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Evaluation of experimental work on high strength concrete deep beam with various opening size and locations

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ABSTRACT: This paper focuses on the laboratory test undertaken on HSC deep beams with various opening sizes and locations on the web. These tests cover an area where limit scope of previous research. Apart from highlighting the experimental setup, failure loads, and typical crack patterns of the test specimens are also reported. Experimental results are then compared with predicted estimation by existing design methods. The comparison indicates that the predictions are overestimated on the ultimate strength of the beams and the reduction of the ultimate strength due to web openings did not considered sufficiently. To rectify the current design formulae, more experimental tests with various opening configuration considering shape and location of openings are required

1 INTRODUCTION

Reinforced concrete deep beam can be used in various design situations, these include beams as integral components in high rise building, offshore structure and foundations. Although reinforced concrete deep beams are of considerable interest in structural engineering practice, the major codes of practice (AS3600 2001; ACI318-05 2008; CSA 1984) still offer little guidance for the design of high strength concrete deep beams in particular when openings in the web region are provided for essential services and accessibility (Kong, 1990). The need for an accurate design method for deep beams with openings is becoming increasingly necessary with the subsequent growth in the use of deep beams in construction industry.

The web openings in a deep beam significantly affect its structural behaviour as demonstrated in the existing study (Kong & Sharp 1977, Kong *et al*. 1978, Mansur & Alwis 1984, Ray 1990, Almeida & Pinto 1999, Ashour & Rishi 2000, Maxwell & Breen 2000, Tan *et al*. 2003). A simple structural idealization for predicting the ultimate shear strength of deep beams with web openings was proposed some thirty years ago based on a series of laboratory testing conducted by Kong and Sharp (1977), Kong *et al*. (1978) and Tan et al. (2003). The structural idealization shows the lower and upper paths of load transfer when a web opening is present. It offers a good indication of the ultimate load-carrying capacity of the beam which is affected by the size and location at which the natural load path is interrupted by an opening. (Guan & Doh, 2007).

Hence, the purpose of this project is to investigate the behaviour of normal and high strength concrete deep beams with various web opening sizes and locations. To achieve this, an experimental program has been undertaken to obtain data for the modification of applicable formulae, such as the Australian Standards (AS3600-2001). The data obtained from test results will include the ultimate load, crack patterns and failure modes.

The test data will then be compared with currently available design equations. A new design formula will be generated using the previously available test data incorporated with current studies. This new design formula for deep beams with web openings is then compared with the experimental test results.

The following paper will detail the test procedure and analysis of eight high strength concrete deep beams with varying web opening size and locations. These beams were distributed into two groups, in which for the first group the web openings were moved at certain intervals away from the critical load path along a horizontal plane and for the second, along a vertical plane.

Data obtained from testing was then compared to the predicted results from both Kong et al. (1977) and Tan et al. (2003) and to the experimental results of both Kong et al. (1977) and Yang et al (2006). This information was then used to produce a design equation that can accurately equate the ultimate load characteristics of all beams tested and which is primarily focused on the Mohr's circle failure criteria.

2 DESIGN FORMULA FOR DEEP BEAM WITHOUT OPENINGS

2.1 *Existing design method*

Based on experimental studies, Kong et al. (1970, 1978) and Kong & Sharp (1973, 1977) derived design equations for normal and lightweight concrete deep beams with web openings. The ultimate shear strength equations for reinforced concrete deep beams are:

$$Q_{ult} = C_1\left[1-0.35\frac{x}{D}\right]f_t bD + C_2\sum A_w \frac{y}{D}\sin^2\alpha \quad (1)$$

for solid deep beam, and

$$Q_{ult} = C_1\left[1-0.35\frac{k_1 x}{k_2 D}\right]f_t b k_2 D + \sum \lambda C_2 A_w \frac{y_1}{D}\sin^2\alpha_1 \quad (2)$$

for deep beam with web opening

where, A_w = Area of individual web bar, C_1 = empirical coefficient (1.40 for normal strength concrete, 1.35 for light weight concrete), b = breadth (thickness) of beam, D = overall depth, f_t = cylinder-splitting tensile strength of concrete, x = clear-shear-span distance, C_2 = empirical coefficient (300N/mm^2 for deformed steel bar, 130N/mm^2 for plain steel bar), y = depth at which a typical bar intersects the potential critical diagonal crack in solid deep beam, which is approximately at the line joining the loading and reaction points, and λ = an empirical coefficient, equal to 1.5 for web bars and 1.0 for main bars. Other geometric notations are described in Figure 1.

