SHEAR SPAN BEHAVIOR OF REINFORCED CONCRETE BEAMS WITH CIRCULAR AND RECTANGULAR OPENINGS

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DOI: https://doi.org/10.59382/pro.intl.con-ibst.2023.ses1-25

ABSTRACT: In reinforced concrete (RC) beams, opening is frequently required for the passage of utility ducts and/or pipes. The presence of such web openings leads to a reduction of the strength and sitffeness of the beam. This paper aims to contribute to better understanding the shear behavior of RC beam with web opening in the shear span. The study is based on an experimental program carried out on three RC beams. All beam specimens were 850 mm long with a cross section of 150 × 250 mm and a shear span to beam depth ratio (a/d) of 1.48. One beam without any openings served as the control specimen, while the remaining two beams featured circular or rectangular openings within the shear span. The test results obtained from this experimental program offer insights into the shear behavior of beams with openings. Furthermore, a simplified calculation was conducted to determine the shear strength of the test specimens, considering the influence of openings. This calculation provided a deeper understanding of how openings contribute to the reduction in the shear strength of RC beams.

KEYWORDS: Beams, Opening, Shear, Failure, Strut-and-Tie model.

1. INTRODUCTION

In reinforced concrete (RC) structures, the inclusion of openings in the beams is frequently used to accommodate essential such as electricity, water supply systems, air conditioning, telephone lines, internet cables… These openings can take various shapes, including square, rectangular, and circular, and are classified as small or large openings based on the ratio of the opening height to the beam depth. For circular openings, if the ratio exceeds 40%, it is classified as a large opening. Similarly, for square or rectangular openings, if the ratio exceeds 25%, it is considered a large opening [1- 8].

The incorporation of openings in reinforced concrete structures provides several benefits, including the avoidance of additional storey heights required for accommodating ducts and pipes. By incorporating these openings, the overall height of the building can be reduced, resulting in lower loads on the structural members and foundation. This reduction in loads contributes to a more economical design of the building, leading to cost savings. This concept has been studied and supported by references [1-3], which further emphasize the advantages of utilizing openings in reducing building height and achieving structural and economic efficiency.

When an opening is planned before casting the beam, it is possible to arrange internal deformed steel bars around the opening to address the structural requirements. However, in existing RC structures where ducts or pipes need to be installed but no pre-formed openings exist in the beams, creating openings in the beam has proven to be an efficient solution, which has been implemented in numerous real projects. However, it is important to note that this approach results in a reduction of the cross-sectional area, shear capacity, and stiffness of the beam.

In recent years, there have been numerous experimental and numerical research dedicated to investigating the behavior of RC beams with openings. These studies have examined various aspects including the shear span to beam depth ratio, opening geometry, concrete compressive strength, flexural reinforcement ratio, loading conditions, and strengthening techniques [1-4]. The findings from these studies consistently show that the introduction of an opening in the web of an RC beam leads to the early formation of diagonal cracks and a substantial reduction in both shear capacity and stiffness of the beam. This reduction in shear capacity and stiffness highlights the detrimental effect of openings on the structural performance of RC beams.

This research investigates the shear behavior of beams containing openings with a shear span to beam depth ratio a/d of 1.48, which is less than 2. The experimental program included testing of three

RC beams with/without opening in shear span. This research aims to provide experimental evidence to assess the behavior of RC beams with openings in the shear span. The experimental research was conducted at the Laboratory of Construction Testing and Inspection, Ha Noi University of Civil Engineering (HUCE).

