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Finite Element Modeling of Shear Strength for Concrete Deep Beams (Part II)

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Abstract

Deep beams behaviors are considerably different from those of regular beams. Moreover, taking into account their numerous applications in reinforced concrete, bridges, and sky scrapers, the importance of studying and analyzing them become more outstanding than ever. In this current study shear capacity and failure load capacity of rectangular concrete deep beams are computed using strut and tie model (STM), and the results were compared with experimental results which were derived using ACI and AASHTO regulations. Finite element numerical model was utilized for analyzing these beams and the results of which reveals acceptable congruency. Besides, STM method will be approved as a suitable method for concrete deep beam analysis.

Keywords: Rectangular concrete deep beams, STM method, shear strength, failure load, finite element analysis.

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1. Introduction

Deep beam is a reinforced concrete component the whole span or shear span depth of which is shorter than its height. From among the application of such beams we can refer to deep beams utilized in bridges, sky scrapers, marine structures, and foundations and piles of structures. There are plenty of researchers who have studied various subjects related to deep beams. In the last decades concrete deep beams were designed simply through experimental relations, formulas, and simple estimations [1]. As to the complexity of this concrete component, estimation of strength and deep beam capacity calculation is of high difficulty. Recently, STM model has been considered as a common model in beam modeling and this approach is fixed in American designing or modeling

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regulations like AASHTO [2] LRFD which is a transportation association, and American concrete association (ACI 318) [3]. In AASHTO and ACI regulations the concrete deep beams that are chosen are those in which the ratio of aperture shear to effective depth is less or equal to 2 [4]. Based on this approach the STM model is represented according to regulations of AASHTO LRFD and ACI318-08 [5]. Many of the researchers have deliberated different factors of concrete deep beams and other elements like types of applied loads [6-8], shear response [9], using different CFRP strips under sustained loading on T-beams [10], identifying the location and depth of a crack [11] in beam by concurrent effect of vertical and horizontal reinforcement in failure of load in order to be compared with experimental results. Wang et al. [12] presented a new modified model for predicting shear strength of concrete deep beams (MSTM). This model was actually designed for predetermined simple structure beams. In addition, analytical tools for example ADBUFEM and ADINA can be used for analysis of deep beams [13]. Based on the midspan deflection, reinforcement tensional strain, and surface strain of the deep beam have been accompanied with simple supporting tool for a high strength self-consolidating concrete (HSSCC) [14]. Effects of a/d and length of inhibitory on the strength of strut and load transmission mechanism have been scrutinized in experimental results [15]. Deep beams' behavior in comparison with shallow beams' is a counterpart for arcane behavior versus bending behavior. Moreover, experimental results have revealed that as the length of deep beams increase, the shear strength also enhance [16]. STM model has been indicated conservatively in ACI318-02 regulation's appendix for anticipating shear strength of deep beams. STM model has the lowest standard deviation among various patterns of designing. In addition, this study aims at identification of hooking connections (through ACI regulation) at the extreme positive anchor through steel mechanical halter and estimation of shear behavior in deep beams [17]. The analysis of concrete deep beams behavior and strength has been carried out using four identical samples of beams based on experimental results. The results derived from STM model show that there is a reasonable congruency in experimental results while deep beams are utilized alongside continuous support [18]. There have been so many researches done aiming at analyzing the effect of STM model in deep beams; however, anticipation and comparison between critical loads of the beams have never been taken into account by the two regulations, nonlinear finite element modeling, and experimental results. While using STM the components of ACI and AASHTO regulations are utilized. Finally, as to the nonlinear behavior of deep beams, nonlinear modeling is chosen using ABAQUS software. The main objective of this study is analyzing deep beams under critical load and comparing the result of analysis with experimental results already attained. The primary data is extracted from the literature review of the studies with the same subject. At long last, the ending of the study is dedicated to suggestion and standard selection with the aim of coordinating the standard of design with experimental results and finite element modeling.

