Finite Element Analysis of Steel Fiber Tapered Deep Beams Under Monotonic load

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Abstract. This study illustrates the numerical investigations of the performance of steel fiber reinforced concrete tapered deep beams under static loading nature. Three simply supported specimens (two tapered members and the last is prismatic one) were selected from the experimental work of previous study carried by the authors. The selected specimens included a member having steel fiber and without vertical and horizontal reinforcement and another member having steel fibers without horizontal reinforcement. The third selected specimen having vertical and horizontal reinforcement and excluding steel fibers. On the other hand three other parametric studies were adopted using the FEA. Finite element analysis software (ABAQUS) investigate the effect of steel fiber ratio, a/d ratio and type of loading. On the other hand, three other parametric studies are adopted using finite element analysis (FEA). ABAQUS software was used to investigate the effect of steel fiber ratio, a/d ratio and type of loading.

1. Introduction
Tapered beams has been arisen in the first half of the 20th century, these type of beams are often used in continuous and simply supported bridges in midrise Buildings, continuous bridges and metro train pier cap. The American Concrete Institute AC1318M-11 [1] does not include specifications for tapered deep beams. Three simply supported steel fiber reinforced concrete tapered deep beams tested earlier by the authors of this study [2] were modelled using nonlinear finite elements. A model considering the plastic damage in concrete developed earlier by BS EN 1992-1-1:2004 ((BS) 2004) was considered [3]. The stress-strain relationship for concrete in (tension) was assumed to consist of a linear ascending section with slope equal to the modulus of elasticity of concrete (E) and exponential descending part [4]. To ensure the simulation compatibility against experimental data, additional components is to be adopted to simulate reinforced concrete. For example, the steel reinforcement bar response represented by the Bauschinger effect which is used in the modelling, the reinforcing bars exhibit an elastic-plastic bilinear kinematic hardening model. The selected model adequately accounts for the Bauschinger effect. The Menegotto-Pinto [5] model was used to simulate the steel response. Validation of the simulation models will be made and a comparison of results against the experimental results is carried out. Numerical parametric studies will be adopted to investigate the effect of variations in compressive strength, steel fiber content and a/d ratio.

2. Description of the Previous Experimental Study
The dimensions, loads and boundary conditions of the specimens that were tested in the experimental program carried by the authors [2] were also used for the finite element models [Figure (1)]. All the specimens have a total length L = 1100 mm. The effective span for all specimens was L = 900 mm and the
width was \( b = 150 \text{ mm} \). The considered angles of slope of the haunch from horizontal line were: \( 0^\circ \), \( 5.71^\circ \) and \( 11.3^\circ \). The haunched length at both beam ends was one-third the effective span of the beam \( L_h = L/3 = 300\text{mm} \). The bearing length at both beam ends was 75 mm. The linear tapering was adopted by keeping a constant depth \( h_{\max} = 250\text{mm} \) at the beam ends while varying the depth of the beam at the middle third from 250 mm (prismatic) to 190 mm, that is, \( h_{\min} = 250, 220 \) and 190 mm. Beams were simply supported and tested under monotonic loads as shown in Figure 1. The cryptogram used for the identification for the steel fiber reinforced concrete tapered deep beams (STαR0, STαVR AND TαVHR) where: (α) is an index represents the tapering angle, S indicates the utilization of steel fibers, R0 indicates the absence of vertical and horizontal reinforcement, VR indicates using of vertical reinforcement and VHR represents the utilization of vertical and horizontal reinforcement as shown in Figure 2.

![Figure 1. Geometry, boundary conditions and loads [2].](image1)

![Figure 2. Steel reinforcement detail [2] (a.STα0VR, b.STα5.71R0 and c. Tα11.3 VHR)](image2)
The parametric study presented in this paper consists of analyzing three tapered deep beams that have been modeled using the damaged plasticity model presented in ABAQUS. The parameters considered in this numerical study are: compressive strength, steel fiber content ratio and a/d ratio.

