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SHEAR STRENGTH OF RC DEEP BEAMS WITH AND WITHOUT WEB OPENINGS

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Abstract: Experimental database of tests reported have been analyzed to demonstrate the significance of factors influencing the performance of reinforced concrete (RC) deep beams. The shear strength of the deep beams increases with an increase in compressive strength, and with increase in the vertical web reinforcement ratio at high percentage tension reinforcement. As the percentage of orthogonal web reinforcement increases at a higher quantity of tension reinforcement, the shear strength increases. In deep beams with shear span-to-depth ratio less than or equal to 1.0, increase in concrete strength, percentage tension reinforcement and vertical web reinforcement improves the performance. The web opening intervenes the force transfer path and reduces the shear carrying capacity of deep beams. Proper reinforcement detailing of corners of opening controls crack propagation and failure. The deep beams with rectangular openings exhibit better shear strength than those with square openings. The opening-area ratio adversely affects the shear strength. The shear strength of deep beams with different opening shape depends on the angle of strut connecting the opening corner with the load or support point. The strut angle controls the shear strength, which is also influenced by the opening location. A quantitative measure of influence of factors on shear strength of deep beams is required for the refined design procedures.

1 INTRODUCTION

RC deep beams are encountered in structural systems to transfer heavy loads such as transfer girders, foundation pile caps, bridge pier caps, shear walls, corbels, offshore structures, etc. RC deep beams are classified based on the aspect ratio by IS 456:2000 [1] and EN 1992-1-1:2004 [2], effective span-to-overall depth ratio (l/d) should be less than 2.0 and 3.0 respectively; ACI318-19 [3] and AASHTO LRFD 2020 [4] limit the shear span-to-depth ratio (a/d) to 2.0. Web openings in RC deep beams facilitate services like water supply, electricity, telephone, air conditioning ducts and computer network cables. The beam bending theory does not apply to design of deep beams due to discontinuity regions. The presence of web openings in deep beams further complicates shear behavior due to development of higher non-linear strain regions. These openings significantly influence the shear behavior of deep beams, with reduced strength, degradation of stiffness, excessive cracking, stress concentration, and increased deflections. The strut-and-tie method has been widely adopted by several international codes for the design of deep beams. However, there is a need to revise the design guidelines for deep beams in IS 456:2000. Currently, there is a lack of established design guidelines for deep beams with openings.

The shear strength of deep beams is significantly influenced by concrete compressive strength and a/d ratio [5].

Londhe [6] tested twenty-seven deep beams with different percentages of tension reinforcement. It has been revealed that shear capacity increases linearly till 1.80% of tension reinforcement, beyond that it was not effective. Yang et al. [7] found that web opening bypasses the load transfer path around the opening as two paths, and each consisting of two struts. The inclination of the strut connecting the opening corner to support point or loading point seems to be a significant factor influencing the shear strength.

The efficiency of load transfer path and stress concentration around the opening depends upon detailing of web reinforcement [8]. Appa Rao and Sundaresan [9] developed a size-dependent shear strength equation for deep beams using a refined strut-and-tie model. The shear strength influencing parameters such as strut angle, percentage tension reinforcement and shear reinforcement ratio were analysed with proposed model. Hu et al. [10] performed tests on six deep beams to study the effect of openings and shear span-to-depth ratio. The size, shape, and location of web openings were identified as significant factors influencing the shear behaviour.

Kondalraj and Appa Rao [11,12] conducted experimental studies on deep beams with and without web reinforcement. The results indicated that shear strength was strongly influenced by a/d ratio and compressive strength of concrete. The orthogonal web reinforcements are highly effective in controlling crack width.

In most of the studies and codes, the estimation of shear capacity primarily relies up on compressive strength of concrete as the major factor. Some authors have included the a/d ratio as an another influencing parameter. A comprehensive understanding of all major influencing parameters are essential to develop an analytical model to estimate accurate capacity of deep beams.

