Shear Strength Comparison of High Performance Reinforced Concrete Deep Beams without Stirrups Between ANSYS vs Experimental Work

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1. INTRODUCTION

Reinforced concrete deep beams are used as load-distributing structural elements, such as transfer girders pile caps, foundation walls, and offshore structures. The shear strength evaluation of reinforced concrete beams has been the subject of several studies that aimed to determine the influences of major parameters. The combination of stresses (bending and shear) in the shear span results in inclined cracks, which transform the beam into a tied arch. In general, reinforced concrete deep beams should have adequate shear reinforcement to prevent sudden and brittle failure after the formation of diagonal cracks, as well as to keep crack width at an acceptable level. Shear force presents in beams at sections at which bending moment changes along the span; it is equal to the rate of change of the bending moment.

Using of deep beam in construction sector has increased due to its improved properties compared to ordinary beams. Shear resistance is one of most intensive area of research in deep beams. To Estimate the shear resistance of beams, researchers and standard codes have specified different formula considering different parameters into consideration. Choosing an appropriate model for predicting shear resistance of reinforced concrete deep beams was difficult.
because of disagreement between researchers and different codes that considered too many parameters. Therefore, an extensive research work on shear behavior of deep beams casting with different strength: normal strength concrete (NSC), high performance concrete (HPC), and high strength concrete (HSC), which is a concrete with a specified compressive strength of 55MPa or greater (ACI, 2013a). HPC is a concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituent materials and normal mixing, placing, and curing practices(ACI, 2013b).

The major researchers in this field include (Bazant Z.P. , 1986), (Zsutty T.C., 1971), (Aziz O.Q., 2014), (Yaseen S.A., 2016), and many more. Estimation of shear resistance of different strength deep beams is still controversial therefore it’s a thrust area for research.

The shear failure of reinforced concrete beams without web reinforcement is a distinctive case of failure which depends on various parameters such as shear span to effective depth ratio, longitudinal tension steel ratio, aggregate type, strength of concrete, type of loading, and support conditions, etc. Most of the researchers concluded that failure mode is strongly dependent on the shear span to depth ratios \(a/d\). Given the small span–depth ratio of a deep beam, its strength is typically controlled by shear strength rather than by flexural strength if the normal amount of longitudinal reinforcement is applied (Gaetano Russo, 2005, Shyh-Jiann H., 2000). Several experimental studies have been conducted to understand the various modes of failure that could occur because of the possible combination of shear and bending moments acting at a given section. The main obstacle to the shear problem is the large number of parameters involved (Boris B., 1963, Dileep K.).

(Berg F. j., 1962), (Taylor R., 1960) study a shear capacity of varied shear span to effective depth ratio in Reinforced concrete beams. (Sudheer Reddy L., 2011) studies evaluation of shear resistance of high strength concrete beams without web reinforcement using ANSYS. (Fanning P., 2001) evaluated reinforced and post tensioned concrete beams using the ANSYS.

The present study analysis twelve different strength deep beam ANSYS model using finite element analysis. One of the main advantages of ANSYS is the integration of the three phases of finite element analysis: preprocessing, solution, and post-processing. Pre-processing routines in ANSYS involve defining the model, boundary conditions, and loadings. Displays may be created interactively on a graphics terminal as the data are entered to assist model verification. Post-processing routines may be used to retrieve analysis results in a variety of ways. Plots of the deformed shape of a structure and stress or strain contours can be obtained in the post-processing stage. The analysis of the tested beams is carried out in ‘ANSYS’ package considering perfect bond between the tension reinforcement and the surrounding concrete. The predicted results using ‘ANSYS’ model, have been compared with the corresponding test data in (Yaseen S.A., 2016).

