Parametric Study of Reinforced Concrete Deep Beams with Rectangular Web Openings Subjected to a Static Monotonic Loading

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Abstract:

Transverse openings in beams are commonly used to accommodate utility lines like pipes, cables and ducts. Past studies have shown that these openings can reduce the flexural and shear strength of beams, particularly in reinforced concrete (RC) deep beams. Deep beams, which are often used as transfer girders to support columns, carry heavy concentrated loads. This study focuses on investigating the impact of parameters such as the degree of interruption of the load path, opening size, aspect ratio of opening sides, and compressive strength of concrete in RC deep beams with rectangular web openings. The investigation is conducted through numerical simulations using non-linear finite element analysis (FEA). A total of 73 numerical simulations were conducted to investigate various parameters in RC deep beams with rectangular web openings. The study focused on failure load, maximum deflection, cracking load, and maximum crack width as the main output parameters. Results indicated that when openings were placed within the shear span of the beam, increased interruption in the load path and larger opening sizes led to a significant reduction in failure load (shear strength) of the beams, with strength reductions of more than 50% was observed. However, when openings were placed within the flexural region, failure load was similar to solid beams without openings, but there was a substantial increase in deflection (up to 39%). Additionally, cracking load decreased with larger opening sizes within the shear span. Furthermore, It was observed that increasing the compressive strength of the concrete was effective in compensating for strength loss only when the openings were small (opening area < 8.59% of the shear span area). For larger openings, increasing the concrete grade had an insignificant effect on failure load (shear strength).

Key Words: Deep Beam, Finite Element Analysis, Reinforced Concrete

1 Introduction

1.1 Study Background and Problem Statement

Reinforced concrete deep beams are versatile load-bearing elements in various structures, functioning as transfer girders, pier caps, and pile caps. They efficiently transmit column loads in buildings, bridges, and foundation systems.

These beams, characterized by their considerable depth relative to span length, exhibit distinct load-resisting behavior (Macgregor and Bartlett, 2000).There are no clear demarcation lines defining the zone of deep beams based on span to depth ratio's, several design codes recommend different span to depth ratio's for deep beams. ACI considers a span-to-depth ratio less than 4, Euro code 2 suggests a ratio of 3, and the Canadian and Japanese codes propose ratios under 2 for simply supported RC deep beams.

The main difference between deep beams and slender beams is their load resistance mechanism. Deep beams transfer a significant portion of the load to the supports through compression struts when subjected to a loading. In contrast, slender beams rely on a combination of flexural and bending stresses as well as shear stresses to resist loads. The deep, stocky geometry of deep beams allows them to redistribute loads through compression fields in their depth, rather than solely relying on bending resistance like more slender beams. Moreover, traditionally reinforced concrete beams and frames are analyzed using linear elastic methods based on the plane sections remaining

Plane assumption (Kong, 2002). However, this Elementary Bernoulli beam theory is not applicable for deep beams, even under linear elastic assumptions, as neither the stress nor strain distribution is linear when they are loaded. Most codes recommend alternative analytical methods like strut-and-tie or nonlinear finite element for reinforced concrete deep beams, since significant shear and axial stresses experienced by their stocky profile under loading.

In modern buildings, pipes and ducts for utilities like plumbing, HVAC, electricity etc. are often placed underneath beams, reducing floor heights. Alternatively, allowing these services to pass through web openings in floor beams can provide higher floors with more open and comfortable spaces (Mansur and Kiang-Hwee, 1999). However, design codes offer little guidance on deep beams with web openings. Engineers generally permit small embedded pipes but are reluctant to scientifically analyze large openings, instead relying on experience, which can lead to failures if not properly designed. There is a need for research on deep beams with web openings to optimize building design and ensure structural safety.



Figure 1 Three-Span Deep Beam, Brunswick Building, Chicago.

Previous studies on RC deep beams with web openings (Wen-Yao Lu, et al., 2020, Mabrouk, et al., 2021, Mansur, et al., 1991, Al-Sheikh & Ahmed, 2014; Campione & Minafò, 2012, etc.) Indicate that opening shape, opening size, opening location and span to depth ration of the beam are some of the main parameters the affect its load resistance.

In a study conducted by M Mansur and Kiang-Hwee (1999), it was found that the most critical opening location in RC deep beams with web openings is within the shear zone, which disrupts the natural load path between the applied load and support reaction. In separate research, Kong (2002) emphasized the importance of quantifying the degree of interruption and it's noted that past studies had not investigated the effects of varying degrees of interruption to the natural load path on the overall behavioral response of beams containing web openings.

Further, in research by Senthil et al (2018) on RC deep beams with rectangular openings, visible stress concentrations were observed at the corner points of the openings. This was found to depend on the aspect ratio of the opening sides. However, the effect of the rectangular opening aspect ratio has not been thoroughly investigated in past studies. Moreover, increasing the compressive strength of the concrete to counteract strength loss, as described by Wen-Yao Lu et al (2020), is a commonly employed technique but its effectiveness has also not been investigated in detail.

Moreover, deep beams with web openings primarily experience shear failure, evidenced by diagonal cracking upon failure, As a result shear strength has predominantly been the focus of past research since flexural failure is uncommon in deep beams with web openings. However, serviceability limits such as controlling excessive cracking to maintain durability and avoid reinforcement corrosion, as well as deflection lim its to preserve structural aesthetics, are also important design considerations that codes mandate (Bhat et al, 2014). These serviceability parameters and others have not been thoroughly explored.

Accordingly, this research aims to address the observed gaps regarding the impact of rectangular opening aspect ratios on stress distributions and the effectiveness of increasing concrete strength to mitigate strength reductions in beams with web openings. A numerical investigation of RC deep beams with rectangular web openings is conducted. The study parameters investigated include L/D ratios, concrete compressive strength, and aspect ratio of opening sides, opening

size & location and degree of interruption of natural load path.

1.2 Objective of the Research

1.2.1 General Objectives

The objective of this research is to determine the effect of the above listed parameters (i.e. Opening location, opening size, aspect ratio of opening sides and compressive strength of concrete) on the behavior of reinforced concrete deep beams with rectangular web openings subjected to a two-point monotonic loading.

1.2.2 Specific objectives

The specific objective of the research is to determine the influence of different parameters on cracking load, shear strength, crack width and mid span deflection of RC deep beams with rectangular web openings subjected to a two-point static monotonic loading. The parameters are listed below: -

- Variation of Degree of interruption of the natural load path (i.e. L-Intercept /L-path) connecting the applied load and the support reaction for rectangular openings located in the shear span (i.e. the zone between the applied load and support reaction),
- Variable Opening sizes within the shear span and flexural zone,
- Variable Aspect ratios of opening sides (i.e. Ly/Lx)
- Different Concrete compressive strength
- Variable Span to depth ratio of the beam (i.e. L/D)

2 Literature Review

2.1 Behavior of Reinforced Concrete Deep Beams with Web Openings

In reinforced concrete beams, openings are sometimes necessary, but their presence can affect the overall behavior of the beam. Openings can be classified as small or large, depending on their impact on the beam's strength, deflection, and crack formation. Research suggests that openings with depths less than 40% of the overall depth of the beam can be considered small. However, the introduction of openings creates stress concentrations and early cracking, which disrupt the normal stress distribution. To prevent excessive crack width and premature failure of the beam, special reinforcement and strengthening methods are usually employed (Mansur and Kiang-Hwee, 1999).