2 DATABASE OF RC DEEP BEAMS WITH AND WITHOUT WEB OPENINGS

A comprehensive study has been conducted using database on deep beams comprising 540 solid and 240 with openings, obtained from the literature [5-50]. The database has been selected to include deep beams failing in shear with a/d ratio less than 2.0, by careful selection of beams for analysis. The filtered dataset comprised of 151 solid deep beams without web reinforcement and 128 with web reinforcement, along with 69 deep beams with square openings and 28 with rectangular openings. The parameters considered for the analysis include concrete compressive strength, shear span-to-depth ratio, effective span-to-overall depth ratio, effective depth, percentages tension, vertical and horizontal web reinforcement, opening area-to-shear span area ratio, opening depth-to-overall depth ratio, and the diagonal distance between the opening corner and support point. The impact of these parameters on the nominal shear strength (V_u/bd) has been addressed through the analysis of database, where V_u represents the ultimate load capacity, b and d denotes the width and effective depth of the beam section, respectively.

3 ANALYTICAL INVESTIGATION ON SOLID RC DEEP BEAMS

The distribution of variables in the database of solid deep beams has been analyzed to evaluate the influence of various parameters, as shown in Figure 1. The analysis of the database revealed that 63% of the beams had concrete compressive strength less than 50 MPa. The a/d ratio was less than 1.0 in 30% of the beams and 53% of the beams had a/d ratio greater than 1.0. The effective depth ranges between 500 to 1000 mm in 36% of the beams, while 4.0% of the beams had effective depth greater than 1000 mm. The percentage tension reinforcement varies; 26% of the beams had reinforcement between 0.50 and 1.00%, 16% of beams had reinforcement between 1.00 and 1.50%, and 21% of beams had 1.50 to 2.00% reinforcement. The distribution of vertical reinforcement showed that 29% of the beams had reinforcement between 0.20 and 0.40%, and another 29% had reinforcement between 0.40 and 0.60%. However, there is a lack of information on the influence of horizontal web reinforcement on the shear strength. The variation of the nominal shear strength with different influencing parameters has been determined by fitting trend lines from the distribution of scattered points. The analysis of influence of various parameters on shear strength has performed according to the trend lines as shown in Figure 2.

3.1 Compressive strength of concrete

The variation of nominal shear strength vs. compressive strength is shown in Figure 2(a). It can be observed that, the shear strength increases with increase in compressive strength. However, the influence of concrete strength on shear strength is significantly higher in beams with *a*/*d* ratio less than 1.0. The shear strength improvement with high-strength concrete greater than 50 MPa is insignificant than ordinary strength concrete indicates that lesser contribution of aggregate interlocking on shear strength. However, conclusions for compressive strengths above 60 MPa cannot be drawn due to insufficient data available in the test reports.

3.2 Shear span-to-depth ratio

Figure 2(b) shows the influence of nominal shear strength vs. *a*/*d* ratio for beams with different percentages of tension reinforcement. The *a*/*d* ratio significantly affects the shear strength. As the *a*/*d* ratio increases, the shear strength decreases due to a reduced arch action. There is a significant reduction in shear strength with decrease in *a*/*d* ratio at a given percentage of tension reinforcement. Beams with *a*/*d* ratio less than 1.0 exhibit higher shear capacity than that of beams with *a*/*d* ratio greater than 2.0, indicating that the arch action contributes significantly on shear carrying capacity. Furthermore, a steeper strut angle improves shear strength than less steep ones. The influence of *a*/*d* ratio on shear capacity is closely associated with concrete's compressive strength, percentages of tension reinforcement, and web reinforcement.

3.3 Percentage tension reinforcement

The relationship between percentage tension reinforcement and nominal shear strength of beams without web reinforcement is shown in Figure 2(c). In deep beams with *a*/*d* ratio less than 1.0, the nominal shear strength increases with increase in tension reinforcement, ρ_t up to 1.80%, beyond which there is no significant improvement.

