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Prediction of the Shear Behavior of Reinforced Concrete Deep Beam Strengthened by Transverse External Post-tension using Finite Element Method

Naruebet Sattaratphaijit[1], Sayan Sirimontree[1*], and Boonsap Witchayangkoon[1]

[1] Department of Civil Engineering, Thammasat School of Engineering, Thammasat University, THAILAND.
**Corresponding Author (Email: ssayan@engr.tu.ac.th).*

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Abstract

This article presents the shear behavior of the reinforced concrete deep beams strengthened by transverse external post-tension using the finite element method (FEM). These have been carried out by the ABAQUS program. A finite element model has been developed that uses the results of past researchers' experiments as data to verify the model. Deep beams are divided into two groups. Each has two beams, group B1 and B2 control span-to-depth ratio 1.5 and 2.0. A beam from each group incorporates shear strengthening from the post-compression stresses of 653 MPa. The one is used as a reference, without shear strengthening. The results obtained from the finite element analysis are close to the test results with a difference of not more than 7.8% on average. Results show that the span-to-depth ratio is the most important parameter that controls the behavior of reinforced concrete deep beams. Transverse external post-tension delays the diagonal cracking of concrete and results in a significantly increased shear strength of the beam.

Disciplinary: Civil Engineering & Technology (Structural Engineering).

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1 Introduction

Beams that are subject to heavy loads, such as transfer girders in high-rise buildings, have considerable depth compared to the shear span, which is classified as deep beams. Beams with a ratio between shear span to an effective depth not more than two are classified as deep beams while beams with a ratio greater than two are classified as slender beams. Shear transfer in deep beams by compression strut and tension tie called arch-action, while slender beams shear transfer mainly by beam-action. Deficient shear strength of reinforced concrete deep beam can be efficiently strengthened by transverse external post-tension as shown in the experiments performed by Sirimontree et al. (2010). They found that the ultimate load-carrying capacity of all shear strengthened specimens significantly improves over the reference specimen and the failure mode shifts from brittle shear failure closer to ductile flexural failure, with higher ductility and stiffness. The experiment is restricted to time and cost, however, previous researchers studying behaviors of deep beam used in a finite element method (FEM) of the tested beam specimens are simulated by the numerical model. ABAQUS is an efficient and easy-to-use computer program that uses the finite element method to analyze the behavior of concrete structures. This paper presents the analysis of reinforced concrete deep beams strengthened by transverse external post-tension using a finite element model using ABAQUS and compares it with the results obtained from the experiments of Sirimontree et al. (2010).

2 Literature Review

A substantial number of researchers have investigated the finite element of RC deep beams. The behaviors of deep beams are different from that of normal flexural members; the strength of deep beams is most controlled by shear rather than flexure. There are classified as non-flexural members, in which the plane sections do not remain plane in bending. The elastic behavior is characterized by deep beams before cracking. After that major redistribution of stresses and strains, significant effects of stress and shear deformation take place therefore strength of the beams are estimated using the nonlinear analysis or finite element analysis. Failures are due to crushing or splitting in diagonal compressive strut, so it is based on D-region behavior. According to Hassan et al. (2018), Lafth and Ye (2016), and Ismail et al. (2017), the shear strength of deep beams is a function of many factors such as loading, horizontal and vertical web reinforcement, span-to-depth ratio, and concrete compressive strength. Several techniques have been investigated for strengthening of reinforced concrete deep beams, including External Post-Tension, Fiber Reinforced Polymers (FRP), etc.

Rai and Phuvaeavan (2019) tested the RC deep beam strengthened by V-shaped external rods using concrete damaged plasticity in the ABAQUS program compare with reference beams. They found that the stress obtained from the theoretical approach was relatively close to Finite element analysis than their experimental result. Hafezolghorani et al. (2017) developed the damage plasticity model. This model combined a stress-based plasticity part with a strain-based damage mechanics model for the unconfined prestressed concrete beam based on four concrete grades. In concrete damage plasticity models, uniaxial compressive behavior is characterized by either experimental tests or existing constitutive models, such as those proposed by Park (1971) for unconfined concrete. However, this study employs the parabolic constitutive model for unconfined concrete, expressed by

$$\sigma_c = \sigma_{cu}\left[2\left(\frac{\varepsilon_c}{\varepsilon_c^{'}}\right)-\left(\frac{\varepsilon_c}{\varepsilon_c^{'}}\right)^2\right] \quad (1),$$

where σ_c and ε_c are nominal compressive stress and strain, respectively. σ_{cu} and $\varepsilon_c^{'}$ are ultimate compressive strength and the strain of the unconfined cylinder specimen, respectively. The stress-strain relationship of concrete in tension was assumed to be linear up to the uniaxial tensile strength. For the tension softening part, the relationship is determined using the exponential function proposed, which is expressed in Equation (2), where σ_t and ε_t are nominal tensile stress and strain, respectively.