Kong & Sharp (1973, 1977) and Kong et al. (1978) made significant contributions to the development of the British Standard. The first term on the right side of Equation (1) and Equation (2) expresses the load capacity of strut. When an opening is in the natural loading path, the first term considers the lower load path. The second term on the right side of the equation articulates the contribution of reinforcement in deep beams. However, these equations are only applicable for the concrete strength less than 46 MPa.

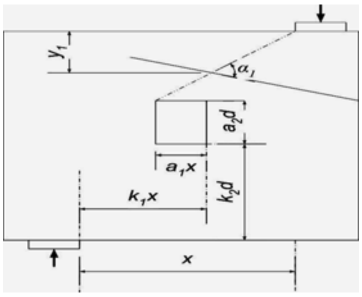


Figure 1. Notation for size and location of opening (half length) (Kong and Sharp, 1977).

Tan et al. (1995, 1997 & 2003) and Leong & Tan (2003) investigated the effects of high strength, shear span to depth ratios and web reinforcement ratios of the beams using both experimental program and numerical analysis. The design formula for high strength concrete deep beams is

$$V_n = \frac{1}{\dfrac{\sin 2\theta_s}{f_t A_c} + \dfrac{1}{f'_c A_{str}\sin\theta_s}} \quad (3)$$

(2)

where

$$f_t = \frac{2A_s f_y \sin\theta_s}{\dfrac{A_c}{\sin\theta_s}} + \frac{2A_w f_{yw}\sin(\theta_s+\theta_w)}{\dfrac{A_c}{\sin\theta_s}}\cdot\frac{d_w}{d} + f_{ct} \quad (4a)$$

and

$$\tan\theta_s = \frac{h - \dfrac{l_a}{2} - \dfrac{l_c}{2}}{a} \quad (4b)$$

in which, θ_s = angle between the longitudinal tension reinforcement and the diagonal strut, f_t = combined tensile strength of reinforcement and concrete, A_c = area of concrete section, A_{str} = cross-sectional area of diagonal strut, f_y = yield strength of longitudinal steel reinforcement, A_w = area of web reinforcement, f_{yw} = yield strength of web reinforcement, θ_w = angle between the web reinforcement and the axis of beams at the intersection of the reinforcement and diagonal strut, d_w = distance from the beam top to the intersection of the web reinforcement with the line connecting the support centre and the load centre, d = effective depth, f_{ct} = tensile strength of concrete, h = overall height of deep beam, l_a = height of bottom node, l_b = width of support bearing plate, and a = shear span measured between concentrated load and support point.

Equation (2) has limitation on the web opening size and location with respect to x/D ratio within the 0.25 to 0.4 range. However Equation (3) does not give any design limitations in regards to the size, location or orientation of the opening size; or for that fact, the geometry of the beam itself, including the x/D or the L/D ratio. Either they have not considered the effect of these variables, or they are confident that the equation will work under any circumstance.

Experimental test

2.2 *Test specimen*

In attempt of investigate on the performance of existing design equations, 8 beams were tested to failure. The opening sizes were of 60mm×60mm and the opening locations are detailed in Table 1 with Figure

2. The compressive concrete strengths were 80 and 84.1 MPa.
The beams were constructed with a consistent shear span to depth ratio, depth, reinforcement arrangement and clear span length. Each specimen had a length of 2400mm, depth of 600mm and a width of 110mm. This allowed for a clear span length of 1800mm and a shear span length of 900mm, which resulted in a clear span to depth ratio of 3 and a shear span to depth ratio of 1.5. The test model of the second last symbols O, C and D indicate opening locations were varied horizontally and vertically, respectively. The last digit following the symbols denotes the distance from the shear parts to openings. Details of geometric notations are presented in Figure 2.

Each beam consisted of two longitudinal reinforcement bars and yield stress of 500MPa deformed steel bars with a diameter of 20mm. Each bar had a length of 2700mm and a 90 degree cog at each end causing a vertical section of length 200mm; this was done to prevent end anchorage failure.

