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FLEXURAL AND SHEAR BEHAVIOR OF REINFORCED CONCRETE HOLLOW BEAMS UNDER REVERSED CYCLIC LOADS

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ABSTRACT

In this paper, flexural and shear behavior of reinforced concrete hollow beams under reversed cyclic loads are discussed. The ultimate deformation capacity and the energy dissipation property as well as the stirrup strains are investigated experimentally and are compared with those of the solid beams without hollow part. Shear resistant mechanism of these beams are also discussed by focusing mainly on the deterioration of concrete shear resistance.

KEYWORDS

Reinforced concrete hollow beams; flexural behavior; shear behavior, reversed cyclic loads; diagonal cracks; ultimate deformation; shear resistant mechanism; energy dissipation; strain of stirrups; principal strain

INTRODUCTION

In the design of highly elevated reinforced concrete bridge piers, hollow section is often adopted in order to increase flexural rigidity and reduce the self-weight of piers. However, there is possibility that RC members with a hollow section may not have enough plastic deformation capacity and energy dissipation since it is generally difficult to ensure effective confinement of the concrete and the thinner web causes the deterioration of shear resistance of the members. For earthquake safety of the bridge piers, these behaviors shall critically be investigated.

In this paper, the effects of the existence of the hollow part on the flexural and shear behavior under reversed cyclic loads are mainly investigated. Shear resistant mechanism of RC hollow beams under combined shear and flexure is also investigated by using the modified compression field theory (Collins *et al.* 1991). In addition, shear design method according to Standard Specification for Design and Construction of Concrete Structures (Japan Society of Civil Engineers, 1991) is discussed considering the test results.

OUTLINE OF LOADING TESTS

Specimens used are reinforced concrete (RC) hollow beams having a cross section of width × full depth = 20 × 20cm. In the center of the section of these specimens, hollow part of 12cm ×10cm is arranged.

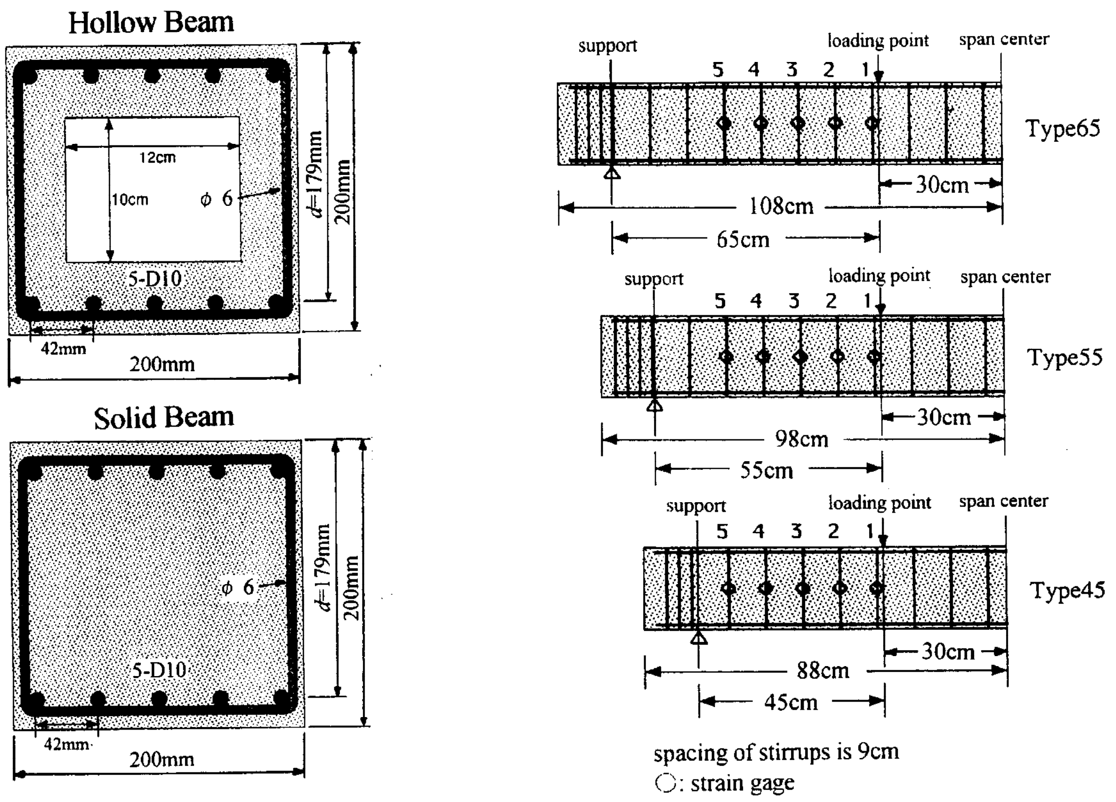
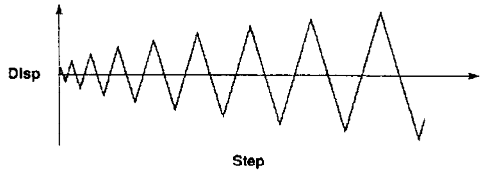


