Flexural Behavior and Strength of Reinforced Concrete Beams with Multiple Transverse Openings

by Bengi Aykac, Sabahattin Aykac, Ilker Kalkan, Berk Dundar, and Husnu Can

Reported are the results of experiments on 10 rectangular reinforced concrete (RC) beams with and without multiple web openings. The effects of opening geometry, the use of longitudinal stirrups in the posts between the openings, the use of diagonal reinforcement around openings, and the longitudinal reinforcement ratio on the flexural behavior of RC beams with openings were investigated. The stirrups in the posts were shown to have a significant contribution to the ductility of an RC beam with openings if no diagonal reinforcement is used. For the same reinforcement details, RC beams with circular openings were found to have higher load capacities and ductilities than beams with rectangular openings. The experiments indicated that the posts between the openings need to be prevented from undergoing shear failure to avoid Vierendeel truss action and allow a beam to develop its ductility and bending capacity.

**Keywords:** diagonal reinforcement; plastic mechanism; reinforced concrete beam; shear failure; shear reinforcement; Vierendeel truss; web crushing failure; web opening.

**INTRODUCTION**

Ducts and pipes associated with the mechanical, electrical, and sewer systems in a building are usually located underneath the floor beams, resulting in a considerable loss in the usable floor height. Passage of these ducts and pipes through web openings in floor beams offers an effective way to utilize the entire floor height, providing a more economic and compact design. Nevertheless, the presence of opening(s) in a reinforced concrete (RC) beam reduces its load-carrying capacity and increases its service-load deflections. The studies on concrete beams with transverse openings in the literature focused on providing these beams with strengths and rigidities comparable to their solid counterparts by proper reinforcement detailing. In this way, the negative effects of the stress concentrations around the openings could be eliminated, the load-carrying capacities increased, and the deflections decreased.

Different types of services, including cooling and ventilation systems, power and sewer systems, and technology and communication services, need to be effectively located and distributed within structures. The presence of multiple openings in a beam is needed to accommodate several pipes and ducts related to various services. Steel beams with multiple web openings (cellular beams) are commonly used for this reason. In this study, the presence of multiple openings in RC beams was considered to improve the design of RC structures.

In an extensive experimental study on continuous RC beams with a large rectangular opening, Mansur et al. (1991) established that the failure of these beams is generally related to Vierendeel truss action. The deformations in a beam with an opening were shown to increase and the collapse load to decrease as the opening is moved to a more highly stressed portion of span. As the opening length and depth increase, Mansur et al. (1991) found that the Vierendeel action becomes more pronounced, and the decrease in the collapse load increases. Mansur et al. (1992) proposed that the deflections of an RC beam with a large rectangular opening can be approximately estimated by assigning reduced flexural and shear rigidities to the parts of containing the opening. Tan and Mansur (1996) proposed design guidelines for the strength and serviceability limit states of RC beams with large openings. Mansur (1998) identified different shear failure modes of RC beams with web openings and developed design equations. The tests carried out by Tan et al. (2001) on RC beams with circular openings indicated that the use of diagonal reinforcement offers an effective method in crack control. Mansur (1999) developed design equations for RC beams subject to torsion in addition to bending and shear. The equations correspond to the beam failure as a whole, termed as beam-type, and failure of the top and bottom chords separately, termed as frame-type. Mansur et al. (2006) concluded that flexural rigidities of RC beams with large circular openings can be closely estimated using strut-and-tie models. Yang et al. (2006) investigated the strength and behavior of RC deep beams with web openings, and showed that the failure of a deep RC beam is caused by the diagonal cracks projecting from the corners of the opening.

In all aforementioned studies, RC beams with one or two openings were considered. The failure in these beams is generally related to the shear because the openings are usually located in shear spans. In a recent experimental program (Dundar 2008; Egriboz 2008; Aykac and Yilmaz 2011), the influence of multiple openings in the span was investigated. The presence of multiple openings was assumed to provide a more efficient design by helping the stress concentrations around openings to be distributed to the entire beam length. Furthermore, the presence of openings in the central zone in addition to shear spans was assumed to shift the failure mode of the beam from brittle shear failure to ductile flexural failure. Attempts were made to prevent the brittle modes of shear failure (beam-type and frame-type), and the ductilities of the beams were increased.
by proper detailing: short stirrups in the chords, and posts and full-depth stirrups next to openings. Furthermore, RC beams with different opening geometries were tested within the scope of the program to establish the geometry which affects the strength and ductility of an RC beam to a lesser extent. This paper reports 10 experiments carried out within the program. The influence of the use of diagonal reinforcement around the openings, the use of stirrups in the posts, and the opening geometry are the main test parameters. A comparison of the experimental results with the estimates from the theoretical methods yielded valuable conclusions.

