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Sensitivity Analysis of Reinforced Concrete Deep Beam by STM and FEM (Part III)

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Abstract

The behavior of deep beams is significantly different from that of normal beams. Because of their proportions, deep beams are likely to have strength controlled by shear. This paper presents a strut-and-tie model (STM) to determine the strength of deep beams that were conducted experimental research in before researches, by using the ACI and ASHTO provisions. The behavior of the deep beams is investigated in failure mode that will happen in shear or flexural mode and so predict the total load that the beam can sustain. The gained load is verified with the exposed failure load in the laboratory. Comparison of the results obtained by using two standards that is closer to experimental data also conducted. Also there are several analytical tools available for analyzing deep beams. Among all the available analytical methods, finite-element analysis (FEA) by software's offers a better option. The results from this study were compared with results from renowned finite-element software (ABAQUS), and the results obtained were shown to reasonably agree.

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1. Introducion

A reinforced concrete member in which the total span or shear span is exceptionally small in relation to its depth is called a deep beam. Some examples of deep beams include bridge bent caps, transfer girders, and pile caps. Historically, reinforced concrete deep beams were designed with empirical methods or simple approximations.

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Evaluating the ultimate strength of concrete deep beams has been a great challenge because of the complexity of these structural members. Within the last decade, strut-and-tie, modeling has become the preferred method for designing deep beams in U.S. design specifications, such as the Bridge Design Specifications of the American Association of State and Highway Transportation Officials (AASHTO LRFD, 2008) and the Building Code Requirements for Structural Concrete of the American Concrete Institute (ACI 318-08). In AASHTO LRFD 2008 and ACI 318-08, beams or components are considered deep when the shear-span-to-depth ratio (a/d ratio) is less than or equal to 2 [1]. In addition, background information on strut-and-tie modeling, including a comparison with the STM design provisions of AASHTO LRFD (2008) and ACI 318-08 is provided. There are some researches, which has been applied various types of loading, web and longitudinal reinforcement to concrete deep beams to present both effect of web and longitudinal bars in failure load and comparison with gained experimental results. Recording of deflection at two points along the deep beam length, web strains, tensile bars strains and the strain at the concrete surface with simply supported high-strength self-compacting concrete (HSSCC) deep beams in the laboratory is performed [2]. The effect of a/d and anchorage length on strut strength and load transfer mechanism observed for the laboratory results is presented [3]. It is well known that deep beams behave very differently from shallow beams as arch action rather than flexure dominates the behavior, after diagonal cracking has occurred. An experimental program is carried out to investigate the possible causes of size effect, typically represented by a reduction in shear strength by an increase in the height of deep beams [3]. In predicting a strength of deep beam, Strut-and-Tie Model of Appendix A in ACI 318-02 was conservative and showed lowest standard deviation among several design methods. Also investigation, whether the standard hook anchorage designed according to ACI318-02 at the ends of the positive moment region can be replaced with mechanical anchorage using steel head and to estimate the shear behavior of deep beams [1]. An evaluation was conducted of the behavior and strength of deep reinforced concrete beams based on results from the monotonic test of four beam specimens. The test specimens were designed with two different approaches, which consisted of: 1) the procedure described in Sections10.7 and 11.8 of the ACI 318-99 code; and 2) the Strut-and-Tie Method given in Appendix A of the ACI 318-02 Building Code, which is intended to replace the procedure given in Section 11.8 of the ACI 318-99 Code [1-0]. The comparison between ANSYS results with Non-linear material properties, and experimental test results were made in terms of strength, flexural strain and deflection of concrete beams. The analytical and experimental flexural strains were compared at mid-section of the beam for different L/D ratios. Flexural strains were measured experimentally at mid-section of the beam and also the failure crack-patterns of the beam for different L/D ratios were also observed [2]. The modified model that is based on Mohr Coulomb's failure criterion, for simply supported deep beams (SSDBs) is evaluated using 233 test results, and it gives better agreement than the original model. The modified STM is further applied to concrete continuous deep beams (CDBs) and is in good agreement for a total of 54 experimental results [3].There is some research, which has been a study of STM in different application of the rectangular deep beam, but none of them studied prediction and verifying the critical load by two standards and analysis them by finite element and so experimental results.