As indicated in figure 2-1 below, regardless of whether an opening is positioned below or above the neutral axis (NA) intercepting the failure plane, there is a notable reduction in the shear strength of the beam. Since, shear resistance involves a combination of factors, including shear in the compression zone, aggregate interlock in the inclined crack region, and dowel action from re-bar.

And reinforcement, and the presence of shear reinforcement intercepting the crack

as shown in Figure 2. The introduction of an opening diminishes the effectiveness of shear transferred by aggregate interlock and reduces the number of shear reinforcements intercepting the crack. As a result, the overall shear strength of the beam decreases. Mansur (1998) proposed an adjustment to the conventional shear resistance formula to account for openings. the modified concrete shear resistance (Vc) and shear resistance provided by the web reinforcements (Vs) are given as:

$$V_c = \frac{1}{6}\sqrt{f_c'}\,bw(d - d_0) \quad \text{... Eqn. (2-1)}$$

$$V_s = \frac{A_v f_{yv}}{s}(d - d_v) \quad \text{.....Eqn. (2-2)}$$

Where bw is width of the web, Av is area of shear reinforcement per unit width, f_{yv} is yield strength of shear reinforcement, f_c is concrete compressive strength

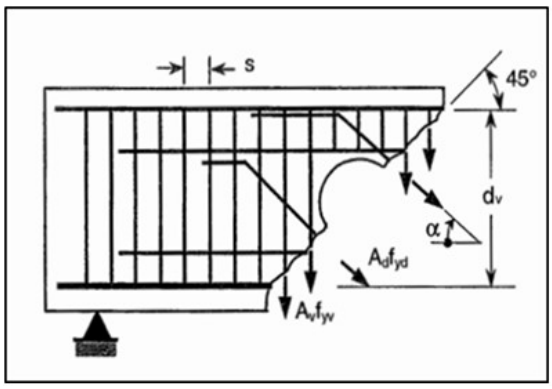


Figure 2 Shear Resistance of RC Section with Web Openings

In addressing the predominant shear failure mode characterized by diagonal tensile or compression cracking in deep beams with web openings, Kong (2002) introduced an empirical equation through an extensive study involving various test specimens encompassing diverse opening sizes, locations, and loadings. This equation's applicability is specific to openings positioned within the designated EFGH region within deep beam webs, as illustrated in Figure 3 diagram. The opening size conforms to conditions a1X XN/2 and a2D 0.3D. Additionally, the eccentricities ex and ey of the opening must not exceed XN/4 and 0.6D/4 in the x and y directions, respectively. This empirical equation provides a means to calculate

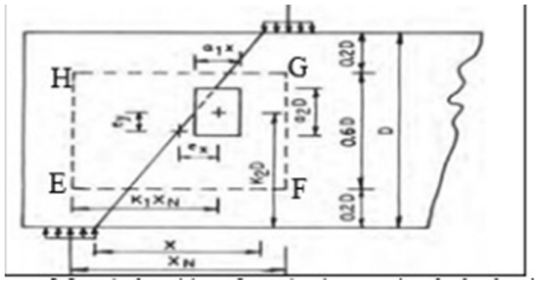


Figure 3 Typical Position of Opening Intercepting the Load Path

the ultimate shear strength of RC deep equation is given subsequent listed equations 2.3 to 2.6:

$$\lambda_1 = \left[1 - \frac{1}{3}\left[\frac{K_1 X_N}{K_2 D}\right]\right] \quad \text{for} \quad \frac{K_1 X_N}{K_2 D} \le 1 \qquad (2\text{-}3)$$

$$\lambda_1 = \frac{2}{3} \quad \text{for} \quad \frac{K_1 X_N}{K_2 D} \ge 1 \qquad (2\text{-}4)$$

$$\lambda 2 = 1 - m \qquad (2\text{-}5)$$

$$\lambda_3 = \left[0.85 \pm 0.3\left(\frac{e_x}{X_{net}}\right)\right]\left[0.85 \pm 0.3\left(\frac{e_y}{Y_{net}}\right)\right] \qquad (2\text{-}6)$$

After evaluating the parameters, and the general shear strength of the deep beams with web openings can be calculated by summing up the contributions of concrete (i.e. Pc), longitudinal reinforcement(i.e. Ps) and web reinforcement (i.e. Pw) as shown in the equations 2.7 to 2.10 below:

$$Pu = = Pc\,(\lambda_1).(\lambda_2).(\lambda_3) + \Psi_s P_s + \Psi_w P_w \quad (2\text{-}7)$$

$$P_c = \frac{cbD}{\sin\beta\cos\beta(\tan\beta + \tan\Phi)} \quad (2\text{-}8)$$

$$P_s = F_s\left[\frac{\tan\beta\tan\Phi - 1}{\tan\beta + \tan\Phi}\right] \quad (2\text{-}9)$$

$$P_w = F_w\left[\frac{\sin\alpha\cos\beta + \cos\alpha}{\left[\frac{\tan\beta + \tan\Phi}{\tan\beta\tan\Phi}\right]} - \frac{\cos\alpha}{\left[\frac{\tan\beta + \tan\Phi}{1 - \tan\alpha\tan\beta}\right]}\right] \quad (2\text{-}10)$$

2.2 Studies on RC deep beams with web openings

2.2.1 Experimental investigation

In recent years, numerous experimental studies have investigated the behavior of reinforced concrete deep beams containing various opening shapes and locations. Tests typically involve loading beams to failure and observing parameters such as load-deflection response, ultimate capacity, and crack patterns. When openings are incorporated, they reduce stiffness, leading to redistributed internal forces and moments. This loss of Stiffness causes increased deformations under loading, influencing both strength and serviceability performance.

One such study by Mansur et al. (1991) tested continuous beams with openings in positive and negative moment regions. Results showed final failure occurred via plastic hinges forming at opening ends, indicative of a flexural mode. While ultimate load decreased with openings in higher moment locations, the failure mode remained the same. Additionally, opening location had little effect on the load initiating first cracking. Thus, openings primarily reduced flexural capacity in a ductile manner but did not significantly impact initial cracking loads dependent more on other design factors. Through varying configurations, researchers have aimed to better understand how opening features impact structural response. Opening shape is another important parameter studied by researchers. Common shapes include circular, rectangular, and square, which occur based on the application (e.g. pipes, ducts). Al-Sheikh and & Ahmed and S (2014) tested beams with these shapes in shear and flexural zones under twopoint loading. Circular openings exhibited the lowest ultimate strength reduction. For small openings in flexural regions, strength was reduced up to 1.5%, while those in shear zones saw reductions as high as 10%. Thus, shape and location influence how much capacity is lost. In a similar study, Nair and P.E (2015) tested deep beams with circular and rectangular openings of 100mm diameter/side under one-point loading. Results showed ultimate load reductions of 39% for circular openings and 60% for square openings. Rectangular and square openings intercepting the natural load path between load and support create higher stress concentrations, especially at corner points. This leads to greater capacity reductions compared to circular openings when openings intercept the load path.