**RESEARCH SIGNIFICANCE**

This study investigates the effects of different shear reinforcement schemes and the opening geometry on flexural behavior of RC beams with multiple transverse openings. RC beams with different longitudinal reinforcement ratios were tested, and different failure modes of RC beams with openings were investigated within the course of the study. The experimental results were compared with estimates from different theoretical formulations in the literature to provide background knowledge for establishing design rules for RC beams with multiple openings. The findings of the present study will also guide further studies in the field.

**EXPERIMENTAL STUDY**

**Test specimens**

A total of 10 rectangular RC beams, each 150 mm (5.9 in.) wide, 400 mm (15.7 in.) deep, and 4.0 m (13.1 ft) long, were tested. Four specimens had 200 x 200 mm (7.9 x 7.9 in.) square openings, and four specimens had Ø200 mm (Ø7.9 in.) circular openings. The reinforcement details of the beams are illustrated in Fig. 1 and 2. In terms of flexural reinforcement ratios, the beams denoted with letter “n” were moderately reinforced (tension reinforcement ratio \( r_t = 0.0078 \)), and the beams denoted with letter “b” were heavily reinforced (\( r_t = 0.014 \)). The letter “x” in the specimen names corresponds to the presence of Ø10 nonprestressed cables spiraling around openings (Fig. 3), and “c” corresponds to short stirrups in posts in longitudinal direction (Table 1).

**Material properties**

Table 2 tabulates the compressive strength of concrete of each specimen on the test day obtained from 150 x 300 mm (6 x 12 in.) cylinder tests. The mean values and standard deviations of these material tests are tabulated in Table 2 together with the number of material tests. The mean values and standard deviations of the yield and tensile strengths of the S420 reinforcing bars and the number of samples for each bar size are tabulated in Table 2.

**Test setup and procedure**

A 200 kN (45 kip) capacity steel frame was used for the tests. The load, applied by a hydraulic cylinder and measured by an electronic load cell, was equally distributed to four loading points by main and secondary spreader beams (Fig. 4). In this way, the simply supported beams were loaded at two points, each located at a distance of 300 mm (11.8 in.) from midspan, and two points, each located at a distance of 1200 mm (47.2 in.) from midspan. Six-point bending was adopted instead of four-point bending to more closely simulate the moment distribution in a beam subjected to uniform distributed loading, which is the most common loading condition in real practice. The midspan vertical deflection, the support settlements, and the distortions in
openings were measured with the help of linear variable displacement transducers (LVDTs). The load and deflection measurements were recorded by a data acquisition system. The beams were loaded up to failure, and the cracks were marked and the crack widths measured.

**FAILURE MODES AND THEORETICAL EQUATIONS**

**Failure modes of reinforced concrete beams with openings**

Beam- and frame-type shear and web crushing failures are the three common types of shear failure in RC beams with openings. In beam-type failure (Fig. 5(a)), a single crack extending through the entire depth results in failure. This diagonal crack is assumed to pass through the center of opening. The frame-type shear failure (Fig. 5(b)) takes place when two distinct cracks form in the top and bottom chords, and one of the chords fails due to this cracking. Web crushing failure (Fig. 5(c)) is caused by crushing of concrete between the diagonal cracks.

Based on the plastic hinge method, RC beams with openings are prone to failure due to formation of a collapse mechanism that is composed of four plastic hinges. This type...
of failure is denoted as Vierendeel truss action (Fig. 5(d)) because the beams behave similar to a Vierendeel panel. Vierendeel action causes an RC beam to fail at moments below its bending capacity. Preventing Vierendeel action and various forms of shear failure ensures that an RC beam with openings will reach its bending capacity and fail in a tension-controlled flexural mode due to crushing of concrete in the compression zone, which is denoted as flexural failure (Fig. 5(e)).

In the present study, the plastic methods based on truss analogy (plasticity truss and strut-and-tie methods) were not used. In these methods, the load capacity of an RC beam is obtained from the axial capacities of different struts and ties, obtained from the reinforcement available in each truss member. RC beams with openings contain numerous B- and D-regions, and these beams are modeled with a larger number of truss members compared with RC beams without openings, causing lengthy and tedious calculations.