2. Strut and tie method (STM) for various standards

The strut-and-tie method (STM), which is a generalization of the truss analogy, has been proposed for analysis and design of linear and nonlinear structures. The STM method is based upon an assumption that any stresses within a structure are transferred from one point to another along a valid and consistent path. A strut and tie model consist of three parts, which represent particular aspect of a structure [4, 5]. These are strut, ties and nodes (figure 1 (a) (b) and fig 1(c) , Fig 2 (a) (b) (c)). in the figure 3 and 4 the route of stress is shown in a deep beam modeling in concrete and reinforcements that is under two points loads

The strut-and-tie modeling technique has been included in the Canadian standard for the design of concrete structures (CAN-A23.3-M84 1984), in the AASHTO LRFD bridge specifications (AASHTO 1994), in the American concrete Institute (ACI 318-2002) and in the Australian standard (AS3600). Currently, section 7 of AS3600-09 is devoted to "Strut-and-tie Modeling". The following two subsections cover the relevant recommendations on the design of deep beams by the AASHTO and American standards [1].

2.1. Nonlinear Finite element modeling

Before verifying the design methods, it is necessary to develop a finite element model for reinforced concrete deep beams. The general purpose FE software ABAQUS was employed to generate FE models to simulate numerically the structural response of the previously described reinforced concrete deep beams. A three dimensional finite element model was developed for the beams. The concrete damage plasticity model (CDPM) was used to present the behavior of concrete in RCDBs. This model uses damage plasticity formulation in compression and cracking combined with damage elasticity in tension [6, 7].

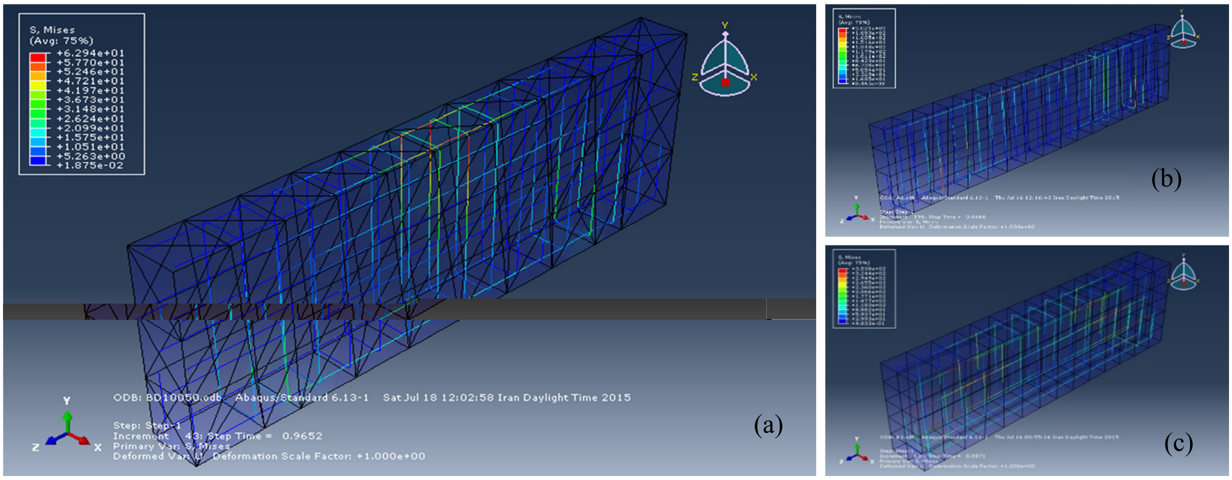

Fig.1. (a) Modelling beam A-6[4], (b) Modelling beam B-2 [8], (c) Modelling beam BD1.0-0.50 [9].

3. results and discussion

The effect of shear reinforcement on the shear strength is shown in Figure 5 (a) (b) and Fig 5 (c). As shown, in order to calculate the bending capacity in the STM method changing in shear reinforcements amount would not change the shear strength by assuming the concrete strength and the a/d ratio as constant. So, these values are the same for both codes by this method and are consistent with each other. But, in order to determine the shear capacity by two codes it is shown that increasing of the shear capacity occurs by increasing of the ratio of the cross-section to the shear longitudinal reinforcements distance. But it has significant increase for different ratios of A_s/S_V. In order to better comparison of these graphs, a graph is drawn based on the results obtained from the experimental data [10].

3.1. Ratio of Shear Span Length to Beam Height

Graphs 12 and 13 show the effect of the ratio of the shear span length to the beam height. In the STM method, as shown in the following graph the shear capacity of the deep beam decreases by increasing of the a/d ratio [11]because by increasing of the shear span the beam length and the moment increase. But in the method of the ACI and ASHTO codes, the shear capacity does not depend on the length of the beam, so by changing the length of the shear span this value remains constant.

