Numerical analysis of RC deep beams strengthened in shear with NSM CFRP bars

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Abstract

This paper investigate the shear behavior of the reinforced concrete deep beams strengthened using externally bonded fiber reinforced polymer FRP-Near Surface Mounted (NSM) - anchor bar (embedded through section) by using finite elemental analysis (FEA). FEA modeling have been carried out by using ABAQUS. The properties of CFRP bars and reinforced concrete deep beam were collected from previous experimental work. Simulation of models was performed by considering two configurations for strengthening in shear. Previous experimental works have shown good enhancement in shear carrying capacity for the RC deep beams as 17.3% to 25.5%. All models were analyzed under two-point load with shear span to depth ratio av/d of 0.864. FRP bar used at 5 mm diameter with 90° angle of orientation and 100 mm with 150 mm spacing between installed bars. FEA results show a good agreement with the experimental results, while the error is limited to less than 10 %.

Keywords: RC deep beams, shear strengthening, NSM, FRP bars, nonlinear analysis.

1. INTRODUCTION

Shear and flexural are the most common failures occur due to several disorders in RC members. The durability of reinforced concrete members is gradually reduced by time, corrosion of steel, environmental affects and others. Therefore, providing maintenance for reinforced concrete is essential and compulsory as the re-construction cost is very high. Several techniques are being applied for improvement and maintenance of the structures by using FRP composite as externally bonded (EB) and embedded through the section, but the most recent technique: near-surface-mounting (NSM) of FRP bars is an efficient and effective technique for providing support for the flexural and shear failure zones and solution to such challenges. Also because of the easy installation & application, less amount of site workers are required to handling, practically economical, effective and efficient for strengthening to negative moment region of RC beams & slabs and minimized the ductility problems [1]. In recent times many researches have been conducted to examine the bond-slip relations for NSM- FRP bars through experimental and numerical approaches [2]. However, the most of the earlier research focused on the experimental investigations of shear or flexural behavior for RC beams, slab and masonry wall, but still there is insufficient research focused on the behavior of RC deep beam [3-4 & 5].

Although there are numerous techniques of strengthening the RC beams to find the appropriate ductility, NSM technique helps to provide more ductility as compared with other techniques by its transverse strengthening and the concrete confinement effects. El-Hacha & Rizkalla, 2004 [6] found significant increase in ductility obtained by using NSM technique and it is more than any other technique that uses externally bonded methods. Furthermore; Ceroni, et al 2012 [7] experimentally investigate the effectiveness of the usage FRP composite with near-surface-mounted system than other externally bonded (EB) systems and found that it’s very effective to enhance the ductility of deep beams. Also, De Lorenzis & Teng 2007 [8] examined the performance of NSM and other EB reinforcement systems and claimed that the NSM technique is an effective method for achieving better ductility.

Additionally, many researched has been worked to investigate the shear behavior of RC beams by using numerical models. Such numerical studies presented by Singh et al 2012 and Rasheed, Naylor, & Melhem 2004 by [9-10] used experimental results for obtaining relationship for moment-curvature of reinforced concrete members.
strengthened with FRP bars through predicting load-displacement curve response and also attained that the interface failure occurs in between the bonding material and concrete under high strain loading on the RC beams. Likewise, the numerical models developed and analyzed by Weidong et al 2010 and Ferracuti et al 2006 [11-12] for FRP bars and plates bond behavior with concrete to develop slip – bond stress relationships.

NSM has become an interesting topic to discuss in recent researches. Some researchers showed the effective guidelines for using NSM-FRP bars in real structures. Whereas; some design and guidelines have been developed by American Concrete Institute ACI 440.2R [13] for using FRP as externally bonded, but yet still there are much more areas which still uncovered.