**Theoretical equations used in analysis**

*Shear strength and shear forces in chord members—*

Following the ACI approach (ACI Committee 318 2005), Mansur (1998) was able to develop the following formula for beam-type failure

\[
V_a = 0.17 \cdot \sqrt{f'_c \cdot b \cdot (d - d_o)} + \frac{A_s' \cdot f_{st}}{s} \cdot (d'_v - d_o) + A_d \cdot f_{yd} \cdot \sin \alpha
\]

where \( f'_c \) is the concrete strength; \( b \) is the beam width; \( d \) is the effective depth; \( d_o \) is the depth of opening; \( d'_v \) is the distance between the centroids of extreme tension and compression reinforcement layers; \( s \) is the stirrup spacing; \( A_s \) is the area of stirrups; \( A_d \) is the cross-sectional area of the diagonal reinforcement within the failure surface; \( f_{st} \) and \( f_{yd} \) are the yield strengths of the stirrups and diagonal reinforcement, respectively; and \( \alpha \) is the angle of inclination of diagonal reinforcement.

The Architectural Institute of Japan (1988) gives the following formula for the beam-type shear failure of RC beams with openings

\[
V_a = \frac{0.092 \cdot k_u \cdot k_p \cdot (f'_c + 17.7) \cdot (1 - 1.61 \cdot \frac{d'_v}{h})}{M \cdot V \cdot d + 0.12 + 0.846 \sqrt{\rho'_w \cdot f_{yw}}}
\]

where \( h \) is the beam depth; \( k_u \) is a size coefficient, varying from 0.72 to 1.0; \( k_p \) (Eq. (3)) is a factor accounting for the reinforcement ratio; \( M \) and \( V \) are the bending moment and shear force at critical section, respectively; and \( \rho'_w \) (Eq. (4)) is the web reinforcement ratio within \( d'_v \)

\[
k_p = 0.82 \left( \frac{100 \cdot A_s}{b \cdot d} \right)^{0.23}
\]

\[
\rho'_w = \frac{A_t + A_y (\sin \alpha + \cos \alpha)}{b \cdot d}
\]

where \( A_t \) is the area of tension reinforcement. Mansur (1998) modified the maximum allowable shear force \( (V)_{\text{max}} \) formula of ACI 318 (ACI Committee 318 2005) for RC beams with openings.
Table 3—Analytical and experimental ultimate load values