The concrete was supplied by the local ready-mix company. The concrete requirements were a compressive strength, 80 MPa, a slump of 80 mm and a maximum aggregate size of 10 mm.

The test frame was designed to support a jack of 80 tonne capacity. Dial gauges were used to measure the vertical deflections of the beams at the middle of soffit during testing (see Fig. 3 (a) & (b)). The beams were loaded in about 0.1 kN increments up to failure. At each load increment, crack patterns and the deflections were recorded.

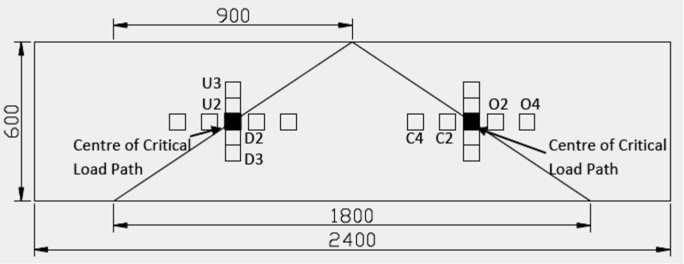
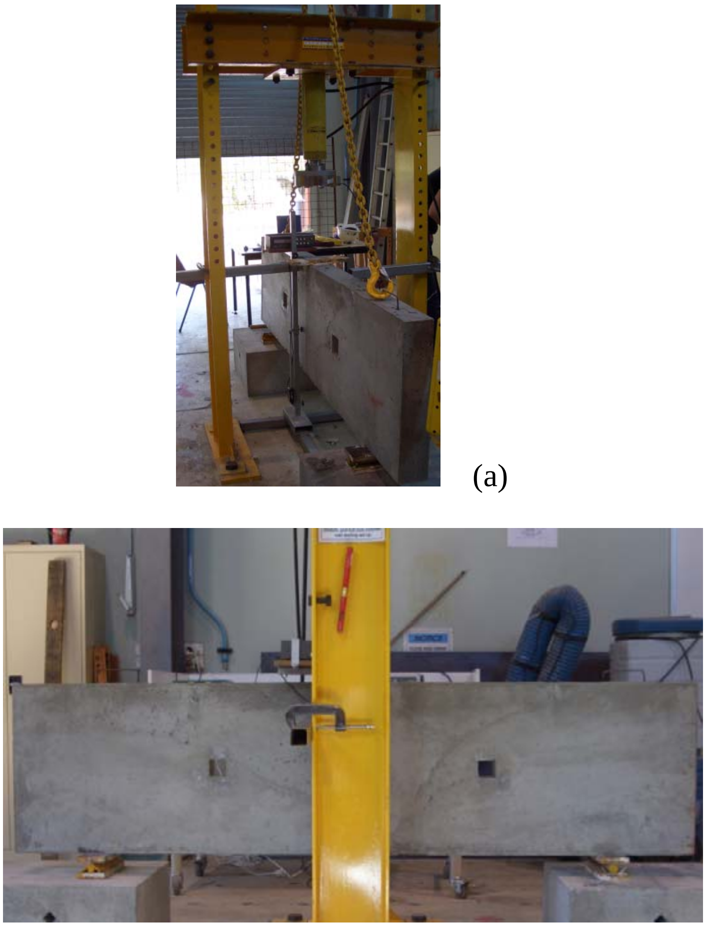


Figure 2. Opening configuration.

Table 1. Opening location and concrete strength.

Classification	Distance From Edge (mm)	Distance From Bottom (mm)	f’c (MPa)
RO80O4	510	270	84.1
RO80O2	630	270	84.1
RO80C2	810	270	84.1
RO80C4	930	270	84.1
RO80D3	720	150	80
RO80D2	720	210	80
RO80U2	720	330	80
RO80U3	720	390	80



(a)

(b)

Figure 3. Test setup.

3 ANALYSIS AND DISCUSSION

3.1 *Crack Pattern*

Figure 4 shows the typical crack patterns of the deep beam after failure. In most of the beams, the first crack to be seen was the flexural crack, however once the shear crack had formed, these cracks ceased to propagate.