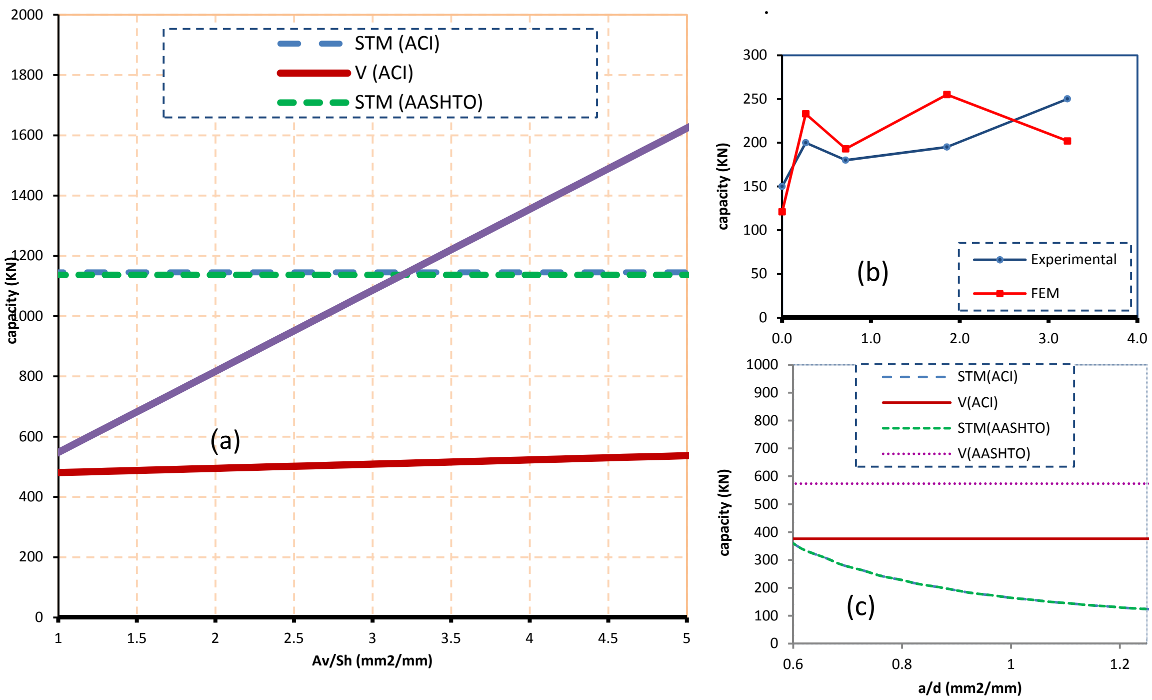

Fig.2: Plot of shear capacity vs. (a,b) the cross-sectional area of reinforcement for varies to its distance and (c) shear capacity changes vs. shear span to beam height ratio

In Figure 3, contour of interval reinforcement of the longitudinal shear beam load testing, to different heights deep bow is shown [5]. As the figure suggests, it can be fixed for a distance transverse to longitudinal shear reinforcement, Triple H had a different capacity.

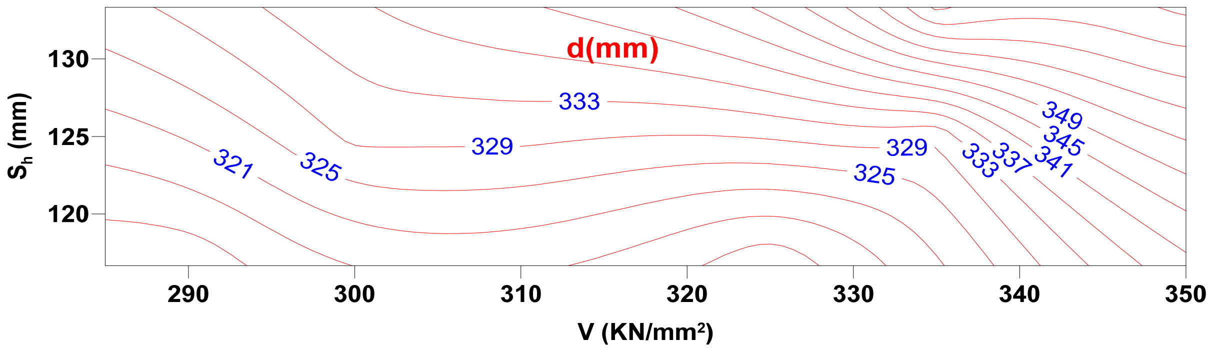

Fig.3: Effect of longitudinal reinforcement amount on shear vs. capacity of deep beam.