<table>
<thead>
<tr>
<th>Beam</th>
<th>Failure mode</th>
<th>Test $P_{ut}$, kN (kip)</th>
<th>Todeschini et al. (1964) $P_{ut}$</th>
<th>ACI Committee 318 (2005) $P_{ut}$</th>
<th>$P_{ut}/P_{ac}$</th>
<th>$P_{ut}/P_{ac}$</th>
<th>Neutral axis depth, mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRxn</td>
<td>Beam-type flexural</td>
<td>163.8 (36.8)</td>
<td>164.7 (37.0)</td>
<td>160.5 (36.1)</td>
<td>0.99</td>
<td>1.02</td>
<td>59.4 (2.3)</td>
</tr>
<tr>
<td>RRxb</td>
<td>Beam-type flexural</td>
<td>245.8 (55.2)</td>
<td>291.7 (65.6)</td>
<td>289.0 (65.0)</td>
<td>0.84</td>
<td>0.85</td>
<td>95.6 (3.8)</td>
</tr>
<tr>
<td>RRxcn</td>
<td>Vierendeel truss</td>
<td>156.4 (35.2)</td>
<td>159.6 (35.9)</td>
<td>156.9 (35.3)</td>
<td>0.98</td>
<td>1.00</td>
<td>62.5 (2.5)</td>
</tr>
<tr>
<td>RRxcb</td>
<td>Beam-type flexural</td>
<td>169.3 (38.1)</td>
<td>159.6 (35.9)</td>
<td>156.9 (35.3)</td>
<td>1.06</td>
<td>1.08</td>
<td>62.5 (2.5)</td>
</tr>
<tr>
<td>RRxcb</td>
<td>Vierendeel truss</td>
<td>232.2 (52.2)</td>
<td>288.8 (64.9)</td>
<td>286.8 (64.5)</td>
<td>0.80</td>
<td>0.81</td>
<td>94.2 (3.7)</td>
</tr>
<tr>
<td>RCb</td>
<td>Vierendeel truss</td>
<td>255.1 (57.3)</td>
<td>288.8 (64.9)</td>
<td>286.8 (64.5)</td>
<td>0.88</td>
<td>0.89</td>
<td>94.2 (3.7)</td>
</tr>
<tr>
<td>RBn</td>
<td>Beam-type flexural</td>
<td>269.3 (60.5)</td>
<td>288.8 (64.9)</td>
<td>286.8 (64.5)</td>
<td>0.93</td>
<td>0.94</td>
<td>94.2 (3.7)</td>
</tr>
<tr>
<td>RBb</td>
<td>Beam-type flexural</td>
<td>272.3 (61.2)</td>
<td>288.8 (64.9)</td>
<td>286.8 (64.5)</td>
<td>0.94</td>
<td>0.95</td>
<td>94.2 (3.7)</td>
</tr>
<tr>
<td>RCb</td>
<td>Diagonal tension</td>
<td>278.5 (62.6)</td>
<td>289.3 (65.0)</td>
<td>287.2 (64.6)</td>
<td>0.96</td>
<td>0.97</td>
<td>93.3 (3.7)</td>
</tr>
<tr>
<td>RCc</td>
<td>Beam-type flexural</td>
<td>284.1 (63.9)</td>
<td>289.3 (65.0)</td>
<td>287.2 (64.6)</td>
<td>0.98</td>
<td>0.99</td>
<td>93.3 (3.7)</td>
</tr>
<tr>
<td>RCxb</td>
<td>Beam-type flexural</td>
<td>284.1 (63.9)</td>
<td>289.3 (65.0)</td>
<td>287.2 (64.6)</td>
<td>0.98</td>
<td>0.99</td>
<td>93.3 (3.7)</td>
</tr>
</tbody>
</table>


(5)

$$V_s \left( \frac{V_{ut}}{V_{ut}} \right) = 5 \cdot 0.85 \cdot \left[ 0.17 \cdot \sqrt{\frac{d}{b}} \cdot (d - d_a) \right]$$

For frame-type shear failure, Mansur (1998) suggested that the shear capacities of both chords should be checked against the shear forces calculated from the following equations, proposed by Nasser et al. (1967)

$$V_{ut} \left( \frac{V_{ut}}{V_{ut}} \right) = V_s \cdot \frac{A_t}{A_t + A_b}$$

where $A_t$ and $A_b$ are areas of the top and bottom chords, respectively; $V_s$ is the shear force in the section; and $V_{ut}$ and $V_{ut}$ are the shear forces at the top and bottom chords, respectively. Tan and Mansur (1996) suggested that the shear force in the section should be distributed to the chords in accordance to their flexural rigidities rather than their cross-sectional areas.

**Flexural modes of failure**—The bottom and top chords in RC beams with openings are subjected to axial and shear forces and bending moments. Due to axial forces and moments in the chords, the liability of an RC beam to develop a failure mechanism composed of four hinges can be evaluated with the help of interaction diagrams as established by Tan and Mansur (1996) and Mansur and Tan (1999). Considering that the hinges at the top and bottom chords are subjected to compression and tension, respectively, and the differences in the directions of moments at different hinges, an interaction diagram is prepared for each hinge and checked against the forces and moments that develop in the hinges at service loads. Tan and Mansur (1996) proposed that the axial forces in the chords can be obtained from

$$N_x = -N_t = \frac{M_x}{z}$$

where $N_t$ and $N_x$ are the axial forces in the top and bottom chords, respectively; $M_x$ is the bending moment at the section of hinging; and $z$ is the distance between the centroids of the chords.

**ANALYSIS OF TEST RESULTS**

**Failure modes, ultimate loads, ductilities, and rigidities of beams**

Both reference beams (RBn and RBb) underwent tension-controlled flexural failure (Fig. 6). In both beams, the load was preserved, while the cover concrete crushed and later dropped suddenly resulting in failure when the top bars buckled and concrete crushing initiated. In both beams, no considerable diagonal cracking took place in shear spans (Fig. 7(a)). Table 3 indicates that the experimental ultimate load of RBn was in close agreement with the values calculated from the rectangular stress block analysis of ACI 318-05 (ACI Committee 318 2005) $P_{ac}$ and from the Todeschini et al. (1964) stress-strain model $P_{ut}$. The load capacity of RBb remained below the bending capacities calculated from both models. Furthermore, Table 4 indicates that the ultimate shear forces $V_s$ in both beams at failure were smaller than their respective shear strength values $V_{ut}$, implying that shear had no influence on failure.