$$\sigma = \sigma_t\left(\frac{\varepsilon_t}{\varepsilon}\right)^{0.4} \quad (2).$$

3 Method

3.1 Detail of Modeling

A 3D model of the beam specimen used in Sirimontree's (2010) experimental test is simulated in ABAQUS. Eight beams are divided into two groups. Each has two beams, groups B1 and B2 control span-to-depth ratio 1.5 and 2, respectively. A beam from each group incorporates shear strengthening from post-compression stresses of 653 MPa. The one is not shear strengthening. All the beam specimens are 3000mm in length, 200mm in width, and 600mm in height. Five deformed steel bars of 20mm diameter are longitudinally placed in two layers in the bottom of beams as flexural reinforcement, and two steel bars are placed in the top. Stirrups are spacing of 250mm using steel bars of 6mm diameter. The beam details are indicated in Figure 1. Groups B1 are simply supported over the two steel plates and tested under a four-point bending configuration, see Figure 2(a). On the order hand, group B2 is tested under a three-point bending configuration in Figure 2(b).

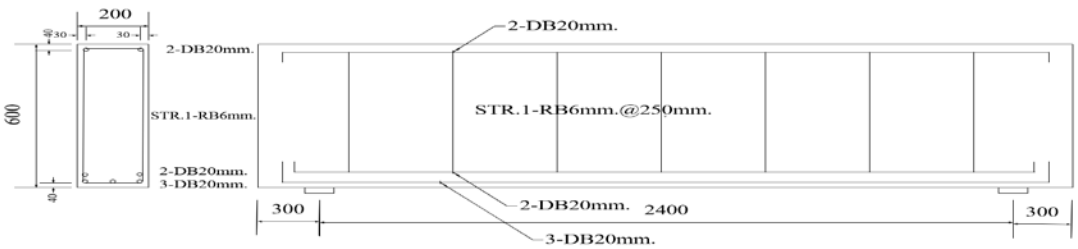

Figure 1: Beam details (units in mm)

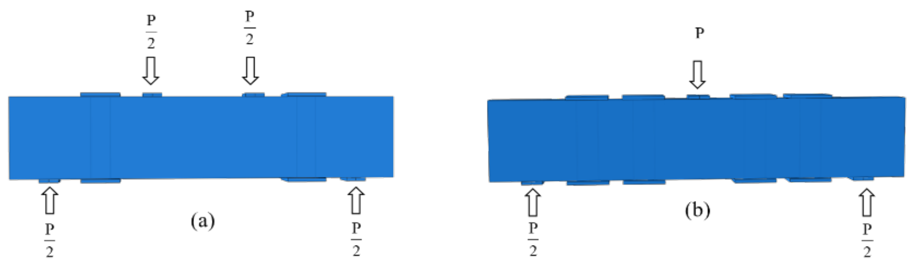

Figure 2: (a) four-point bending in group B1 (b) three-point bending in group B2.

3.2 Element of Modeling

In this study, steel reinforcements, like longitudinal reinforcement, vertical reinforcement, and wire strands, are modeled using a 2-node truss element (T3D2), and the concrete and plate were modeled using an 8-node solid finite element (C3D8). Figure 3 shows the meshing schemes assigned in the model. Mesh sizes are assigned for the concrete elements with an element size of 20mm × 20mm × 20mm. The element sizes of streel reinforcement are 20 mm. The plate mesh size is 25mm × 25mm × 25mm. The steel reinforcements are embedded in the concrete, and wire strands are embedded in the plate of the wire strand. All of the plates, as supports, plates of wire strand, and bearings, are tied in the concrete.