Mode of failure is an important parameter studied for RC deep beams with and without openings. Ductile flexural failure provides more warning

than brittle shear failure. Campione and Minafò (2012) tested over 20 beams with and without circular openings under four-point loads. Results showed failure mode and cracking load were mainly influenced by opening presence and location rather than web reinforcement or depth. Openings within shear spans reduced ultimate capacity by 18-30%. Capacity reduction was greater for

Openings in the shear zone versus mid-span. Further, it was observed that vertical stirrups also increased capacity by around 15% according to the study. Overall, opening location significantly impacted beam performance. As depicted in Figure 4. It can be seen that at failure load the crack propagates from the loading point to the top of the opening and from the support bearing to bottom of the circular opening separately. This type of failure is termed as shear failure by diagonal cracking.

Various solutions exist to strengthen beams with web openings, such as using fiber polymers, but these can be expensive and unavailable. More economical methods like using higher strength concrete are commonly employed, though not scientifically validated. Yang et al. (2006) found that concrete strength had less impact on beams' carrying capacity when openings were present compared to solid beams. Still, maximum crack width under service loads decreased with stronger concrete in opening beams.

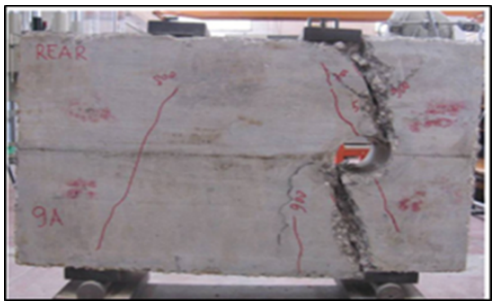


Figure 4 Specimen with Openings with in the Shear Zone (Campione and Minafò, 2012)

Conversely, Wen-Yao Lu et al (2020) reported that shear strength for deep beams with openings significantly increased with higher concrete strength. Due to discrepancies in findings, further research is needed to draw appropriate conclusions on the effectiveness of increasing concrete strength in offsetting losses from web openings. More study is warranted to validate economical strengthening solutions

Opening aspect ratio is another understudied parameter that could impact beam performance. A study by (S et al, 2016) preliminarily suggested narrow rectangular openings may reduce strength loss versus square or circular shapes. However, detailed investigations varying aspect ratios over a range of values are still needed. Without such research, no definitive conclusions can be made regarding how different opening dimensions may influence structural response. Further study of aspect ratio effects is warranted.

2.2.2 Numerical and Analytical Investigations

In recent decades, some researchers have applied finite element modeling for

investigating RC deep beams with web openings. S and S (2016) numerically tested beams with circular, rectangular, and square openings at mid span under one-point loading using ANSYS. For minimum shear stresses, the best opening size was 1-5% of the beam area. For two rectangular openings, the best positions were 0.17L and 0.28L from one edge along the length, and 0.29D-0.36D from the top to the opening centers, where D is total depth and L is total length. The study provided preliminary guidance on optimal opening sizes and locations based on finite element analysis. In a similar study, Mohamed et al (2014) numerically studied such beams using ABAQUS. When openings intercepted the load path, ultimate strength reductions up to 35% occurred. However, reductions were only 6-8% when openings did not intercept the path. Further, it was observed that openings less than 20% of total depth caused 10% reductions.

Overall, accuracy of FEA results can be checked against identical experimental tests, with generally good agreement on failure load and deflection (Mohammad & Ibrahem, K, 2007). Senthil et al (2018) noted that Nonlinear FEA can also fairly estimate stress/deformation distributions, within 6% aspect ratio of opening sides, and concrete compressive strength across different span-to-depth ratios (Figure 6).

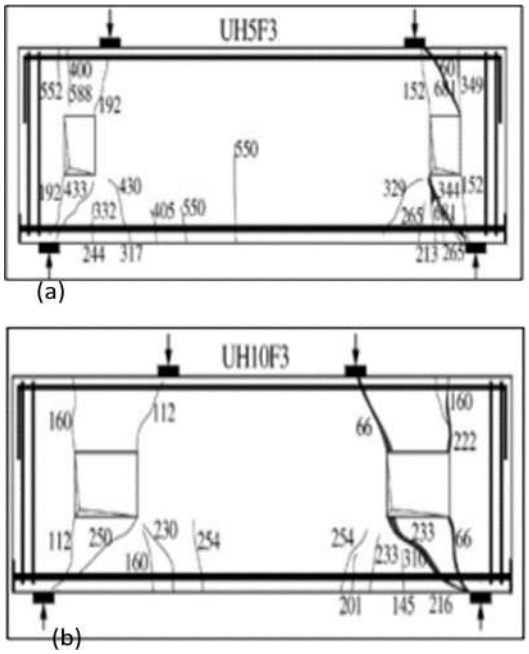


Figure 5 Crack Pattern at Failure (a) for Rectangular Opening with High Aspect Ratio of (Yang et al, 2006)

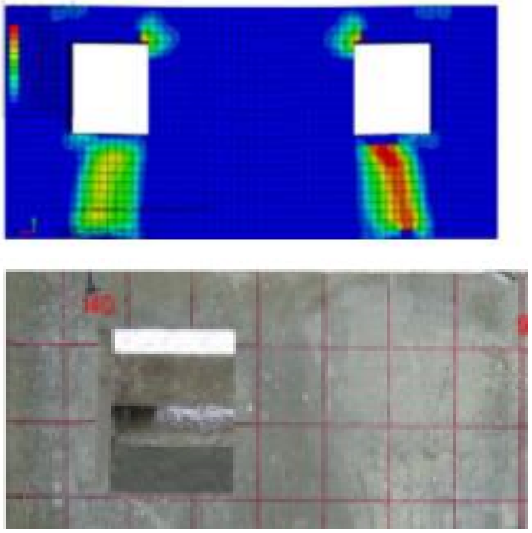


Figure 6 Deformed Profile of Experiment and Profile (Senthil et al, 2018)

3 Methodology

This study employs numerical analysis using FEA software package VECTOR to investigate the behavior of transverse rectangular web openings in RC deep beams.

The software's capacity to account for material and geometric nonlinearities, as well as tension stiffening and softening, renders it suitable for this research. Validation involved comparing numerical simulations of RC deep beams with and without web openings to experimental results of A.Jasim, et al. (2018. Subsequently, 73 RC deep beams were numerically simulated to assess the impact of various parameters. These included the degree of opening's interaction with the natural load path, opening size, aspect ratio of opening sides, and concrete compressive strength across different span-to-depth ratios.

3.1 Modeling in VECTOR2D

3.1.1 Geometric Modeling

Geometric modeling of RC deep beams involves defining distinct regions for concrete, reinforcement, web openings (voids), support, and loading plates. In VECTOR 2D, concrete regions are established using xy coordinates for corners, with hybrid rectangular plane elements.

3.1.2 Material Modeling

A distinct concrete model is assigned to describe its behavior under uniaxial compression, differentiating between pre-peak and post-peak phases. For specimens with compressive strength 40MPa, the congested (parabola) model is chosen, while Popovics (high strength) model is used for specimens > 40MPa. The modified Park and Kent model applies to post-peak behavior for all compressive strength levels.

Vecchio 1992-A softened model was selected for representing Compression softening in cracked concrete, which is the reduction of compressive strength and stiffness relative to the uniaxial compressive strength, due to coexisting transverse cracking. Further, a bilinear model is selected for tension softening behavior and modified bentz model is selected to model tension stiffing effect. For reinforcement, an Elastic-Perfectly Plastic stress-strain model is adopted. Steel, with a yield strength divided by an elastic modulus of 200GPa, is used for loading and support plates. Ultimate strain at failure is set at 0.01. Shear and skin reinforcements follow the same stress-strain relationship, employing a smeared reinforcement approach that modifies concrete behavior.