Table 5 tabulates the deformation ductility index (DDI) and rigidity values of the specimens. DDI is the ratio of a beam’s deflection at the instant when the applied load drops to 85% of the ultimate load to the deflection at yielding of tension reinforcement. DDI is an indicator of the deformability of a beam without a significant reduction in load. The rigidity values in the table correspond to the slope of the initial linear branch of the load-deflection curve. In RC beams, it is quite cumbersome to determine the slope of the moment-curvature diagram due to variation of the flexural stiffness along the span caused by the discrete flexural cracks. Therefore, slope of the load-deflection curve was adapted.

Four different types of failure were observed in beams with openings. RRxn and RRxb failed due to the formation of plastic failure mechanism (Fig. 8(a) and (b)). In both RRxn and RRxb, two hinges formed at the ends of the top and bottom chords of the opening closest to the end
support (Fig. 8(b)). The two beams differed in the locations of the remaining two hinges, which formed at the right ends of the top and bottom chords of the fourth opening in RRxn (Fig. 9(a)) and the fifth opening in RRxb (Fig. 9(c)). Unlike RC beams with one or two openings, the considerable distance between the hinging locations provided that the stresses in the mechanism were distributed to greater portions of the beam and the reversal of curvature took place over a longer length. The posts inside the failure mechanism were also observed to fail in shear (Fig. 8(b)), which was primarily related to the lack of stirrups in the posts.

RRxn failed at an applied load close to its ultimate capacity (Table 3), implying that the failure of a moderately reinforced concrete beam with multiple openings due to formation of a mechanism does not result in significant reductions in its load capacity. The formation of mechanism caused greater reductions in the capacity of RRxb. Table 5 and Fig. 7(b) show that both RRxb and RRxn had ductile behaviors up to failure, with the DDI value of RRxb only 20% smaller than RBb, and the DDI of RRxn 40% smaller than RBn. The fact that RRxn and RRxb exhibited ductilities and load capacities comparable to their respective reference beams originated from two reasons. First, the diagonal reinforcement in the beams carried the shear loads in the posts even after the failure of the posts. Second, the significant longitudinal distance between the hinges prevented the excessive stress concentrations around hinges.

Figures 9(b) and (d) illustrate the linear approximations of the interaction diagrams of RRxn and RRxb, respectively. Because the top chords are subjected to compression and bending, the yield planes above the bending moment axis are composed of two linear segments, which intersect at the point corresponding to balance failure. The yield planes below the moment axis correspond to the bottom chords subjected to tension as well as bending. The points corresponding to the axial forces and moments at the hinges at failure are also shown in the diagrams. Both figures indicate that all of the points corresponding to the hinges remain inside the yield surfaces implying that no hinging was expected at failure. Nevertheless, the plastic hinging at locations shown in Fig. 9(a) and (c) and failure of RRxn and RRxb due to hinging might be induced by the excessive shear deformations in the posts causing additional stresses.

RRxcn, RCcb, RCxb, and RCxcb failed in flexure after yielding of tension reinforcement (Fig. 8(c)). The final failure was caused by the crushing of cover and core concrete and buckling of compression bars. In these beams, the shear cracks initiated in the chords and posts at the beginning of loading did not widen and propagate in further stages of loading, and the flexural cracks at the central part of the beam controlled the behavior (Fig. 7(a)). Table 3 indicates that all of these beams failed at loads close to their respective bending capacities. RCcb, RCxb, and RCxCB exhibited greater ductilities than their reference beam RBb, with relative DDI values greater than unity, and had rigidities close to the rigidity of the reference (Table 5). The neutral axis depth values given in Table 3, calculated using the Todeschini et al. (1964) stress-strain model, indicate that the compression zone in each beam remained within the top chord up to failure and was not affected from the openings.