2. STM model

STM model which works based on truss logic is utilized for analyzing and designing linear and nonlinear structures. The model is fixed on transmission of tension from one point to other in a structure. STM model is comprised of three components which are representative of special characteristics of a structure. These components are Strut and Tie which are linked together in lump sections and illustrated in Figs.1

The tension direction in modeled deep beam in concrete and reinforcement which are under two applicable loads are illustrated in Fig.2 and Fig.3. STM model is introduced in standard regulations of Canada for designing concrete structures (CAN-A23.3-M84 1984), AASHTO LRFD, ACI and their counterparts in Australia (AS3600).

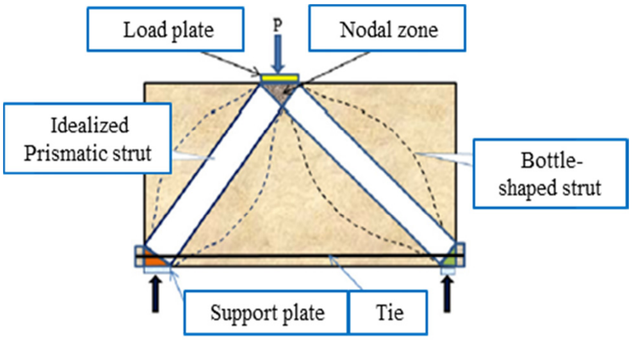

Fig. 1. STM model components in deep beam which is under point load

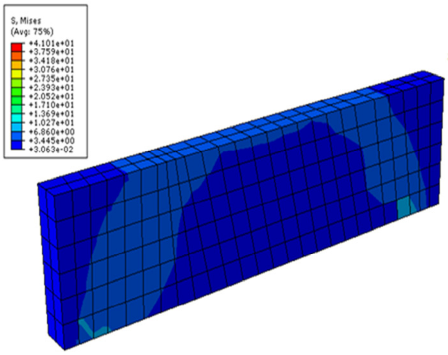

Fig. 2. Tension direction in deep beam

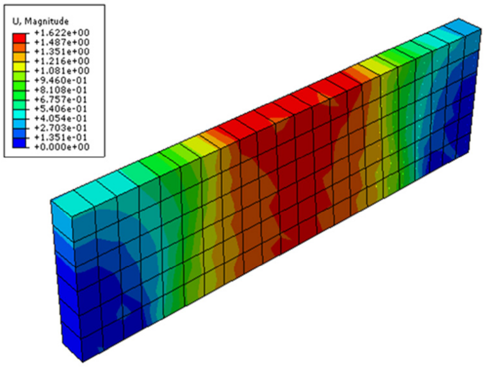

Fig..3. A sample of Zhang's et al experimental beam modeling [18].

1.1 STM model introduced by ACI regulations

Effective strength formula of Strut is as follow:

$$f_{cu} = 0.85\beta_s f_c \tag{1}$$

Effective strength formula of Node is as follow:

$$f_{cu} = 0.85\beta_n f_c \tag{2}$$

Tie strength or Fnt is calculated based on the following formula:

$$F_{nt} = A_{st} f_y \tag{3}$$

Applicable Shear power or Vcu should meet the following condition:

$$V_u \leq \varphi(10\sqrt{f_c}bd) \tag{4}$$

The shear strength capacity of tension in deep beam's concrete is greater than the capacity in normal beams [19]. The extreme amount of this capacity is presented in the following formula:

$$V_c \leq 6\sqrt{f_c}bd \tag{5}$$

Shear strength of concrete section is as follow:

$$V_c = 0.83\sqrt{f_c}\,b\,d \tag{6}$$

Whenever vu excels Vc, the section of beam requires shear reinforcement. This amount is computed as follow:

$$V_s = \frac{\left[\frac{A_v}{S_v}\left(\frac{1+\frac{\ln}{d}}{12}\right)+\frac{A_{vh}}{S_h}\left(\frac{11-\frac{\ln}{d}}{12}\right)\right]f_y d}{4.45}\left(\frac{N}{mm^2}\right) \tag{7}$$

