EXPERIMENTAL STUDY OF STEEL REINFORCED CONCRETE BEAMS WITH WEB OPENINGS

C.-C. Chen[1], C.-Y. Li[2] and M.-C. Kuo[2]

[1] *Professor, Dept. of Civil Engineering, Chiao Tung University, Hsinchu, Chinese Taiwan*
[2] *Graduate student, Dept. of Civil Engineering, Chiao Tung University, Hsinchu, Chinese Taiwan*
Email: chrischen@mail.nctu.edu.tw

ABSTRACT

The openings in the webs of beams in building are necessary for the passage of utility ducts. This study aims to investigate the behavior of steel reinforced concrete (SRC) beams with an opening, including the effects of various opening shapes and different values of moment to shear ratio on the strength. Thirteen full-scale SRC beams were designed to have different opening shapes and tested at different moment to shear ratios. Test results indicate specimens with high moment to shear ratio demonstrated ductile behavior due to the confinement attributed to the stirrup and structural steel. Specimens with low moment to shear ratio failed owing to the shear cracking. An interaction between bending and shear was examined for tested SRC beams.

KEYWORDS: web opening, steel reinforced concrete, shear failure, interaction, SRC

1. INTRODUCTION

The transverse holes in the webs of beams in buildings are necessary for the passage of service ducts and piping in order to minimize the story height and to attain economic requirements. The web openings of the beam result in the decrease of flexural and shear strengths, flexural stiffness, and the increase of the deflection. The reinforcement at the opening is needed to ensure the proper strength and stiffness of the beams.

Numerous experimental and analytical studies have been conducted to investigate the strength of reinforced concrete flexural members with openings. The design for a flexural member with a large opening had been proposed that the top and bottom cross members of the opening could be assumed to behave like a vierendeel panel. The top and bottom chord members were expected to carry shear and axial force acted from the bending moment (Nasser et al. 1967; Mansur et al. 1985). Further, ACI design provisions specify that the openings in the web of a member can reduce the shear strength, and the effect of any openings on the shear strength shall be considered (ACI 318 2005).

Meanwhile, numerous studies for structural steel beams, including steel beams supporting a reinforced concrete slab, with web openings have been carried out and design provisions have been recommended. AISC specifications specify that the effect of web openings on the nominal shear strength of beams shall be determined, and adequate reinforcement shall be provided if necessary (AISC 2005). Several strength limit states may control the design of a flexural member with web openings, such as local buckling of the compression flange or the web, yielding or local buckling of the tee-shaped compression zone, and moment-shear interaction. Moreover, the design procedure is given in the literature (ASCE 1999; Darwin 1990).

Although many investigations have been conducted on reinforced concrete and structural steel beams with opening, there is very little information on the behavior for concrete-encased steel beams, or so called steel reinforced concrete (SRC) beams, with web opening (Hsu and Lee 2002; Sugimoto et al. 2000; Arata et al. 2000). This paper presents experiments of SRC beams containing openings of various shapes under different moment to shear ratios. Tests were conducted on 13 SRC beams and test results are presented and discussed.

2. EXPERIMENTAL PROGRAM

This experiment was conducted to study the behavior of the SRC beams with various opening shapes under combined bending and shear at the location of the opening. Thirteen specimens were designed and fabricated. All the specimens consisted of the same amount and arrangement of reinforcement and structural steel shape. Specimens were well instrumented to collect the global and detailed deformation during the testing.

2.1. Test Specimens

Thirteen specimens were designed to have the test variables of opening shape and the values of moment to shear ratio at the opening. The SRC beams used in this study consisted of structural steel shape and reinforced concrete. The cross-sectional dimensions of the beams were 30×50 cm. All the specimens had the same design: H300×150×6.5×9 structural steel, four No. 8 (25 mm-diameter) longitudinal bars at each corner of the cross section, No. 3 (10 mm-diameter) transverse bars at a center-to-center spacing of 12 cm, and 13 mm-diameter shear studs at 15 cm spacing. Additional four No. 6 (19 mm-diameter) longitudinal bars were reinforced at the four corners of the opening. The structural steel confirmed to ASTM A36 material. The longitudinal bars were Grade 60, while the stirrups were Grade 40. The configuration of the beams and details of the reinforcement at the opening are presented in Figure 1. All the openings located at the mid-depth of the cross section.