3.4 Percentage vertical and horizontal web reinforcement

The effect of vertical and horizontal web reinforcement vs. shear strength is shown in Figures 2(d) and 2(e) respectively. The shear strength increases with increase in percentage vertical web reinforcement. A substantial improvement of shear strength up to 0.45% of vertical web reinforcement in beams with ρ_t greater than 1.50%. However, no further improvement in strength beyond this limit. Since the data is limited, constructive remarks on the influence of horizontal web reinforcement on shear strength could not be drawn.

3.5 Effective web reinforcement

The influence of orthogonal web reinforcement vs. shear strength is shown in Figure 2(f). The shear strength of deep beams increases with the increasing percentage of orthogonal web reinforcement with higher percentages of tension reinforcement.

4 ANALYTICAL INVESTIGATION ON RC DEEP BEAMS WITH OPENINGS

The frequency distributions of variables of deep beams with openings are shown in Figure 3. It shows that 68% of the beams cast with concrete compressive strength below 50 MPa. 86% of the beams had *a*/*d* ratio less than 1.0, while 14% had greater than 1.0. The effective depth ranges from 500 to 1000 mm in 61% of the beams, with 5% having in excess of 1000 mm. 62% of the beams possesses 0.50 to 1.00% tension reinforcement and 23% provided with 1.50 to 2.00%. The percentage vertical reinforcement ranges from 0.30 to 0.40% in 22% of the beams, and 0.40 to 0.60% in 39% of the beams. The percentage horizontal reinforcement ranges between 0.20 to 0.40% in