3.2 Numerical Model for Validation of Software Result

Finite element models were created based on the experimental test specimens from A.Jasim, et al. (2018) to validate the numerical simulation. The 1st model was a solid control beam with a span to depth ratio of 3. The other included two symmetrical 200x200mm square openings within the shear span. Both had a shear span to depth ratio of 0.9, with a shear span of 450mm and depth of 500mm. The concrete compressive strength of both of beams was27Mpa Both

also had 3φ16 bottom reinforcement and similar web/skin reinforcements.

In the experiment, the specimens underwent two-point loading via 1.5cm thick loading and support plates. Table 1 summarizes the test specimen parameters used in the FE model validation.

Two mesh sizes (50mm and 25mm) were used in the FE model since accuracy depends on meshing (Figure 7). This aimed to identify the suitable element size. Maximum iteration and convergence criteria were set to 100 and 1.00001 respectively. A 1.2kN/step load increment was applied for two-point loading, including self-weight via 2450kg/mˆ3 density gravitational forces. Pin and roller supports restrained movements at opposite ends. Flexural bars were discrete while web/skin used reinforcement ratios. Concrete cover was plain concrete and interior concrete used smeared ratios. Comparisons of experimental and FEA results are shown in Figures 8 and 9 to validate the numerical model.

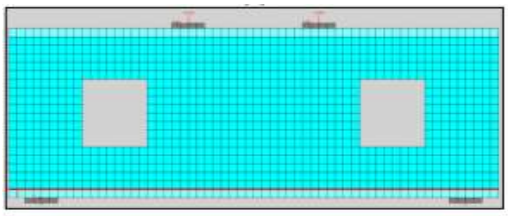


Figure 7 FEA Model of the Experimental Test Beam

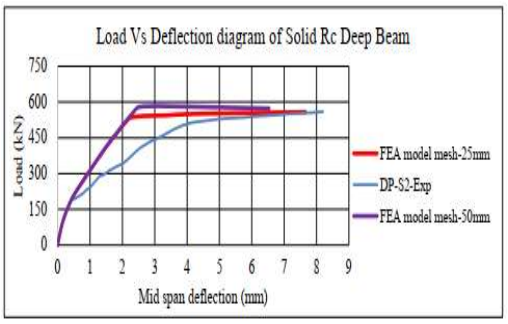


Figure 8 Load Vs Deflection diagram of Solid RC Deep Beam

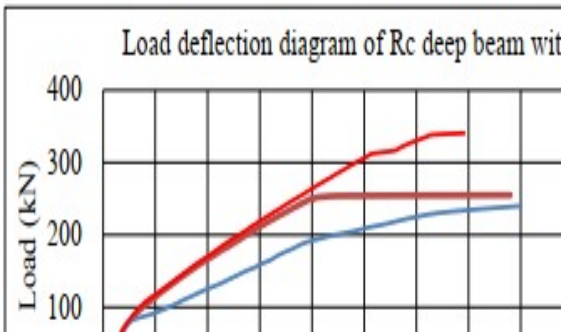


Figure 9 Load Vs Deflection Diagram of Beam with Rectangular Opening

3.3 Numerical Simulation for Parametric Study

The variable parameters considered in the parametric study are opening location, opening size, aspect ratio of opening sides, and degree of interruption and compressive strength of concrete while parameters like flexural reinforcement, web reinforcement, skin reinforcement and yield strength of all the reinforcements are held constant. In trying to investigate the effect of one parameter, the investigated parameter is varied while all other parameters are held constant.

Each finite element models are assigned a unique designation letters. The first

number character indicates the width of the opening, after the number character the following three characters containing an alphabet, hyphen and a number (e.g.A-1.5) indicates the aspect ratio of the opening sides (i.e. w /L). The next alphabet letter written as either S or F indicates the location of the opening, where S indicates opening is within the shear span and F indicates that opening location is in the flexural zone. The next alphabet letter ranges form letter P to Letter V; they indicate the degrees of interruption of natural load path by the opening within the shear span. P, S, T, U, V indicate degree of interruption of 28.5%, 20%, 15%, 8%, 0.8% and 0% respectively.

The consecutive three characters containing a letter and two numbers indicate the cubic compressive strength of the concrete (i.e. C25). Finally, the last character containing a combination of letters, numbers and symbols indicate the span to depth ratio of the beam (LD-2.5). For instance, a designation of finite element model 100A-1.5SPC25LD-2.5 means a beam having web opening width of 100mm with 1.5 opening side's aspect ratio, the opening is located within the shear span of a beam and the beam has length to depth ratio of 2.5 and has 25Mpa cubic compressive strength of concrete.

Overall, there are three control beams with different span to depth ratio, they are designed, by using the strut-and-tie-method according to ACI318M code to withstand a factored load of 130kN.

Table 3 Experimental Test Specimen Data

fck, cylindrical compressive strength	27MPa
fyd, yield strength flexural reinforcement	624MPa
fyds, yield strength stirrup and skin reinforcement	569MPa
fydp, yield strength of steel and loading plates	400MPa
Length of the beam	1500mm
Depth of the beam	500mm
Shear span of beam	450mm
Width of the beam	150mm
Flexural reinforcement	3Ø16mm
Stirrup spacing	Ø6mm c/c 90mm
Skin reinforcement	Ø6mm c/c 86mm

3.3.1 Opening Location

a. Shear Span

A total of eighteen numerical simulations are conducted to investigate the effect of degree of interruption of the natural load path connecting the reaction points of the support and the load Point by the web openings. Degree of interruption is calculated by dividing the intercepted path by the opening to the total load path connecting the support and the load point (i.e. L-intercept/L-path).

While investigating the effect of degree of interruption other parameters like opening size, compressive strength of concrete and aspect ratios of opening sides are held constant. On all of the 18 finite element models Opening size was 100mmx150mm, the aspect ratio calculated was 1.5 and C25/20 concrete strength were chosen. The degree of interruption is expressed in percentage by the following equation.

$$\text{Degree of interruption} = \frac{L_{\text{int}ercpet}}{L_{path}} x100 \quad (3.1)$$

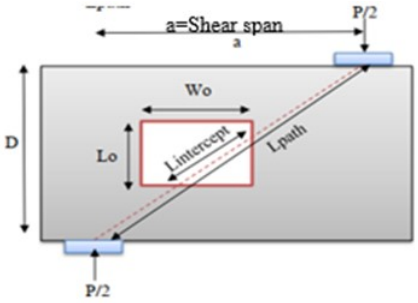


Figure 10 Shear Span Section Deep Beam with Web Opening

Table 2 Calculation of Degree of Interruption

Finite element model	L-path (mm)	L-intercept (mm)	L-intercept / L-path (%)
100A-1.5SPC25LD-3/2.5/2	610.33	174.91	28.5%
100A-1.5SRC25LD-3/2.5/2	610.33	135.0	22.0%
100A-1.5SSC25LD-3/2.5/2	610.33	91.43	15.0%
100A-1.5STC25LD-3/2.5/2	610.33	48.04	8.0%
100A-1.5SUC25LD-3/2.5/2	610.33	4.25	0.8%
100A-1.5SVC25LD-3/2.5/2	610.33	0	0%

b. Opening Location in the Mid Span (Flexural Region)

Finite element models were employed to analyze deep beams with three distinct opening locations within the flexural zones, specifically between the point loads. For the first opening location, the edge of the opening side coincided with the point of load application, while for the second location, the center of the opening coincided with the center of the section between the applied load and the beam center point. The third opening location had its center coinciding with the midpoint of the beam (mid-span). A parametric study was conducted through seven numerical simulations to explore the influence of web opening locations in the flexural zone. Throughout these simulations, parameters other than the opening location were held constant. It is expressed with a dimensionless parameter 0.5L/Lo Where Lo is opening center from support and 0.5L is half beam length (i.e. for open center at mid-span 0.5L/Lo = 1).