Fig. 1. Dimensions of specimens and details of cross section

Specimens without hollow section (called solid beams) were also fabricated for comparison. The details of the cross section of these specimens are shown in Fig.1. Design compressive strength of concrete was 400kgf/cm^2 [39.2 N/mm^2] for all the beams and D10 deformed bars (f_{sy}=3380kgf/cm^2 [331N/mm^2]) were used for longitudinal reinforcement. ϕ 6mm vertical stirrups (f_{sy}=3760kgf/cm^2 [369N/mm^2]) were arranged at the spacing of 9cm as web reinforcement in order to prevent premature shear failure.

These beams were loaded under symmetrical two points load with different shear span - effective depth (*a/d*) ratios, that is, 2.51, 3.07 and 3.63 corresponding to the shear span length of 45cm, 55cm and 65cm, respectively. Flexural span length, on the other hand, was fixed to 60cm for all the beams (Fig.1). The details of specimens are listed in Table 1.

Table 1. Details of specimens and failure mode

specimen	cross section	shear span ratio *a/d*	longitudinal reinforcement ratio, *p*(%)	loading pattern	failure * mode
H45	hollow	2.51	0.996		SF
S45	solid	2.51	0.996		SF
H55	hollow	3.07	0.996		SF
S55	solid	3.07	0.996		SF
H65	hollow	3.63	0.996		SF
S65	solid	3.63	0.996		F

* SF: shear failure after flexural yielding F: flexural failure

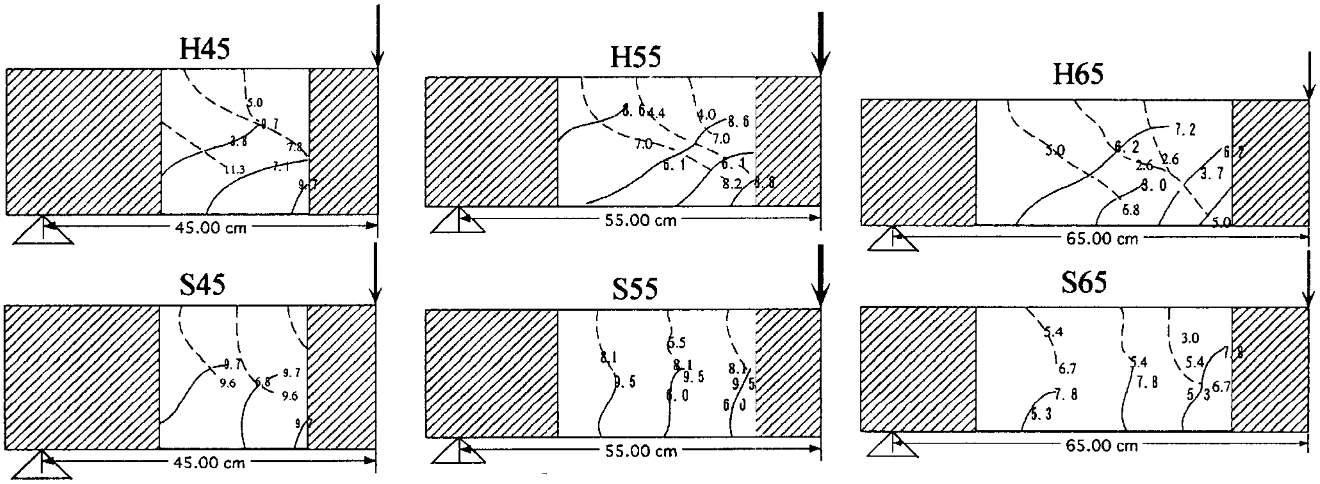


Fig. 2. Crack pattern in the shear span

All the beams were subjected to gradually increased reversed cyclic loading with load reversals at ± δ_y (δ_y: yield deflection, 7mm), ±2 δ_y, ±3 δ_y, ±4 δ_y, ±5 δ_y, ・・・・up to failure as shown in Table 1. The whole loading system was controlled by a personal computer and the deformation rate of the actuator was kept constant through the loading test.

