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Shear and Bending Performances of Reinforced Concrete Beams with Different Sizes of Circular Openings

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Abstract: The present study pertains to the effects of transverse opening diameters and shear reinforcement ratios on the shear and flexural behavior of RC beams with two web openings across different spans, i.e., a single opening in each half-span. Within the scope of the study, a total of 12 RC beams with five different opening diameter-to-beam depth ratios (0, 0.20, 0.27, 0.33, 0.40, and 0.47) and two shear reinforcement ratios were tested to failure under four-point bending. The load capacities, ductilities, rigidities and energy dissipation capacities in the elastic and plastic ranges of beam behavior were compared. Furthermore, the load capacities of the beams were compared to the existing analytical shear strength formulations in the literature. The test results indicated that whether an RC beam with openings has adequate or inadequate amounts of shear reinforcement, the frame-type shear failure becomes much more pronounced with increasing opening diameter. The reductions in the load capacity and modulus of toughness with increasing opening diameter are more considerable in the presence of inadequate amounts of shear reinforcement, while the beam ductility is less affected in shear-deficient RC beams with openings as compared to the ones with adequate shear reinforcement.

Keywords: transverse opening; chord; frame-type shear failure; shear-tension failure; beam ductility; modulus of resilience; modulus of toughness

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1. Introduction

Most structures are made from reinforced concrete due to various advantages [1–5]. Therefore, investigation of concrete has been increasing year by year [6–10]. In practice, the accommodation of services such as telephone communication, water supply, air conditioning, electricity, and sewage involves providing a network of ducts and pipes throughout the structure. More commonly, channels and pipes are located underneath the soffits of floor beams, creating an unusable space within the floor height. Suspended ceilings are used to cover these pipes and ducts, which produce additional unusable places in each floor [11]. The provision of openings in RC (reinforced concrete) beams is a useful solution to avoid the use of suspended ceilings, which have a considerable negative influence on the use and cost of structures, especially in multistory structures. The existence of openings also creates variations in the performances of RC beams. These openings, which were not foreseen in the design stage, are responsible for the possible losses of load capacity and premature failure of the beams [12]. The openings can be in circular, rectangular or undefined geometries, in most cases positioned near the supports where shear stresses are high. These openings trigger different forms of failures in RC beams [13]. The influence of these openings, drilled close to the support zones, on the shear stress distribution is very significant. These openings can be responsible for different types of diagonal failures (diagonal tension or compression) and high-stress concentrations at the boundaries of openings, leading to the degradation in shear strength [14–16].

In the literature, various studies have been conducted on RC beams with web openings. In the majority of these studies, rectangular and circular opening geometries were adopted. The circular opening geometry can be assumed to be the most common one, since circular holes can be easily drilled with the help of core drilling equipment. For this reason, a good number of studies in the literature focused on the effects of opening location (distance to supports), opening size and number on the behavior of RC beams with a couple of or multiple transverse openings along the span. In one of these studies, Ashour and Rishi [17] performed tests on 16 two-span continuous deep RC beams with transverse openings. The test parameters were the size and location of the web openings and the web reinforcement details. This study revealed that the location of openings plays an important role in the failure types of the beams. Mansur et al. [18] developed a methodology for the calculation of ultimate strengths of RC beams with a single large rectangular opening, subjected to concentrated loading. Mansur et al. [18] found out that the distribution of shear forces among the top and bottom chords and the failure loads of an RC beam with openings mainly depend on the location and size of the opening(s). Osman et al. [19] conducted both experimental and numerical (finite element) studies on RC beams with openings with an emphasis on the shear span-to-depth ratio, opening size and location. The study indicated that that the openings located in a high shear region of the beam caused premature failure of the beams. Furthermore, the numerical and experimental results were shown to be in close agreement, revealing the efficiency of finite element analysis tools in analyzing RC beams with web openings. Ahmed [20] examined the influence of the presence of numerous circular web openings on the shear strengths of RC beams. Furthermore, a 3D finite element model was developed, primarily for analyzing these beams. This study showed that the opening diameter has greater influence on the beam behavior as compared to the shear span length. Similarly, the size of opening was found to have greater effects on the beam behavior than the number of openings. The American ACI 318-05 code requires that the influence of web openings on the shear strength of RC beams should be taken into account [21].

Yamada [22–24] conducted finite element analyses and tests on RC beams with a number of openings in the shear spans and investigated the influence of longitudinal reinforcement ratios on the beam failure. The location of debonding cracks at the tension reinforcement level, the crack widths and the opening location were some of the test and analysis parameters in these studies. The tested and analyzed beams did not contain any shear reinforcement and the openings were available during the concrete cast. These studies emphasized the importance of the fact that the presence of openings has a much lesser effect on the beam strength as the openings facilitate the predominance of the arch mechanism in the beam rather than the beam mechanism. Torunbalci [25] performed nonlinear finite element analyses in the search for developing an analytical method for the estimation of load capacities of RC beams with large openings. The study focused on the effects of web openings and web reinforcement on the load-carrying capacities of RC beams with openings. The finite element analysis estimates were also compared to the experimental results and a close agreement between the numerical and experimental results were reached.