In this paper, the numerical study for the shear strengthening of RC deep beams through NSM-CFRP bars has been carried. The supporting data for this research work has been chosen from the previous experimental results. Figure 1 show all the three deep beams as detailed and described along with the reference beam. All deep beams have the same dimensions as 450x140x1200 mm with 0.864 shear span to effective depth ratio. Control beams with shear reinforcement as ø 12mm @200 mm spacing from support. Both RC deep beams strengthened with Anchored CFRP NSM-CFRP bars installed at 900. Furthermore, both beams were strengthened at two different spacing of 150 mm and 100 mm as shown in Table 1. All RC deep beams has been validated with various configurations of application of NSM-CFRP bars with experimental results of Samad et al 2017 [5] and showed that the use of NSM provides an improvement in the shear capability as 17.5% and 16.7% range as compared with the control beams. Finally, this research work will discuss the shear strengthening enhancement by CFRP bars, load-displacement response and the mode of failure.
2. Numerical analysis

2.1 Numerical modelling of RC deep beams using Abaqus

Due to its complexity and the time-consuming nature, the behavior of composite deep beam in terms of numerous parameters: groove width, the orientation of bars and spacing between grooves cannot be fully understood and obtained through experimental investigation. Besides its numerical modeling can help to provide detailed understanding of the RC beams for the shear behavior. But the numerical modeling limitations cannot solve fully the required problem. Therefore, numerical modeling along with experimental investigations is essential to conduct for further studying the shear strengthening behavior of RC deep beams. The numerical model developed through Abaqus was used for simulate the RC deep beam [15]. Furthermore, to study the non-linear concrete behavior under compression and tension; “Concrete- damaged plasticity model” (CDPM) of Abaqus was used. However, the results was used for conducting this research to obtain the stress-strain relationships.

Cohesive interface elements were used to model the interface between the adhesive material (epoxy) and concrete. Normally, the fracture occurred at the concrete-epoxy zone. To define the interface between the linear elastic traction-separation law preceding to damage and a linear damage evolution is grounded on energy dissipation and it was assumed as Abaqus documentation section 29.5.1 [15]. The obtained simulation results were compared with the experimental results for the control and strengthened deep beams.

<table>
<thead>
<tr>
<th>specimen</th>
<th>NSM-CFRP bars configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>-</td>
</tr>
<tr>
<td>S1</td>
<td>Strengthened with anchored bar as 90° @ 100 mm c/c</td>
</tr>
<tr>
<td>S2</td>
<td>Strengthened with anchored bar as 90° @ 150 mm c/c</td>
</tr>
</tbody>
</table>

2.2 Material properties

Proper information of the properties of the material properties is the most important factor in any numerical simulation. The results obtained through simulation were compared with the results achieved through experimental work and the maximum error was maintained with less than or equal 10%. The materials: concrete, steel, epoxy and CFRP bars used for the modeling in this research work are shown in Table 2. However; the CFRP bars properties were considered as used in Samad et al 2017 [5], where the behavior of CFRP linear until the peak value of the load and it failed by brittle failure suddenly.

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>Properties (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Compressive strength</td>
<td>25</td>
</tr>
</tbody>
</table>
Furthermore, in the current simulation, the modulus of elasticity was calculated by using below equation (1) as quoted by ACI 318-08 [16] and the values of uniaxial stress-strain were chosen from the calculation procedure of stress-strain curve proposed in Desai & Krishnan 1964 and Gere & Timoshenko 1997 [17-18]. However, equations (2) and (3) were used for calculating the yield stress and inelastic strain values.

$$E_C = 4733\sqrt{f_c}$$  \hspace{1cm} (1)

Where $E_C$ and $f_c'$ are the modulus of elasticity and the ultimate compressive strength respectively of concrete.

The damage parameters in compression and tension behavior were calculated by using equation (2) as highlighted in Lubliner et al 1989 and Lee & Fenves 1998 [19-20].

$$f = \frac{\varepsilon E_c}{1 + (\frac{\varepsilon}{\varepsilon_0})^2}$$  \hspace{1cm} (2)

$$\varepsilon_0 = \frac{2f_c}{E_c}$$  \hspace{1cm} (3)

$$E = (1 - d)E_o$$  \hspace{1cm} (4)

$$f_c = 0.62\sqrt{f_c'}$$  \hspace{1cm} (5)

Where $E_o$ is the initial (undamaged) modulus of the material. The variable “d” is the stiffness degradation and it is the function of stress state and the uniaxial damage variables. Whereas; “dc” and “dt” are damage variables and considered as the quantities for non-decreasing material point. During analysis, any increment will result the new damage variable and it obtained on the basis of maximum difference between the previous increment value at the end and the current stage value correspondingly. The tensile behavior of concrete is linear until failure and beyond it; the formation of micro cracks is represented macroscopically with a softening stress-strain response. The softening of stress-strain induces strain localization in the concrete structure. Furthermore, equation (5) highlighted in ACI 318-08 [21] was used to obtain ultimate tensile stress. The final input values of yield stress and inelastic strain used for RC deep beams material are presented in Table 2. These values are calculated by using analytical equations proposed in Abaqus analysis user’s manual [15].