During the loading tests, strains in longitudinal bars and stirrups, principal tensile and compressive strains in concrete at the shear span, and curvature within the flexural span were measured in addition to the applied load and mid-span deflection.

RESULTS OF TESTS AND DISCUSSIONS

Crack Pattern and Failure Mode

In Fig.2 are shown the crack patterns in the shear span of each beam after the loading cycle of ± δ_y. The angle of cracks observed in the hollow beams is considerably different from that in the solid beams. In the hollow beams, diagonal shear cracks are generated at an early stage of loading irrespective of *a/d* ratio. In the solid beams, on the other hand, flexural cracks generated firstly and these cracks turned gradually to flexural-shear cracks. However, significant diagonal cracks were not observed except for the beam S45 after the loading cycle of ± δ_y.

Almost all the beams except for the beam S65 failed finally in shear after yielding of longitudinal bars due to the reduction in concrete shear resistance (V_c) although these beams were designed to fail in flexure under unidirectional monotonous load. These facts indicate that shear design of the members subjected to earthquake load is very important, especially in case of the members with hollow section.

Load - Deflection Relationship

Figure 3 shows the load - mid-span deflection (P- δ) hysteresis loop of each beam. From Fig.3, it is observed that the ultimate deflection, in which the load carrying capacity reduces abruptly, is smaller in the hollow beams than that in the corresponding solid beams. In the former beams, the reduction in load carrying capacity after the ultimate deflection is more significant due to the considerable deterioration of concrete shear resistance.