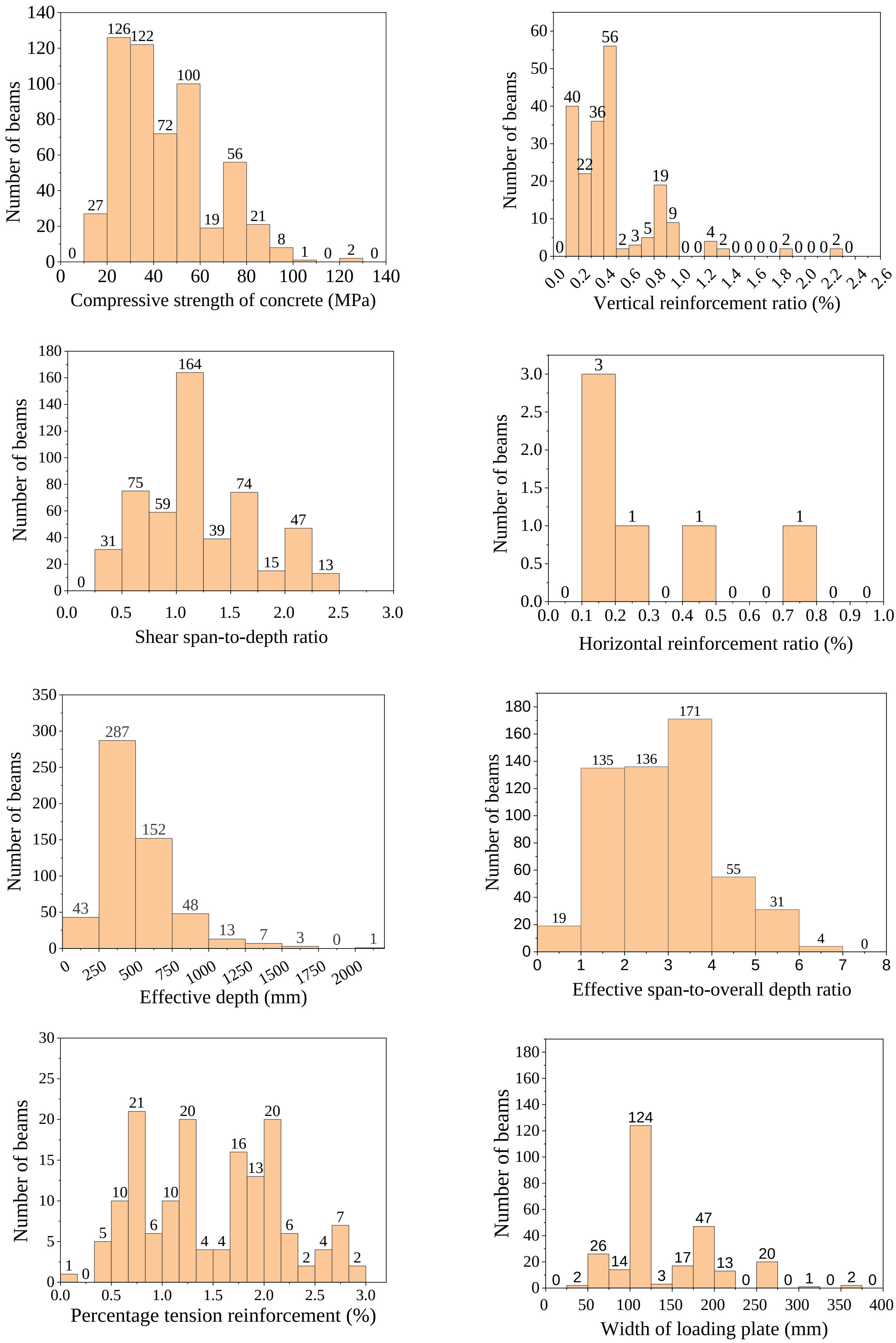