Table 3 Concrete yield stress and corresponding inelastic strain values

<table>
<thead>
<tr>
<th>Yield stress (Mpa)</th>
<th>Inelastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>0.0000381</td>
</tr>
<tr>
<td>14.927</td>
<td>0.0000681</td>
</tr>
<tr>
<td>19.3</td>
<td>0.00082</td>
</tr>
<tr>
<td>22.31</td>
<td>0.001281</td>
</tr>
<tr>
<td>24</td>
<td>0.001582</td>
</tr>
<tr>
<td>25</td>
<td>0.0017938</td>
</tr>
<tr>
<td>24.7</td>
<td>0.00198</td>
</tr>
</tbody>
</table>
23.45 | 0.0027153  
21.82 | 0.00312  
20.16 | 0.0038485  
18.62 | 0.0044151  
15.94 | 0.005548

2.3 Yield criteria and other parameters

The theory of failure defines the critical state of stress which leads to the plastic deformation for obtaining the condition of failure. Different yield criteria have been developed to evaluate the strength of the material in case of tension and compression Lubliner et al. 1989 [19] and proposed classic yield criterion which finally developed finally by Lee & Fenves 1998 [20] as adopted for concrete damage plasticity (CDP). Mainly, the failure criterion is defined by using parameters through concrete damage plasticity model (CDPM). The parameter $f_{bo}/f_{co}$ is referred to the state of stress which applied on the specimen or the condition of the load applying on the specimen. It represents the ratio of the biaxial stress under compression to the uniaxial stress.

The second parameter is called viscosity “$\mu$”. It is the cohesion of the materials or the material resistance to flow and demonstrates the relationship between shear stress and shear rate. For this research, the default value of “0.0” was chosen and supposing the independent rate analysis. The value of flow potential eccentricity $\varepsilon = 0.1$ was chosen and basically it is the material which have almost same dilatation angle for pressure stress wide range quantities. Whereas the parameter $K_c$ was taken as $=2/3$. It represents that it is not perfect cone shape in three-dimensional spaces. Mainly, it is the ratio between “second stress invariant on the tensile meridian” to the “similar stress in the compression meridian” at the initial yield of any given pressure $P$ as shown in the Figure 2.

![Figure 2. Failure surface of deviotoric surface.](image)

While dilation angle or friction angle $\varphi$ represents the angle of the tangent that drawn using maximum stresses values obtained by a triaxial test of specimens with a various value of principal stresses in each direction by using Mohr circle theory. Mohr Circle theory used to find out the maximum stresses in each circle or take the equivariant stress and pressure plane as shown in Figure 3.
2.4 Modeling the Interface of Concrete-Epoxy

Cohesive zone model generally used to model the fracture failure which normally occurs in specific zones of the structure. Generally, the failure occurs when the separation occurs between two materials due to the stress and the delamination between the concrete-epoxy interfaces. Thus, cohesive behavior is important in the portion of contact between concrete and epoxy. The cohesive model based on traction separation law in which the behavior is linear elastic at initial stage and followed by damage initiation, whereas, the evolution is depended on energy dissipated on account of failure as shown in Figure 4. The area under curve called fracture energy and was calculated by using in Remmel 1994 [22] study.

\[ G_f = 65 \ln \left(1 + \frac{f_c}{10}\right) \]  

(6)

Where \( f_c \) is concrete compressive strength and \( G_f \) is fracture energy of concrete measured in N/m. Concrete compressive strength in this study is equal to M25 and the fracture energy of 81.5 N/m. For the stiffness penalty linear elastic behavior earlier to damage commencement was used to describe and it is related to the shear and tensile loading, while it is unaffected by pure compression.