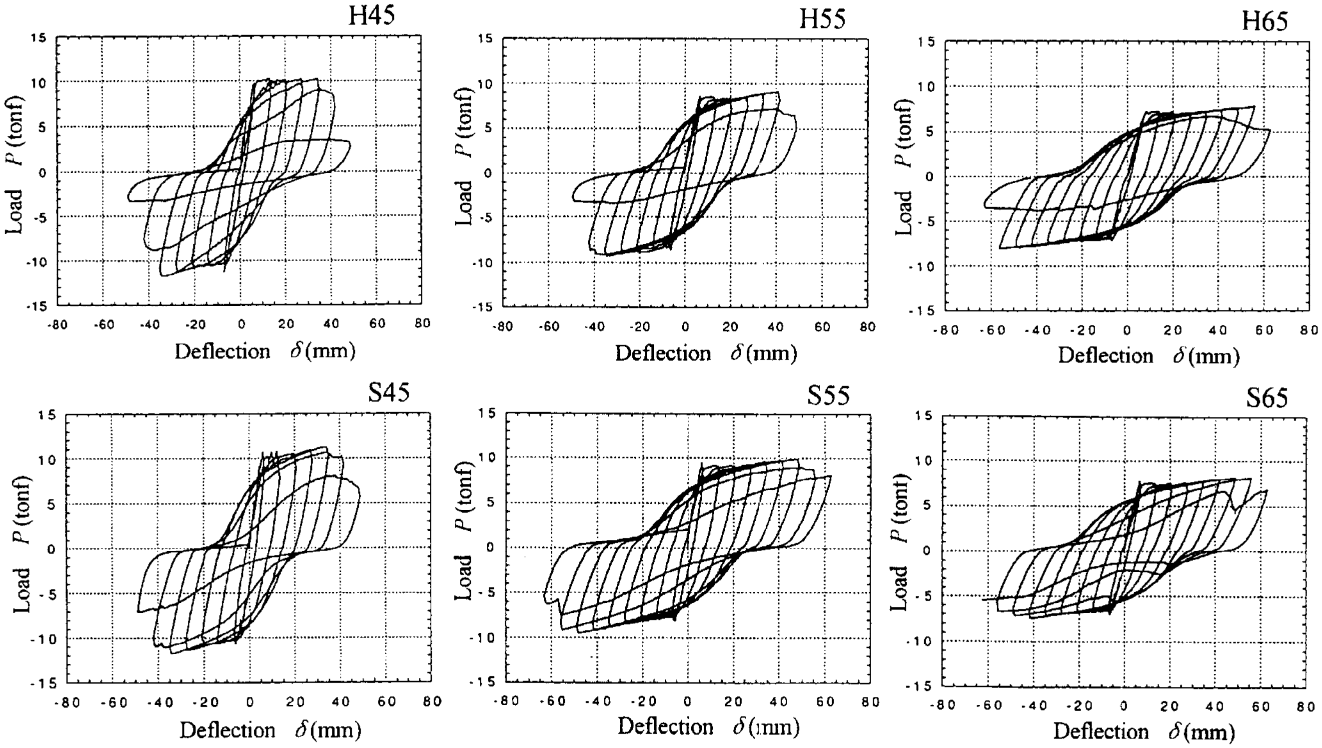


Fig. 3. Load - deflection hysteresis loop

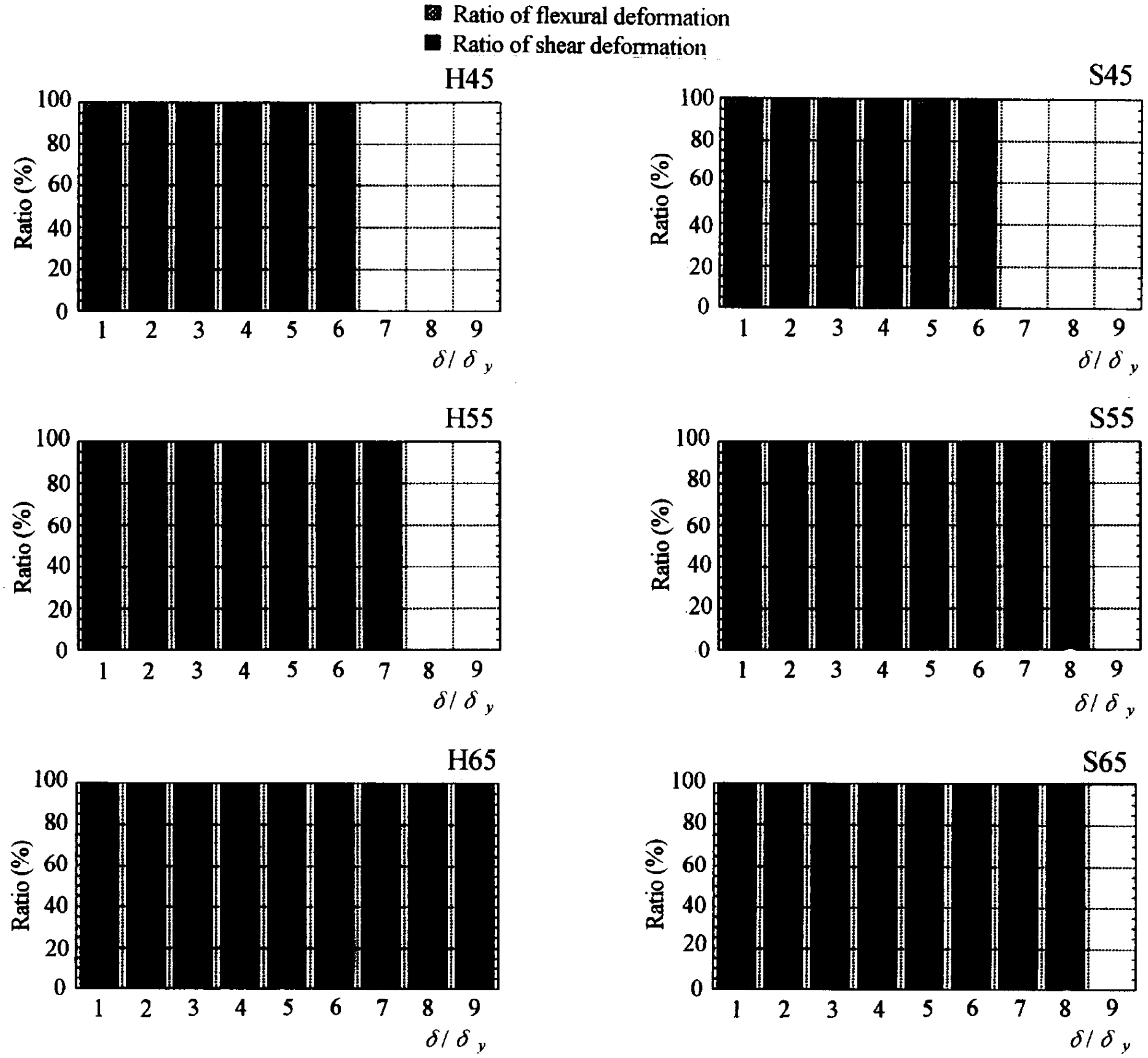


Fig. 4. Ratio of the flexural deformation and the shear deformation to the total mid-span deflection