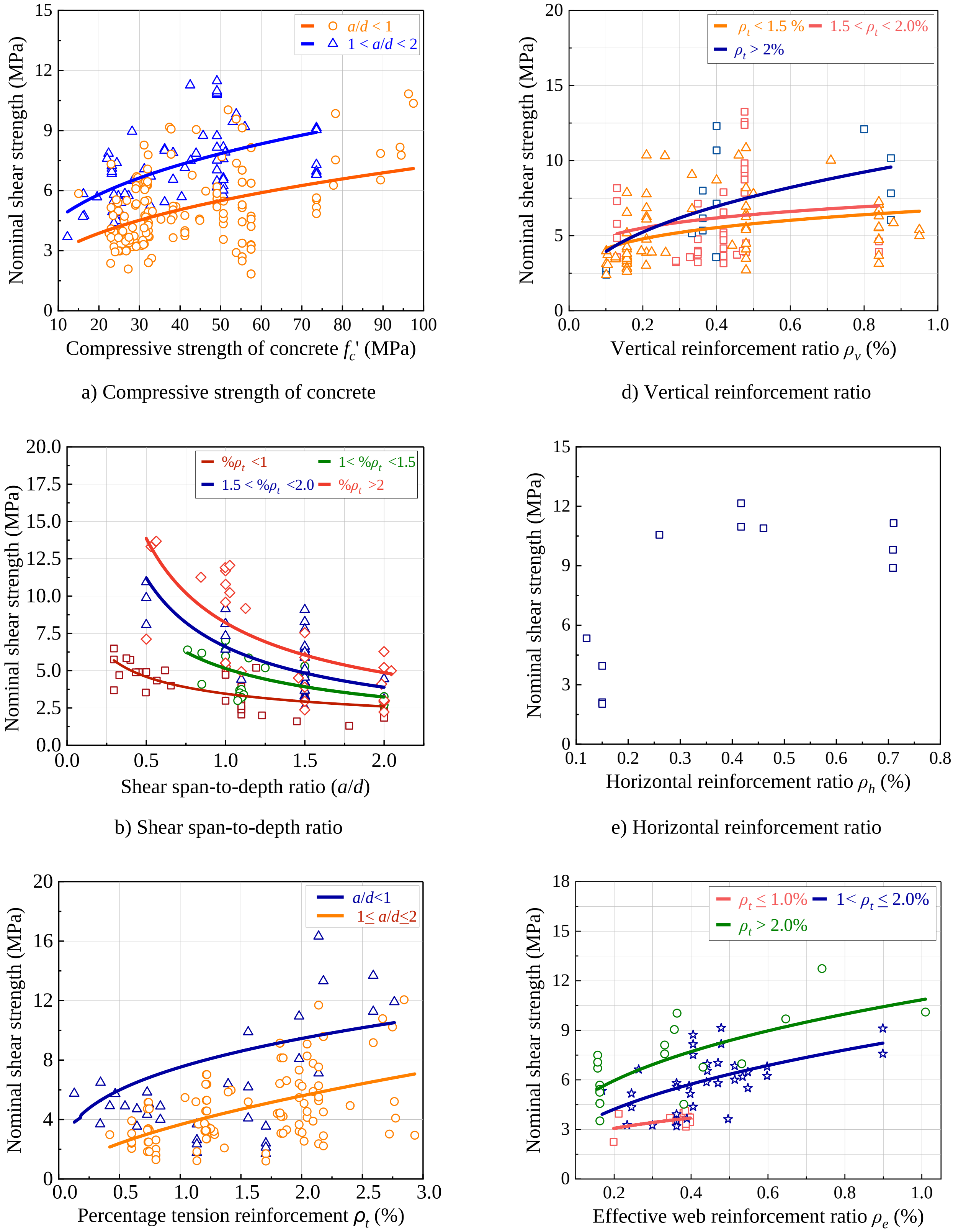