RCb underwent frame-type shear failure (Fig. 8(d)) due to severe shear cracking in the chords of the opening closest to the left end (Fig. 7(a)). Despite the final failure being originated from shear, RCb exhibited a ductile flexural behavior up to failure, and the longitudinal reinforcing bars in the beam yielded before failure. This explains why the load capacity of the beam was only 7% smaller than its calculated capacity (Table 3), and its DDI value was almost equal to the DDI value of the reference beam (Table 5). Table 4 indicates that the nominal shear strengths of the chords were significantly smaller than the shear forces in the chords at failure. The use of short stirrups (Fig. 2) in the chords could not prevent the frame-type failure. Table 4 shows that RCcb was also liable to frame-type shear failure considering the significant discrepancies between the nominal shear strengths of the chords and the shear forces in the chords at failure. RCcb, however, failed in flexure, which can be attributed to the presence of stirrups in posts.

RRxcb failed due to web crushing in the chords above and below the second opening (Fig. 7(a) and 8(e)). Due to this failure, RRxcb could not reach its bending capacity (Table 3), and had a limited ductility (Table 5). The failure of the beam was not a diagonal tension failure because both the chords and the beam had adequate shear strengths (Table 4).
Nevertheless, both the chords and the entire beam were subjected to shear forces above their maximum allowable shear forces calculated from Eq. (5), which caused crushing of concrete between the diagonals. Table 6 indicates that RRxb, RCb, RCcb, RCxb, and RCxcb were also prone to web crushing because the shear forces at failure exceeded the maximum allowable shear forces. None of these beams, however, underwent web crushing failure. The maximum allowable shear is calculated from Eq. (5) by assuming that the depth of each chord is constant along its length, which is an over-conservative assumption for circular openings. In chords above and below circular openings, the chord depth increases from mid-length of the chord to sides. Therefore, the maximum shear force tolerable by a chord in an RC...
beam with circular openings is greater than the value from Eq. (5). This might be the reason that none of the specimens with circular openings failed in diagonal compression. Web crushing in the chords might have affected the failure of RRxb, which eventually failed due to Vierendeel action.

**Effect of diagonal reinforcement on beam behavior**

Figure 10 indicates the load-deflection curves of beams with and without diagonal reinforcement. The load-deflection curves indicate that the use of diagonal reinforcement in an RC beam increases its energy absorption capacity. The DDI, rigidity (Table 5), and ultimate load (Table 3) values of RCxb are higher than the values of RCb, implying that diagonal reinforcement contributes to the flexural behavior if no stirrups are used in the posts. RCxCB, on the other hand, had ultimate load and rigidity values greater than those of RCcb, while the DDI value of RCxCB exceeded the value of RCxCB. The rigidity and load capacity of an RC beam with openings can be increased by using diagonal steel if the posts are reinforced with stirrups, but the diagonal reinforcement does not contribute to the ductility in this case.

**Effect of stirrups in posts on beam behavior**

Figure 7(b) illustrates that the stirrups in the posts significantly contribute to the energy capacity if no diagonal reinforcement is used. The DDI value of RCcb (Table 5) is also considerably greater than the value of RCb, implying the significant contribution of the stirrups to the ductility in the absence of diagonal reinforcement. In beams with rectangular openings, it appears that the use of stirrups in the posts does not contribute to the ductility and energy capacity of the beam if the beam has diagonal reinforcement. The DDI values of RRxcn and RRxCB were considerably smaller than the values of RRxn and RRxb, respectively. In beams with circular openings and diagonal reinforcement, the stirrups in the posts have almost no contribution to the ductility. The DDI value of RCxCB is approximately equal to the value of RCxb. Table 3 indicates that, in all cases, the use of stirrups has a positive but minor effect on the load capacity. To summarize, the stirrups in the posts improve the behavior of a beam when the beam does not have diagonal reinforcement. In the presence of diagonal reinforcement, the stirrups in the posts have little or no contribution to the flexural performance. The use of stirrups in the posts in addition to diagonal reinforcement causes the posts to be too strong, shifting the failure to the chords. If the chords fail in brittle modes (Vierendeel truss action, diagonal tension, or compression), the beam exhibits limited ductility.

