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# The influence of web openings on the structural behavior of reinforced high-strength concrete deep beams

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**Abstract**

The objective of this study is to experimentally and analytically estimate the influence of web openings in reinforced concrete deep beams. Thirty-two reinforced high-strength concrete deep beams with or without openings were tested under two-point top loading. Test variables included concrete strength, shear span-to-depth ratio, and the width and depth of the opening. Test results indicated that the strengths at diagonal crack and at peak were closely related to the angle of the inclined plane joining the support and the corner of the web opening. Also, the influence of concrete strength on the ultimate shear strength remarkably decreased in deep beams with openings rather than solid deep beams. From comparisons of predictions and test results, the equations proposed by Kong and Sharp, and Tan, Tong and Tang would be suitable for reinforced high-strength concrete deep beams with openings and $\theta_3 \geq 30°$.


*Keywords:* Deep beam with opening; High-strength concrete; Shear span-to-depth ratio; Ultimate shear strength

## 1. Introduction

Reinforced concrete deep beams are members in which a significant amount of the load is carried to the support by a compression thrust joining the loading and reaction point. ACI 318-02 Section 11.8 [1] specifies that deep beams should be loaded on loading points and supported on reaction points so that compression struts can develop between the loads and supports. For many years, the deep beam has been designed based on empirical methods for slender beams. However, some experimental results and analytical reports have indicated that shear strength, redistribution of internal forces before failure, and internal force mechanisms in deep beams are quite different from those in slender beams. Thus, in recent years, the methods for reasonable deep beam design, such as the strut-and-tie model, have been created.

Openings are inevitably installed in deep beams to facilitate conduits, air conditioning, electricity, and computer network cables. If the openings interrupt the load path joining the loading and reaction point, it is obvious that the simple load path changes to a more complex one, and the shear capacity will be reduced. In spite of significant effects of the openings on the structural behavior of deep beams, there is no clear design guidance for deep beams with openings. In addition, most of its tests have focused on solid deep beams except for only very few research papers on deep beams to have compressive strengths in the range of 18–30 MPa including the effects of openings [2,7,8,10].

Based on the test results of high-strength concrete deep beams, Tan et al. [11] and Yang et al. [13] concluded that the effect of concrete strength on the nominal shear strength appears more significant in deep beams than in slender beams because most load is transferred by concrete struts. Thus, the application of high-strength concrete to deep beams is gradually increasing with the enhancement in concrete strength. Nielsen [9] proposed that the effective load-carrying capacity of a strut decreases with the increase in concrete strength. Also, in the Canadian Code [3] it is assumed that the effective strength of the strut is expressed as a function of the transverse tensile

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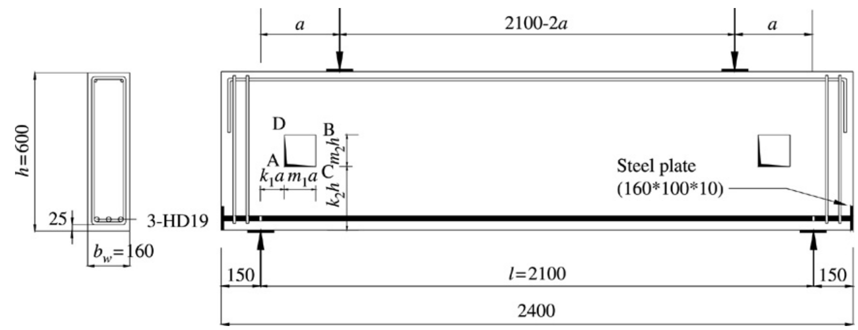


Fig. 1. Typical specimen details (unit: mm).