After the flexural cracks had formed, it took several more load iterations to produce the shear crack. In all cases the shear crack formed near the corners closest to the loading and support position (A and C in Fig. 4) with an explosive sound. This was unlikely predicted by Kong et al (1977) in which the cracks would form from the support to corner D. Once the shear crack had formed it began to increase in size and propagate towards the loading and support position; failure of the beam was seen to happen once this crack had propagated into the bearing compressive area below or above the loading or support position. Only one of the beams (RO80U2) failed instantly when the shear crack appeared, this is most likely due to the location of the opening and the effect it has on the shear path. In some cases a vertical crack (see Fig. 4, 3a or 3b) appeared on the opposite corner of the opening, B or D to that of the shear and would either propagate to the top or the bottom of the beam, it was believed that this crack had no major affect on the beam itself. Table 2 shows the loads at which these cracks were observed to begin, however most vertical cracks were not recorded as they appeared during failure. Unlike what was expected, the beams with the lowest ultimate strength presented flexural cracks at a higher load value then compared to that of a beam with a higher ultimate strength. This suggests that the rigidity of the weaker beams is higher than that of the stronger beams whilst the beam is below a load of 200kN. The crack patterns observed on the web faces beams after failure are shown in Figures 5 to 10.

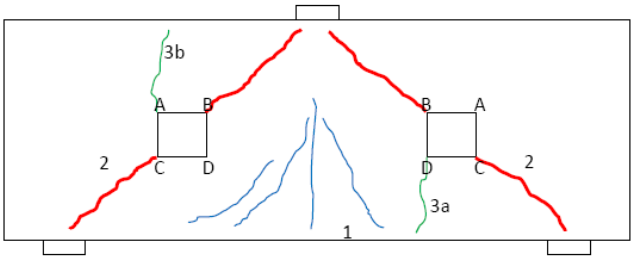


Figure 4. Typical crack patterns.

Figure 5. Crack pattern of RO80U3.

Figure 6. Crack pattern of RO80U2.

Figure 7. Crack pattern of RO80D3-60.

Figure 8. Crack pattern of RO80C4.

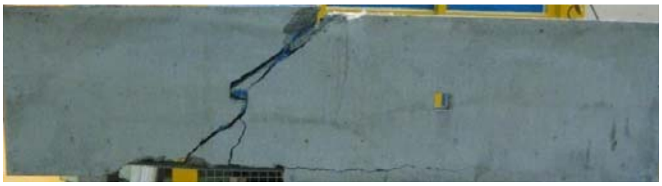


Figure 9. Crack pattern of RO80C2.

Figure 10. Crack pattern of RO80O4.

Table 2. Flexural, Shear and Failure Load.

Classification	Flexural Crack (kN)	Shear Crack (kN)	Ultimate Load (kN)
RO80C4-60	123.31	166.28	415.75
RO80C2-60	106.73	171.58	352.77
RO80O2-60	110.85	145.87	427.81
RO80O4-60	125.57	161.57	420.22
RO80U3-60	118.21	201.2	240.54
RO80U2-60	107.91	167.75	267.11
RO80D2-60	89.07	123.70	347.67
RO80D3-60	93.29	142.93	401.82

3.2 *Varying Opening sizes*

To obtain an idea of the affects of these variables within a deep beam with openings, Yang et al (2006) experimental test results were analysed and produced the following results.

As can be seen within Figure 11, the web opening size increases with decreased in the ultimate strength. This means by not taking into account the width and depth of the opening inaccurate results will be produced that over estimate the ultimate strength of the beam. These variables were not accounted for within the final proposed design methods by Kong et al (1977) and Tan et al (2003) as it believed that the critical load path angle would suffice. Thus meaning these design procedures will produce inaccurate results as the opening size differs from the dimensions of the test specimens used by both authors.

