beam concrete beam reduces the shear capacity especially when the opening located near supports or under applied loads [2]. Perforation size and shape slightly effects on deep beam behavior and strength [3]. The location, shape and size of opening influence on the shear resistance of deep beam [4]. Increases in opening dimensions reduce the stiffness of deep beam and increases the cracks [5]. When the applied load increase, the sudden failure will occur due to the reduction in the beam stiffness [6]. First crack load when there was a hollow core along the deep RC beam strengthened by CFRP relay on the core geometry, CFRP layers and the location of the core, furthermore, the diagonal cracks occur at 45° near the beam support [7].
2. Aim and Significant Research

The aim of this paper is to check out the full performance and efficiency of deep beams with longitudinal perforations amending by CFRP using numerical analysis – finite element approach by ANSYS. Load capacity, cracks pattern, deflection and mode of failure of all models are evaluated and discussed.

3. Model Geometry

All deep beam models are simulated base on the experimental test [7]. Loads, support conditions, geometry and core with the CFRP treatments are adapted. All models have the same dimensions as (150x300x1200 mm) with (shear span/depth =1.52), Figure 1 shows the typical details of the mode and Tables 1 lists the model parameters. The mechanical properties of all adapted material are listed in Table 2 to 4. Figure 1 represents the geometry, layout, reinforcements and cores details for deep beam [7].

4. Beam Strengthening Based on ACI-440.2R

The strengthening of reinforced concrete deep beam by FRP family such as CFRP based on ACI-440.2R-02 [8]. Flexural and shear strengthening of deep beam relay on the reduction in flexural or shear strength capacity due to the presence of longitudinal perforation along the beam length. The limit state design principles are applied in the present study that related to the serviceability and strength [9,10]. The actual flexural strength of a deep beam with presences of CFRP computed by:

\[ M_n = A_f f_f (d - \beta_1 \frac{e}{2}) + \psi_f A_f f_{Fe} (h - \beta_1 \frac{e}{2}) \]  

The actual shear strength of a deep beam with presence of CFRP matching the equation below:

\[ \phi V_n \geq V_n \]  

In which:

\[ \phi V_n = \phi (V_c + V_s + \psi_f V_f) \]  

The shear contribution by CFRP as follow:

\[ V_f = \frac{A_{Fe} f_{Fe} (\sin \alpha + \cos \alpha) d_f}{s_f} \]
The CFRP area by applying equation (5)

\[ A_{pf} = 2nt_f w_f \]  

(5)

The tensile stress in CFRP at ultimate is calculated by apply equation (6):

\[ f_{fu} = \varepsilon_{fu} E_f \]  

(6)

The limit of strain in CFRP is:

\[ \varepsilon_{fu} = \kappa \varepsilon_{fu} \leq 0.004 \]  

(7)

In which the value of bond reduction factor \( \kappa \) relay on the concrete strength, CFRP strip stiffness and the wrapped type as follow:

\[ \kappa = \frac{k_1 k_2 L_c}{11900 \varepsilon_{fu}} \]  

(8)

The active bond length \( L_c \) and modifications factors \( k_1 \) and \( k_2 \) calculated as follow:

\[ L_c = \frac{23000}{(nt_f E_f)^{0.58}} \]  

(9)

\[ k_1 = \left(\frac{f_c}{27}\right)^{\frac{3}{2}} \]  

(10)

\[ k_2 = \frac{d_f - 2L_c}{d_f} \]  

(11)

5. Assumptions

Assumptions adopted in deep beam analysis included the reinforcements, surrounding concrete isotropic, homogeneous materials and has the same nodes without fractions between the two materials (discrete simulation of reinforcements) [11,12]. The concrete interfaces with CFRP are the full degree of interaction through the embodiment of the coating epoxy layer, in order not to allow any slip (full bond between the two different materials due to the full interactions). Plane sections remain plane before and (no geometric nonlinearity) [13,14]. The stress-strain for reinforcements is elastic-full plastic, and for CFRP, it is of a linear relationship [15,16].
6. Numerical Approach Analysis

Average load capacity that are taken from previous test [7] are simulated in ANSYS [16,17] and checked the whole behavior of control deep beam and other specimens under four-point static loading condition. The model is divided into a number of small (48) elements in a longitudinal direction, (6) elements in width and (12) depth directions. The connection between rebar nodes is similar to the concrete solid nodes so that the concrete and steel reinforcement nodes are merged. This technique provide the perfect bond. The same approach was adopted for CFRP composites. The tolerance value of (0.05) is used as displacement control during the nonlinear solution for convergence [18,19].