Figure 1: Distribution of variables of solid deep beams experimental database



a) Compressive strength of concrete

d) Vertical reinforcement ratio

b) Shear span-to-depth ratio

e) Horizontal reinforcement ratio

c) Percentage tension reinforcement

f) Effective web reinforcement

Figure 2: Comprehensive influence of variables of solid deep beams

23% of the beams, while 19% of the beams provided with greater than 0.40%. The beams provided with openings, opening width-to-shear span ratio, indicate that 5% of the beams had the ratio less than 0.20, 26% had between 0.20 and 0.40, and 69% had the ratio greater than 0.40. The distribution of the opening depth-to-overall depth ratio shows that 24% of the beams had a ratio less than 0.20, 67% had a ratio between 0.20 and 0.40, and 9% had a ratio greater than 0.40. The effect of nominal shear strength of deep beams with openings on different influencing parameters as shown in Figure 4.

4.1 Compressive strength of concrete

The variation of nominal shear strength vs. compressive strength is shown in Figure 4(a). Beams with *a*/*d* ratio less than 0.5 demonstrate a greater increase in shear strength as concrete compressive strength increases, whereas beams with *a*/*d* ratio between 0.5 and 1.0 exhibit a relatively lesser increase. However, there is a lack of database on beams with compressive strength greater than 50 MPa.

4.2 Shear span-to-depth ratio

Figure 4(b) shows the variation of shear strength with *a*/*d* ratio of beams with rectangular and square openings. It can be observed that the shear strength decreases as the *a*/*d* ratio increases. This can be attributed to the weak strut mechanism between the nearest corner of the opening and the loading or support points.

4.3 Opening-area ratio

The opening-area ratio is defined as the ratio of opening area-to-shear span area. Influence of opening-area ratio on shear strength of beams with rectangular and square openings is shown in Figure 4(c). The web opening intervenes the force transfer path, which results load being distributed into two separate paths around the opening. Consequently, the shear strength is reduced due to the decrease in the area of the compression and tension zones above and below the opening.

4.7 Opening shape

The deep beams with rectangular openings have higher shear strength than those with square openings, as shown in Figure 4(c). The greater reduction in beam depth above and below square openings and shorter diagonal distance between opening corner and loading or support points, resulting in higher tensile strain concentration and lower shear strength. Hence, the opening shape significantly influence the capacity of shorter diagonal struts around the opening, which controls the capacity of deep beams. Beams with square openings exhibit a substantial reduction in shear strength compared to those with rectangular openings.