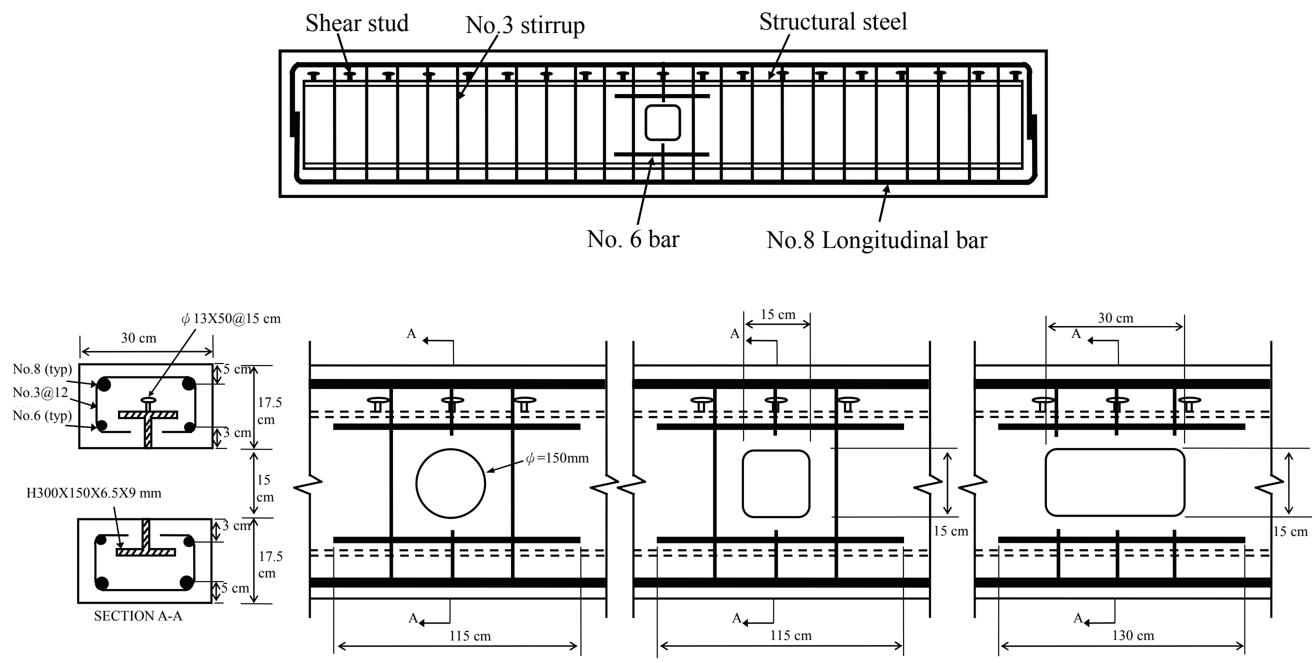


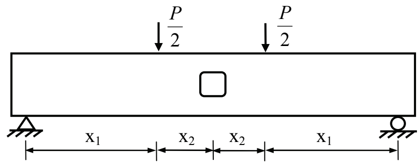
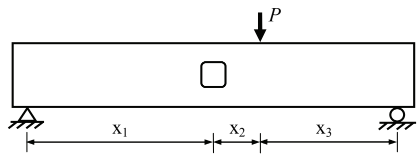
Figure 1 Configuration and details of the reinforcement of the specimens

In the labeling of the specimens, alphabetic characters N, C, S and R refer to the specimens without opening, and specimens with an opening of circular, square and rectangular hole, respectively. The second character was numbered to reflect the variable of moment to shear ratio at the opening, with 1 referring to pure bending, and others referring to different moment to shear ratio. The openings for C-, S- and R-series specimens were 15 cm-diameter circular hole, 15×15 cm square hole, and 15×30 cm rectangular hole, respectively.

2.2. Test setup

To achieve the beams subjected to different combination of bending and shear, the locations of applied load and supports were varied to obtain various values of the moment to shear ratio. Table 1 tabulates the loading configuration for the specimens.

Table 1 Loading configuration

Specimen	x_1 (cm)	x_2 (cm)	x_3 (cm)	M/V (m)	Loading configuration
N1	145	50	-	∞	
C1	145	50	-	∞	
S1	145	50	-	∞	
R1	145	50	-	∞	
C2	120	30	150	1.20	
C3	40	20	100	0.40	
C4	20	20	175	0.20	
S2	120	30	150	1.20	
S3	50	20	200	0.50	
S4	20	20	80	0.20	
R2	195	30	165	1.95	
R3	90	40	165	0.90	
R4	27	27	80	0.27	

The test setup is shown in Figure 2. The beams were simply supported and subjected to concentrated loads. The specimens were loaded monotonically by a hydraulic actuator through stroke control to attain the test data during the post-peak range. Testing was terminated until the applied load dropped significantly.