**Effect of opening geometry on beam behavior**

Figure 11 illustrates the load-deflection curves of beams with the same reinforcement details but with different opening geometries. Both plots indicate that RC beams with circular openings have much greater energy capacities than the beams with rectangular openings. The DDI and

---

**Table 5—Ductilities and rigidities of beams**

<table>
<thead>
<tr>
<th>Beam</th>
<th>DDI Absolute</th>
<th>DDI Relative</th>
<th>Rigidity Absolute, kN/mm (kip/in.)</th>
<th>Rigidity Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBn</td>
<td>17.8</td>
<td>1.00</td>
<td>10.12 (57.8)</td>
<td>1.00</td>
</tr>
<tr>
<td>RRxn</td>
<td>10.7</td>
<td>0.60</td>
<td>5.77 (32.9)</td>
<td>0.57</td>
</tr>
<tr>
<td>RRxcn</td>
<td>8.4</td>
<td>0.47</td>
<td>5.87 (33.5)</td>
<td>0.58</td>
</tr>
<tr>
<td>RBb</td>
<td>6.4</td>
<td>1.00</td>
<td>12.05 (68.8)</td>
<td>1.00</td>
</tr>
<tr>
<td>RRxb</td>
<td>5.6</td>
<td>0.88</td>
<td>8.86 (50.6)</td>
<td>0.74</td>
</tr>
<tr>
<td>RRxCB</td>
<td>1.0</td>
<td>0.16</td>
<td>8.62 (49.2)</td>
<td>0.72</td>
</tr>
<tr>
<td>RCb</td>
<td>6.1</td>
<td>0.95</td>
<td>8.87 (50.6)</td>
<td>0.74</td>
</tr>
<tr>
<td>RCcb</td>
<td>9.5</td>
<td>1.48</td>
<td>9.32 (53.2)</td>
<td>0.77</td>
</tr>
<tr>
<td>RCxb</td>
<td>7.8</td>
<td>1.22</td>
<td>10.80 (61.7)</td>
<td>0.90</td>
</tr>
<tr>
<td>RCxCB</td>
<td>8.1</td>
<td>1.27</td>
<td>11.03 (63.0)</td>
<td>0.92</td>
</tr>
</tbody>
</table>
rigidity values of RCxb and RCxcb are significantly higher than the values of RRxb and RRxcb, respectively (Table 5). Furthermore, the ultimate loads carried by RCxb and RCxcb considerably exceeded the ultimate loads of RRxb and RRxcb, respectively (Table 3). The less favorable behavior of RC beams with rectangular openings is mainly due to the stress concentrations in the corners. In beams with rectangular openings, the shear cracks in the posts were observed to project from these sharp corners (Fig. 12), and these cracks caused reductions in the rigidities and load capacities. Secondly, the smaller areas of the circular openings compared with the rectangular ones resulted in less reductions in the beam capacities.

Although rectangular openings have more adverse effects on the beam behavior compared with circular openings, provision of rectangular openings in RC beams might be unavoidable, considering that the air-conditioning ducts in buildings are usually rectangular. RC beams with rectangular openings should be more carefully designed because they are more prone to Vierendeel action and shear failure of the chords.

**SUMMARY AND CONCLUSIONS**

Two reference beams, four RC beams with multiple circular, and four beams with multiple rectangular openings were tested to determine the flexural performance of RC beams with openings. Three of the beams had moderate amounts of flexural reinforcement, while the remaining beams were heavily reinforced. Each beam with openings had longitudinal bars and full-depth stirrups adjacent to openings and short stirrups in the chords. The longitudinal reinforcement ratio, opening geometry, and use of diagonal reinforcement and longitudinal stirrups in the posts were the main test parameters. The experiments and comparison with theoretical formulations yielded the following conclusions:

- The use of diagonal reinforcement contributes to the ductility and load capacity if the posts are not reinforced with stirrups in longitudinal direction. Similarly, the stirrups in the posts increase the ductility and capacity of RC with openings in the absence of diagonal steel.
- The simultaneous use of diagonal reinforcement and stirrups in the posts has minor or no contribution to ductilities and load-carrying capacities of RC beams with openings. The presence of diagonal reinforcement and stirrups in the posts causes the posts to be overly strong, which leads to failure of the chords rather than the posts.
- For the same reinforcement details, RC beams with circular openings have higher ductilities and load capacities compared with the beams with rectangular openings. The experiments indicated that the stress concentrations at corners of rectangular openings result in cracking, which leads to the reductions in the flexural rigidities without exhibiting full ductility.
- In RC beams with multiple openings, the considerable distance between the hinging locations causes the stresses in the failure mechanism to be distributed to greater portions of the beam compared with the beams with one or two openings. Therefore, RC beams with multiple openings exhibit a more ductile behavior even if they fail due to Vierendeel action. The posts
remaining inside the failure mechanism in Vierendeel action were observed to fail in shear. Diagonal reinforcement around the openings was found to carry the forces in the posts and prevent the complete failure of an RC beam, even after the failure of the posts. The large shear deformations in the posts were shown to cause Vierendeel action.