4.4 Opening location

The influence of diagonal distance between support point to the opening corner vs. shear strength of the beams is shown in Figure 4(d). As the diagonal distance decreases, the shear strength reduces due to higher strain concentration at that opening corner. It indicates that, web opening in the shear span region significantly influence the shear strength.

4.6 Effective web reinforcement

The variation of the nominal shear strength of beams with effective web reinforcement with rectangular, and square openings is shown in Figures 4(e) and 4 (f) respectively. It is evident that the shear strength increases significantly as the effective web reinforcement ratio increases in beams with rectangular and square openings with *a*/*d* ratio less than 0.5 compared to *a*/*d* ratio greater than 0.5. The effectiveness of web reinforcement depends up on the strut angle, which is primarily influenced by *a*/*d* ratio and opening location.

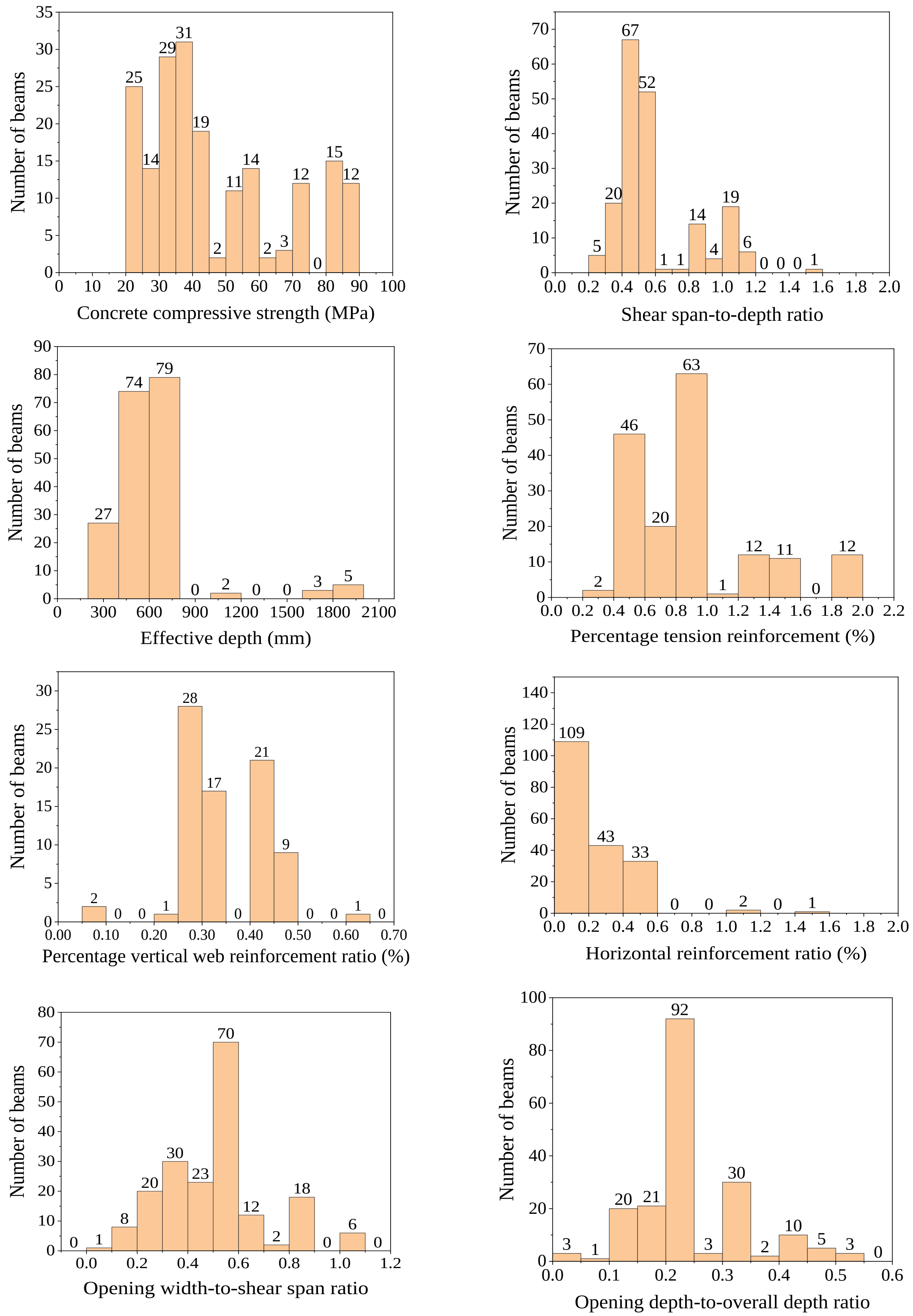
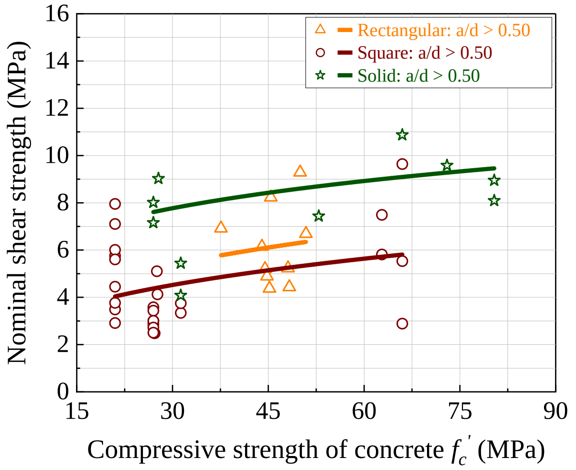
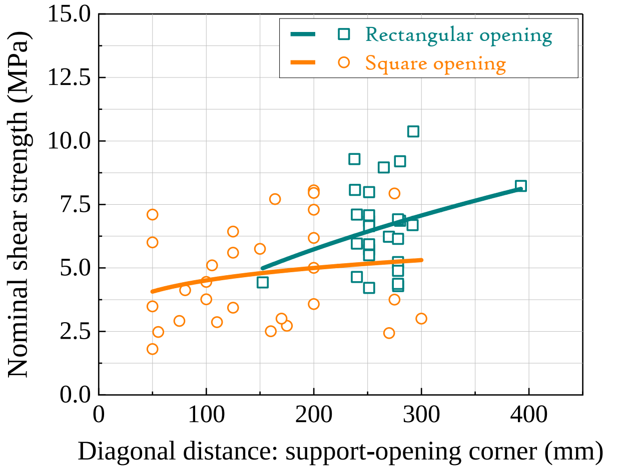