In the literature, FE modeling is now accepted as a powerful way and an economical alternative to experiments in examining the influence of various parameters on member behavior [26,27]. In a majority of these finite element studies, the efficiency of strengthening RC beams containing circular openings with CFRP fabrics was examined. The ultimate load capacity, ductility, stiffness and energy dissipation values and the failure modes of the RC beams were determined using these analyses. In one of these studies, Aksoylu et al. [28] examined the influences of the D/H (opening diameter-to-beam depth) ratio on the load capacities of the RC beams with inadequate amounts of shear reinforcement and the effects of CFRP strengthening on the behavior of these shear-deficient beams. The study showed that CFRP strengthening contributed to the beam capacity to a major extent by working in perfect harmony with concrete. In a similar study, Fu et al. [29] investigated the influence of the presence of multiple small circular openings ($D/H = 1/10$) on the shear behavior of RC beams without shear reinforcement and described the shear resistance mechanism. The angle of the lines connecting the centers of openings (35°, 40°, 45°, 50°) was the main test parameter. The center lines in each of the beams passed through the loading points. Similar to the findings of Yamada [22–24], Fu et al. [29] underscored the increase in the shear strengths of RC beams with openings as the arch action predominates the beam behavior. Fu et al. [29] also showed that the failure mode of the beam can be altered from diagonal tension to shear compression and the crack orientation can be adjusted by changing the slope of the lines connecting the centers of openings. In another study, Amiri et al. [30] focused on precast prestressed RC deep beams with T or rectangular cross-sections and web openings. RC beams with rectangular and circular openings were examined within the scope of the study and detailed conclusions on the influence of dimensions and position of openings on the beam strength were drawn. Daniel [31] tested five RC beams with long openings. The main parameter of this study was the opening length. This study showed that increasing the opening length results in reductions in both shear and flexural strength values of RC beams. Mohammad Ali and Saeed [32] carried out tests on 12 RC beams to examine the influence of depth, length, and location of opening on the ultimate shearing resistance of high-strength RC beams with openings. The study revealed that the depth and length of the openings in high-strength concrete beams have significant negative influences on the beam shear resistance.

Although there are many other studies in the literature [33–38] on the flexural behavior of RC beams with web openings, the influence of stirrup spacing (transverse reinforcement ratio) and the ratio of opening diameter to beam depth (D/H) on the shear and bending strengths of RC beams with openings has not been studied extensively. The present study focuses on these two parameters based on a total of 12 beam tests on RC beams with five different opening diameters and two different shear reinforcement ratios. A reference beam without circular openings was also tested for each of the beam groups with identical shear reinforcement. The test results were compared to analytical estimates from existing formulations in the literature.

2. Materials and Method

The investigational program consisting of 12 small-scale beam specimens was performed at Necmettin Erbakan University. All specimens had cross-sections of 100 mm × 150 mm and lengths of 1000 mm. Longitudinal tension reinforcement of 2ϕ10 and compression reinforcement of 2ϕ6 were used in each and every specimen. The specimens were under-reinforced with a reinforcement ratio of 0.0074. In addition, ϕ6 stirrups with two different spacings were used in the specimens so that both shear and flexural types of failure can govern the beam behavior. These spacings were 100 and 160 mm. The specimens with 100 mm stirrup spacing are referred to as bending specimens and the ones with 160 mm stirrup spacing as shear specimens in the following discussion. Each specimen contained two transverse openings, one in each half span. Five different opening diameters, including 30, 40, 50, 60, and 70 mm, were adopted in the present study. These diameters correspond to D/H (opening diameter-to-beam height) ratios of 0.2, 0.27, 0.33, 0.4, and 0.47, respectively.

The openings were drilled at 150 mm, i.e., the beam height (H), away from the end. The information on the specimens, along with their notations, is presented in Tables 1 and 2. The drilling process of the transverse openings is depicted in Figure 1. The reinforcement layout used in the specimens is illustrated in Figure 2.

Table 1. Details of the bending specimens.

Specimen Notation	Tensile Longitudinal Reinforcement	Compression Longitudinal Reinforcement	Stirrups (mm)	Opening Diameter (*D*) (mm)	*D*/*H*
B0	2ϕ10	2ϕ6	ϕ6/100	0	0
B30				30	0.20
B40				40	0.27
B50				50	0.33
B60				60	0.40
B70				70	0.47

Table 2. Details of the shear specimens.

Specimen Name	Tensile Longitudinal Reinforcement	Compression Longitudinal Reinforcement	Stirrups (mm)	Opening Diameter (*D*) (mm)	*D*/*H*
S0	2ϕ10	2ϕ6	ϕ6/160	0	0
S30				30	0.20
S40				40	0.27
S50				50	0.33
S60				60	0.40
S70				70	0.47

Figure 1. Preparation of beams with circular openings.

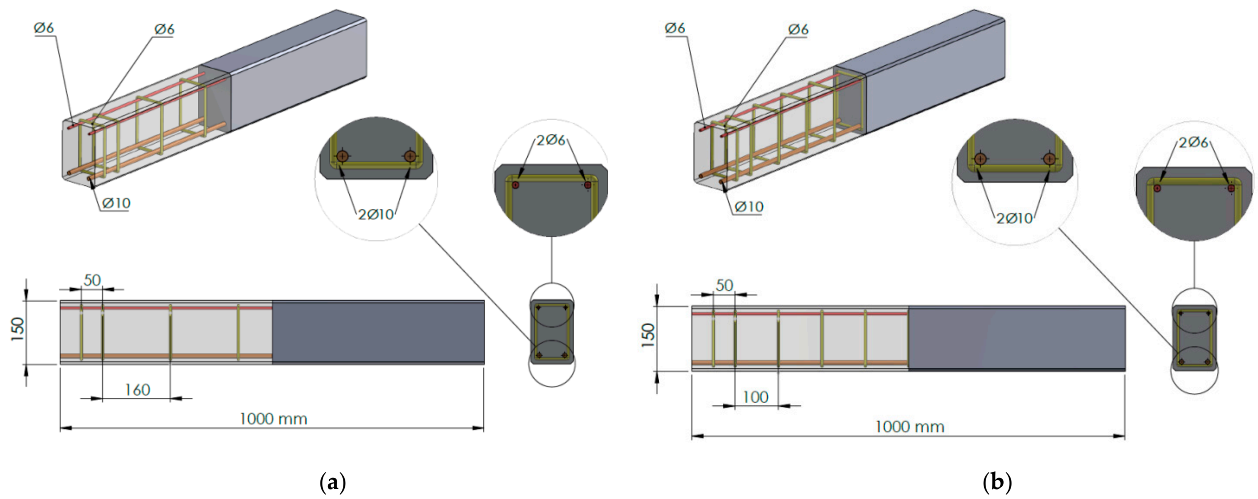

Figure 2. Details of the beams. (**a**) Shear beams; (**b**) Bending beams.

The specimens were tested under four-point bending. The specimens were positioned on two kinds of supports, namely hinged and roller support. The shear span (a_v) to effective depth (d) ratio was 3.1 for each specimen. Loads and displacements were recorded instantly in the computer environment during the experiments. The test setup is presented in Figure 3.