$$A_{v_{min}} = 0.0025b\, S_v \tag{8}$$

$$A_{vh_{min}} = 0.0015b\, S_h \tag{9}$$

1.2 STM model introduced by AAHSTO regulations

AAHSTO regulations introduce STM model based on Collins et al theoretical model (1986). Compressive capacity of Struts is computed as follow:

$$\varphi F_{ns} = \varphi f_{cu} A_{cs} \tag{10}$$

In which f_{cu} is concrete's compressive strength in strut, Acs concrete's section in Strut and φ is reduction coefficient. The concrete's compressive strength in strut is as follow:

$$f_{cu} = \frac{f'_c}{0.8 + 170\mathcal{E}_1} \tag{11}$$

In this introduction $\mathcal{E}_1$ is the main tensile strain in Strut which is defined as follow:

$$\mathcal{E}_1 = \mathcal{E}_s + \frac{\mathcal{E}_s + 0.002}{\tan^2\theta} \tag{12}$$

$\mathcal{E}_s$ Is tensile strain in concrete toward the direction of Tie, and θ is the smallest angle between strut mile and horizontal Tie. Tie strength is computed based on the following formula:

$$F_{nt} = \varphi f_y A_{st} \tag{13}$$

Based on AASHTO the concrete's compressive tension in nodal points should not excel the following amounts.
The node which ends in Strut and loading section:

$$0.85\,\varphi_c f'_c \tag{14}$$

The node which ends in Tie:

$$0.75\,\varphi_c f'_c \tag{15}$$

The node which ends in Tie with more than one direction:

$$0.85\,\varphi_c f'_c \tag{16}$$

φ_c is concrete's strength coefficient which is appointed with the amount of 0.6.

3. Experimental data

This study has utilized experimental data of former researchers for data analysis and determination of shear capacity of deep beams. Table 1 represents details of beams' construction, including beams' dimensions to the surface of utilized reinforcement and the distance among them for only three references is shown.

In this table d and b are effective height and length of the beam in turn, a is the shear opening of the beam, As represents cross section of longitudinal bars, Asy is cross section of lateral shear bars, and Ash is cross section of longitudinal shear bars.

1. Finite element modeling (FEM)

Performing finite element modeling in the realm of deep beams for comparing models and introducing the best model besides introducing the best standard, which is closest to reality, is an essential requirement. The general modeling objective in ABAQUS software is producing finite element modeling, which represents structural reaction of deep beams considered formerly, more accurately and in a simpler way. As to introduce strain tension's curve of the concrete which is used in ABAQUS, we make use of analytical estimations in former results [21]. One of these estimations is Tudchini Curve [21] which is computed and drawn based on Equation (14).

$$f_c = \frac{1.8 * f'_c * (\frac{\varepsilon}{\varepsilon_0})}{1 + (\frac{\varepsilon}{\varepsilon_0})^2} \qquad (17)$$

$$\varepsilon_0 = \frac{1.8 * f'_c}{E_c} \qquad (18)$$

Table 1. Characteristics of experimental specimens.

d (mm)	b (mm)	L (mm)	a (mm)	fc (N/mm2)	As (mm2)	Asv (mm2)	Sv (mm)	Ash (mm2)	Sh (mm)	Researcher
313	80	1050	350	25.9	314	56.2	150	0	-	Zhang and Tan [18]
454	115	1500	500	27.4	688	56.2	150	0	-	
642	160	2100	700	28.3	1257	100	150	0	-	
904	230	3000	1000	28.7	2502	157	150	0	-	
581	155	1220	610	29.4	400	25.1	102	75.38	150	Breña and Roy [16]
405	152	1215	607.5	32.7	400	25.1	102	50.25	150	
303	155	1212	606	34.7	400	25.1	102	25.1	127	
200	150	930	465	60	750	0	-	0	-	Rao and Sundaresan [20]
450	150	1680	840	60	1500	0	-	0	-	
700	150	2430	1215	60	2250	0	-	0	-	