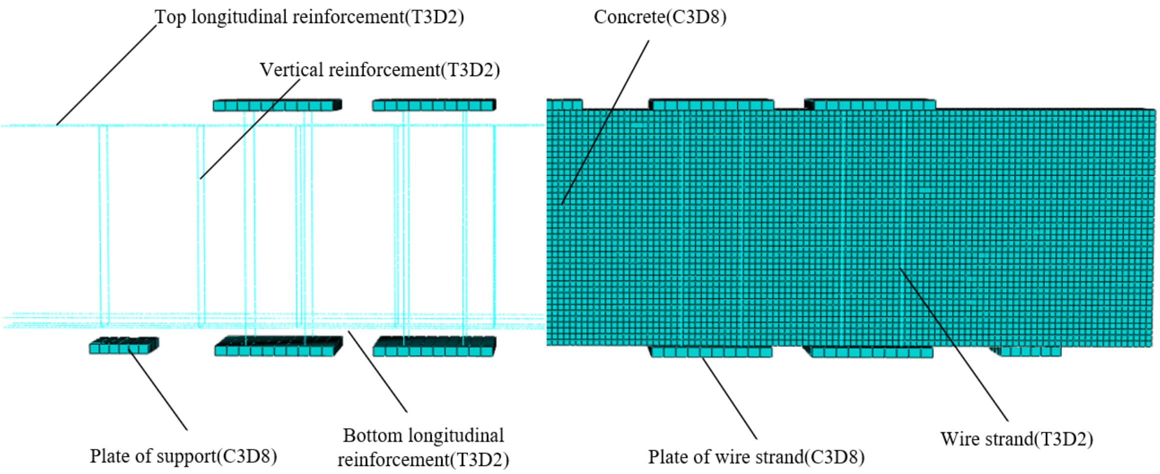

Figure 3: Types of mesh sizes in the model

3.3 Material of Modeling

The modeling techniques are concrete modeling in ABAQUS, both a smeared crack model and a concrete damaged plasticity model. The concrete damaged plasticity model of concrete is required the concrete compressive and tensile constitutive relationship. The substantial parameters adopted in this research are shown in Table 1.

Table 1: Material properties for concrete with CDP model in 20 MPa

Compressive Strength (MPa)	20	Plasticity parameters	
		Dilation Angle	35
		Eccentricity	0.1
Concrete elasticity		fbo/fco	1.160
E (GPa)	2.30	K	0.667
Poisson's Ratio	0.18	Viscosity Parameter	0.007985
Tensile Behavior		Compressive Behavior	
Yield Stressc (MPa)	Cracking Strain (mm/mm)	Yield Stress (MPa)	Inelastic Strain (mm/mm)
2.40	0.00E+00	10.00	0.00E+00
1.33	2.62E-04	15.20	9.20E-05
0.74	6.70E-04	20.00	8.61E-04
0.61	8.60E-04	14.88	3.19E-03
0.41	1.42E-03	10.75	4.96E-03
0.37	1.60E-03	6.00	8.32E-03

Table 2 shows the parameters of steel reinforcements used in this study, steel was thought to be a multipurpose splendidly plastic material and identical in tension and compression. This study uses elastic modulus 210,000 MPa and Poisson's ratio of 0.3.

Table 2: Material properties for steel reinforcements

Designation	Grade	Diameter (mm)	Yield strength (MPa)	Ultimate tensile strength (MPa)
DB20	SD40	20	390.00	684.45
RB6	SR24	6	235.00	489.97
Wire strand	1860	12.77	1792.26	1914.65

4 Result and Discussion

The shear behaviors of the deep beam using the finite element method are considered by the relationship of the load-deflection response and the crack pattern. The results of the analysis are consistent with the test results shown in Figures 4 and 5. The predicted maximum load-carrying capacity, represented shear strength, from the finite element model differs by no more than 7.8% from the test results.