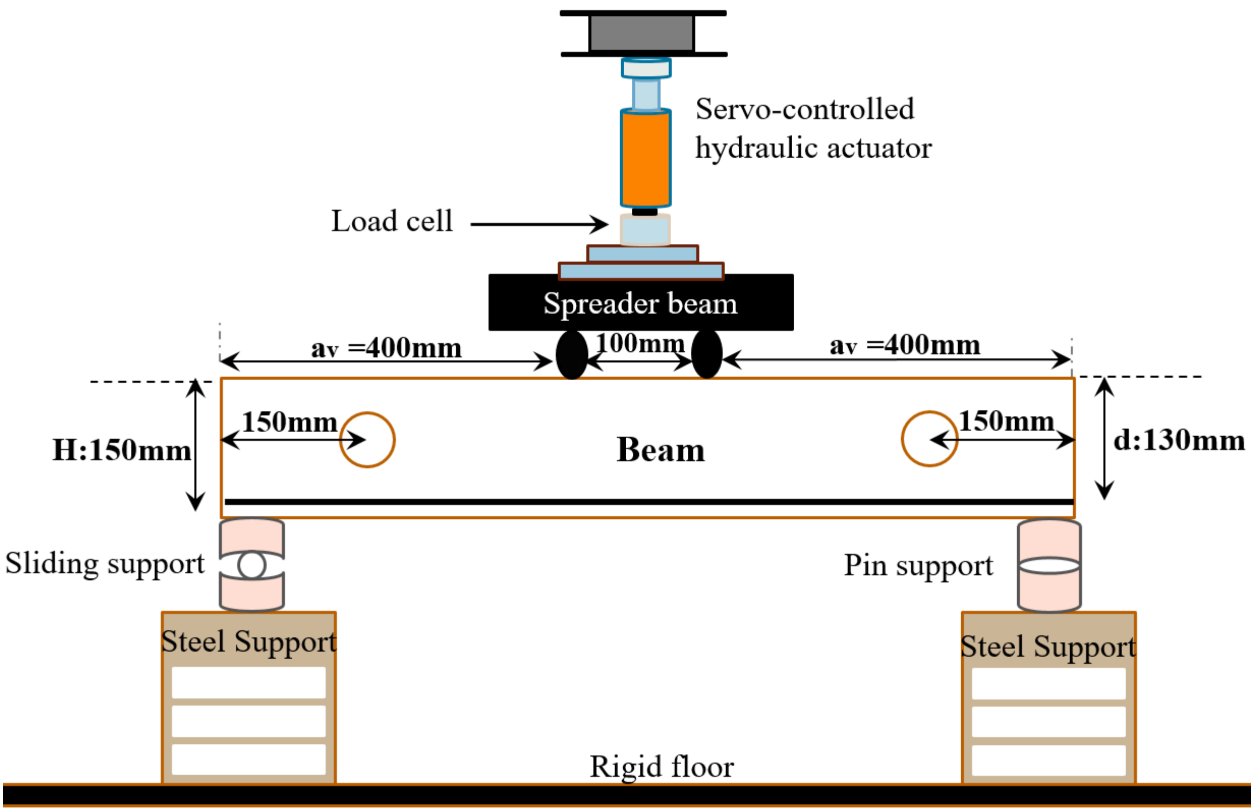

Figure 3. Test setup.

All of the reinforcing bars in the specimens were of grade B420c. Furthermore, the mean value of the concrete compressive strength was determined as 28.5 MPa according to the material tests on 150 mm cubic specimens.

2.1. Influence of D/H Ratio on Beam Behavior

In this section, the influence of the variation in the D/H ratio on the failure type of bending behavior of RC beams with circular openings was discussed. The section is divided into two subsections for two groups of beams. The first beam group denotes the specimens with a stirrup spacing of 100 mm (B0, B30, B40, B50, B60 and B70). The second group, on the other hand, refers to the ones with a stirrup spacing of 160 mm (S0, S30, S40, S50, S60 and S70).

2.1.1. First Group of Beams

The D/H ratio of the beams in this group changes as 0, 0.20, 0.27, 0.33, 0.40, and 0.47, while the spacing of stirrups is fixed to 100 mm. The load–displacement relationships of the beams in this group are compared in Figure 4. Furthermore, the failure types of the beams are illustrated in Figure 5. The load capacities of the beams are tabulated in Table 3 together with the deformation, ductility and stiffness values. Furthermore, the energy dissipation capacities of the specimens are shown in Table 4.