3.3.2 Opening Size

a) Shear span

Sixteen numerical simulation were conducted, in an attempt to investigate the effect of opening sizes located within the shear span of the beam on the behavior of RC deep beams. While investigating the effect of this parameter other parameters like opening location, aspect ratio of opening sides and compressive strength of concrete are kept constant.

Opening size is expressed as a ratio of opening area to the shear span area. In addition, the detail Calculation of the percentage calculation of opening size can be seen from Table 3.

$$\text{Opening size ratio} = \frac{\text{Area of opening size}}{\text{Area of shear span}} \times 100 = \frac{Wo \times Lo}{a \times D} \times 100 \quad (3.2)$$

b) Opening in the mid span (Flexural zone)

The effect of opening size located within the flexural zone is investigated by finite element models. The different opening sizes are placed at the center of the mid span of the beams. Others parameters like

aspect ratios of opening sides and compressive strength of concrete are kept constant.

3.3.3 Aspect Ratio of Opening Sides

Numerical simulation of RC deep beams having the same opening size area but with different ratios of openings sides were conducted in an attempt to investigate the effect of aspect ratio. Twentyone FE models were created for deep beam with variable length to depth ratios. Aspect ratio is calculated by dividing the length of the opening by the width of the opening (i.e. Lo/Wo). The locations of the openings were held constant through all the models and the center of the openings coincides with the center of the shear span.

Overall, five different aspect ratios were considered for beams having different span to depth ratios, the aspect ratios considered are 0.25, 0.5, 1, 1.5 and 2.

3.3.4 Compressive Strength of Concrete

In order to investigate the effectiveness of increasing concrete compressive strength to offset loss of strength loss due to web openings, Seven finite element models were conducted to in an attempt to investigate the effect of compressive strength of concrete on the behavior of RC deep beams with web openings. Other parameter like opening location, opening size and aspect ratio of opening sides were kept constant. The cubic compressive strength of concrete considered were C25, C30, C40, C50 and C60.

Table 3 Opening Size Percentage Calculation

Finite element model	Opening size		Shear span		$\frac{Wo \times Lo}{a \times D} \times 100$ (%)
	Wo (mm)	Lo (mm)	a (mm)	D (mm)	
50A-1.5SPC25LD-3/2.5/2	50	75	350	500	2.14
100A-1.5SPC25LD-3/2.5/2	100	150	350	500	8.57
150A-1.5SPC25LD-3/2.5/2	150	225	350	500	19.3
200A-1.5SPC25LD-3/2.5/2	200	300	350	500	34.3
250A-1.5SPC25LD-3/2.5/2	250	375	350	500	53.57
275A-1.5SPC25LD-3/2.5/2	275	412	350	500	64.74

3.3.5 Summary

In general, from the 73 FEA models, three represent solid control beams with no transverse web openings, while the remaining models represent beams with openings that vary in location and size. A typical FEA model is shown in Figure 35, where cyan square shapes represent the concrete, a red line at the bottom level indicates the longitudinal reinforcement bar provided in Table 3-2, and grey square shapes represent the loading and support plates. The openings within the shear spans of the models are indicated by empty rectangular spaces within the concrete sections.

4 Result and Discussion

4.1 Validation of FEA Models

4.1.1 Solid RC deep beam.

Two FE models were created with different mesh sizes (50mm, 25mm) to accurately predict load-deflection behavior of an RC deep beam under two-point loading.
Based on the experimental test, the solid beam failed at 560kN with 8.2mm mid span deflection. The 50mm mesh FE model failed at 572.8kN (2.3% error) with 6.53mm deflection (21% error). Since deflection error exceeded 10%, finer meshing was needed.

The 25mm mesh FE model failed at 558.2kN (0.3% error) with 7.662mm

deflection (6.5% error). Both errors were below 10%, indicating accurate prediction. It was concluded the 25mm mesh FE model captured beam response sufficiently, without need for further refinement. This validation exercise demonstrated the importance of proper meshing for numerical precision and identified a suitable element size for further FE analyses of test beam geometries and loadings.

4.1.2 RC Deep Beam with Web Openings

For the FE model with a square web opening, failure load and mid span deflection were compared to experimental results. The experiment test results shoes, maximum failure load was 240kN and deflection was 4mm.

The 50mm mesh FE model failed at 340kN and had 3.45mm deflection errors exceeded 10%.However, the 25mm mesh FE model failed at 255kN (6.3% error) with 3.9mm deflection (2.5% error). Errors were below 10%, accurately predicting beam response. Figure 11 indicate load-deflection curves for 25mm and 50mm mesh FE models to experiment.

This validation showed a 50mm mesh was insufficient, but a 25mm mesh captured behavior accurately without need for further refinement. The 25mm meshed model was thus suitable for parametric analyses of beams with web openings.

4.2 Parametric Study

4.2.1 Control Beams

The three control beams had varying span-to-depth ratios of 3, 2.5, and 2, with all other parameters kept constant. As described earlier, the beams were subjected to two-point static monotonic loading until failure. The load-deflection diagrams are shown in Figure 11. Initially, the beams were designed per ACI318 to withstand 260kN total load. However, the observed failure loads were 494kN, 494.4kN, and 495kN for span-to-depth ratios of 3, 2.5, and 2, respectively. The differences in results arises because beams were designed using STM, which is a lower bound analysis providing conservative load estimates below true capacity. Additionally, material safety factors in code design reduce estimated strength for safety. Therefore, actual tested loads exceeded initial code based design loads for these controls beams with varying geometry.

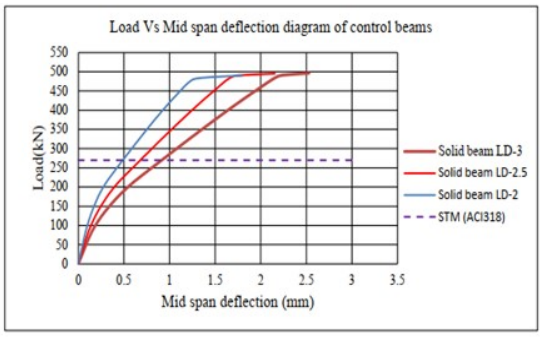


Figure 11 Load Deflection Diagrams of the Control Beams

4.2.2 Opening location

a) Shear span (Degree of Interruption).

18 FE simulations were conducted to investigate the effect of degree of natural load path interruption by openings within the shear span. Figure 12 shows failure load versus degree of interruption for beams with different span-to-depth ratios. Failure load decreases as interruption increases for all beam classes. The

average maximum decrease in shear strength (main failure mode for beams with openings) was 20.1% across all classes when interruption was maximum (opening at shear span center). As the degree of interruption decrease, the strength loss compared to the beam without web openings decrease as well but the rate of strength gain is small.