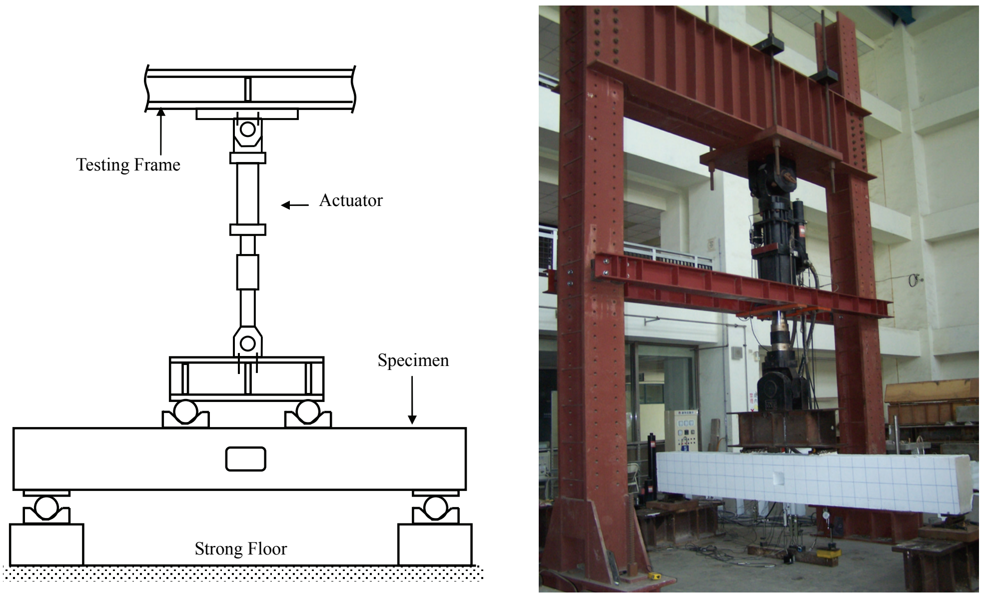


Figure 2 Test setup

2.3. Instrumentation

Test specimens were well instrumented in additional to the installation of strain gauges on the structural steel, longitudinal bars, and transverse stirrups. Beam deflections at various locations were recorded during the test. Meanwhile, the distortion of the openings was calculated by measuring the diagonal elongation or shortening.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Concrete cylinder compressive test and steel coupon test were conducted to obtain the actual material strengths. The concrete cylinder strength was 24.9 MPa measured during the time of testing. The yield and ultimate strengths for structural steel and reinforcement are tabulated in Table 2. General behavior, mode of failure and bending-shear interaction are presented in this section.

Table 2 Material strengths

Material	Yield strength (MPa)	Ultimate strength (MPa)
Steel flange	330	435
Steel web	382	441
No. 8 bar	476	624
No. 6 bar	538	651
No. 3 bar	420	532

3.1. Specimens Subjected to Pure Bending

The behavior of specimens N1, C1, S1 and R1 subjected to pure bending was quite similar. While the specimens were loaded, flexural cracks appeared initially on the bottom of the beams. The beams behaved linearly until cracks were observed at the concrete cover within the midspan which subjected to the maximum pure bending. Peak load was developed when the concrete cover in the compression zone started to be crushed, accompanied with the wider flexural cracks. After the beams reached peak strength, the load dropped quickly but only a small amount, and the beams maintained at that strength even though the deformation of the beams was continued to increase. Further, owing to the confinement effect attributed primarily to the transverse reinforcement and the structural steel, the beams developed increasing strength, and the applied load was gradually raised. Except for specimen R1, the beams reached strength even higher than the peak load.

Specimen N1, without opening, reached highest post-peak load as well as the ductile behavior. Because of the wide opening, specimen R1 could not develop strength higher than the peak load during the post-peak range. The ultimate failure of the specimens subjected to pure bending was the complete spalling of the concrete cover, buckling of the longitudinal bars, and local buckling of the steel top flange at the compression zone. A progressive damage and deformed shape of the specimen S1 are presented in Figure 3. The load versus midspan deflection curves for specimens subjected to pure bending are illustrated in Figure 4.

