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ORIGINAL ARTICLE

# Prediction of the behavior of reinforced concrete deep beams with web openings using the finite element method

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**Abstract** The exact analysis of reinforced concrete deep beams is a complex problem and the presence of web openings aggravates the situation. However, no code provision exists for the analysis of deep beams with web opening. The code implemented strut and tie models are debatable and no unique solution using these models is available. In this study, the finite element method is utilized to study the behavior of reinforced concrete deep beams with and without web openings. Furthermore, the effect of the reinforcement distribution on the beam overall capacity has been studied and compared to the Egyptian code guidelines. The damaged plasticity model has been used for the analysis. Models of simply supported deep beams under 3 and 4-point bending and continuous deep beams with and without web openings have been analyzed. Model verification has shown good agreement to literature experimental work. Results of the parametric analysis have shown that web openings crossing the expected compression struts should be avoided, and the depth of the opening should not exceed 20% of the beam overall depth. The reinforcement distribution should be in the range of 0.1–0.2 beam depth for simply supported deep beams.



## 1. Introduction

Structural bending members can be broadly divided into two regions. The first region is the Bernoulli regions (B-Region), where the strain distribution across the section is linear. The second region is the D- or Disturbed regions, where the strain distribution is nonlinear as the case of deep beams. Reinforced concrete deep beams have many useful applications in building structures such as transfer girders, wall footings, foundation pile caps, floor diaphragms, and shear walls. The use of deep beams at the lower levels in tall buildings for both residential and commercial purposes has increased rapidly because of their convenience and

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economical efficiency. It is recognized that the distribution of the strain across the section of deep beams is nonlinear and hence, these structural elements belong to the D-Regions, Nagarajan and Madhavan [1]. Traditionally, the D-Regions have been designed using empirical formulae or past experience. Recently, the Strut-and-Tie Model (STM) has been recognized as an effective tool for the design of both B- and D-Regions and it has found place in many design codes.

The strut and tie model (STM) provides design engineers with a more flexible and intuitive option for designing structural elements. The complex stress flows in a cracked concrete structure are approximated with simple truss elements that can be analyzed and designed using basic structural mechanics. Though the STM is effective for the design of D-Regions, the method has not yet been widely implemented due to many reasons such as: (1) the difficulty in fixing an optimum truss configuration for a given structural member with given loading, (2) the complexity and approximation of the solution and the inability of the STM to predict the failure modes of deep beams, Tan et al. [2] and Yang et al. [3].

It has been recognized that the finite element method can provide realistic and satisfactory solutions for nonlinear behavior of reinforced concrete structures. Therefore, the finite element software, ABAQUS [4], has been used to study the behavior of reinforced concrete deep beams with and without web opening under monotonic loading actions. First, the modeling technique has been verified by comparing the model prediction to experimental work in the literature. A parametric study has been conducted to predict the behavior of simply supported and continuous reinforced concrete deep beams under 3-points and 4-points bending configurations. Also, it examines the effect of the location of web openings in both simple and continuous deep beams. Finally, the effect of the reinforcement distribution on the overall capacity of the beam has been conducted. The results of this study have been compared with the ACI 318-08-Appendix A [5], and the Egyptian Code (EC 203-2006) [6] recommendations.

## 2. Background

Deep beams are defined as members loaded on one face and supported on the opposite face so that compression struts can develop between the loads and the supports. Their clear spans are either equal to or less than four times the overall member depth; or regions with concentrated loads within twice the member depth from the face of the support, ACI 318-08 [5]. The EC 203-2006 [6] adopts the same definition as ACI 318-08, whereas the Euro Code [7] defines a deep beam as a member whose span is less to or equal to 3 times the overall section depth. These structural elements belong to D (Disturbed) regions, which have traditionally been designed using empirical formulae or using past experience.

STM is a recent development in the analysis and design of reinforced concrete structural elements. In STM, the reinforced concrete member is replaced by an equivalent truss, where the compression and tension zones are converted into equivalent struts and ties connected at the nodes to form a truss resisting the applied loads.

Design codes provide an extensive explanation and illustration of the struts, ties and nodes' shapes, classification and detailing. In addition to the permissible stresses in struts and nodes and the corresponding cross sectional areas of struts and nodes [5–7]. Fig. 1 illustrates a schematic representation of the STM developed for deep beams under 3- and 4-points bending configurations respectively.

The STM has been subjected to ongoing debates due to the difficulty in constructing the optimum truss configuration for a given loading. Traditionally, STM has been developed using load path method or with the aid of stress trajectories. However, this STM is not unique and varies with the designer's intuition and past experience. In order to overcome the limitations associated with the development of the STM, the Finite Element Method (FEM), is applied in the present study to predict the behavior of reinforced concrete deep beams. Results are compared to the corresponding code provisions for the design of deep beams using the STM.

FEM has proven to be a versatile tool for studying the nonlinear behavior of reinforced concrete structures. Current advances in computational capabilities have motivated the development of large number of commercial finite element codes. These codes have shown the adequate reliability and accuracy to study the behavior of reinforced concrete structures. In the present study, the damaged plasticity model, as implemented in the general purpose finite element software ABAQUS [4], is used to study the behavior of reinforced concrete deep beams. This constitutive modeling has proved to be the most stable regime for modeling concrete nonlinear behavior. It shows the ability to capture the whole concrete behavior up to failure with reliable accuracy when compared to the experimental results, Saeed [8].

The concrete damaged plasticity model in ABAQUS [4] is based on the models proposed by Lubliner et al. [9] and Lee and Fenves [10]. The model uses the concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete. The model consists of the combination of non-associated multi-hardening plasticity and scalar (isotropic) damaged elasticity to describe the irreversible damage that occurs during the fracturing process. The elastic behavior of the material is isotropic and linear. The model is a continuum, plasticity-based, damage model for concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The evolution of the yield (or failure) surface is controlled by two hardening variables linked to failure mechanisms under tension and compression loading, respectively. Fig. 2 shows the uniaxial tensile and compressive behavior of concrete, respectively, used in the concrete damaged plasticity model. As depicted from the figure, if the concrete is unloaded at any point on the softening branch, the elastic stiffness is reduced. The effect of the damage is different in tension and compression, and the degraded response of concrete is taken into account by introducing two independent scalar damage variables for tension and compression respectively.

## 3. Research program

The research program includes two parts; the first part is the validation of the proposed model using experimental data from literature. The second part is concerned with the parametric study.