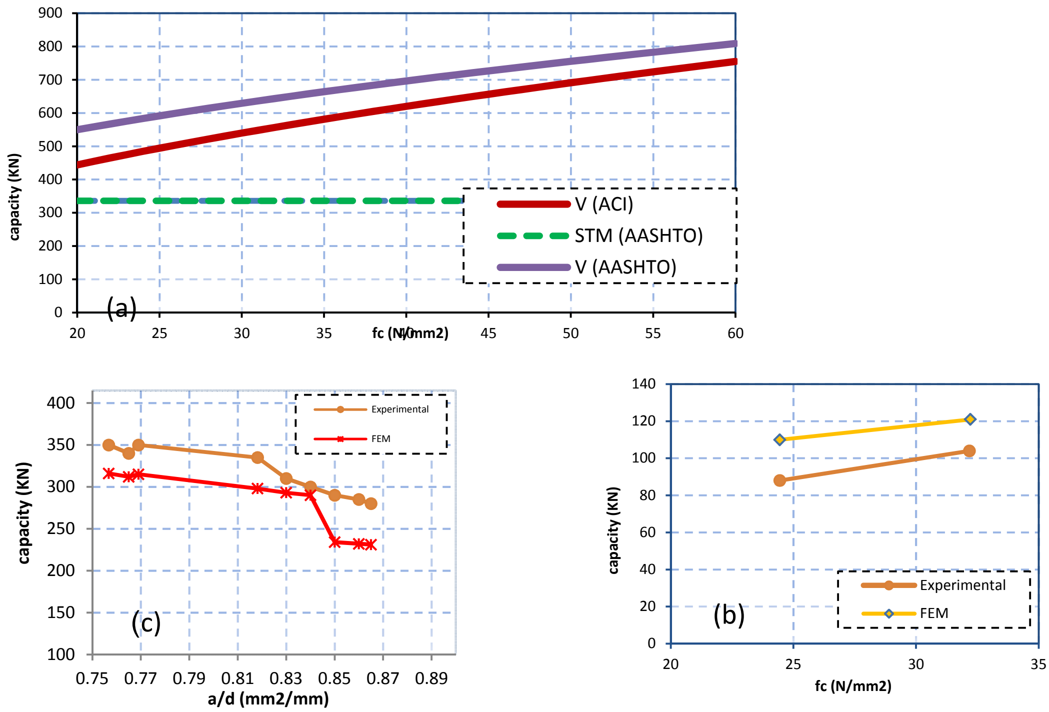

Fig.4: Shear capacity vs. (a, b) concrete compressive strengths and (c) span to beam high ratio

3.2. Concrete Compressive Strength

In the ACI and ASHTO codes, the concrete compressive strength has the maximum effect on the shear strength of deep beams. Graphs 14 and 15 show the relationship between the shear strength of the beam and the concrete compressive strength [12]. According to this graph, by increasing of fc the shear strength of the beam increases. But in the STM method for both codes, the concrete compressive strength has no effect on the beam bending capacity, but the minimum concrete strength is required to satisfy the limits based of equations 1, 2 and 11 as shown in below Fig 4 (a) (b) & (c).

3.3. Longitudinal Bending Reinforcements

In STM, the longitudinal force of reinforcements and consequently the assumed truss members force increase because they are directly affected by longitudinal bending reinforcements. These forces are equal for both codes according to STM because the truss members are the same. This increasing trend is observable for different cross-sections of longitudinal bending reinforcements in tested samples [12, 13]

According to the code formulas, there is no need to consider the effect of longitudinal bending reinforcements for calculating the shear capacity, thus this value is the same. [12, 13].

Next, the graph of is drawn based on the experimental work [12, 13]. According to this figure, by increasing and decreasing longitudinal bending reinforcements we can decrease or increase the ratio of the transverse shear reinforcement cross-section to their distance for a desire capacity.

4. Results

In this paper, finding a method and standard which has closet results to the experimental and non-linear modelling is desired. The deep beam capacity of 120 fabricated samples in the past along with the conducted nonlinear modelling which its concrete stress-strain curve is based on the Tudchini curve were compared with the shear and bending capacities obtained from the STM method and ACI and ASHTO codes. Then, the sensitivity analysis of the beam capacity was investigated with dependent parameters.