3.2. Specimens Subjected to Combined Bending and Shear

For specimens under combined bending and shear, the behavior and mode of failure depended on the values of the moment to shear ratio. As presented in Figure 5, the progressive damage of specimens S2, S3 and S4 indicate that specimen S2 failed due to the combined flexural and shear cracking. Specimens S3 and S4 were mostly damaged by the shear cracks occurred at the corners of the opening. The failure of the specimen S4 mainly caused by the shear cracking at the opening. Severe shear deformation occurred at the opening can be seen from Figure 6 which indicates the rhombic shape of the steel web after removal of the concrete. Load versus deflection curves for specimens C-, S- and R-series are presented in Figure 7.

The failure of R-series specimens under bending and shear was in a completely different mode from others, as observed from the tests. When the R-series specimens failed, the shear deformation at the opening was evident due to the wide opening. Shear strength was much lower than those of the specimens with other opening shape, which led to the considerable decrease of the applied load, as indicated in Figure 7. It is evident that for a wider opening width in the web of the structural steel section, a larger reduction factor needed to be considered for the shear strength (Darwin 1990).

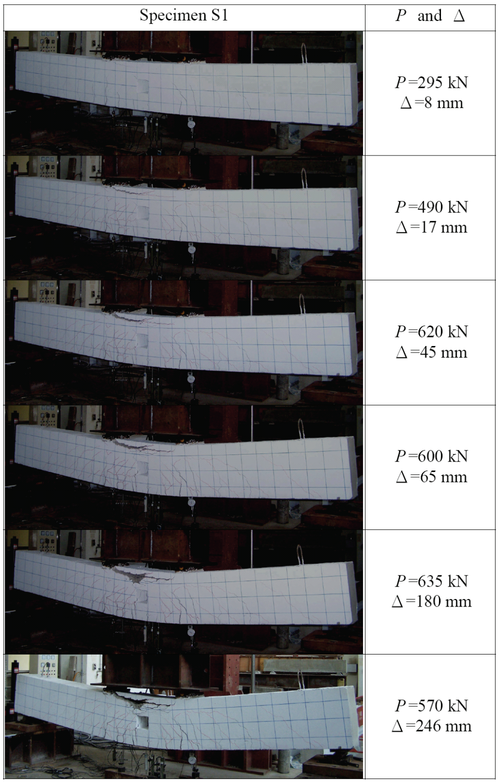