In Fig.4 are shown the ratio of the flexural deformation and the shear deformation to the total mid-span deflection at each deflection amplitude for all the beams, where the flexural deformation is calculated from the measured moment - curvature relationship and the shear deformation is simply defined as the remaining part calculated by subtracting the flexural one from the total deflection. At the relatively small deflection amplitudes ($\pm 1\ \delta_y \sim 3 \pm\ \delta_y$) , the ratio of shear deformation is very small except for the beam H45. However, the ratio of shear deformation increases with increasing the applied deflection amplitude, and becomes more than 50% in the hollow beams at the ultimate deflection while it indicates relatively small values in the corresponding solid beams. These facts suggest that shear deformation cannot be negligible at a larger deflection amplitude, especially in the hollow members.

Energy Dissipation Property

The hysteretic dissipated energy of the hollow beams, which is defined as the area surrounded by the P- δ hysteresis loop at each deflection amplitude, is compared with that of the solid beams in Fig.5. Comparing at the same deflection amplitude, the dissipated energy of the hollow beams is somewhat smaller than that of the corresponding solid beams. It is also indicated that the deflection amplitude at which the dissipated energy commences to decrease is smaller in the hollow beams that that in the solid ones. This deflection amplitude is associated with the ultimate deflection.

Stirrup Strains

Figure 6 shows the stirrup strains of each beam at the location of 10.5cm from the loading point, where the value of the strain tended to indicate the maximum among the measuring points. The stirrup strain in the hollow beams shows relatively large values (more than 500×10^{-6}) at $\pm 1\ \delta_y$ due to the significant extension of diagonal cracks, while the value in the corresponding solid beams is very small even at the deflection amplitude of $\pm 3\ \delta_y$. This suggests that a thinner web width causes an earlier deterioration of concrete shear resistance under reversed cyclic loads. It is also indicated that the value of the stirrup strain becomes larger with