The failure mode in deep beams depends on the beam dimensions and considered shear and bending reinforcements percent, so that by increasing longitudinal bending reinforcements the beam bending capacity increases and the possibility of the beam shear failure increases as well.

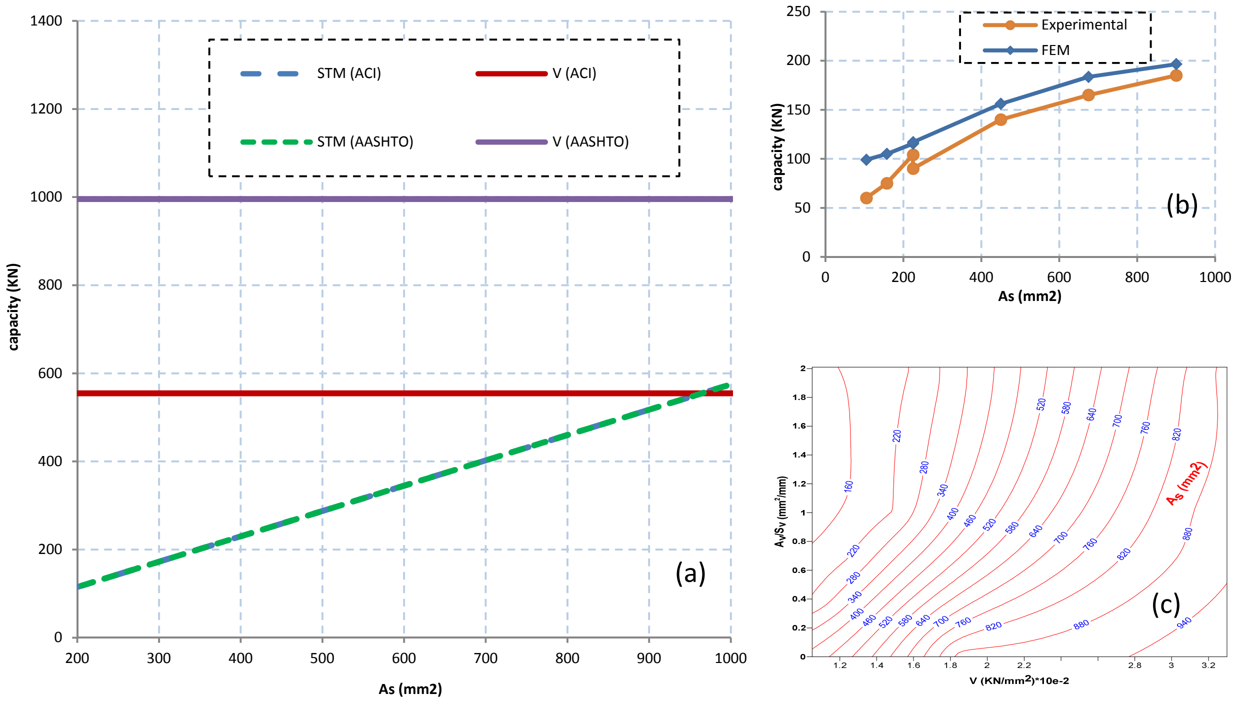

Fig.5:Effective depth variations vs. capacity and space of longitudinal shear reinforcement(a,b), changes of flexural reinforcement vs. sectional area of stirrups /space(c)

In the STM method, the obtained capacity has more realistic approximation to experimental results compared to the code method. In the code comparison, the capacity obtained from this method has similar results, but the ACI results are closer to the capacity obtained from the experimental work compared to ASHTO.

For most cases, the bending capacity obtained from STM is always determined to the shear capacity. In the other words, the beam failure occurs in the force transmission to the strut support region.

Longitudinal shear reinforcements similar to transverse shear reinforcements or stirrups have an important role in deep beams shear capacity. By increasing the shear reinforcements cross-section or decreasing their transverse distance, the deep beam shear capacity increases.

Parameters such as the ratio of the longitudinal bending reinforcements in determination of the deep beam shear capacity and parameters such as the cross-section and the stirrups distance have no effect on determination of the beam shear capacity obtained by the STM method.

Experimental studies and the finite element modelling and also using different codes show that in most cases in real dimensions and characteristics of deep beams, the shear capacity is determinant instead of the bending capacity and in the other words in such cases inclined cracks occur in the beam struts.

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