2. EXPERIMENTAL RESEARCH

2.1. Specimen and material properties

A total of three test specimens were designed as simply supported RC beams with a cross-section size of 150 × 250 mm and a length of 850 mm. The details of the test specimensare provided in Figure 1. The parameters studied in this research included the shape of the opening (circular and rectangular). The test specimens were subjected to three-point bending, with an effective span of 650 mm and a short shear span of 325 mm. The design of the specimens aimed to induce shear failure before any flexural distress occurred. Each beam had a main tensile steel reinforcement area of 401.9 mm2, comprising two 16 mm diameter deformed bars with a yield strength of 380 MPa. The compression steel reinforcement consisted of two 10 mm diameter deformed bars. Shear reinforcements were not utilized in the shear span with openings to investigate the effect of the openings. Detailed information about the test specimens is provided in Figure 1.

Regarding the openings, the rectangular opening had dimensions of 80 × 120 mm, while the circular opening had a diameter of 110 mm. These dimensions were chosen to ensure that both openings had the same area. The center of the openings in all test beams was positioned at the center of the shear span region and aligned with the natural load path, which is the line connecting the load and support points. The circular opening was created by inserting a circular polyvinyl chloride (PVC) pipe into the beam before concrete casting, while the square rectangular opening was formed by using a plywood box.

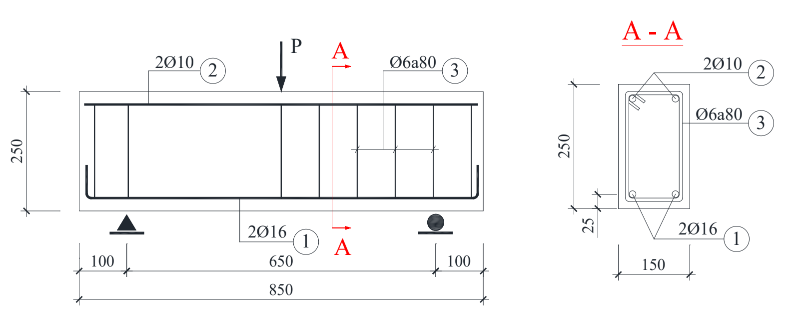
All beam specimens were cast using the same batch of concrete mix, the composition of which is provided in Table 1. The average compressive strength of the concrete cylinders, measured at 28 days, was found to be 34.7 MPa.

Table 1. Mixture proportions for 1m^3 of concrete (kg/m^3)

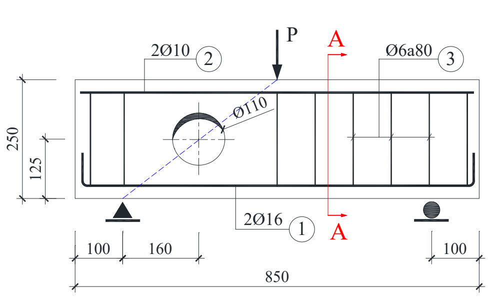
Cement PCB40	Sand	Coarse aggregate	Water
365	680	1230	175

2.2. Test setup and instrumentations

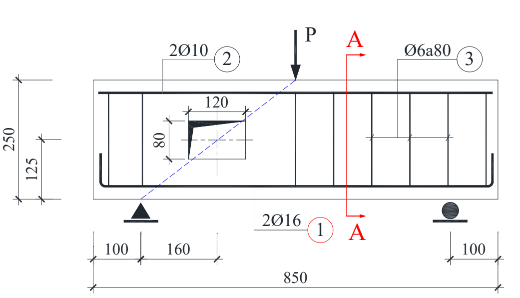
Figure 2 depicts the typical test setup employed for the experimental investigation, as well as an image of a test in progress. All three beam specimens underwent testing using a three-point bending configuration. The load was applied at the mid-span of the beam using a hydraulic jack. An electronic force measuring instrument (load cell) was utilized to determine the applied load. Three linear variable differential transformers (LVDTs) with an accuracy of 0.001 mm, designated as LVDT-1, LVDT-2, and