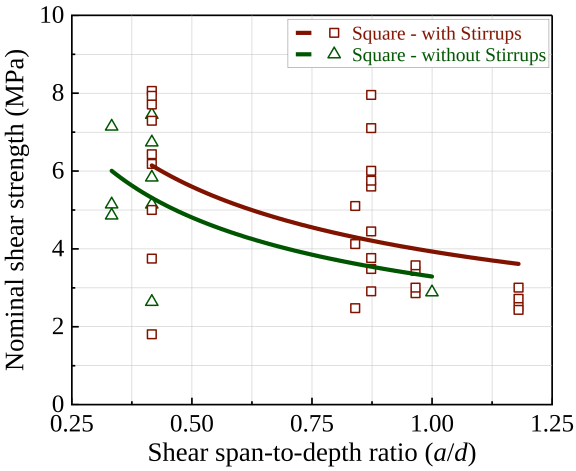
Figure 3: Distribution of variables of deep beams with openings experimental database



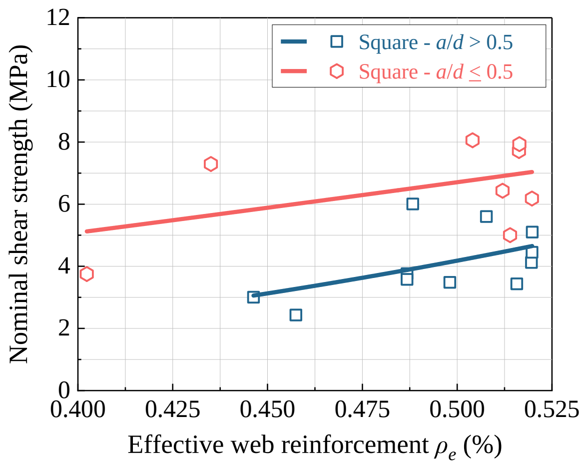
a) Compressive strength of concrete



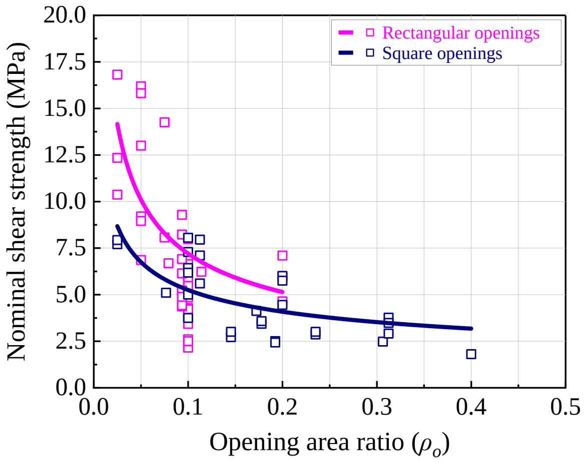
d) Diagonal distance between support and opening corner



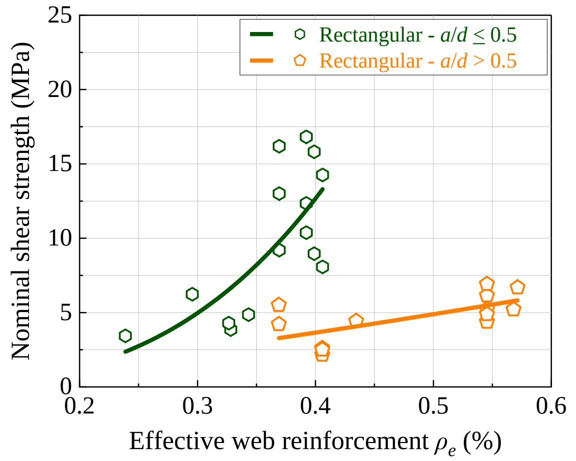
b) Shear span-to-depth ratio



e) Effective web reinforcement - Square openings



c) Opening-area ratio



f) Effective web reinforcement - Rectangular openings

Figure 4: Comprehensive influence of variables of deep beams with openings

5 CONCLUSIONS

Based on the study on influence of various parameters on the shear strength using the analysis of experimental database on deep beams, the following conclusions have been drawn.

1. Compressive strength of concrete, *a*/*d* ratio, percentage tension reinforcement, and percentage web reinforcement influence the shear strength of deep beams.
2. The shear strength increases with increase in percentage tension reinforcement up to 1.80%. In deep beams, up to 1.50% tension reinforcement, the shear strength increases with vertical reinforcement up to 0.45%.
3. The increase in shear strength with an increase in concrete compressive strength is pronounced more in beams with openings when *a*/*d* ratio is less than 0.5.
4. The strut angle controls the effectiveness of web reinforcement on shear strength, which is also influenced by *a*/*d* ratio and opening location.
5. Increase in the opening-area ratio adversely affects the shear strength and further influenced by opening shape. The beams with rectangular openings shows higher shear strength than those with square openings.

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