Figure 3 Progressive damage of specimen S1

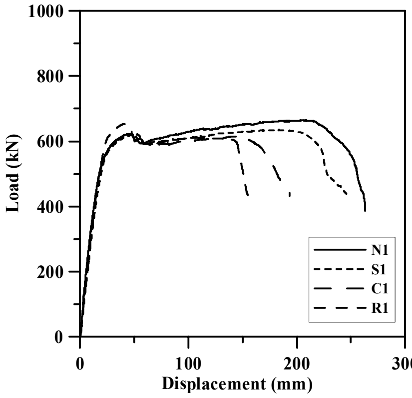


Figure 4 Load versus midspan deflection for specimens subjected to pure bending

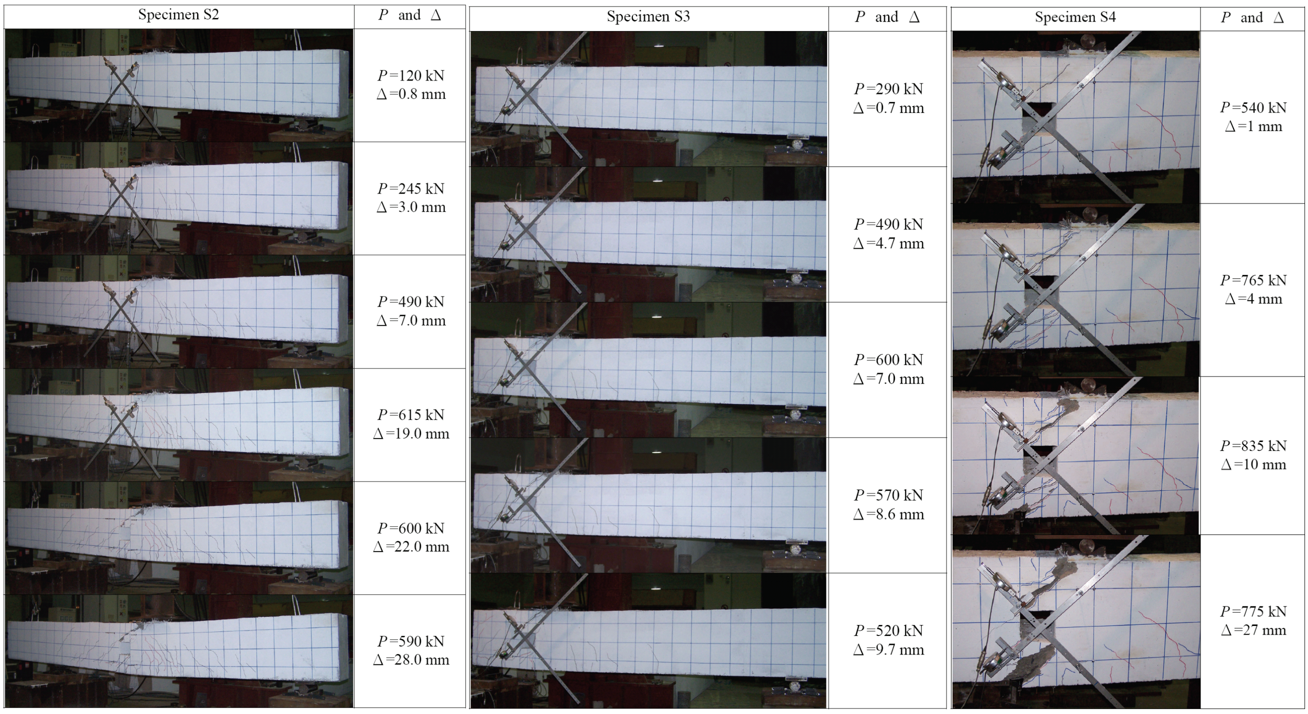


Figure 5 Progressive damage of specimens S2, S3 and S4

Figure 6 Shear deformation of the steel web of specimen S4

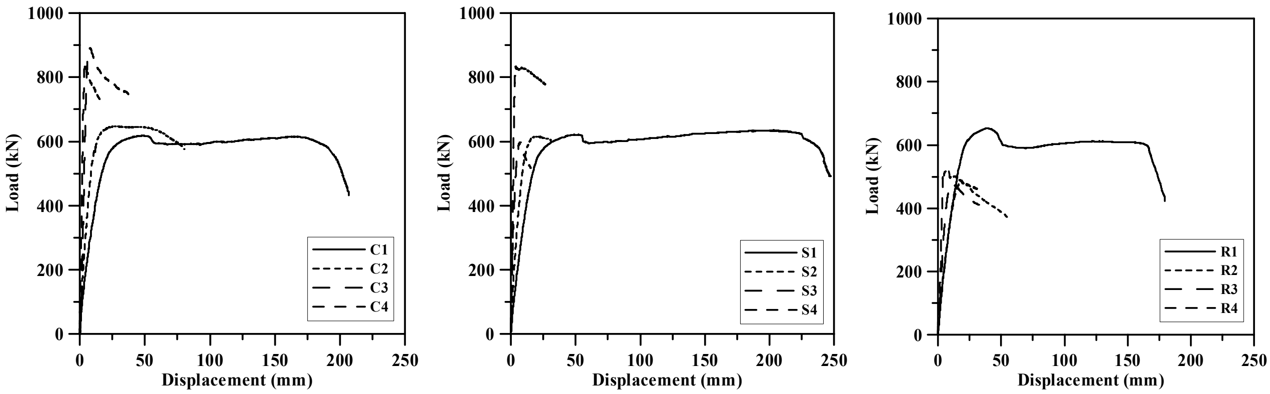


Figure 7 Load versus deflection curves for specimens C-, S- and R-series

3.3. Mode of Failure

The beams subjected to high moment to shear ratio, predominant bending, developed minor shear cracks at the corners of the opening in addition to flexural cracks occurred on the bottom of the beams close to the load applied region, and the failure was primarily attributed to the flexural failure associated with minor shear cracking. Nonetheless, shear failure at the opening was the major cause of the beam subjected to low moment to shear ratio, predominant shear.

Compared to reinforced concrete (RC) beams, steel reinforced concrete beams have additional structural steel encased in the concrete, which made the behavior of SRC beams different from the RC beams, when the beams subjected to combined bending and shear. In the SRC beams, the strength decreased gradually after the beams reached the ultimate strength, and it is because the structural steel provided additional shear strength while the reinforced concrete failed in shear.