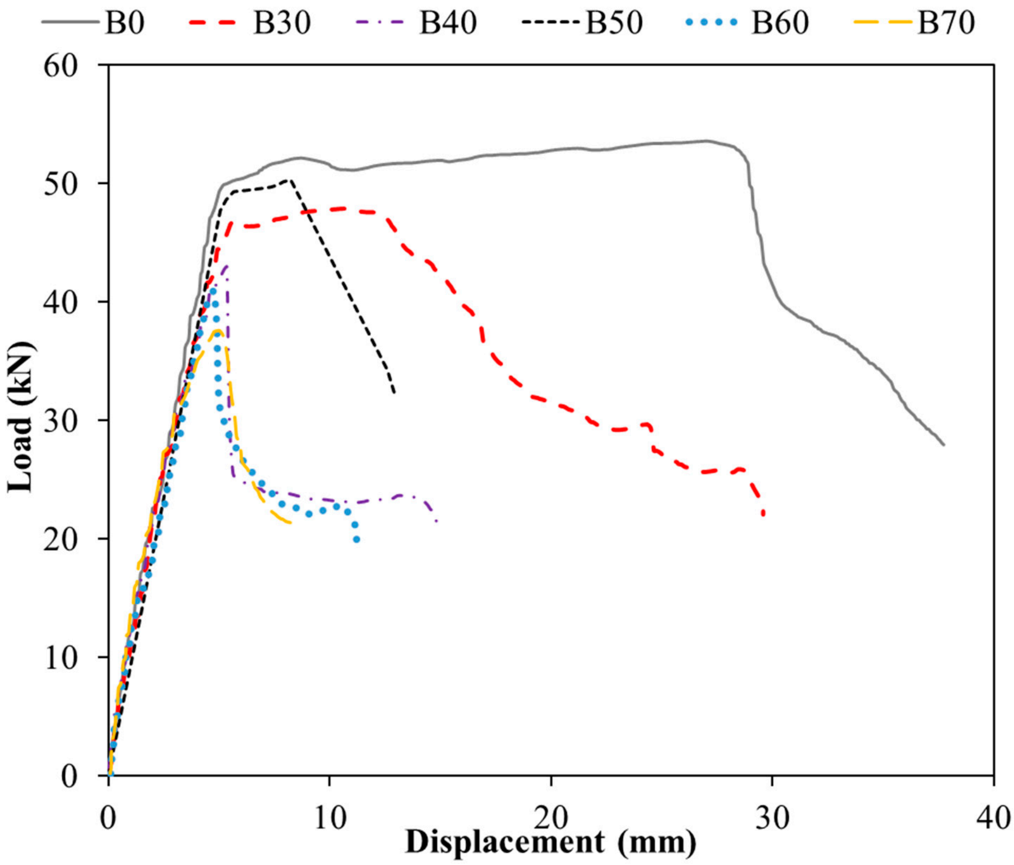

Figure 4. Load–displacement behavior of RC beams in the first group for different *D*/*H* ratios.

According to Figure 4, thew beam B0 without openings reached a maximum load of 53,58 kN at a deflection of 29.44 mm. Beam B30 with a D/H ratio of 0.20 reached an ultimate load of 47.88 kN under a deflection of 15.69 mm. Similarly, the maximum load of the beam B40 with a D/H ratio of 0.27 was determined as 42.96 kN at a vertical deflection of 5.41 mm. Furthermore, the maximum load of B50, having a D/H ratio of 0.33, was obtained as 50.51 kN at a mid-span deflection of 10.29 mm. Finally, the load capacities of beam B60 and B70, with D/H ratios of 0.40 and 0.47, were measured as 40.94 kN and 37.59 kN at deflection values of 4.94 and 5.57 m, respectively.

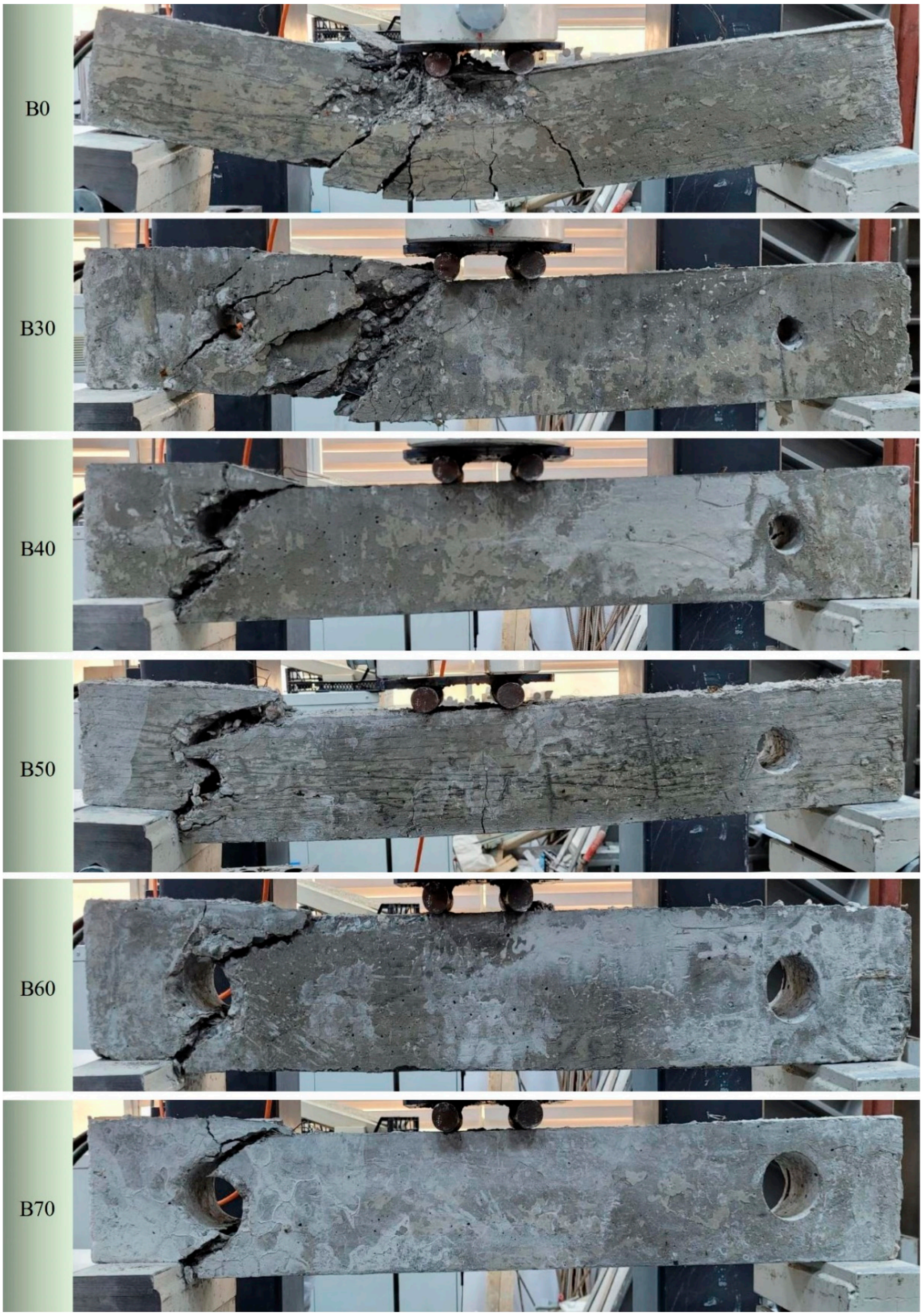

Figure 5. Failure modes of the beams with closely spaced stirrups (100 mm).