a. Control beam B-0



b. Beam with circular opening B-1



c. Beam with rectangular opening B-2

Figure 1. Reinforcement details of test beam specimens

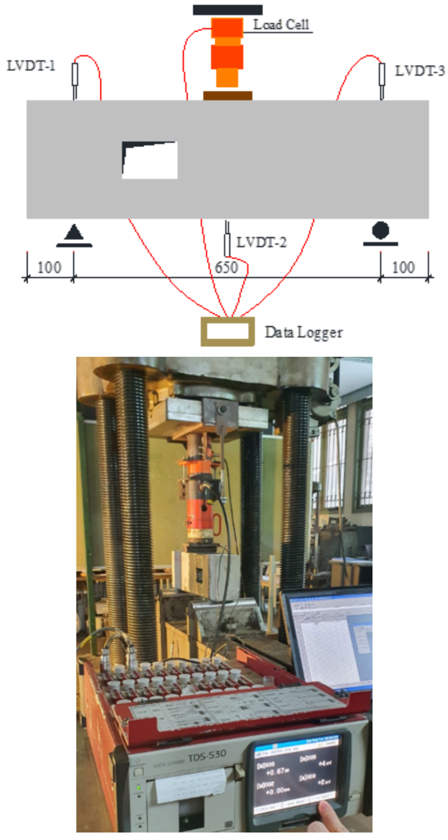


Figure 2. Test setup and image of test in progress

a. Specimen B-0

b. Specimen B-1

c. Specimen B-2

Figure 3. Failure modes of all test specimens

LVDT-3, were positioned at the two supports and in the middle of the test specimen, respectively. These LVDTs were employed to measure the displacement of the beams during loading. The maximum deflection of the middle cross-section of the test specimens was determined based on the measurements obtained from the LVDTs. The force and displacement measuring instruments were connected to a TDS 530 data logger, enabling continuous and automatic recording of experimental data at one-second intervals. The tests were conducted until the failure of the specimens.

3. TEST RESULT AND DISCUSSION

3.1. Overall behavior and failure mode

Figure 3 presents the failure modes observed in all test specimens, with each specimen exhibiting shear mode failure. In the case of the control specimen (Figure 3.a), the crack originated at the support and propagated diagonally towards the loading point, forming an angle of approximately 45 degrees to the longitudinal axis of the beam. The crack patterns at failure for the two beam specimens with opening, B-1 and B-2, are depicted in Figures 3(b), 3(c). It is evident from these figures that both specimens failed due to the development of diagonal cracks in the top and bottom chords. Based on these results, it is indeed crucial to consider the arrangement of longitudinal and shear reinforcement in the top and bottom chords of RC beams with openings in the shear span. Proper reinforcement placement in these areas plays a significant role in enhancing the overall performance of the beams and preventing crack propagation.

3.2. Load-deflection relationship and the evaluation of strengthening effectiveness

Figures 4 present the relationship between applied load and deflection at the mid-span of three test specimens. These plots provide a visual representation of the structural response and deformation behavior of the beams under increasing loads. Table 2 provides a summary of the ultimate load, denoted as P_{max}, which represents the maximum load that the specimen can sustain before failure. It also includes the corresponding maximum shear resistance, denoted as V_{max}. These values are important indicators of the beam's capacity to resist shear forces. In addition, Table 2 presents the reduction in shear resistance observed in the two beams with openings in the shear span compared to the control beam B-0.

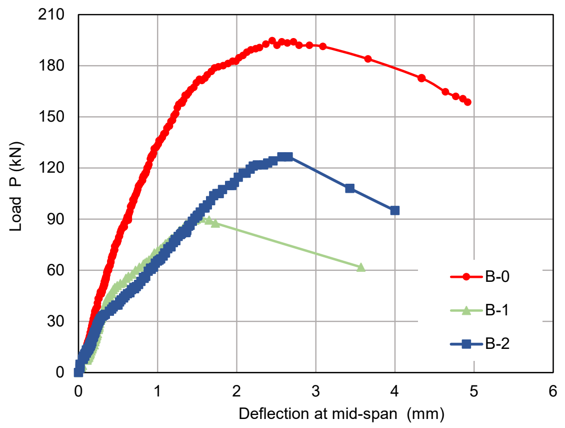


Figure 4. Load-deflection relationship of test specimens

Table 2. Test results

Test specimen	Ultimate load P_{max}(kN)	Shear resistance V_{max} (kN)	Reduction in shear resistance due to opening (%)
B-0	192	96	0
B-1	90	45	57.3
B-2	127	64	29.1