The main reason for decreasing failure load with increasing interruption is that deep beams resist loads through direct stress transfer between loading and support points via in-plane compression struts (natural load path). Any opening interruption along this path causes significant stress redistribution and high stresses near rectangular opening corners, significantly reducing shear strength. The line connecting load and support approximates the natural load path affected by openings.

Table 4 FEA Analysis Results for Control Beam

Beam designation	L/D ratio	$P_{failure}$ (kN)	P_{crack} (kN)	Δmax(mm)	W(mm)
Solid beam LD-3	3	494	66.61	2.53	1.88
Solid beam LD-2.5	2.5	494.4	67.06	2.15	1.7
Solid beam LD-2	2	495	70	1.79	1.4

Where $P_{failure}$ is failure load, P_{crack} is first cracking load and Δ_{max} is maximum deflection and W is maximum crack width

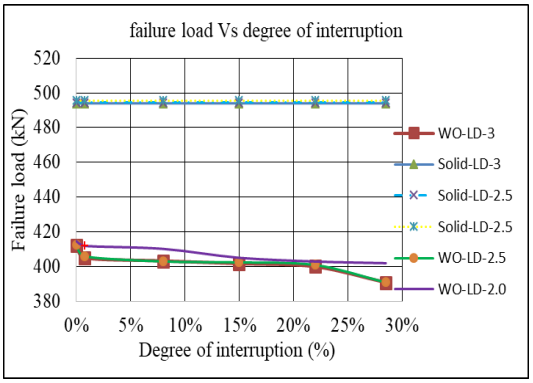


Figure 12 Failure Load vs Degree of Interruption Diagram

Where WO means with opening and LD means span to depth ratio

Compared to a web opening inducing a 28.5% degree of load path interruption, the strength gain for a beam with 0.8% interruption is only 4.9%.On average, the rate of strength increase for each 1% reduction in degree of interruption is 0.35%.

This indicates that while shear strength is affected by load path interruption degree, the impact is not very significant. As long as a web opening Interrupts the natural load path in anyway, there will be a sizable strength loss in the beam regardless of the exact interruption degree value. In other words, web openings causing even small degrees of interruption can still produce sizable reductions in shear strength, similar to openings inducing larger interruption degrees.

In summary, while strength is somewhat dependent on interruption degree, the influence is minor any opening impacting the load path results in substantial weakening, with little difference between small and large designated interruption.

b) Flexural region

Six FE models were analyzed to study the effect of opening location within the flexural beam zone. All openings were between load points. Figure 13 shows failure loads of beams with flexural openings are almost identical to solid beams (without openings). Strength reduction compared to solid beams was less than 0.5%. This is because flexural openings do not intercept compression struts identified for two-point loaded deep beams.

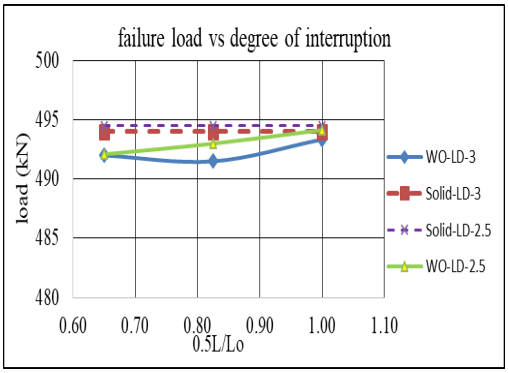


Figure 13 Failure Load vs Opening Location in Flexural Region

Where Lo is opening center from support and 0.5L is half beam length (midspan 0.5L/Lo = 1).

In summary, openings located in pure flexural regions have insignificant effects on failure loads. As they do not disrupt compression stress fields, flexural openings do not notably weaken beams. On the other hand, the effect of flexural opening location on mid span deflection was also investigated. Figure 4-4 shows a considerable increase in deflection for beams with openings compared to solid beams, especially when openings are at mid span. The analysis found around a 20% rise in deflection in this case.

Meanwhile, openings near load points produced 3-4.5% increases. Therefore, openings located close to the shear span boundary have little impact on maximum mid span deflection. In general, the influence of flexural openings is more pronounced on deflection rather than failure load. Increased deflection occurs because openings reduce beam section stiffness around the opening, decreasing the moment of inertia in that region. As deflection strongly relates to moment of inertia incrementally, decreases in inertia ultimately lead to higher vertical displacements.

In summary, flexural openings most affect deflection, especially those at mid span. Their primary impact is stiffness reduction locally around the opening rather than weakening of structural capacity.

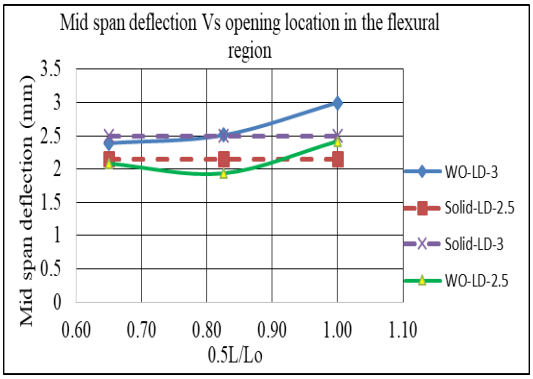


Figure 14 Mid Span Deflection vs Opening Location in Flexural Region

4.2.3 Opening size.

a. Shear span.

Another important parameter addressed was the effect of opening size on beam failure load for openings within the shear span.12 FE models were analyzed. Figure 14 shows failure load decreases

drastically as opening size increases. Openings over 34% of shear span area produced over 80% strength reduction in beams with span-to-depth ratios of 3, 2.5 and 2. The average maximum reduction was 95.7% for a 64.4% opening size. Larger openings further interrupt the natural load path, causing significant stress redistribution around openings and concentration at rectangular corners. This leads to early cracking and diagonal tension failure along lines connecting corners to support points. While medium openings interrupt inclined compression struts only, wider openings may also disrupt horizontal struts connecting loads, causing even more drastic weakening.

Analysis shows a 1.8% average strength loss for each 1% increase in opening size within the shear span. The decrease is due to greater disruption of compression stress fields with larger unreinforced regions.

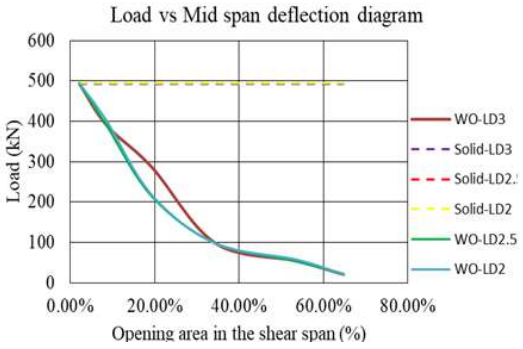


Figure 15 Failure Load vs Opening Size in Shear Span

The locations of first cracking and maximum crack widths were observed for varying opening sizes. For openings less than or equal to 8.57% of the shear span area, the first crack occurred at mid span. However, for larger openings above 8.57%, the first crack occurred at the bottom corner closest to the support point. The maximum crack width was always observed to occur at the upper corner of the opening nearest to the load point across all FE models.

Regarding cracking loads, the first cracking loads ranged from 67.8kN to 9.8kN for opening sizes between 8.57% to 64.74% of the shear span area. Correspondingly, the decrease in magnitude of the cracking load was between 0.17% to 85.6% over this opening size range. Additionally, the increases observed in maximum crack widths was also significant For openings sizes from 8.57% to 64.74%, the maximum crack width rises were calculated to be between 25.7% to 173.9%.