The current stage former nonlinear modeling is carried out and analyzed with the help of finite element modeling under static load [22]. For better comparison of outputs the STM model is utilized based on ACI and AASHTO regulations introduction alongside with experimental experiments. Samples are modeled using nonlinear finite element modeling through ABAQUS software. Analyzing and comparing the attained capacities for deep beams, it is revealed that STM model which is derived from ACI regulation claims more realistic results in comparison with AASHTO's model [23]. Fig.. shows a sample of finite element modeling of experimental beams (Zhang model [18]) using ABAQUS software. Mentioning the amount of leap represented in the length of beam, it can be perceived that the extreme amount of leap is in the midpoint of beam, and as we approach the support section this amount is reduced. Building on this, the amount of leap increases in the depth of leap as the height of beam reaches further position apart from the support point. Hence the extreme amount of leap is in the midpoint of beam where the load will be applied. In FEM model derived from Breña and Roy [16] studies, the range of reinforcement displacement in beam's length is indicated as the lowest amount in supporting areas. As the reinforcement approach the middle of supporting points the amount of displacement increases consequently to the extent that the highest displacement is viewed in midpoints of beam and close to where the load is applied concrete's compressive strength remain static.

2. Comparison of results

Some of results of experimental data were analyzed based on ACI and AASHTO standards and their limitations. FEM model is utilized for the purpose of measuring the validity of experimental results and available regulations.
The following diagrams are depicted for comparing and deliberating anticipations. As it is shown in Fig. 4(a)Fig. , by looking into Zhahng's [18] experimental results it can be observed that the resulted shear strength from ACI relations represents more congruency with experimental results when the height of beam is higher than 800 mm; however, when the height mentioned is more, the relations of STM works more accurately with AASHTO regulations as show in below Table 2.

Table 2. Measurement of deep beams' shear capacity.

Vexp (KN)	Vstm (ACI) (KN)	VACI (KN)	Vstm (AASHTO) (KN)	VFEM (KN)	Researcher
99.5	97	85	89	147	Zhang and Tan [18]
186.5	227	185	210	293.2	
427	436	399	403	420	
775	885	885	814	510.6	
338.5	237	740	118	207	Breña and Roy [16]
229.5	166	463	83	154	
156.5	124	358	62	103	
100	126	145	126	95	Rao and Sundaresan [20]
160	314	325	312	180	
280	507	506	482	356	