2. OBJECTIVES

i. Study the shear response of concrete beams without shear reinforcement by taking the variables, compressive strength (normal strength concrete, 40 MPa; high strength concrete, 60 MPa; and high performance concrete, more than 100MPa), shear span-to-depth ratio \(1, 1.5, 2, 2.5, \) and \(3\), and the ratio of the amount of flexural steel bars \(1.35\%, 2.40\%, 3.76\%, \) and \(6.108\%)\) into consideration.

ii. Develop and analyze different strength concrete deep beam models in ANSYS and compare the results with the experimental data; and

3. FINITE ELEMENT MODEL
**REPRESENTATION**

As mentioned previously, the ANSYS computer program was used to analyze all the tested beams. The finite element modeling and analysis techniques used to simulate the behavior of high performance reinforced concrete deep beams are described following the element definition in the aforementioned program. The element types utilized to construct the FEM are discussed below.

### 3.1. Finite element model of fiber reinforced concrete

Concrete members consist of concrete and steel fibers. The finite element idealization should be able to represent concrete cracking, crushing, and the interaction between concrete and reinforcement. The interaction between the two materials is needed to reduce crack growth and the capability of concrete to transfer shear stress after cracking via an aggregate interlock.

Three-dimensional elements are used to investigate failures in which shear stress plays a major role. A 3D solid element with eight nodes was used to model the concrete (SOLID-65). The element comprised eight corner nodes (Fig. 1), and each node had three degrees of freedom (u, v, and w in the x, y, and z directions, respectively). The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The steel fibers used in this study were straight steel wire fibers (undeformed). The fibers showed an aspect ratio (l/d) of 80, a nominal diameter of 0.2 mm, a nominal length of 40 mm and the volume fracture is $V_f = 1\%$. Internal reinforcement (flexural and shear stirrups) was modeled using 3-D spar elements (Link180), which allow the elastic–plastic response of reinforcing bars (ANSYS, 2011).

**Figure (1): Three-dimensional eight-node solid element**

### 3.2. Finite element model of reinforcement bars

The finite element modeling of steel reinforcement can be realized with three techniques (ANSYS, 2011), namely, discrete, embedded, and smeared (distributed) representations (Fig. (2)). The steel reinforcements (tensile, compressive, stirrups, and dowel bars) were represented by using a two-node discrete representation (LINK-8) and were included within the properties of eight-node solid elements. In general, reinforcement bars are assumed capable of transmitting axial forces only, and a perfect bond is assumed to exist between the concrete and the reinforcing bars.

To provide the perfect bond, this study connected the link element for the steel reinforcement bar between the nodes of each adjacent concrete solid element such that the two materials shared the same nodes. The stress–strain curve of steel reinforcement for the FEM was based on the actual stress–strain curve obtained from the tensile tests.
3.3. Steel plates
A 12.5 mm-thick steel plate was added at the support locations to avoid stress concentration problems and to prevent the localized crushing of concrete elements near the supporting points and load application locations. These plates were modeled by using Solid185 elements to ensure an even stress distribution over the support area. The element was defined with eight nodes, each of which had three degrees of freedom and translations in the nodal x, y, and z directions (ANSYS, 2011).

4. MODELING OF MATERIAL PROPERTIES
4.1. Stress–strain relationship model for concrete
Concrete is a quasi-brittle material with different compression and tension behaviors. It is assumed to be homogeneous and initially isotropic. Figure (3) shows a typical stress–strain curve for NWC (Desayi P., 1964). However, this ideal stress–strain curve was not used in the finite element material model because the negative slope portion leads to convergence problems. The compressive uniaxial stress–strain relationship for the concrete model was obtained by using the following equations to compute the multilinear isotropic stress–strain curve of concrete (Bangash, 1989).

\[ f = \frac{E_c \epsilon}{1 + (\frac{\epsilon}{\epsilon_o})^2} \]  \hspace{1cm} (1)

\[ \epsilon_o = \frac{2f'_c}{E_c} \]  \hspace{1cm} (2)

\[ E_c = \frac{f}{\epsilon} \]  \hspace{1cm} (3)

\[ f = \text{Stress at any strain} \]
\[ \epsilon = \text{Strain at stress} \]
\[ \epsilon_o = \text{Strain at the ultimate compressive strength} f'_c \]