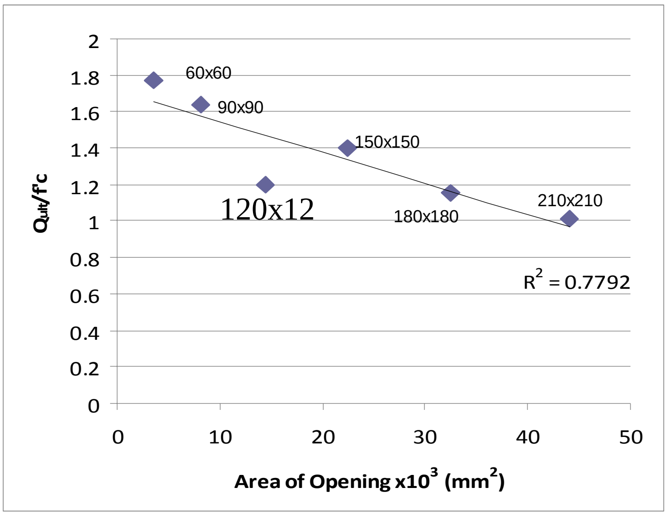


Figure 11. size of opening vs ultimate load/f'$_c$ (Yang et al. 2006).

3.3 *Horizontal Opening Variation*

Horizontal positions of opening versus ultimate load of deep beam were plotted in Figure 12 with previously available test results conducted by Yoo et al. (2008). The previous tested deep beam model (M) had same dimension and material properties of current models except concrete strength of 94 MPa. This can be seen to be the evidence as Figure 12 that as the opening position moves away from the critical shear part, the strength of the beam should increase.. It is however to be noted that beams RO80O4 and RO80O2 failed at approximately the same value, therefore emphasising the fact that the shear acts in a non-linear path within these the beams. It also can be seen in Figure 12 that an opening located in the flexural region of the beam will have a larger decrease in ultimate load then that of an opening with a similar distance from the critical load path outside of the flexural. This is due to the opening decreasing the effective compressive area of concrete in both the critical load path and the flexural region.

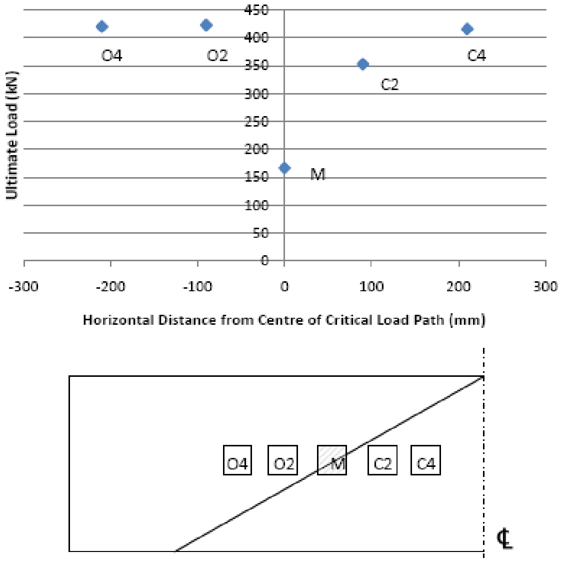


Figure 12. Horizontal Position of Opening versus Ultimate Load.

3.4 *Vertical Opening Variation*

Once again previous researches suggest that as the opening moves away from the critical load path the strength of the beam will increase, this is however not the case for the vertical position of the opening. It still can be seen from Figure 13 that an opening positioned on the critical load path will result in the lowest ultimate load; however the strength of the beam increases as the opening is moved lower.

By lowering the position of the opening, the effective depth of the neutral axis is also lowered, thus meaning there is more concrete in compression. Due to concrete being highly effective in compression rather than tension, the area gain in compression has a larger effect than the decrease of area in tension, resulting in a larger ultimate load. This characteristic suggests a relationship between Mohr's circle and the ultimate load of the beam.

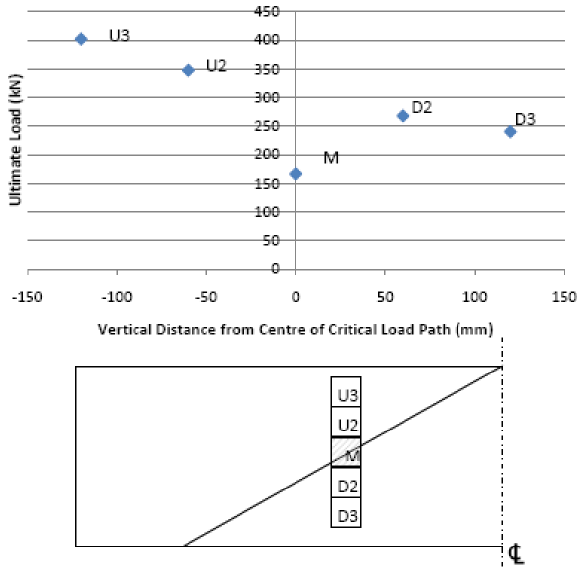


Figure 13. Vertical Position of Opening versus Ultimate Load.