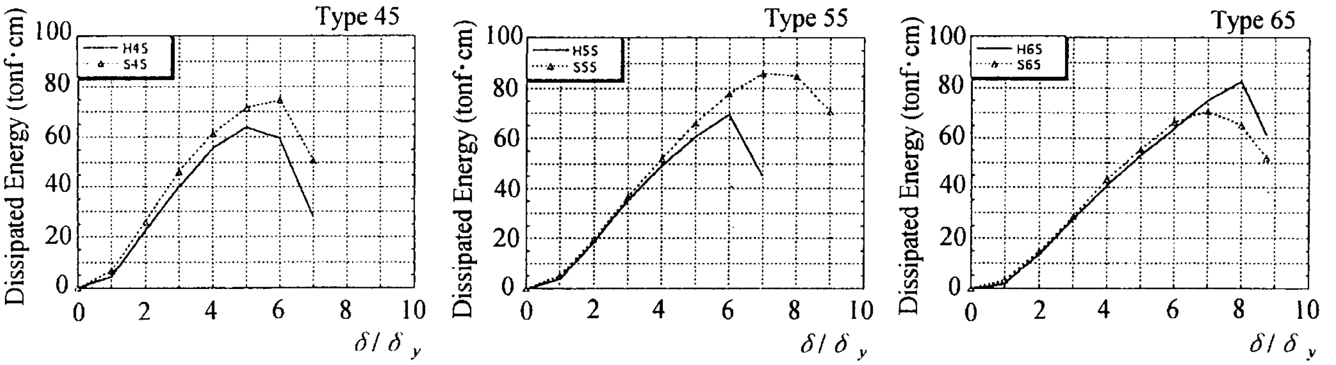


Fig. 5. Dissipated energy at each deflection amplitude

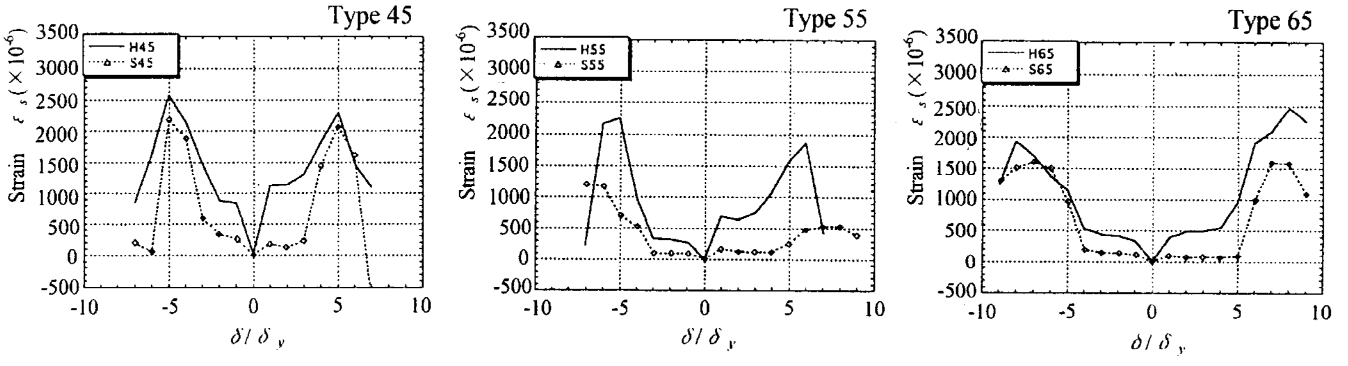


Fig. 6. Stirrup strains at the loaction of 10.5cm from the loading point

decreasing the a/d ratio comparing at the same deflection amplitude.

Shear Resistant Mechanism

In the present JSCE Standard Specification for Design and Construction of Concrete Structures (JSCE Code), the design shear capacity of linear RC members (V_{yd}) is given by the following equation.

$$V_{yd} = V_{cd} + V_{sd} \tag{1}$$

V_{cd} is design shear capacity of linear members without shear reinforcement, obtained by Eq. (2),

$$V_{cd} = f_{vcd} \cdot b_w \cdot d / \gamma_b \tag{2}$$

where, $f_{vcd} = 0.9\beta_d \cdot \beta_p \cdot \beta_n \cdot \sqrt[3]{f'_{cd}}$ (kgf/cm^2), $\beta_d = \sqrt[4]{100/d}$, $\beta_p = \sqrt[3]{100 p_w}$, $\beta_n = 1 + M_0 / M_d$, γ_b: member factor, f'_{cd}: design compressive strength of concrete, d: effective depth, p_w: ratio of longitudinal reinforcement area to area of web concrete, M_0: decompression moment and M_d: design moment. Note that β_d and β_p are less than 1.5 and β_n is less than 2.0 in case of N'_d>0 (N'_d: design axial compressive force). On the other hand, V_{sd} is design shear capacity carried by shear reinforcing steel obtained by Eq.(3) in case without prestressing steel as shear reinforcement,

$$V_{sd} = [A_w f_{wyd}(\sin\alpha_s + \cos\alpha_s) / s_s] z / \gamma_b \tag{3}$$

where, A_w: area of shear reinforcement over the interval s_s, f_{wyd}: design yield strength of shear reinforcement not greater than 4000kgf/cm^2, α_s: angle between shear reinforcement and member axis, s_s: spacing of shear reinforcement and z: distance from compression resultant to centroid of tension steel (generally be taken as d/1.15).

In Fig.7 is shown the hysteresis of the stirrup strain of each hollow beam at the location of 10.5cm from the loading point. V_c and V_s, which are calculated from Eq.(2) and Eq.(3) respectively by setting the value of γ_b as 1.0, are also indicated together with the actual yield strain of stirrup (ε_{sy}). In these figures, the solid line