Figure (4) shows the simplified compressive uniaxial stress–strain relationship that was used in this study. The simplified stress–strain curve for each beam model comprises six points connected by straight lines. The curve starts at zero stress and strain. Point No. 1 at 0.40f'_c is calculated from the stress–strain relationship of the concrete in the linear range (Equation (3)). Points No. 2, 3, and 4 are obtained from Equation (1), in which \( \epsilon_o \) is calculated from Equation (2). Point No. 5 is at \( \epsilon_o \) and \( f'_c \). In this study, perfectly plastic behavior was assumed after Point No. 5.

The behavior of normal concrete under compression is illustrated in a typical uniaxial stress-strain curve, as shown in Fig. 4, and consists of two parts, linear and nonlinear. The limit of the linear portion is defined as 30% of the maximum compressive strength, the modulus of elasticity (Ec) and Poisson’s ratio (calculated from the linear portion). The nonlinear elastic behaviors of concrete can be defined by the multi-linear stress-strain relationships, as illustrated in Fig. 3-4.

For concrete, ANSYS requires input data for material properties as follows: Elastic modulus (Ec), Ultimate uniaxial compressive strength (f’c), Ultimate uniaxial tensile strength (fr), Poisson’s ratio (\( \nu \)), Shear transfer coefficient (\( \beta \)), and the Compressive uniaxial stress-strain relationship for concrete.

The elastic modulus (Ec), compressive strength (f’c) and modulus of rupture (fr) were obtained experimentally. Poisson’s ratio for the
concrete was assumed to be 0.2 (67) for all four beams. The default values used by the ANSYS which was 0.001 (for values and type of conversion criteria). The shear transfer coefficient represents conditions of the crack face. The value of $\beta$ ranges from 0 to 1, with 0 representing a smooth crack (complete loss of shear transfer) and 1 representing a rough crack (no loss of shear transfer).

Figure (3): Typical uniaxial compressive and tensile stress – strain curve of concrete (ACI, 2013a)

Figure (4): Simplified compressive uniaxial stress – stain curve of concrete (ACI, 2013b)

4.2. Geometry and FE modeling of HPC and steel Reinforcement
All the tested beams measured 1,250 mm long and had an overall cross section of 100 mm $\times$ 200 mm (effective depth $d=167$ mm). All the tested specimens were simply supported over a clear span of 1,000 mm. The tested beams were divided into four groups. Figure (5) and Table (1) present the properties and details of the tested specimens [12]. Half of the full beam was used for modeling by taking advantage of the symmetry of the beams. This approach reduced computational time and computer disk space requirements significantly.

5. MESHING
After the creation of volumes, a finite element analysis requires meshing of the model. In other words, the model is divided into a number of small elements, and after loading, stresses and strains are calculated at the integration points of these small elements. In this study, good results were obtained by setting up the mesh such that square or rectangular elements were created (Fig. (6)).

6. TEST MODEL AND EXPERIMENTAL DATA

Table 1 - Detail of the Tested Specimens (Yaseen S.A., 2016)

Figure (5): Detail of the tested specimens
7. SETTING OF BOUNDARY CONDITIONS AND LOADING POINTS

The best simulation model can be created when the actual boundary conditions used in the modeling act in the same way as the experimental tested beam. Displacement boundary conditions are needed to constrain the model and obtain a unique solution. The model being used is symmetrical about one plane. The boundary conditions for both the support and planes of symmetry are shown in Figure (6). The boundary conditions need to be applied at points of symmetry and at points where support and loading exist.