[a]$V_{max} = P_{max}/2$

Concerning the effect of openings, the findings from both Figure 4 and Table 2 clearly illustrate the significant impact of openings on the shear capacity and behavior of the RC beams. The presence of openings in the beams leads to a notable reduction in beam stiffness, as evidenced by the increased deflection under applied loads. This reduction in stiffness directly affects the shear capacity of the beams. Furthermore, the results highlight that the shape of the opening influences the shear strength of the beams. Specifically, when comparing circular openings to rectangular openings with the same opening area, it is observed that circular openings with a greater opening height result in a larger

These findings emphasize the importance of considering the shape and dimensions of openings when evaluating the shear capacity of beams with openings. Circular openings with increased opening height should be carefully analyzed and accounted for in the design process, as they may have a more pronounced effect on the reduction of shear strength and overall structural response. Proper consideration of the opening shape and dimensions is crucial to ensure the desired level of shear capacity and structural performance in beams with openings.

4. CALCULATION OF THE SHEAR STRENGTH OF BEAMS WITH OPENING

In this section, a simplified model based on the Strut-and-Tie Model (STM) according to ACI 318-2019 [12] will be proposed. The model aims to predict the shear capacity of RC beams with a small shear span to depth ratio and with an opening in the shear span.

The schematic of the shear resistance calculation according to the STM is presented in Figure 5. The model involves dividing the beam into various regions, including the strut region, tie region, and nodal zone. The strut region represents the compressed concrete strut that transfers the applied shear forces. The tie region represents the tension reinforcement that resists the shear forces. The nodal zone represents the region where the forces are concentrated.

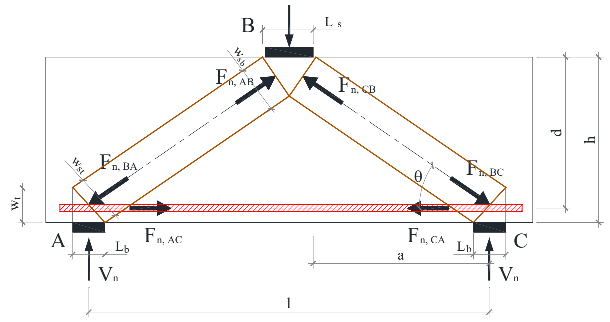


Figure 5. Schematic of the calculation of the shear resistane according to STM model

Using the STM to calculate the shear resistance of RC beams can be summarized through the following steps:

- Calculation of strut nodal dimensions:

$$w_t = 2(h-d) \; ; \; w_s = 0,8w_t \; ; \quad jd = h - 0,5w_t - 0,5w_s \qquad (1)$$

- The inclination angle of the diagonal compressed concrete strut AB and BC to the longitudinal axis of the beam:

$$\theta = \tan^{-1}\left(\frac{jd}{a+\frac{L_s}{2}}\right) \qquad (2)$$

The width of the diagonal struts AB and CB at the bottom and top of the strut is determined by the following formula:

$$w_{sb} = L_s \sin\theta + w_t \cos\theta \;; \quad w_{st} = L_b \sin\theta + w_s \cos\theta \qquad (3)$$

In the case of an opening with the heigh of d_0 in shear span, propose a simple formula to determine the width at the bottom, w^o_{sb}, and at the top, w^o_{st}, of diagonal compressed strut:

$$w^o_{sb} = \left(1 - \frac{d_0}{d}\right) w_{sb} = \left(1 - \frac{d_0}{d}\right)(L_s \sin\theta + w_t \cos\theta) \qquad (4)$$

$$w^o_{st} = \left(1 - \frac{d_0}{d}\right) w_{st} = \left(1 - \frac{d_0}{d}\right)\left(L_b \sin\theta + w_s \cos\theta\right) \qquad (5)$$