The greater stress concentrations present at the rectangular opening corners lead to larger principal tensile strains in this region. As cracking in concrete is directly related to tensile strain levels, this helps explain both the decreasing cracking loads and wider maximum cracks produced with enlarging opening sizes. In essence, the concentrated stresses dictate cracking behavior in the vicinity of openings.

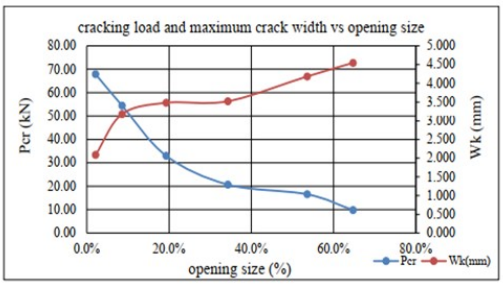


Figure 16 Cracking Load and Maximum Crack Width vs Opening Size (Shear Span) Diagram

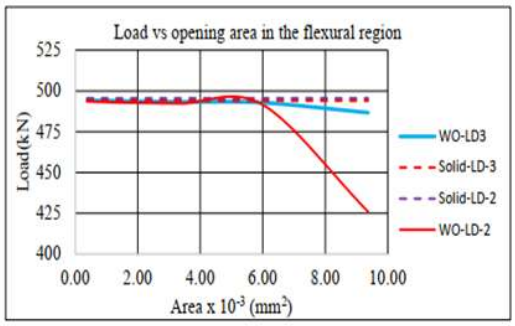


Figure 17 Failure Load vs Opening Size in Flexural Region

b. Flexural Region

As previously discussed, opening size within the shear span significantly impacts beam shear strength. For openings in the mid span, their effects on strength are not expected to be as great. Ten FE models were analyzed to determine effects openings in flexural region. Openings less than or equal to 93,750mmˆ2 (250x375mm) showed strength reductions under 0.24% and 0.81% for beam span/depth ratios of 3 and 2, respectively. The highest reductions were 1.48% and 14% for ratios of 3 and 2. For smaller openings, strength decreases are insignificant because openings do not intercept compression struts transferring load to supports. Thus, no substantial stress redistribution or concentration occurs by openings.

The sudden 14% strength reduction observed for a 93,750mmˆ2 opening in a span/depth=2 beam is likely due to interception of the horizontal compression strut by the larger opening size as the opening area increases. While strengths are largely maintained, mid span openings can significantly impact serviceability through increased deflections and crack widths.

The effect of mid span openings on maximum mid span deflection is much more significant than their effect on strength loss. As shown in Figure 17, deflection increases as the size of the centered mid span opening increases. For an opening area of 3,750 mm2, deflections increased by 3.44% and 0.56% for span/depth ratios of 3 and 2, respectively. Larger openings of 93,750 mm2 produced increases of 13.2% and 176% respectively. The latter demonstrates nearly a doubling in deflection.

The maximum increase in deflection occurs at different opening sizes for beams with varying span/depth ratios. This is because web openings decrease the beam's flexural stiffness. Flexural stiffness (moment of inertia) and deflection are inversely related. Therefore, as openings induce loss of stiffness, deflection increase's more noticeably compared to strength impacts. In summary, mid span openings have a much greater effect on deflection serviceability than load-carrying strength. Their primary impact is stiffness reduction rather than structural weakening.

The sinusoidal deflection curve for beams for deep beam Span to depth 2 ratio is caused as a result of interception of the horizontal compression strut which in turn will cause a sudden strength lose and a drastic increase in deflection.

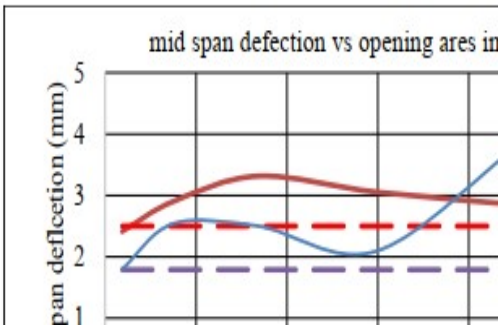


Figure 18 Mid Span Deflection vs Opening Size in Flexural Region

For mid-span openings, the cracking load and location of first crack are almost identical to solid beams without openings. The location of first crack was the bottom mid span fiber for all opening sizes. Only a slight 20% average decrease occurred in cracking load for the largest 93,750 mmˆ2 opening. However, crack widths increased compared to solid beams. Figure 19 shows a general direct incremental relationship between opening area and crack width. Across FE models, maximum crack widths occurred either above the upper Opening corner or at the midsection of an inclined compression strut between load and support points.

In summary, while cracking loads were similar for both RC deep beams with and without opening, mid span openings led to wider cracks than solid beams due to their effect of increasing tensile strains without significantly diminishing strength capacity. The largest crack widths arose near regions of concentrated stress or principal strain.

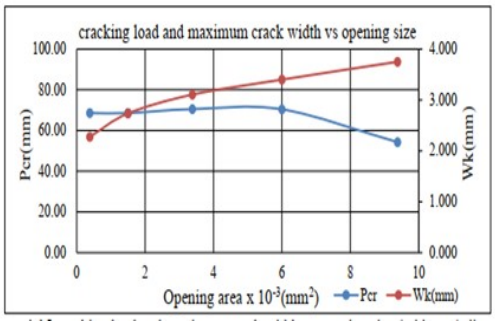


Figure 19 Cracking Load and Maximum Crack Width vs Opening Size (Mid Span) Diagram

4.2.4 Aspect ratio of opening sides

Another important but lesser explored parameter is the effect of opening aspect ratio on beam shear strength, especially for openings within the shear span. Even with identical opening areas and locations coinciding with the shear span center, FE analyses found varying aspect ratios produced different strength properties. Figure 20 clearly shows a direct relationship between opening aspect ratio and beam shear strength as the ratio of opening sides decreased, strength decreased as well.

Of the FE models, the maximum strength reduction compared to solid beams was 56% average and occurred for the lowest aspect ratio of 0.25. Meanwhile, the minimum 34.3% average reduction happened for the highest ratio of 2. Aspect ratios from 0.5 to 1.5 resulted in average strength losses ranging from 48% to 38%.

In summary, besides other factors, changing the proportions of a shear opening while retaining its total size and location within the shear span can substantially influence beam strength

capacity according to these analyses. Squatter openings induced greater weakening compared to more elongated configurations.

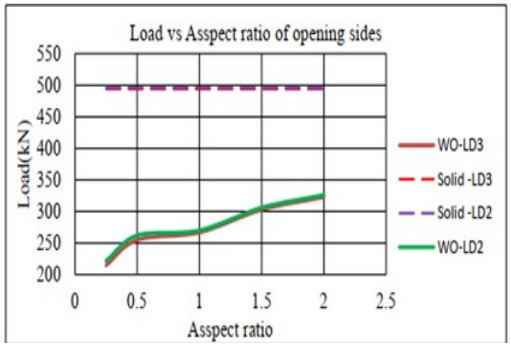


Figure 20 Failure Load vs Aspect Ratio of Opening Sides

The direct relationship between lower opening aspect ratio and lower beam shear strength can be explained by examining stress trajectories in beams with web openings. Openings intercept principal compressive and tensile stresses acting transverse to compression struts. An opening can be ideally represented as a hollow beam supported on its sides and loaded by compression at its top (Figure 21). Openings with lower aspect ratios have a higher span length in the x-direction. A larger span creates a higher bending moment, and thus larger tensile stress at the bottom of the opening.