A vertical plane through the beam center at the mid-span defines the section of the plane of symmetry. To model the symmetry, nodes in this plane must be constrained in the longitudinal direction. Therefore, in this study, the displacements were set as zero in the plane along the X-direction, (UX = 0). The support was modeled such that a roller was created. A single line of nodes on the plate was given a constraint in the Y and Z directions, a displacement value of zero (UY=0, UZ=0) was applied. Thus, the beam was allowed to rotate at the support. Force P was applied across the entire nodes of the steel plate.

8. PREDICTED RESULTS FROM THE FINITE ELEMENT MODEL (FEM)

The results from the ANSYS-FEM include the following:
1. Ultimate load capacity and failure modes
2. Ultimate shear stress and strain distribution
3. First shear and flexural cracking loads
4. Load deflection curve
5. Pattern of propagating cracks

9. ULTIMATE LOAD CAPACITY (FAILURE LOAD)

The theoretical ultimate load capacity (which was considered the last converged load in the FEM analysis) and the mode of failure for all the tested beams are listed in Table (2) and shown in Figures (7) and (8). The figures explain half of the loaded beam according to the symmetry section. Thus, one support and a loading point appear to show a failure region between the two points (loading point at the top and supporting point at the bottom of the beam).

The predicted load shows good agreement with the experimental results. The overall percentage of the experimental load to the predicated load (ANSYS model) was 100%, thereby indicating indicates the perfect calibration of the ANSYS-FEM to perform the simulations close to reality.
10. MAXIMUM SHEAR STRESS AND STRAIN INTENSITY

The maximum shear stress for all the tested beams is shown in Table (2). The maximum shear stress was considered as the (XY) shear stress at the last converged iteration before failure.

The overall theoretical results were higher than those from the experimental work by approximately 1%. The stress distribution across the side surface of the beam specimen (G3-4) shown in Figure (9) exhibited a maximum shear stress of 17.24 MPa. The strain intensity for the beam specimen (G3-4) is shown in Figure (10), which clearly depicts the likelihood of diagonal tension failure.

11. FIRST CRACKING LOAD

The theoretical first (shear or flexural) cracking load is the load step where the first signs of cracking occur in concrete elements. Cracking became visible on the sides of the beam at 23%–33% of the ultimate load in the experimental data and at 19%–29% in the prediction model. As expected, this cracking consisted of inclined cracks in a region of shear load. The result of the first cracking load for the tested beams in the predicted model was compared with that from the experimental data, as shown in Table (2). The ratio of comparison between the experimental results and the predicted results was 108% for shear load and 111% for flexural load. The load needed in the first crack in the experimental data results was greater than that obtained by the predicted model. This outcome can be explained as
follows. The experimental cracking load is the load at which the first visible crack (shear or flexural) appeared, whereas the theoretical cracking load is the load step in which one of the principal stresses in the concrete element reached the maximum limit.

12. LOAD-DEFLECTION CURVES

In the experimental beams, direct current displacement transducers were used to measure the deflections at mid-span at the center of the bottom face of the beams. In the ANSYS-FEM, mid-span deflection was calculated at the same location as that for the experimental beam. The load-deflection curves from the FEM and the experimental results for the beam specimens (G1-5), (G2-3), (G3-4), and (G4-3) are shown in Figures (11), (12), (13), and (14), respectively.

The graph shows that the load-taking capacity of the specimen in the predicted model was slightly greater than that of the experimental data for all the beam specimens. As a result, the predicted load-deflection curves show good agreement with those in the experimental work. The deflection capacity was improved in the model, and the cracks were reduced in all modeled specimens. The ANSYS model results were stiffer than the experimental results possibly because of the following:

1- The non-consideration of the micro-cracks in concrete (because of drying shrinkage)
2- The bond slip of the reinforcement and the assumed perfect bond between the concrete and the reinforcement bar in the FEM, which may not be true for actual beams
3- The first cracking loads obtained from the ANSYS-FEM being lower than those from the experimental results in the pre-cracking stages.