Determie the effective compressive strength of concrete, f_{ce}, based on the characteristic compressive strength of concrete f'_c, according to the following formula:

$$f_{ce} = 0{,}85\beta_s f_c^{'} \text{ with } \beta_s^A = 0{,}8 \text{ and } \beta_s^B = 1{,}0 \qquad (6)$$

The shear strength capacity of strut nodal A (or C) and B:

$$V_{n,A1} = f_{ce} L_s b \quad V_{n,A2} = f_{ce} w_t b \tan\theta \quad V_{n,A3} = f_{ce} w_{sb} b \sin\theta \qquad (7)$$

$$V_{n,B1} = f_{ce} L_b b \quad V_{n,B2} = f_{ce} w_s b \tan\theta \quad V_{n,B3} = f_{ce} w_{st} b \sin\theta \qquad (8)$$

The compressive capacity of diagnal AB with opening can determine:

$$w_{eff} = \min(w^0{}_{st}; w^0{}_{sb}) \qquad (9)$$

$$V_{n,AB} = V_{n,CD} = f_{ce} w_{eff} b \sin\theta \qquad (10)$$

The shear resistance contribution from the tie region or the tensile capacity of strut AD is determined based on the yield strength (fy) and area (As) of the longitudinal steel reinforcement:

$$F_{n,AD} = A_s f_y \qquad (11)$$

The shear resistance of beam, V_n, can determine as following formula:

$$V_n = \min(V_{n,B1}; V_{n,B2}; V_{n,B3}; V_{n,A1}; V_{n,A2}; V_{n,A3}; V_{n,AB}; V_{n,BC}; V_{n,AD}) \qquad (12)$$

Table 3 presents the results of calculating the shear resistance of beams with openings based on the proposed formula for determining the width of the compression bar. A comparison with the experimental results shows that the calculation of shear resistance for reinforced concrete beams with and without openings yields consistent results with small errors.

5. CONCLUSIONS

The results of the above-mentioned research have improved the understanding of the behavior of RC beams with a shear span to beam depth ratio (a/d) of 1.48, which is less than 2, and with rectangular or circular openings in the shear span. Based on the results obtained in this study, the following conclusions can be drawn :

- For RC beams, the inclusion of openings in the shear span led to a significant increase in both the shear strength and stiffness of the beams. This indicates that the presence of openings can have a substantial impact on the structural performance of the beams, resulting in enhanced shear capacity.

- It was observed that beams with circular openings, which have a greater opening height compared to beams with rectangular openings, exhibited a larger decrease in shear strength. This

Table 3. Calculation and testing of shear resistance of beam specimens

Beams	Opening heigh d_0 (mm)	Width of compressive diagonal strut		Calculation shear resistance (kN)	Experiment shear resistance (kN)	Difference (%)
		w_{sb} (mm)	w_{st} (mm)			
B-0	0	103	56	92.2	95.0	3.9 %
B-1	80	66	36	59.2	63.5	7.3 %
B-2	110	52	28	46.0	46.5	1.1. %

suggests that the geometry of the opening plays a significant role in determining the extent of shear strength reduction in beams with openings.

- Calculating the shear strength of the tested specimens according to STM allowed for a deeper understanding of the effects of openings. The calculated shear capacities aligned closely with the experimental results, indicating the reliability and accuracy of the calculation method.

It is worth noting that the specific findings of this study should be considered in the context of the experimental conditions and parameters investigated. The conclusions drawn from this research can provide valuable insights into the behavior of RC beams with openings in shear span. However, further studies and investigations are recommended to validate and expand upon these findings, considering different design configurations, opening sizes, and strengthening approaches.

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