7. Finite Elements Modeling

Numerical analysis use finite elements approach by ANSYS software to simulate all reinforced concrete beam strengthened by CFRP including the control model. Different elements are selected to represents the actual behavior of concrete, plate support, plate under loads, reinforcements as the main, stirrups and CFRP layer. SOLID65 element is selected for concrete material in which three degrees of freedom at each node plus translations. LINK180 element is adapted to simulate all steel reinforcement. SOLID185 is chosen to represent the steel plates that is located under the applied loads and supports. SHELL181 element is used to simulate the CFRP layer due to the fact that this element having membrane (in-plane) stiffness [17]. Smear crack is the best representation of reinforced concrete members such as adapt beam. The open and close coefficients for concrete cracks are (0.2) and (0.7) respectively. The materials nonlinearity for steel rebars and concrete behaved as elastic – full plastic for reinforcements and also linear up to 0.3/$c'$, elastic up to 0.85/$c'$ and full plastic up to (0.003) as the maximum value of concrete strain. The main assumptions of numerical analysis are the plane section remain plane before and after applying loads, the concrete is homogeneous, with full bonds between concrete and reinforcements [18,19]. Full interactions between the concrete and CFRP layers [20] and the material nonlinearity of CFRP is linear up to failure and the self-weight of beam is not considered in an analysis that matches the experimental tests [21,22,23]. Figure 2 shows the finite element model mesh; while Figure 3 shows the wireframe for whole beam components such as top, bottom and stirrups reinforcements with supports condition as a simply supported
beam. The left support is the roller and the right support is pin that restrained in vertical and horizontal directions.

8. Results Analysis and Discussion

Five finite element models are analyzed by ANSYS software that adopted the mechanical properties and applied loads from experimental tests [7]. Based on analysis results all models failed as shear, Figure 10 shows that the Von Mises failure of control, showing the diagonal stresses started from supports up to the locations of applied loads.

Figures 11 to 20 show the deflection at failure and the first crack load stage. The beam performance indicates that the maximum deflection occurs in the middle of the point underneath the models. The central deflection represents the cumulative of deflection that is recorded from zero deflection at support to the location of the middle beam span.

A Figures 21 up to 25 show the cracks propagations for all models that is compared with the actual cracks from experimental tests. The diagonal cracks indicate that the mode fails in shear. First, second and third cracks of all models describe the cracks that developed in the longitudinal, depth and thickness of the deep beam. The cracks developed due to an increase in internal stress at the tension zone on the ACI-318-2014 [24] as a requirement for modulus of rupture (0.62fc’1/2); and the concrete crush occur when the internal stress at compression zone become more than the characteristic compressive strength [24,25]. The cracks intensity becomes less in cases of the presence of CFRP layer at the bottom, referring to an enhancements in the elastic deformation of the model due to the high tension resistance of the CFRP.

Figure 26 and 27 shows the full performance of load-deflection for all models as scatter with smooth lines and radar respectively. The first crack load differs from each model that relies on the model resistance to the applied load, leading to developing internal stress inside the mode. This stress becomes more than the modulus of concrete rupture where the crack will begin. Model DB3 with double layers and CFRP width more than other model DB1, DB2 and DB5, the ultimate load more and the load cause first crack that become high due to an increase in tensile resistance due to the presence of CFRP strips that increased in model stiffness. All models start as linear up to inflection point that represents the formation of the first crack. After this point, the model performance becomes in horizontal axis due to an increase in load and deflection that leads to a reduction in model stiffness up to failure. The performance of all models becomes
nonlinear after the point of inflection. Table 5 lists the load that causes the first crack and the ultimate failure load with load ratio for all models. Table 6 lists the comparisons between the experimental and numerical analysis, resulting from the same applied load in experimental investigation. The mean value for all models rounded to unities, referring to close results. Figures 28 and 29 shows the points of distributions around the 45° line that represent experimental and numerical approach for deflection at first crack and failure load. Most points lie above the straight line, referring to conservative. Table 7 lists the maximum load capacity based on ACI-318 and ACI-440-2R that compare with the experimental test results.

9. Discussions

According to the finite element analysis results of five reinforced deep beams with longitudinal different section perforation and strengthened by CFRP, the following points are drawn:

1. The load caused the first crack to rely on different parameters and mainly affected by the presence of CFRP that increases the concrete ductility, leading to the enhancement of the elastic deformation of concrete, in order to increase it.

2. All models fail due to propagations of shear cracks, not as a result of flexural.

3. The presence of the CFRP layer at the model bottom increases the strength capacity as flexural, yet CFRP strips at each side improve the shear strength capacity and reduce the cracks concentrations.

4. Due to the composite behavior between concrete and CFRP that lead to an increase in equivalent modulus of elasticity and moment of inertia, reflecting an increase in model stiffness, in order to increase the slop of load-deflection.

5. No spalling of CFRP is spotted from the concrete up to failure when the failure was pointed out in the concrete.

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Table 1: Models parameters

| Model mark | Hollow shape | Hollow dimensions (mm) | CFRP size (LxW) mm | CFRP Layers Strengthening |
|------------|--------------|-----------------------|--------------------|---------------------------|
| DB1        | Control      | ---                   | ---                | ---                       |
| DB2        | Square       | 50x50                 | 700x50             | Single                    |
| DB3        | Square       | 50x50                 | 700x50             | Double                    |
| DB4        | Circle       | Diameter 50           | 700x50             | Double                    |
| DB5        | Circle       | Diameter 50           | 700x50             | Single + Side             |