3. Finite Element Analysis
All steel fiber tapered deep beams were modeled using three dimensional finite element technique. In ABAQUS [6], the standard 3D stress elements are used to model the concrete. These elements are represented with appropriate integration rules depends on the experimental response of the specimen. Quadratic brick elements are used to provide higher accuracy for elements with high distortions. Three different element types: Solid, shell, and cohesive have been used to model the geometry. For the solid part (concrete), the three dimensional eight-node linear brick element with reduced integration and hourglass control (C3D8R) was used [7, 8]. The reinforcing rebars can be modelled using solid, beam and truss elements. The use of solid elements is computationally difficult and therefore was not used herein. Truss elements are chosen because the reinforcing bars doesn’t provide a very high bending stiffness. Perfect bond is supposed to occur between concrete and steel bars over the entire analysis. So the T3D2 (A 2-node linear 3-D truss element) was used to model the reinforcing bars. In case of using a reduced integration the model acquire essentially softer, parameters of the tension stiffening are necessary to be adjusted to match experimental value [9].

Material modeling of concrete which is quasi-brittle material is depend mainly on the compressive stiffness recovered upon crack closure as the load changes from tension to compression [3]. The tensile stiffness is not recovered as the load changes from compression to tension as larger micro-cracks have developed. This behavior, which c matches to \( w_t = 0 \) and \( w_c = 1 \), is the default used by ABAQUS. Figure (3), illustrates a uniaxial load cycle assuming the default behavior. The three dimensional (3D) finite element meshes were adopted for the deep beam specimens as shown in Figure (4a). Linear brick elements are used to simulate the concrete and truss elements are used to simulate the steel bars. The bearing plates at the top and bottom faces of the specimen are simulated by using linear elements with full contact between bearing plates and the specimen. The applied load and boundary conditions are subjected to the members as shown in Figure (4b).

![Figure 3](image_url)

**Figure 3.** Uniaxial load cycle (tension-compression-tension) default values for the stiffness recovery factors: \( w_t = 0 \) and \( w_c = 1 \). [6]
Figure 4. Finite element mesh are used to simulate of deep beam specimens and Boundary and loading conditions.

3.1 The Selected Mode of Parameters
The damaged plasticity model is mainly used in structures subjected to dynamic or cyclic loading because of its ability to simulate the behaviour of the test up to failure. [10]. For that reason, the damage plasticity model has been used in the analysis. The tension and compression damage parameter curves for estimating the stiffness degradation under monotonic loading for the tapered beams is shown in Figures (5) and (6) and Tables (1) to (3).

Figure 5. Uniaxial compressive stress-strain behavior of concrete  [10]

Figure 6. Uniaxial tensile stress-strain behavior of concrete  [10]
Table 1. Material properties for concrete

| Parameter          | Symbol | 0% steel fiber content | 0.5% steel fiber content | 1% steel fiber content |
|--------------------|--------|------------------------|--------------------------|------------------------|
| Compressive strength | \( f'c \) | 37.8                   | 42.3                     | 44.6                   |
| Splitting strength  | \( f \)  | 4.04                   | 4.73                     | 5.2                    |
| Elastic modulus     | \( E_s \) | 28.85*                 | 30.04**                 | 33.074**               |

\*\( E_c = 4700 \times \sqrt{f'c} \) [1]
\**\( E_{cf} = E_c V_f + (1-V_f) E_f \) [11]

Where:
\( E_c \): elastic modulus for N.C, \( E_{cf} \): elastic modulus for SFRC, \( E_f \): elastic modulus of fiber material, \( V_f \): fiber volume fraction

Table 2. Material properties of the FE model for reinforcing steel

| Parameter                  | Symbol | Units | Longitudinal Reinf. (Ø 16) | Longitudinal Reinf. (Ø 12) | Shear Reinf. (Ø 8) |
|----------------------------|--------|-------|----------------------------|----------------------------|-------------------|
| Elastic modulus            | \( E_s \) | MPa   | 200000                     | 200000                     | 200000            |
| Poisson’s ratio            | \( \nu \) | -     | 0.3                        | 0.3                        | 0.3               |
| Density                    | \( \rho \) | kg/m3 | 7850                       | 7850                       | 7850              |
| Yield stress               | \( f_y \) | MPa   | 458                        | 527                        | 606               |
| Ultimate stress            | \( f_u \) | MPa   | 618                        | 719                        | 734               |