Considering Load-Deformation response, there is some discrepancy at the early stages;

However, the overall trend of the ANSYS response is corresponding the experimental results.
Figure (14): Experimental and predicted curve for beam G4-3

13. CRACK PATTERN

The ANSYS program records a crack pattern at each applied load step. A cracking sign represented by a circle appears when a principal tensile stress exceeds the ultimate tensile strength of concrete. The cracking sign appears perpendicular to the direction of the principal stress. In general, flexural cracks occur early at mid-span. When applied loads increase, vertical flexural cracks spread horizontally from the mid-span to the support. At a high applied load, diagonal tensile cracks appear. Increasing the applied load induces additional diagonal and flexural cracks. Given that the model is a shear beam model (deep beam), no compressive cracks appeared underneath the loading location.

An example of the predicted flexural crack pattern is shown in Figure (15) for beam (G1-1), and the predicted shear crack pattern is shown in Figures (16) and (17) for beams (G1-1) and (G1-2). The stress vector pattern was obtained from the solution of beam (G1-2). The amount of cracks from the ANSYS-FEM analysis is greater than that observed in the experimental test. No more than three cracks can be predicted in each Solid65 element for the FEM. Therefore, the amount of cracks shown is affected by the size of the mesh. Using a large mesh size for Solid65 elements would result in few elements and minimal cracks, whereas using a small mesh size would result in the opposite conditions.
<table>
<thead>
<tr>
<th>Beam No.</th>
<th>Experimental compressive Strength MPa</th>
<th>Experimental First Flexural Cracking Load (kN)</th>
<th>Predicted First Flexural Cracking Load (kN)</th>
<th>% (Experimental/Predicted) First Flexural Cracking Load</th>
<th>Predicted First Shear Cracking Load MPa</th>
<th>% (Experimental/Predicted) First Shear Cracking Load</th>
<th>Predicted Failure Load (kN)</th>
<th>% (Experimental/Predicted) Failure Load</th>
<th>Experimental Ultimate Shear Stress MPa</th>
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<th>% (Experimental/Predicted) Ultimate Shear Stress</th>
<th>Experimental Mode of Failure</th>
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Thus, the cracks shown as contours of the point at which the tensile stress exceeds the tensile strength of concrete are appropriate to consider.

Figure (15): Flexural crack pattern for beam (G1-1)

Figure (16): Shear crack pattern for beam (G1-1)

Figure (17): Shear crack pattern for beam (G1-2)

Figure (18): Stress vector pattern for beam (G1-2)

14. CONCLUSIONS

The following conclusions can be derived from the predicted models based on FEM:

1. The ultimate final deflection, load-deflection curves, and mode of failure predicted with the FEM show good agreement with the experimental results.

2. The effect of additional variables, such as loading type, the value of $\left(\frac{a}{d}\right)$, and the main reinforcement ratio, on the shear behavior of high performance reinforced concrete deep beams was considered in the FEM.

3. The experimental/predicted failure loads for all the tested beams were within 100%, whereas the FEM seemed stiffer than the experimental model during loading. This result is due to the absence of micro-cracks in the FEM and the assumed perfect bond between the concrete and the reinforcement bar.

4. The first (shear and flexural) cracking load predicted with the FEM for all the tested beams was lower than that from the experimental works tested with 108% shear load and 111% flexural load). The experimental first cracking load is the load at which the first visible crack (shear or flexural) appeared, whereas the theoretical cracking load is the load step at which
one of the principal stresses in the concrete element reached the maximum limit.

5. The number of cracks in the FEM was greater than that observed in the experimental test because the amount of cracks shown is affected by the size of the mesh used.

6. The predicted crack pattern can be considered contours of points at which the tensile stress exceeds the tensile strength of concrete instead of as indicators of the number of cracks, crack spacing, or crack width.

7. The predicted ultimate shear stresses were higher than those from the experimental work by approximately 1% for all the tested beams.

8. The predicted shear stress intensity from the FEM can be used to study the shear stress distribution along the deep beam depth in various loading stages.

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