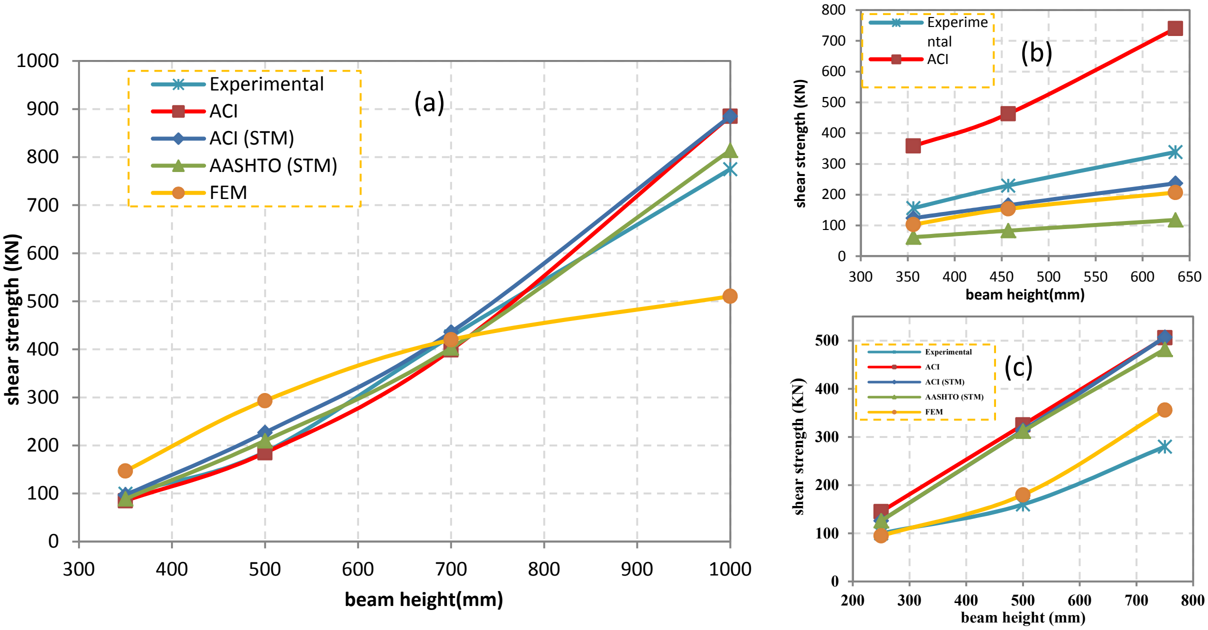

Fig. 4. Comparison of shear strength through regulatory relations and using experimental results of (a) Zhahng et al [18], (b) Brena et al [16], and (c) Rao and Sundaresan [20] with FEM.

ACI regulations' determination of cross section for beams more than 800 mm results in higher shear strength for beams' capacity. On the contrary, results of FEM model within heights between 350 and 800 mm indicate more amounts for deep beam capacity than heights of more than 800 mm. all the regulatory models and numerical model of FEM resulted in approximately close shear capacity for predetermined sections in beams with 800 mm height.

Looking at Fig. 4 (b)Fig. it is self-explanatory that computed shear capacity by the use of ACI regulations' relations have conspicuous variation with experimental results. Moreover, STM model in AASHTO relations indicates lower amount for shear capacity. Results which are derived from STM model in ACI regulations and FEM model entail lower amount of shear capacity than experimental results. However, the extreme congruency with experimental results is perceived for beams with height of 457 mm. generally, as for the experimental results of Breña and Roy [16], whenever the height of beams increases, the variance between indicated amounts by regulations and FEM model enhances as well.

The comparison deep beam's shear capacity, which is computed using regulatory relations and FEM model, and Rao and Sundaresan [20] experimental results are presented in Fig. 4 (c). Obviously, for beams up to 500 mm height the amount of shear capacity of experimental data and FEM model will increase linearly until this height indicates approximate results with experimental results. In cases where the height of beam is more than 500 mm, the shear strength will step away from experimental results and proclaim higher amounts. In all the mentioned three levels, as the beam's height increases, the shear strength will increase linearly and they determine higher amounts of capacity than FEM model has fixed.

3. Conclusion

In this study the capacity of deep beams' shear strength was analyzed and interpreted using STM model of both ACI and AASHTO regulations.

Validity measurement of results was carried out with the aid of finite element modeling through ABAQUS software. For this purpose the shear strength of 12 concrete deep beams were computed. Based on analysis of experimental results and interpretations done, the following conclusions could be considered as ultimate:

The mode of failure (shear or bending) in deep beams depends on beam's dimensions and the percentage of available flexural and shear reinforcement. In STM model the capacity which is attained is closer with experimental results reasonably and realistically than regulatory models. In the discussion of regulatory comparison, STM results almost identical; however, results from STM in ACI are closer to experimental results than in AASHTO.

Experimental studies, finite element modeling and utilization of different regulations show that in most cases of dimension and real properties of deep beams, bending capacity will be the final determinant above shear capacity. In other words, within such cases the diagonal cracks of elements will appear while the beam is bent.

The longitudinal shear reinforcements like lateral shear reinforcement or stirrups play a very important role in determination of deep beams' shear capacity. As the cross section of shear reinforcement enhances, or the lateral distance between them decreases, the shear capacity of deep beams will increase.

The mode of failure in deep beams depends on beams dimension and the percentage of shear or bending reinforcement. Taking this into account it can be perceived that as the bending longitudinal reinforcement increase, the bending capacity of beams will increase and eventually the possibility of beams facing shear failure of normal conditions will enhance as well. In other words, as bending longitudinal reinforcement decrease, the beam will expose bending failure.

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