Table 3. The material properties of the (FE) model for concrete

| Mechanical: Elastic Isotropic | Parameter       | Symbol | Units | Value | Remarks |
|-------------------------------|-----------------|--------|-------|-------|---------|
| Elastic modulus               | \( E_c \)      | (GPa)  | -     | Table (1) | Neville, (1983),[12] |
| Poisson’s ratio               | \( \nu \)      | -      | 0.3   | Neville, (1983),[12] |
| Concrete Damaged plasticity Isotropic | Compressive cylinder strength | \( f'c \) | (MPa) | - | Table (1) |
| Compressive strain at peak    | \( \varepsilon_c \) | mm/mm | 0.0002 | Neville, (1983),[12] |
| Tensile strength              | \( f_{ct} \)  | (MPa)  | -     | Table (1) |
| Dilation angle                | \( \psi \)    | '      | 33    | -       |
| Eccentricity                  | \( \epsilon \) | -      | 0.1   | -       |
| \( fb_0/fc_0 \)               | \( fb_0/fc_0 \) | 1.16   | -     | -       | Figure (5) |
| K                             | \( K \)       | -      | 0.667 | -       | Figure (6) |
| the viscosity parameter       | \( \mu \)     | -      | 0     | -       |
| Inelastic strain of concrete in compression | \( e_{cin} \) | - | - | Figure (5) |
| Cracking strain of concrete in tension | \( e_{ck} \) | - | - | Figure (6) |
4. Results and Discussions

The validation of the finite element predictions with the previous experimental results in terms of ultimate load, mid-span deflection and maximum principal stresses was made are shown in Table (4) and Figures (7-9) which indicates the ratio of FE predictions to experimental ultimate load (Pu EXP./Pu FEA). This ratios ranges from 0.93 to 0.95 and the ratio of the experimental deflection to FEA deflection (Δu EXP./Δu FEA) ranges from (0.94 to 1.05). The predicted results for all tapered beams were in excellent agreement with experimental observations.

| Beam symbol | %steel fiber | Experimental Results | FEA. Results | Pu EXP./Pu FEA. | Δu EXP./Δu FEA |
|-------------|--------------|----------------------|--------------|----------------|----------------|
| STa0R0      | 1%           | 254.02               | 265.318      | 0.95           | 0.97           |
| STa5.71 VR  | 1%           | 237.5                | 252.23       | 0.94           | 0.94           |
| Ta11.3VHR   | 0%           | 204.559              | 217.949      | 0.93           | 1.05           |

**Figure 7.** FEA and Experimental Load Deflection Curves for specimen STa0R0
Concrete cracking and crushing under monotonic load are shown in Figures (10), (11) and (12). The blue contours plot of the beams indicates concrete elastic behavior while the other colors indicate the formation of micro cracks until the beginning of the concrete yielding. The orange color refers to the places of cracks and the red color indicates the full concrete failure. The figures below illustrate that the failure mode of the beams which contain steel fibers in spite of the absence of horizontal reinforcement in STα5.71˚VR and vertical and horizontal in STα0˚R0 changed from brittle to ductile. The steel fibers are simulated through FE-code ABAQUS/CAE with acceptable accuracy by considering it as one component with concrete and use feature concrete damage plasticity to model the behavior of steel fiber concrete depending on (uniaxial compression and tension test).
5. Parametric study

a) Effect of load location

On the behavior of beam STα5.7° VR (steel fiber tapered beam with vertical reinforcement) is recognized in Figure(13). A comparison between the impact of center load and two point load on the behavior of the beam is made. It is clear that the ultimate load when two line loads is applied is so close to ultimate load.
when one line load at center is applied. On the other hand, the deflection is increased by 25% with similar mode failure.