Figure 5 indicates that the reference specimen B0 underwent pure flexural failure, while both shear failure around the left opening and flexural failure under the left loading point played an important role in the final failure of specimen B30. Hence, the final failure of B30 was denoted as a shear-flexural type of failure. The remaining beams in this group experienced pure shear failure, characterized by two separate diagonal cracks in the top and bottom chords of the beam. Since these two cracks were separate and they developed individually, this failure can be denoted as frame-type shear failure, which is different from the beam-type shear failure, characterized by a single diagonal crack extending throughout the entire beam depth.

Table 3. Load, displacement, stiffness and ductility values of the specimens.

Test No.	P_{max} (kN)	Decrease in P_{max} (%)	δ_{Pmax} (mm)	Decrease in δ_{Pmax} (%)	S_{Pmax} (kN/mm)	Decrease in S_{Pmax} (%)	δ_y (mm)	δ_u (mm)	μ (mm/mm)	Decrease in μ (%)
B0	53.58	-	26.95	-	1.98	0	4.50	29.44	6.53	0
B30	47.88	11	10.64	60	4.49	127	4.42	15.69	3.54	46
B40	42.96	20	5.36	80	8.01	305	4.05	5.41	1.33	80
B50	50.51	6	8.24	69	6.10	208	4.54	10.29	2.26	65
B60	40.94	24	4.77	82	8.56	332	3.80	4.94	1.30	80
B70	37.59	30	5.02	81	7.48	278	3.44	5.57	1.61	75
S0	55.39	0	11.97	-	4.62	0	7.57	16.71	2.20	0
S30	50.44	8	9.75	18	5.17	12	6.07	12.29	2.02	8
S40	47.06	15	6.91	42	6.81	47	5.00	7.61	1.52	31
S50	39.78	28	5.53	53	7.18	55	3.70	7.22	1.95	11
S60	33.65	39	4.65	61	7.23	56	3.55	5.49	1.54	30
S70	27.64	50	4.17	65	6.61	43	2.91	5.42	1.86	15

P_{max} is maximum load, δ_{Pmax} is displacement at P_{max}, δ_y is displacement at $0.85P_{max}$, δ_u is ultimate displacement at $0.85P_{max}$, S_{Pmax} is rigidity at P_{max}; μ is ductility proportion.

Table 4. Energy dissipation abilities of the specimens.

Test No.	δ_{max} (mm)	E_{Pmax} (kj)	E_y (kj)	Decrease in E_y (%)	E_p (kj)	E_T (kj)	Decrease in E_T (%)	Failure Type	Ductility Level
B0	37.73	1.278	0.111	0	0.977	1.693	0	FS	Sufficient
B30	29.57	0.393	0.100	10	0.928	1.029	39	FS + S	Partially
B40	14.81	0.142	0.089	20	0.274	0.363	79	S	Deficient
B50	12.93	0.277	0.120	−8	0.353	0.473	72	S	Deficient
B60	11.25	0.111	0.073	34	0.192	0.264	84	S	Deficient
B70	8.56	0.126	0.068	39	0.144	0.213	87	S	Deficient
S0	30.03	0.451	0.220	0	0.988	1.207	0	S	Deficient
S30	28.57	0.340	0.163	26	0.812	0.975	19	S	Deficient
S40	26.77	0.206	0.119	46	0.661	0.780	35	S	Deficient
S50	9.51	0.147	0.078	65	0.200	0.278	77	S	Deficient
S60	7.09	0.094	0.057	74	0.100	0.157	87	S	Deficient
S70	11.67	0.078	0.044	80	0.185	0.230	81	S	Deficient

δ_{max} is maximum displacement, E_{Pmax} is energy dissipation at P_{max}, E_y is energy dissipation at P_y, E_p is plastic energy dissipation ($E_T - E_y$), E_T is total energy dissipation, FS is a flexural shear failure; S is a shear failure (diagonal tension failure).

The values tabulated in Table 3 indicate that the load capacities of the beams in this group decreased with increasing opening diameter. The only exception for this general trend took place in specimen B50. This deviation might originate from possible material and/or geometrical imperfections of this specimen or any deviations from the desired loading and support conditions in the test of B50. The load capacity of B70 was about 30% smaller than the respective capacity of B0. The same reduction trend is valid in the vertical displacements of the specimens at the ultimate load (δ_{Pmax}). The vertical displacement at mid-span decreased by about 80% as the opening diameter increased from 0 to 70 mm.

A similar decrease trend was also observed in ductility (μ) values, which were obtained by dividing the ultimate deflection (δ_u) in each specimen to the yielding deflection (δ_y). δ_u and δ_y correspond to the deflections at 85% of the maximum load (P_{max}) in the descending and ascending branches of the load–displacement curves of the specimens, respectively. A decrease up to 80% was observed in the ductility values with increasing opening diameter.

However, this decrease had a random pattern rather than a regular (steady) pattern with increasing opening diameter. For instance, B70 had a greater ductility compared to B60 despite its larger openings.

As opposed to the other measures, the rigidities of the specimens at P_{max}, i.e., S_{Pmax}, increased with increasing opening diameter. This increase does not stem from the actual increase in the beam rigidity, but from the considerable decrease in the deflection at the ultimate load (δ_{Pmax}). With increasing opening size, the ability of the beams to undergo excessive deflections before reaching P_{max} decreases. The decrease in the δ_{Pmax} exceeds the decrease in P_{max} as the opening diameter increases and the ratio of P_{max} to δ_{Pmax} increases as well. But, this measure is rather misleading since it does not directly correspond to the resistance of the beams against vertical deflections and it is just an average slope up to P_{max}.

Table 4 contains information on four different types of energy absorption values, namely E_{Pmax}, E_y, E_p and E_T. These four energy measures correspond to the amount of energies dissipated up to the ultimate load (P_{max}), 85% of the ultimate load in the ascending branch of the load–displacement curve (yielding load, P_y), in the plastic region of the load–displacement curve and up to the ultimate (failure) deflection (δ_{max}), respectively. Since all of the four measures have similar trends, only E_y and E_T, i.e., energy dissipation values in the elastic range (modulus of resilience) and total absorbed (elastic + plastic) energy (modulus of toughness), the values are discussed and compared in the following discussion. Both E_y and E_T values showed an almost regular reduction trend with increasing opening diameter. The dissipated amount of energy up to failure decreased by 80%, significantly exceeding the reduction in the energy in the elastic range (about only 40%) as the opening diameter increased from 0 to 70 mm.