<table>
<thead>
<tr>
<th>Dilation angle</th>
<th>Eccentricity, ( \varepsilon )</th>
<th>( K_c )</th>
<th>( f_{uo}/f_{co} )</th>
<th>Viscosity ( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>38°</td>
<td>0.1</td>
<td>0.667</td>
<td>1.16</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 4. Traction-separation law

In this research the traction-separation law model was used with respect to three separate components: normal to the concrete-epoxy interface and the two others are parallel to the interface. Cohesive behavior model was taken as uncoupled behavior by using stiffness’s in matrix components. The elasticity matrix is off-diagonal set as zero except the shear, tangential and normal directions (the diagonal).

\[
\begin{bmatrix}
\{t_n\} & \{t_s\} & \{t_t\}
\end{bmatrix} =
\begin{bmatrix}
K_{nn} & 0 & 0 \\
0 & K_{ss} & 0 \\
0 & 0 & K_{tt}
\end{bmatrix}
\begin{bmatrix}
\{\varepsilon_n\} \\
\{\varepsilon_s\} \\
\{\varepsilon_t\}
\end{bmatrix} = E\varepsilon
\]

Where $K_{nn}, K_{ss}$ and $K_{tt}$ are the cohesive layer stiffnesses in normal, shear and tangent directions respectively.

### 2.5 Geometric Modeling

The specimens particulars (strengthened and control) modeling through Abaqus (Manual, 2010) is discussed. All the geometry used in these models dealt separately. For FRP and steel reinforcements 16 mm in tension zone, for steel 12-mm in compression zone and 12 mm for stirrups were modelled. Truss distracted wire elements were modelled by using 3D-Two-Node truss elements (T3D2 element) as shown in Figure 5. Eight-node 3D solid hexahedral elements (C3D8R elements) were used to model the concrete deep beams and grooves. The major embedded elements were used 16 mm for the steel and 12 mm for stirrups. The bond of FRP bar and adhesive material (epoxy) used as perfect bonding, while the concrete-epoxy modelled using interface elements using cohesive properties by considering traction-separation law response. Globule mesh size used for the models was as 15 GB.
3. RESULT AND DISCUSSION

Three deep beams validated by using Abaqus in [15]. One control deep beam model and two remaining deep beam models were strengthened with FRP bars are validated corresponding to experimental results. Load-displacement response curve observed has been validated. The predicted response of load-displacement curve in finite element analysis is shown in Figures 6, 7, and 8 to the corresponding experimental load-displacement response and provides good agreement. For overall deep beams, the error percentage is limited to less than 10% for load and displacement.
The failure mode of all RC deep beams models were predicted in FEA analysis using Abaqus software. Figure 9 (R1, S1 & S2) shows the failure pattern through cracks. Crack patterns of all such analyzed RC beams were compared with the tested through experimental work. The crack patterns of designed RC deep beams generated at 55° which evident that the failure occurred in shear. From FE analysis, the crack initiation starts from support and increasing on account of increasing the load on RC deep beam until reaches the point of applying load. Furthermore, Abaqus shows the visualization, stiffness degradation and stress distribution zone for all RC deep beams and indicating these on both sides at the same region.
Figure 9. Failure mode of reference R1 and strengthened RC deep beam models S1&S2.

The max damage in Abaqus expressed in visualization with various colours and the highest value represented by red color for the stress contour which is obvious that the peak load value carried by the RC deep beam. Interestingly, very less difference was noticed between the experimental and FEA results. It is mainly because of the perfect geometry and the homogeneity of the finite element models as compared with experimental work. Correspondingly, the crack pattern for the R1, S1, and S2 RC deep beam obtained through Abaqus software showed similarity with the crack pattern obtained through experimental work and such was validated well also.

4. CONCLUSION

In this study, the nonlinear analysis carried out to investigate deep beams behavior under shear strengthening by using NSM- FRP bar for three deep beams with various configurations in spacings and number of bars compared with reference RC deep beam. Abaqus was used to model and validate results from the previous experimental results. The percentage of error between the experimental and FEA results is limited to less than 10%. The observation from the study can be concluded as follows:

1. NSM is very effective technique for providing shear strength enhancement of RC deep beams.
2. The closest bar installed using NSM-CFRP embedded-through section bars for the RC deep beams strengthened in shear show higher strength performance.
3. The percentage difference for ultimate shear load between the FEA and experimental results were recorded as 2.85 % for the reference deep beam R1 and 2.9%, 3.4% for both strengthened RC deep beams S1 and S2 respectively.

4. The strengthened RC deep beams shows enhancements in shear strength are limited to 17.5% and 24 % for the anchored bars.

REFERENCES