This results in greater stress concentration at opening corners. Opening aspect ratios less than 1 tend to have a more detrimental effect on beam shear strength compared to ratios greater than 1.In essence, squatter openings experience higher localized bending and stresses, leading to earlier failure compared to more elongated openings under the same loading condition. Aspect ratio influences localized stress fields and concentrations around openings.

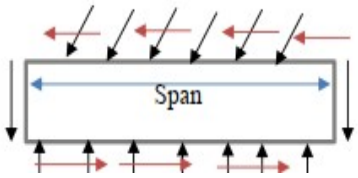


Figure 21 Idealized Free Body diagram of (a) Very low aspect ratio (<< 1 b) high aspect ratio (>>1)

4.2.5 Compressive strength of concrete

When openings are present in deep beams, it is generally assumed load capacity will decrease. Increasing concrete compressive strength is often proposed to counteract strength loss. Ten FE models examined this approach. For small openings (15,000 mm2). Figure 22 shows higher strength lead to notably increase failure load. The minimum strength reduction of 8.36% occurred for 60 MPa concrete, compared to 18.86% for 25 MPa.

For small openings, higher concrete strength substantially recovers shear capacity. However, for large openings (60,000 mm2), were similar at 80.28% for C25 and 75.28% for C60 concrete, despite a 140% compressive strength increase. Failure load rise was minimal at 0.35%.This indicates that for significant openings, concrete strength has little impact due to weakened stress fields from load redistribution and concentration. As a result, strength recovery is limited.

When large openings are present, early cracking occurs due to ten sile stress concentration. Concrete tensile strength does not increase significantly with grade

and Cracks propagate unavoidably. Critical crack widths also increase, ultimately leading to collapse. In summary, increasing concrete grade is only effective for small openings. For large openings, its effect is insignificant and other strengthening methods must be considered.

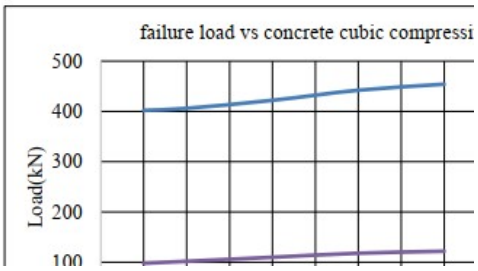


Figure 22 Failure Load vs Concrete Cubic Compressive Strength Diagram

5 Conclusion and recommendation

This research aimed to address knowledge gaps regarding the behavior of reinforced concrete deep beams with web openings. While some previous work had examined this topic, several important parameters had not been thoroughly investigated. These parameters included the degree to which openings interrupt load paths, the aspect ratios of opening sides, and the effects of varying opening sizes and concrete compressive strength. By exploring these factors through finite element analysis, this study sought to provide additional technical insights not found in past research.

Openings in structures like beams and slabs are common due to practical construction needs. However, they are often not properly considered during initial design. Decisions on opening placement and sizing typically occur on site without any applicable code guidelines. This presents challenges to ensuring structural safety and serviceability. For deep beams subjected to concentrated loads, accounting for web openings is an even more complex issue as openings can significantly impact load behavior. Yet standard design procedures do not address this problem. To fill these knowledge gaps, the overarching goal of this research was to develop a deeper understanding of web opening effects on reinforced concrete deep beams. It aimed to provide engineers with useful data to help judiciously locate and size openings according to loading conditions. The findings seek to help practitioners face this industrial design problem with a scientific approach. In the absence of established protocols, enhancing comprehension of web opening behavior will hopefully lead to more rational opening inclusion in deep beam design and analysis.

5.1 Conclusion

The following conclusions can be derived from the results obtained for the numerical simulations:

I. Opening Location

- The maximum strength in reduction in RC deep beams occurs when the opening is located at the center of the natural load path (the line connecting the point load and the support point) or when the degree of interruption of the natural load path is maximum for the given opening size
- The failure load or shear strength of beams with transverse openings with in the shear span decreases when the

degree of interruption of the natural load path Increases. However, As the load as the compression struts are intercepted by openings there will still be a significant strength loss regardless of the magnitude of the degree of interruption (i.e. the rate of loss of strength as degree of interruption increases is small).

- Openings located within the flexural region of the beam (i.e. between the two point loads) have insignificant effect on the failure load of the beam regardless where they are placed in the flexural region as long as the openings do not intercept the horizontal compression strut connecting the two point loads.

II. Opening Size

When the size of openings located at the center of the shear span, increases the failure load (shear strength) of the beam decreases drastically. For percentage of openings sizes, greater than 34% cause a shear strength reduction of more than 80%.

- The size of openings located at the center of the mid span has insignificant effect on the failure load (i.e. failure load remains constant even if the opening size increases) of the beam as long as the opening does not intercept the horizontal compression strut connecting the two point loads.
- The cracking load of the beam decreases when the size of openings located within the shear span of the beam increases. However the magnitude of the cracking load is the same as the cracking load of solid RC deep beams (i.e. beams without web openings)
- The maximum crack width increases when the sizes of openings located within the shear span or mid span of the beam increases and the location of the maximum crack width is the top corner of the opening. The magnitude of the crack width doubles when opening areas within the shear span is greater than 53.57%.

III. Aspect ratio of openings sides

The failure load of beams with openings located at the center of the shear span, decreases as the aspect ratios of the opening sides decreases for the same opening area. Openings having aspect ratio of less than 1 have a lower shear strength or failure load compared to openings with aspect ratio of greater than 1 for the same opening area.

***IV.* Compressive Strength of Concrete**

- The shear strength of beams with small web openings (< 8.57%) located at the center of the shear span increases when the concrete grade increases However, for large openings size, increasing grade of concrete will result in a very small

increase in strength of the beam that is almost insignificant.

5.2 Recommendation

- For RC deep beams subjected to a two point loading, the recommended ideal location and size of rectangular opening is when the left edge of the opening side is just to the right of the loading plate and the opening depth is less than 50% of the depth of the beam which is similar to Test specimens 100A1.5FPC25-LD3/2.5.
- The finding of theses research applies only to simply support RC deep beams with rectangular web openings. The same idea and methodology can be extended to continuous beam with web opening to investigate the effect of continuity on the behavior of such types of beams
- The type of loading considered in this research is a static monotonic load investigating the behavior of RC deep beams with rectangular openings subjected to impact loading is one research area that has not been investigated in detail in the past
- This research attempted to investigate on how to strengthen beams with web openings by only increasing the concrete grade and observing the response of the beams. However, other method of strengthening deep beams with rectangular web openings such as using fiber polymers (i.e. glass fibers, carbon fibers or bamboo) has not been considered.
- The same research can be extended to investigate the effect of rectangular web openings on fiber reinforced concrete deep beams.
- Since building standards and codes do not provides any guide lines on how to analyze such type of beams and this research utilized nonlinear finite element analysis tool to investigate the behavior of such type of beams. If other methods analysis for such type of beams like proposing a strut and tie model for RC deep beam with web openings will further simplify and assist the analysis and design of such types of beams.

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