2.1.2. Second Group of Beams

The D/H ratio of the beams in this group changes as 0, 0.20, 0.27, 0.33, 0.40, and 0.47 while the spacing of stirrups is fixed to 160 mm. The load–displacement relationships of the beams in this group are compared in Figure 6. Furthermore, the failure types of the beams are illustrated in Figure 7.

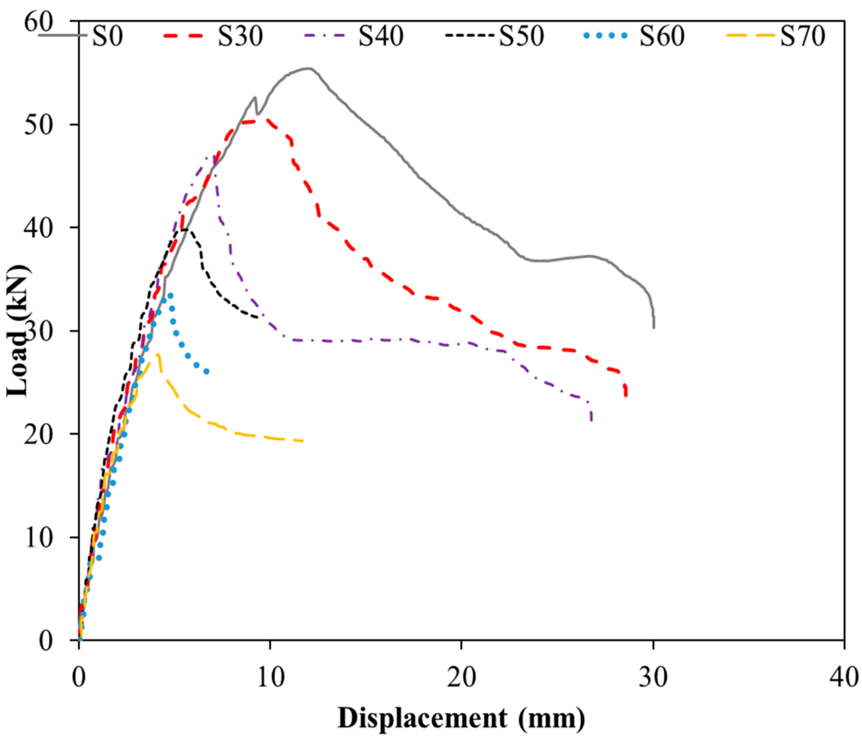

Figure 6. Load–displacement behavior of RC beams in the second group for different *D/H* ratios.

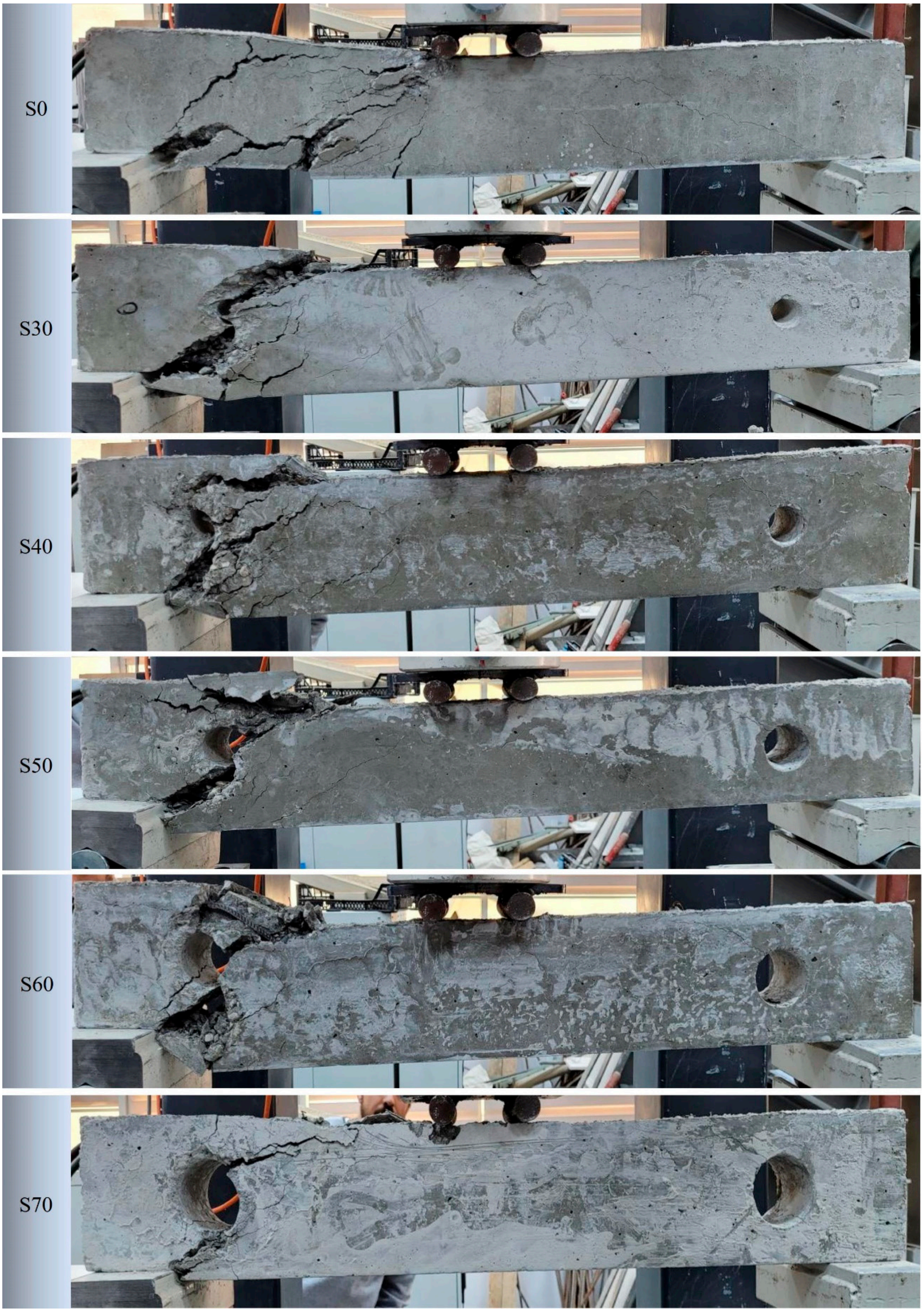

Figure 7. Failure modes of the beams with widely spaced stirrups (160 mm).