b) Effect of span to depth ratio a/d
As shown in Figure (14), it was observed that the behavior of beam STα5.7˚ VR with shear span to depth ratio a/d=0.9 was stiff and resist load more than the beam STα5.7˚ VR with a/d=1.57, and this is may be due to the transformation of the applied load directly to supports through the compression struts which leads to increase the capability of beam to resist higher loads. When a/d is decreased from 1.57 to 0.9, the deflection values is reduced at corresponding load because of increasing shear span leading to increase the bending moment and decrease the moment of inertia and this lead to decrease the rigidity of the flexural zone because of the high flexural stress.

![Figure 14. Effect of a/d ratio in steel fiber tapered beam](image)

C) Effect of steel fiber content
As shown in Figure (15), the load–deflection curve varies when the steel fiber ratio changes from 0.5% to 1%. It is obvious that when the deflection increased, the shear strength is increased because the steel fibers resist the tension stress carried by concrete and therefore increasing the strength of the beam.

![Figure 15. Effect of steel fiber content on tapered beam](image)
6. Conclusion

This study focused on calibrating the finite element analysis with the previous experimental results, the following concluding remarks were observed:

1. A good agreement of numerical and experimental ultimate load ($P_u$) and the corresponding ultimate deflection ($\Delta u$) with an average percentages difference of 8.4 and 5.33, respectively, as compared with experimental results.

2. A good estimation of numerical cracks patterns and damages compared to the experimental results.

3. When the applied load changed from single at mid span to two point loads. The beams' ultimate load values were close while the deflection value increased by about 25% and it has a similar mode of failure.

4. Decreasing the $a/d$ ratio from 1.57 to 0.9 leads to increase the strength capacity about (38.51%) and increasing the deflection value about (22.3%) .

5. Decreasing the steel fiber ratio from 1% to 0.5% leads to decrease the ultimate load about (29.8%) and decreasing the ultimate deflection about (15.5%).

References

[1] ACI Committee 318 2011 Building Code Requirements for Structural Concrete (318-11) and Commentary (318-11) American Concrete Ins., Detroit.

[2] Basma W J and Adel A A 2019 Shear Performance of Steel Fiber Concrete Tapered Beams” paper submitted to the journal of Computer and Concrete.

[3] BS B S 2004 Products and systems for the protection and repair of concrete structures [Online]. [Accessed].

[4] WANG T, HSU T T 2001 Nonlinear finite element analysis of concrete structures using new constitutive models Computers & structures 79 2781.

[5] Menegotto M and Pinto E 1973 Method of analysis for cyclically loaded reinforced concrete plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending,” in IABSE Symposium on the Resistance and Ultimate Deformability of Structures Acted on by Well-Defined Repeated Loads, (Lisbon).

[6] ABAQUS 2011 Theory Manual, User Manual and Example Manual. Version 6.10, Providence, RI.

[7] Tuo L, Jiang Q and Chengqing L 2008 Application of damaged plasticity model for concrete. Structural Engineers 24(2) 22–27.

[8] Harba I S and Abdulridha A J 2017 Finite Element Analysis of RC Tapered Beams under Cyclic Loading Al-Nahrain Journal for Engineering Sciences (NJES).

[9] Al-Shaarabaf I, et al. 2017 Experimental and Numerical Investigation of High Strength Reinforced Concrete Deep Beams with Web Openings under Repeated Loading. Al-Nahrain Journal for Engineering Sciences (NJES).

[10] Daud R, Cunningham L and Wang Y C 2015 Non-linear FE Modelling of CFRP-Strengthened RC Slabs under Cyclic Loading. Athens Journal of Technology & Engineering 2(3).

[11] Salman M M and Qassib M 2018 Shear strength of non-prismatic steel fiber reinforced concrete beams without shear reinforcement Journal of Structural Engineering and Mechanics 67 4.

[12] Neville A M 1983 Properties of Concrete the English Language Book Society & Pitman Publishing, 3rd Edition 566.