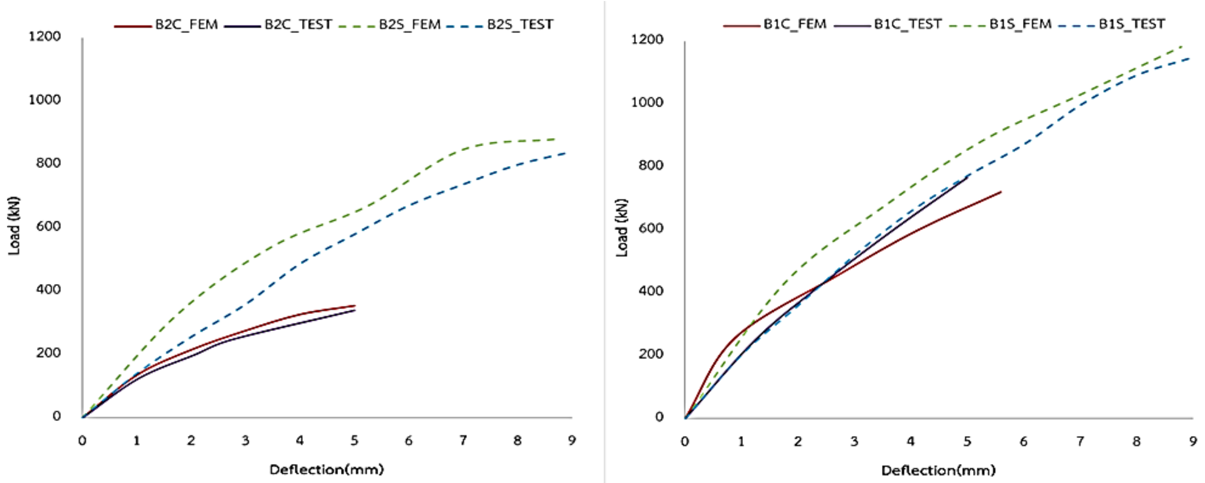

Figure 4: Load-deflection response in both experimental and FEM.

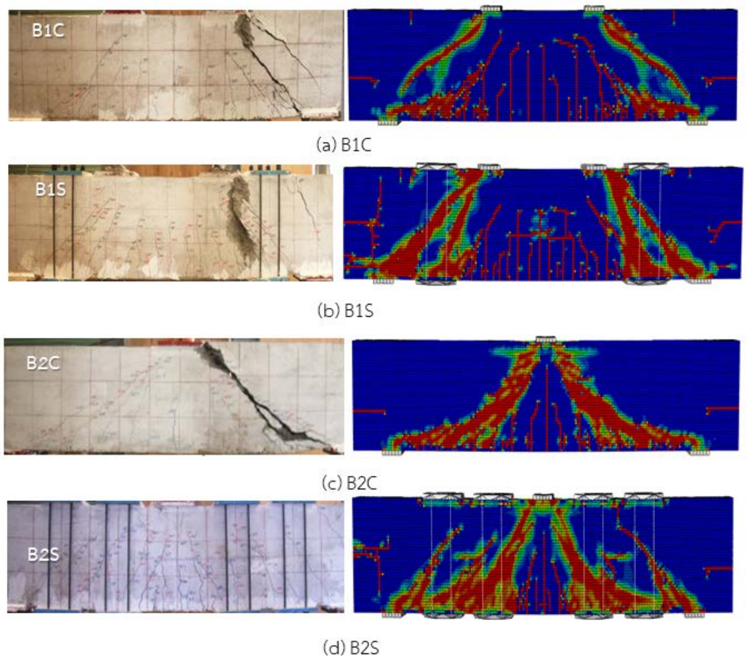

Figure 5: Crack pattern comparison between FEM and experimental.

The crack pattern of the test specimens is compared with the tensile damage of the finite element model (DAMAGET) which indicates cracks in the finite element model due to tensile stresses as shown by Figure 5.

It can be seen that the model can predict the behavior of the deep beam strengthened by external post-tension with sufficient accuracy, which can be used to study the effects of other variables as well.

5 Conclusion

The shear behavior of strengthened RC deep beam is investigated through experimental, so it is based on the load-deflection relationship, ultimate load capacity, ductility, and failure mode. The beam is simulated using the ABAQUS program. The tensile stress on the external prestressing is obtained using a theoretical approach and compared with the experimental and FEM.

From this study, the finite element models used ABAQUS program are effective and accurate to expect the shear behavior of transverse external post-tension to strengthen deep beams. Results show that the ultimate load predicted by the finite element method differs from experimental results by 7.82% on average. The crack patterns using the finite element method give almost similar to the experimental.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

7 Acknowledgement

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Naruebet Sattaratphaijit is a Master's degree student of the Department of Civil Engineering, Thammasat University, Thailand. He earned a Bachelor of Engineering (Civil Engineering and Management) from Thammasat University, Thailand. He is interested in Reinforced Concrete Deep Beams and Finite Element Analysis.

Dr. Sayan Sirimontree is an Associate Professor at Thammasat University Thailand. He earned his Bachelor's degree from Khonkaen University Thailand, Master's degree in Structural Engineering from Chulalongkorn University, Thailand, and PhD in Structural Engineering from Khonkaen University, Thailand. He is interested in Durability of Concrete, Repair and Strengthening of Reinforced, and Prestressed Concrete Structures.

Dr. Boonsap Witchayangkoon is an Associate Professor at the Department of Civil Engineering at Thammasat University. He received his B.Eng. from King Mongkut's University of Technology Thonburi with Honors. He got a PhD in Spatial Information Science & Engineering from the University of Maine, USA. His interests involve Applications of Multidisciplinary and Emerging Technologies to Engineering.