3.5 *Comparison study*

It can be seen from Table 3 that Kong et al (1977) and Tan et al (2003) equations present some accurate results when the opening is close to the idealized linear load path. However the only beams to fall within the 20 % accuracy range were RO80C2 for Kong et al (1977) and RO80O2, RO80C2 and RO80D2 for Tan et al (2003). Therefore only three out of the eight design possibilities are able to be used safely within the design of a major structure.

Both Kong et al (1977) and Tan et al (2003) produce the same trends for both vertical and horizontal locations of the opening. That is, both design procedures predict that the beam will be at its weakest when the opening location is directly in the centre of the flexural region or at the very bottom of the beam; even though it is known that the beam is in fact at its weakest when an opening directly intersects the load path. Thus location of web opening between the centre or the bottom of the beam to the critical load path will result in a significant underestimation of the ultimate strength and that any opening outside of this area will result in an overestimated predicted result.

Table 3. Comparison of Test Results.

Classification	Measured (kN)	Kong et al (1977)		Tan et al (2003)	
		Eq. 2 (kN)	Difference (%)	Eq. 3 (kN)	Difference (%)
RO80O4	415.75	142.4	29.96	319.9	29.96
RO80O2	352.77	247.2	42.66	354.9	0.61
RO80C2	427.81	432.2	2.17	436.2	3.16
RO80C4	420.22	590.1	28.79	543.4	32.77
RO80U3	240.54	604.8	61.33	527.5	54.31
RO80U2	267.11	464.7	42.46	452.0	56.01
RO80D2	347.67	178.7	94.58	293.0	18.67
RO80D3	401.82	37.4	1074.12	207.6	93.53

4 PROPOSED DESIGN METHOD

Kong et al (1977) design procedure presumes that the neutral axis of the beam is always located within the opening, therefore the area above the opening is considered to be in compression and the area below is considered to be in tension. This explains Kong et al (1977) used k_2D (the height from the bottom of the beam to the opening) in their design equation (Equation 3) to calculate the tension characteristics of the concrete. However this statement is not always true, it was found that when the opening is close to the bottom of the beam the neutral axis lies above the opening itself, thus decreasing the amount of area in compression and increasing the area of tension.

In most cases the beams failed in a tension controlled shear failure however, in some cases a compressive shear failure occurred. Due to a lack of information, the exact location of the opening to cause the change in type of shear failure is not known, however it is expected that once the compressive area is less than twenty five percent of the beam a compressive shear failure will occur.

It is to $V_n = abs\ (C_c - R\cos\theta)$ be noted there is a large deviation between the compression and tension values; general common sense can be utilised to determine the correct value to be used for this design procedure. In most cases the incorrect value resulted in a larger ultimate strength than that of a solid deep beam with the same dimensions, therefore it is easy to determine and eliminate.

Therefore the following equations are to be used to predict the ultimate shear load (V_n) of the beam:

For a tensile shear failure:

$$V_n = abs\ (C_c - R\cos\theta) \tag{5a}$$

For a compressive shear failure:

$$V_n = C_c + R\cos\theta \tag{5b}$$

where

$$R = \frac{abs(T) + C}{2} \tag{6}$$

in which Centre of the circle *(C_c) = R – abs(T)*
If opening is above the critical load path:

$$\theta = \tan^{-1}\left(\frac{a_1 + w_o}{k_2 D}\right) \tag{7a}$$

If the opening is below the critical load path:

$$\theta = \tan^{-1}\left(\frac{x_1}{k_2 D}\right) \tag{7b}$$

in which $x_1 = \frac{a_o}{a} w_o$

and other geometric parameters d_u, a a_o and w_o are detailed in Figure 14.