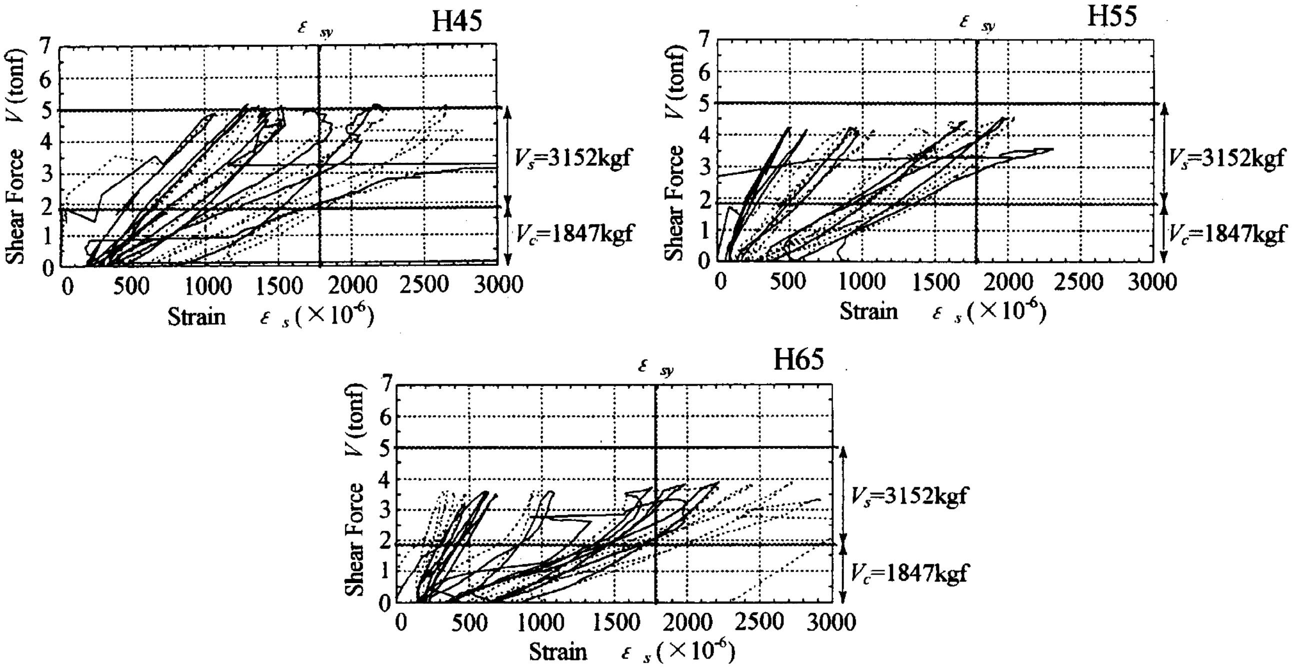


Fig. 7. Hysteresis of the stirrup strain of the hollow beams at the location of 10.5cm from the loading point

and the dotted line show each reading of the strain gages adhered on the two sides of the stirrup, and the applied shear force only in the positive direction is indicated. From these figures, it is recognized that the stirrup strain is very small until the shear cracking load, which is almost the same as V_c calculated by JSCE Code. After that, however, the strain increases with increasing the applied deflection amplitude and reaches its yield strain before the ultimate state although the applied shear force is smaller than the calculated shear capacity V_c+V_s. This implies that concrete shear resistance reduces due to the reversed cyclic loading while the present JSCE Code considers V_c to be constant even under reversed cyclic loads. Therefore, it is necessary to make reconsideration as for the shear capacity of reinforced concrete members subjected to reversed cyclic loads. It is essential especially for hollow section members as tested in this study.

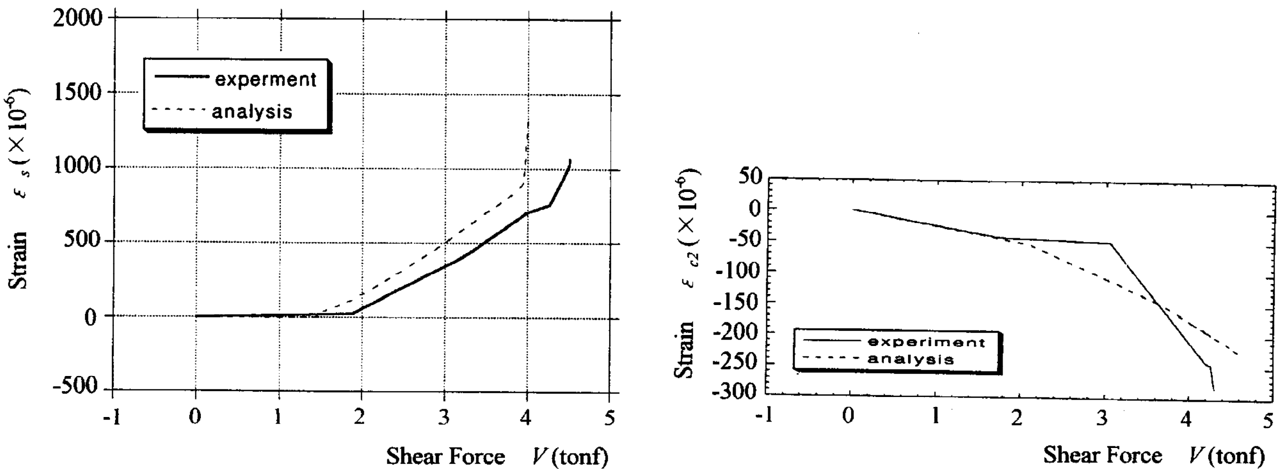
According to the modified compression field theory (Collins *et al.* 1991), on the other hand, shear capacity of reinforced concrete members subjected to pure shear is given as below,

$$V = V_c + V_s = f_1 b_w jd \cot\theta + \frac{A_w f_w}{s_s} jd \cot\theta \qquad (4)$$

where, f_1: principal tensile stress of concrete, jd: flexural lever arm, f_w: tensile stress of vertical stirrup and θ: inclination of diagonal compressive struts. As indicated in Eq.(4), shear capacity according to the modified compression field theory is defined as a function of principal tensile stress of concrete and inclination of diagonal compressive struts although it is given by the summation of concrete contribution and stirrup contribution such as JSCE Code.