According to Figure 6, Beam S0 without openings reached a maximum load of 55.39 kN at a deflection of 16.71 mm. Beam S30 with a D/H ratio of 0.20 reached an ultimate load of 50.44 kN under a deflection of 12.29 mm. Similarly, the maximum load of the beam S40 with a D/H ratio of 0.27 was determined as 47.06 kN at a vertical deflection of 7.61 mm. Furthermore, the maximum load of S50, having a D/H ratio of 0.33, was obtained as 39.78 kN at a mid-span deflection of 7.22 mm. Finally, the load capacities of beam S60 and S70, with D/H ratios of 0.40 and 0.47, were measured as 33.65 kN and 27.64 kN at deflection values of 5.49 and 5.42 mm, respectively.

Figure 7 indicates that the reference specimen S0 underwent shear-tension failure, characterized by the crushing of concrete underneath the left loading point, debonding cracks at the tension reinforcement level in the vicinity of the left support and diagonal tension cracks between the two. The pure flexural failure in Beam B0 turned into the shear-tension failure in S0 with increasing spacing of the stirrups, as expected. All of the remaining specimens (S30, S40, S50, S60 and S70) underwent frame-type shear failure like their counterparts in the specimen group with closely spaced stirrups (B30, B40, B50, B60 and B70).

The values in Table 3 show that the load capacities of the beams in this group decreased with increasing opening diameter. Unlike the specimens in the first group, the reduction followed a quite regular trend. The load capacity of S70 was about 50% smaller than the respective capacity of S0. The reduction in the load capacity was more pronounced in this group as compared to the reduction in the first group with increasing opening diameter. In other words, drilling openings have much more profound effects on the load-carrying capacities of RC beams if they are reinforced with lesser amounts of shear reinforcement. The mid-span vertical displacements of the specimens at the ultimate load (δ_{Pmax}) also decreased with increasing opening diameter. δ_{Pmax} decreased by about 65% as the opening diameter increased from 0 to 70 mm, which is slightly less than the reduction (80%) in the first beam group.

The ductility (μ) values underwent smaller reductions in this group (up to only 30%) with increasing opening diameter as compared to the first group. Similar to the first group of beams, this decrease had a random pattern rather than a regular (steady) pattern with increasing opening diameter. For instance, S70 had a greater ductility compared to S40 and S60 despite its larger openings.

Similar to the first group of beams, the rigidities of the specimens at P_{max}, i.e., S_{Pmax}, increased with increasing opening diameter in the second beam group. However, this increase was much less in the second group (up to about 60%) as compared to the first group (up to about 340%). Again, this increase does not stem from the actual increase in the beam rigidity, but from the considerable decrease in the deflection at the ultimate load (δ_{Pmax}). Therefore, this measure is rather misleading since it does not directly correspond to the resistance of the beams against vertical deflections and it is just an average slope up to P_{max}.

Both E_y and E_T values showed an almost regular reduction trend with increasing opening diameter. The reductions in E_y and E_T reached 80 and 90%, respectively, as the opening diameter increased from 0 to 70 mm. In the second beam group, the reductions in the total dissipated energy were in the same order as the first beam group, while the elastic energies were reduced to greater extents in this group as compared to the first group.

3. Analytical Ultimate Beam Capacity

For calculating the ultimate capacities of the RC beams with opening(s), the analytical model suggested by Mansur and Tan (1999) [14] was employed. The model was adapted from ACI-318 (2014) and commonly utilized by the investigators [39–45] in their studies with or without alterations. The nominal shearing resistance of the RC beams is provided by the shearing resistance of concrete, V_c, the shear reinforcement, V_{sl}, and the diagonal reinforcement, V_{sd} (1).

$$V_n = V_C + V_{sl} + V_{sd} \quad (1)$$

where

$$V_c = \frac{1}{6}\sqrt{f_c}b(d - d_o) \quad (2)$$

$$V_{sl} = \frac{A_{sl}f_{ywl}}{s}(d - d_o) \quad (3)$$

$$V_{sd} = A_{sd}f_{ywd}\sin\theta \quad (4)$$

In these formulations, f'_c is the specified compressive strength of concrete in MPa, f_{ywl} and f_{ywd} are the yielding stress values of the transverse and diagonal shear reinforcement, respectively, in MPa, b is the beam width in mm, d is the effective beam depth in mm, d_o is the diameter of the transverse beam opening in mm, A_{sl} and A_{sd} are the cross-sectional areas of transverse and diagonal shear reinforcement in mm^2, s is the stirrup spacing in mm and θ is the inclination angle of the diagonal reinforcement from the beam axis.

The nominal flexural strength of RC beams is determined with the help of the equivalent rectangular stress block of concrete in the compression zone, as given in (5) [14].

$$M_n = A_s f_{yb}\left(d - \frac{a_{sb}}{2}\right) \quad (5)$$

In this equation,

$$a_{sb} = \frac{A_s \cdot f_{yb}}{0.85 f_c \cdot b} \quad (6)$$

In these formulations, As corresponds to the cross-sectional area of the longitudinal reinforcement in mm^2, f_{yb} is the yielding stress of the longitudinal (flexural) reinforcement in MPa and a_{sb} is the depth of the equivalent rectangular stress block in the compression zone in mm. The applied load values corresponding to the nominal flexural and shear strengths of the beams can be obtained from Equations (7) and (8), based on the loading and support conditions of the experimental setup of the present study.