Table 2: Concrete mechanical properties

| Compressive strength (MPa) | Splitting tensile strength (MPa) | Modulus of rupture (MPa) | Modulus of elasticity (MPa) | Poisson’s ratio |
|---------------------------|----------------------------------|--------------------------|----------------------------|----------------|
| 26.63                     | 2.95                             | 3.5                      | 24750                      | 0.15           |

Table 3: Rebar mechanical properties

| Rebar diameter (mm) | Yield strength (MPa) | Ultimate strength (MPa) | Modulus of elasticity (MPa) | Poisson’s ratio |
|---------------------|----------------------|-------------------------|----------------------------|----------------|
| 6                   | 395                  | 480                     | ≈205000                    | 0.30           |
| 10                  | 421                  | 520                     |                            |                |
| 12                  | 480                  | 570                     |                            |                |
Table 4: CFRP mechanical properties

| CFRP thickness (mm) | % Elongation at break | Yield strength (MPa) | Modulus of elasticity (MPa) | Poisson’s ratio |
|--------------------|-----------------------|----------------------|-----------------------------|-----------------|
| 1.20               | 1.70                  | 2800                 | 165000                      | 0.30            |

Table 5: First crack and ultimate loads for all models

| Model mark | First crack load (kN) | Ultimate load (kN) | % (First crack load / Ultimate load) |
|------------|------------------------|--------------------|--------------------------------------|
| DB1        | 45                     | 150                | 30.00                                |
| DB2        | 40                     | 130                | 30.77                                |
| DB3        | 90                     | 310                | 29.00                                |
| DB4        | 83                     | 250                | 33.20                                |
| DB5        | 65                     | 180                | 36.11                                |

Table 6: Compressions of deflections at first crack and at failure load stage as experimental and numerical analysis

| Model mark | Deflection at first crack load (mm) – Experimental [7] | Deflection at first crack load (mm)-Finite element analysis | Finite element/Experimental Deflection ratio at first crack load | Deflection at failure load (mm)-Experimental [7] | Deflection at failure load (mm)-Finite element analysis | Finite element/Experimental Deflection ratio at failure load |
|------------|--------------------------------------------------------|-----------------------------------------------------------|-------------------------------------------------------------|------------------------------------------------|------------------------------------------------|----------------------------------------------------------|
| DB1        | 0.95                                                   | 0.97                                                      | 1.02                                                        | 8.43                                           | 8.93                                           | 1.05                                                     |
| DB2        | 1.34                                                   | 1.29                                                      | 0.96                                                        | 6.02                                           | 6.25                                           | 1.03                                                     |
| DB3        | 1.01                                                   | 1.10                                                      | 1.08                                                        | 14.31                                          | 16.10                                          | 1.12                                                     |
| DB4        | 0.81                                                   | 0.73                                                      | 0.91                                                        | 8.67                                           | 8.25                                           | 0.95                                                     |
| DB5        | 0.76                                                   | 0.79                                                      | 1.03                                                        | 8.82                                           | 8.85                                           | 1.01                                                     |
| Mean       |                                                         |                                                           |                                                              |                                                |                                                | 1.03                                                     |
Table 7: First crack and ultimate loads for all models

| Model mark | Ultimate load (kN) ACI-318-2014 [10] | Ultimate load (kN) ACI-3440-2R-2002 [8] | Ultimate load - Experimental (kN) |
|------------|--------------------------------------|--------------------------------------|---------------------------------|
| DB1        | 150                                  | ---                                  | 150                             |
| DB2        | ---                                  | 163                                  | 130                             |
| DB3        | ---                                  | 225                                  | 310                             |
| DB4        | ---                                  | 225                                  | 250                             |
| DB5        | ---                                  | 183                                  | 180                             |

Figure 1: Geometry, layout, reinforcements and cores details for deep beam [7]
Figure 2: Finite element model – DB1

Figure 3: Main and stirrups reinforcements for all models

A Figure 4 to 9 represents the full finite element geometry models and CFRP locations and schemes.

Figure 4: Finite element model with longitudinal square opening – 3D and front view

Figure 5: Finite element model with longitudinal circular opening – 3D and front view
Figure 6: DB2 model

Figure 7: DB3 model

Figure 8: DB4 model

Figure 9: DB5 model

Figure 10: Von-Mises stress – DB1
Figure 11: Deflection at failure stage – DB1

Figure 12: Deflection at first crack load stage – DB1

Figure 13: Deflection at failure stage – DB2.
Figure 14: Deflection at first crack load stage – DB2

Figure 15: Deflection at failure stage – DB3

Figure 16: Deflection at first crack load stage – DB3
Figure 17: Deflection at failure stage – DB4

Figure 18: Deflection at first crack load stage – DB4

Figure 19: Deflection at failure stage – DB5

Figure 20: Deflection at first crack load stage – DB5.
Figure 21: Cracks propagations at failure stage for experimental [7] and finite element approach for model DB1.

Figure 22: Cracks propagations at failure stage for experimental [7] and finite element approach for model DB2.

Figure 23: Cracks propagations at failure stage for experimental [7] and finite element approach for model DB3.

Figure 24: Cracks propagations at failure stage for experimental [7] and finite element approach for model DB4.
Figure 25: Cracks propagations at failure stage for experimental [7] and finite element approach for model DB5