3.4. Interaction of Bending and Shear

Moment-shear interaction was proposed for the structural steel section with openings (Darwin 1990). At the web opening, bending and shear interact and result in lower strengths than when the forces act alone. However, the interaction between bending and shear is not distinct. Therefore, the interaction between the design bending and shear strengths, ϕM_n and ϕV_n, for structural steel was proposed as

$$\left(\frac{\phi M_n}{\phi M_m}\right)^3 + \left(\frac{\phi V_n}{\phi V_m}\right)^3 = 1 \qquad (3.1)$$

where M_m and V_m are the maximum nominal bending and shear capacity at the location of an opening, respectively. Figure 8 shows the relations of moment versus shear at the web opening which the specimens developed during the test. As indicated in the figure, the moment-shear interaction of the tested SRC beams did not agree to Eqn. (3.1), proposed for the structural steel, except R-series specimens. Due to the wide opening, R-series specimens had the lowest shear strength among the specimens.

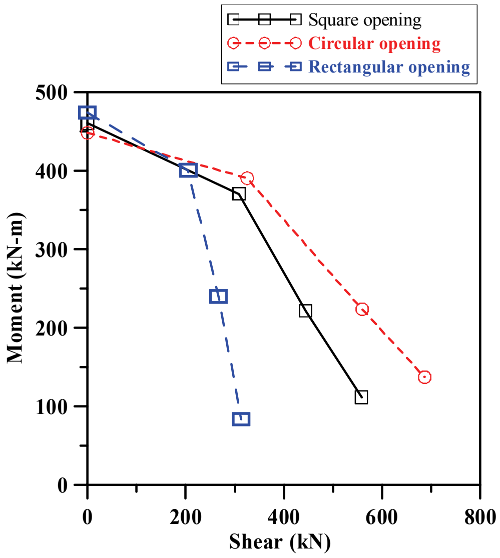


Figure 8 Moment-shear interaction of test specimens

4. CONCLUSIONS

Behavior and strength of the steel reinforced concrete beams with various opening shapes subjected to combined bending and shear were studied. The tests conducted on 13 SRC beams are presented. Test results indicated that the SRC beams with a small opening subjected to pure bending can develop flexural strength as much as the beam without opening. The SRC beams under predominant bending failed primarily attributed to the flexural failure. Nevertheless, the beams subjected to predominant shear failed mainly owing to shear failure at the location of the opening. The moment-shear interaction of the tested SRC beams with openings did not agree to the interaction proposed for the structural steel with an opening.

REFERENCES

ACI. (2005). Building code requirements for structural concrete (ACI 318-05) and commentary (ACI 318-05). American Concrete Institute.

AISC. (2005). Specification for structural steel buildings. American Institute of Steel Construction, Inc. Chicago, IL.

Arata, T., Sugimoto, H., Tanaka, H., Kikumoto, K. and Sato, T. (2000). Experimental study on strengthening effects of steel reinforced concrete beams with an opening (part 5). *Summaries of Technical Papers of Annual Meeting*, Architectural Institute of Japan. 1129-1130.

ASCE. (1999). Specification for structural steel beams with web openings. SEI/ASCE 23-97. American Society of Civil Engineers, Reston, VA.

Darwin, D. (1990). Steel and composite beams with web openings. AISC Steel Design Guide Series No. 2. American Institute of Steel Construction, Inc. Chicago, IL.

Hsu, H.-L. and Lee, J.-H. (2002). Cyclic behavior of steel reinforced concrete members with web opening. *Proceedings of the 6th Conference on Structural Engineering*. Kenting, Chinese Taiwan.

Mansur, M.A., Tan, K.H. and Lee, S.L. (1985). Design method for reinforced concrete beams with large openings. *ACI Journal* **82-46**. 517-524.

Nasser, K.W., Acavalos, A. and Daniel, H.R. (1967). Behavior and design of large openings in reinforced concrete beams. *ACI Journal* **64-3**. 25-33.
Sugimoto, H., Arata, T., Tanaka, H., Kikumoto, K. and Sato, T. (2000). Experimental study on strengthening effects of steel reinforced concrete beams with an opening (part 4). *Summaries of Technical Papers of Annual Meeting*, Architectural Institute of Japan. 1127-1128.