$$P_{u,v} = 2V_n \quad (7)$$

$$P_{u,m} = \frac{2M_n}{a} \quad (8)$$

The ratio of the experimental ultimate load (P_{max}) to the load ($P_{u,v}$) corresponding to the shear strength of the beam is depicted in Figure 8 in the form of a bar chart. The figure clearly shows that all of the specimens, with the exception of specimen B0, failed at load values close to or above their respective theoretical shear strengths. Interestingly, the ultimate load values of even specimens S0, S30, S40, S50, S60 and S70, whose stirrups were spaced more distantly and had lower amounts of shear reinforcement, did not fail prematurely below their shear strength values. A_s mentioned before, the final failure values of all specimens, except B0, were directly or indirectly related to shear forces. Accordingly, Equation (1), originally developed by Mansur and Tan [14] and later adopted by various researchers, can accurately predict the ultimate load values of RC beams with circular openings. The accuracy of this equation increases with a decreasing amount of transverse reinforcement. In the present study, the experimental capacities varied in the range of 0.86–1.22 of the theoretical capacities in the specimen group with narrow stirrup spacing (100 mm), while they varied in the range of 1.03–1.27 in the specimen group with wide stirrup spacing (160 mm).

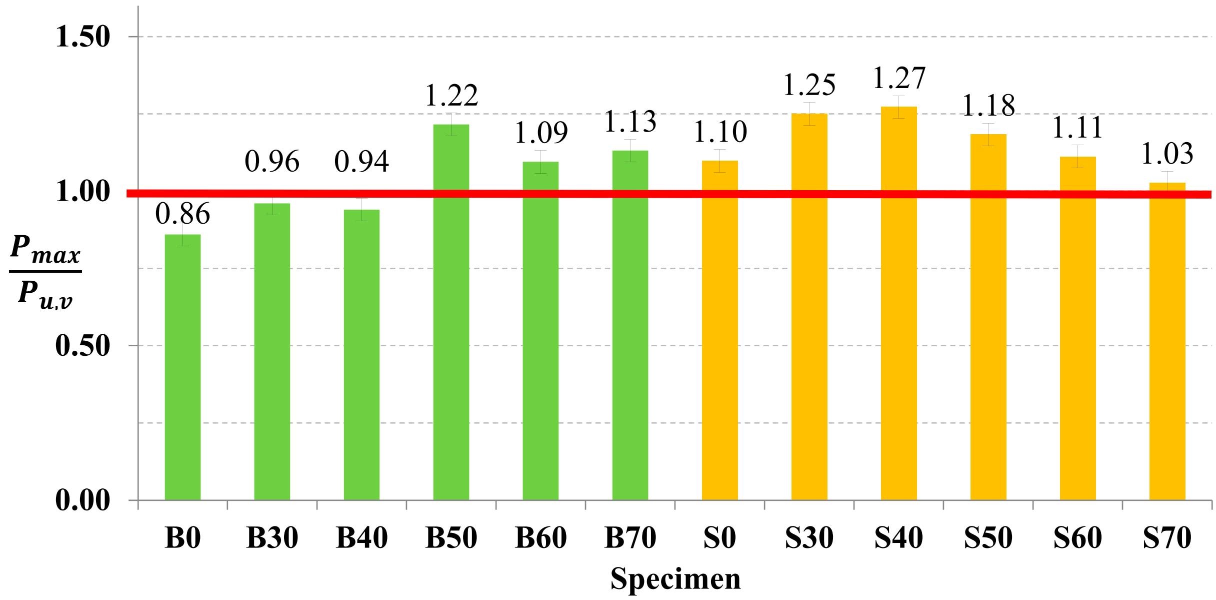

Figure 8. Comparison of the theoretical shear capacities of the beam to the experimental values.

4. Conclusions

The present study pertains to the influences of the opening diameter and transverse reinforcement ratio on the behavior of RC beams with circular web openings. In this scope, a total of 12 RC beams with two different transverse reinforcement ratios and five different opening diameters were tested to failure under four-point bending. The test matrix included two reference specimens without web openings, one for each transverse reinforcement ratio. The applied load and the vertical deflections at mid-span were measured throughout the entire course of loading. The experimental ultimate load values were compared to the analytical load estimates from the available formulations in the literature. The most striking conclusions of the experimental and analytical phases of the study are given as follows:

- The failure type of RC beams with adequate shear reinforcement turns from pure flexural failure to beam- or frame-type shear failure as the diameter of transverse openings in the beam increase. In cases of inadequate shear reinforcement, on the other hand, the reference beams without openings are subject to shear-tension or shear-compression failure, while the specimens with openings experience shear failures similar to the beams with adequate shear reinforcement.
- The tests indicated that the load-carrying capacities of RC beams with circular openings and the vertical deflections at the ultimate load decrease significantly with increasing opening diameter. Furthermore, the reduction in the load capacity increases with a decreasing transverse reinforcement ratio, i.e., increasing stirrup spacing, for identical opening diameters. Larger web openings result in greater reductions in the shear capacities of beams with more widely spaced stirrups, and therefore, RC beams with less shear reinforcement are affected to a greater extent by the introduction of transverse opening. As opposed to the finding about the load capacity, the decrease in the deflection at the ultimate load was found to decrease with a decreasing transverse reinforcement ratio for identical opening diameters.
- With an inadequate amount of shear reinforcement, energy absorption capacities in both elastic and plastic ranges of beam behavior decrease significantly with increasing opening diameter. On the contrary, the amount of energy dissipated in the elastic range decreases to a much lesser extent, while the total energy is reduced significantly in the presence of an adequate amount of shear reinforcement.
- The reductions in the ductilities of RC beams with increasing opening diameter are less pronounced if the beams are reinforced with smaller amounts of shear reinforcement. In both types of beams with adequate and inadequate amounts of shear reinforcement,

the reduction trend in the beam ductility with increasing opening diameter is random rather than regular (steady).

- The theoretical shear strength values of the RC beams with circular openings were found to be in close agreement with the experimental values. The accuracy of the theoretical estimates was shown to increase with a decreasing amount of shear reinforcement in the beam. Accordingly, the shear strength formula, originally developed by Mansur and Tan (1999) and later adopted by various researchers, can be conservatively used for beams with circular openings. None of the beams of the present study failed prematurely at load levels smaller than the analytical estimate provided by this formula.

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