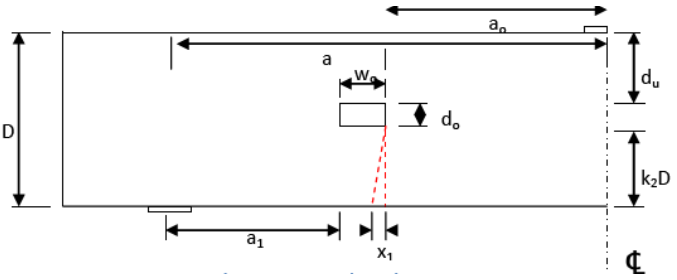


Figure 14. Beam Dimensions.

Comparison studies were carried out with previous available experimental test results in Deep beam with various opening configuration. They are presented in Table 4 This comparison included the test results conducted by Yoo et al. (2008) and Yang et al. (2006).

Table 4. Comparison of predicted ultimate loads and current/previous test results.

Classification	V_n (kN)	Predicted (kN)			Predicted/Measured		
		Proposed	Eq. 2	Eq. 3	Proposed	Eq. 2	Eq. 3
RO80C4-60	415.8	340.0	143.4	319.9	0.82	0.35	0.77
RO80C2-60	352.8	359.6	247.3	354.9	1.02	0.70	1.01
RO80O2-60	422.8	388.7	432.2	436.2	0.92	1.02	1.03
RO80O4-60	420.2	407.8	590.1	543.4	0.97	1.40	1.29
RO80U3-60	240.5	259.6	604.8	527.5	1.08	2.51	2.19
RO80U2-60	267.9	251.1	464.7	452.0	0.94	1.74	1.69
RO80D2-60	347.7	304.2	178.7	293.0	0.88	0.51	0.84
RO80D3-60	401.8	336.9	37.4	207.6	0.84	0.09	0.52
Yoo et al (2008)							
RO94-60*60	166.7	217.2	265.7	267.5	1.30	1.59	1.61
RO94-90*90	154.1	162.9	225.1	247.0	1.06	1.46	1.60

RO94-120*120	112.8	110.7	185.2	227.1	0.98	1.64	2.01
RO78-150*150	109.0	60.9	139.0	180.7	0.56	1.28	1.66
RO78-180*180	90.0	13.6	103.5	163.9	0.15	1.15	1.82
RO78-210*210	78.8	30.8	68.9	147.6	0.39	0.88	1.87
Yang et al (2006)							
N10F1	224.8	221.5	244.1	210.1	0.99	1.09	0.94
N10F2	183.8	150.2	219.7	188.7	0.82	1.20	1.03
N10F3	144.1	77.4	195.2	166.9	0.54	1.36	1.16
N10T3	163.2	142.2	177.4	182.9	0.87	1.09	1.12
N10S3	129.5	76.0	205.9	159.3	0.59	1.59	1.23
UH5F1	514.5	414.9	373.0	381.8	0.81	0.73	0.74
UH5F2	419.4	346.6	325.9	340.0	0.83	0.78	0.81
UH5F3	339.1	269.4	276.9	297.5	0.79	0.82	0.88
UH5T3	394.9	295.6	288.8	332.5	0.75	0.73	0.84
UH5S3	331.2	267.4	272.1	281.8	0.81	0.82	0.85
UH10F1	245.0	264.6	286.9	266.4	1.08	1.17	1.09
UH10F2	198.5	192.9	256.8	241.2	0.97	1.29	1.22
UH10F3	155.0	113.5	226.7	215.8	0.73	1.46	1.39
UH5T3	185.0	181.8	204.7	231.2	0.98	1.11	1.25
UH10S3	140.0	111.9	239.9	208.6	0.80	1.71	1.49
Average					0.84	1.15	1.24
Deviation					0.22	0.48	0.42

The results indicate that the ratios of the test results and the proposed formula varied from 0.59 to 1.46, with a mean of 0.84 and a standard deviation of 0.22. While some ratios are greater than 1 (overestimation), generally there is a good agreement between the test results and Equation (5a & 5b). The results obtained from other available equations are less conservative than the proposed design equation.

5 CONCLUSION

An experimental study was undertaken on eight reinforced concrete deep beams with various openings. The test results indicate that current design equations were found to be inadequate for various opening configurations.

Incorporating the test results in the present study and previously available test results, a new ultimate load formula is developed for reinforced concrete deep beam with various openings. Comparisons with the available test results indicate that the new formula is accurate and slightly conservative.

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