**Notations**

| | |
|---|---|
| $A_c$ | cross-sectional area of beam |
| $A_{\text{str}}$ | cross-sectional area of strut |
| $a$ | shear span distance |
| $b_w$ | width of beam |
| $f_c'$ | cylinder compressive strength of concrete |
| $f_{ct}$ | tensile strength of concrete |
| $f_t$ | combined tensile strength of concrete and steel |
| $f_y$ | yield strength of main longitudinal reinforcement |
| $h$ | overall depth of beam |
| $k_1, k_2$ | coefficients defining the location of opening (Fig. 2) |
| $m_1, m_2$ | coefficients defining the dimensions of opening (Fig. 2) |
| $V_{cr}$ | initial diagonal cracking shear strength in solid deep beams |
| $V_{fl}$ | initial flexural cracking shear strength |
| $V_n$ | ultimate shear strength in solid deep beams |
| $x$ | clear shear span distance |
| $\theta$ | angle of inclined plane joining load and reaction points (Fig. 2) |
| $\theta_1$–$\theta_6$ | angles of inclined plane joining loading and reaction points and corner of opening (Fig. 2) |

strain in the strut. It is potentially desirable to alleviate the effect of concrete strength for enhancing the load-carrying capacity of deep beams with openings, because of higher transverse tensile strains and a great deal of cracking around the corners of openings.

This test program is to understand the structural behavior of, and to evaluate the effect of, concrete strength on shear strength in high-strength concrete deep beams with openings. The test results were compared with predictions proposed by Kong and Sharp [7], and Tan et al. [12].

## 2. Research significance

Although high-strength concrete is being used more and more widely in reinforced concrete deep beams with openings, there is little research related to them. Additionally, there is no clear information regarding the effect of concrete strength on shear strength of deep beams with web openings. Experimental results described in this paper provide more data to explain the structural behavior of high-strength concrete deep beams with openings and concrete strengths greater than 50 MPa. In particular, this paper shows that the effect of concrete strength in enhancing shear strength of deep beams decreases more in deep beams with openings than in solid deep beams.

## 3. Experimental program

### 3.1. Specimen details

The typical details of the specimens are shown in Fig. 1 and Table 1.The test specimens consisted of 32 simply supported beams with rectangular openings. All beams were 160 mm thick and 600 mm deep. The span length $l$ was constant at 2100 mm, and shear span $a$ varied from 300 to 900 mm depending on four shear span-to-depth ratio $a/h$. Each beam had a main longitudinal reinforcement area of $A_{st} = 861$ mm$^2$ ($\rho_t = 1.0\%$), consisting of three 19 mm diameter deformed bars. The longitudinal bars having yield strengths of 820 MPa and 420 MPa were utilized in the deep beams without and with openings, respectively. To prevent anchorage failure, the longitudinal reinforcements had an extended length of 150 mm and were welded to the end steel plates (160 × 100 × 10 mm). The clear cover to longitudinal reinforcements was 35 mm. Shear reinforcements were not used in the shear span in order to investigate the effect of openings.

The design strengths of concrete were 24, 50 and 80 MPa. The test specimens were divided into three series according to concrete strength $f_c'$, resulting in L-series for $f_c' = 24$ MPa, H-series for $f_c' = 50$ MPa, and UH-series for $f_c' = 80$ MPa. Under each concrete series, the shear span-to-depth ratio, the width of opening $m_1 a$, and the depth of opening $m_2 h$ were established as test variables. The shear span-to-depth ratios in L- and H-series beams were chosen as 0.5 and 1.0, and in UH-series 0.5, 0.7, 1.0 and 1.5. The widths of opening were taken as $0.25a$, $0.5a$ and $0.65a$ in H- and UH-series, and $0.5a$ only in L-series. And the depths of the opening were selected as $0.1h, 0.2h$ and $0.3h$ in H- and UH-series, and $0.3h$ only in L-series. The center of the web openings of all beams was positioned at the center of the shear span region as shown in Fig. 1. The identification of symbols utilized in this study is given in Fig. 2.

The specimens were named as follows; the first letter refers to the series number, the following integer number indicates shear span-to-depth ratio $a/h$, the following letter indicates the