- The failure of an RC beam with openings due to Vierendeel action causes greater reductions in the load-carrying capacity as the longitudinal reinforcement ratio of the beam increases.
- The use of short stirrups in the chords is not an adequate measure for prevention of frame-type shear failure. The use of diagonal reinforcement and stirrups in the posts limits the extent of shear cracking in the chords, and prevents the frame-type shear failure.
- RC beams with openings are more liable to web crushing (diagonal compression) failure if the chords and beams have high amounts of shear reinforcement and small widths.

**DESIGN RECOMMENDATIONS FOR REINFORCED CONCRETE BEAMS WITH WEB OPENINGS**

The experimental and analytical results obtained within the scope of the present study indicated that the load capacities and ductilities of RC beams with multiple openings can be increased by proper strengthening of the chords and posts. When the chords are weak in shear, an RC beam with openings is prone to diagonal tension or compression failures of the chords. The use of short stirrups proved to be effective for preventing frame-type shear failure. Furthermore, the chords should be designed to not exceed the maximum allowable shear force to prevent web crushing failure. RC beams with rectangular openings are more prone to different forms of shear failure compared with beams with circular...
openings. Special attention should be given to shear design of beams with rectangular openings.

The shear forces are distributed to the chords in accordance to their cross-sectional areas. The most efficient design is achieved when the openings are placed at mid-depth of the member. When the centers of openings are offset from mid-depth, one of the chords of each opening is weaker than the other, and is more vulnerable to different forms of shear failure.

The presence of several openings proved to be effective in improving the behavior of a beam. Unlike RC beams with one or two openings, the stresses inside failure mechanism were observed to be distributed to greater portions of the beam. The posts inside the failure mechanism should be designed to resist the excessive deformations in the mechanism. The use of longitudinal stirrups in the posts or diagonal reinforcement was shown to effectively delay shear failure of the posts and increase the ductility and load capacity. The present experiments indicated that the use of longitudinal stirrups in the posts with a volumetric ratio of 0.016 provided an RC beam with circular openings with a load capacity and DDI 11 and 48% greater than its reference. Similarly, the use of diagonal reinforcement with a volumetric ratio of 0.017 resulted in an increase of 13 and 22% in the load capacity and DDI of an RC beam with circular openings compared with its reference. RC beams with rectangular openings reached load capacities close to their references in the presence of diagonal reinforcement, with a volumetric ratio of 0.013. Nevertheless, the DDI value of the moderately reinforced RC beam with rectangular openings remained approximately 40% of its reference in this case.

It was found that the simultaneous use of longitudinal stirrups and diagonal steel causes the posts to be overly strong, causing the chords to fail before the posts. In the present study, the beams strengthened with both diagonal reinforcement and longitudinal stirrups in the posts exhibited ductilities more than 50% smaller than the beams with only diagonal reinforcement.

AUTHOR BIOS

Bengi Aykac is a Lecturer in the Civil Engineering Department at Gazi University, Ankara, Turkey, where she received her BS, MS, and PhD. Her research interests include behavior of concrete beams strengthened by jacketing techniques, concrete beams strengthened with steel plates, and crack repair by epoxy injection.

Sabahattin Aykac is an Assistant Professor in the Civil Engineering Department at Gazi University, where he received his BS, MS, and PhD in 1989, 1993, and 2000, respectively. His research interests include strength and repair of concrete beams, earthquake behavior of strengthened concrete beams, and concrete beams with openings.

Ilker Kalkan is an Assistant Professor in the Department of Civil Engineering at Kirikkale University, Kirikkale, Turkey. He received his BS from Middle East Technical University, Ankara, Turkey, in 2004, and his MS and PhD from the Georgia Institute of Technology, Atlanta, GA, in 2006 and 2009, respectively. His research interests include structural stability, fiber-reinforced polymer concrete, and strengthening of concrete beams.

Berk Dundar is a Civil Engineer at Aydiner Construction Company, Turkey. He received his BS from Dokuz Eylül University, Izmir, Turkey, in 2005, and his MS from Gazi University in 2008. His research interests include the behavior of concrete beams with openings.

Husnu Can is a Professor in the Civil Engineering Department at Gazi University, Ankara, Turkey. He received his BS from Ankara Higher Tech-