By using the shear analysis according to the modified compression field theory together with the ordinary flexural analysis, it becomes possible to calculate the principal tensile and compressive strain and the stirrup strain at any location of a member subjected to combined shear and flexure. In Fig.8 are shown some examples of the results of calculation. The stirrup strain and the principal strain in concrete can be well estimated by this analysis.

In Fig.9 is shown an example of the sharing ratio of the concrete contribution (V_c) and the stirrup contribution (V_s) to the applied shear force (V), in which the measured V_c is simply calculated by subtracting V_s estimated based on the stirrup strain from the applied shear force and the analytical V_c and V_s are obtained from the above mentioned method. As seen in this figure, the concrete shear resistance begins to decrease at the level of high applied shear force and the stirrup contribution commences to increase abruptly from that point. The results of



(a) Stirrup strain
H45 (10.5cm from the loading point)

(b) Principal compressive strain of concrete
H55 (19cm from the loading point)

Fig. 8. Examples of the Results of Analysis

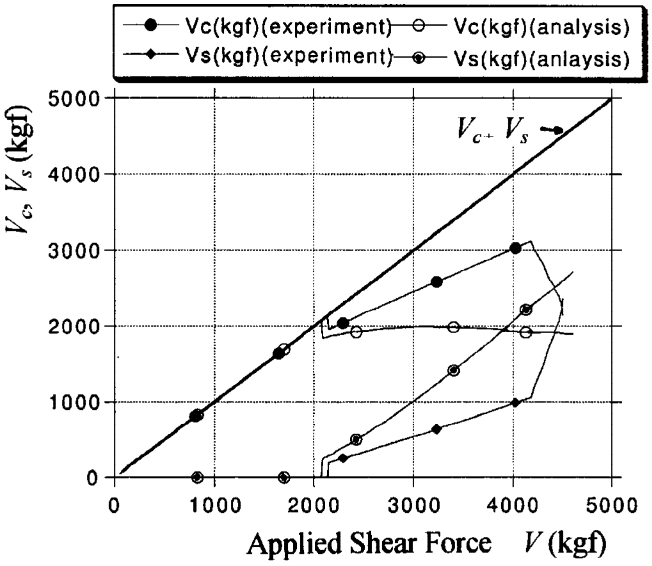


Fig. 9. Sharing ratio of V_c and V_s to the applied shear force V

the combined shear and flexural analysis adopted can express this phenomenon although it yields somewhat conservative results. From these results, it is very important to establish the rational shear design method considering the deterioration of concrete shear resistance due to reversed cyclic loads. It is essential for members with hollow section subjected to earthquake loads.

CONCLUSIONS

In this study, flexural and shear behavior of reinforced concrete hollow beams under reversed cyclic loads are investigated focusing mainly on the inelastic behaviors such as the failure mode, deformation property and energy dissipation capacity. Shear resistant mechanism of these beams, especially the deterioration of concrete shear resistance under reversed cyclic loads is also discussed based on the strain measurement.

Test results show that the ultimate deformation and the energy dissipation capacity of hollow beams are somewhat smaller than those of the corresponding solid beams without hollow part, and the ultimate failure mode of the former is more brittle than that of the latter due to the reduction in shear resistance of concrete. In the hollow beams, diagonal cracks are generated at early stage of loading. This leads to the considerable increase in the strain of stirrups, and the ratio of shear deformation to the total deformation becomes higher near the ultimate state. The strain of stirrups, principal tensile and compressive strains in concrete can be well estimated by the method combining the shear analysis based on the modified compression field theory and the ordinary flexural analysis. In the solid beams without hollow part, on the other hand, significant diagonal cracks do not occur before the yielding of the member and the ratio of shear deformation is relatively small even at the ultimate state.

From the results of this study, it can be said that the reduction in concrete shear resistance should be considered in the design of RC members subjected to earthquake loads, especially in the case of hollow section members. Any description as for the deterioration of concrete shear resistance due to reversed cyclic loads is not found in the present JSCE Code. Therefore, it is essential to establish a rational shear design method which takes account of the shear resistant mechanism under reversed cyclic loads.

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