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BEHAVIOR OF SHEAR WALL WITH OPENING

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SUMMARY

Finite element analysis and experimental work were conducted to study the ultimate strength of shear wall with opening under lateral load. The test results indicate that the shear strength contributed by diagonal reinforcement around opening reached 40% of its yield strength, while the shear strength contributed by the rectangular arrangement reached 20% of its yield strength. The shear strength can be predicted by ACI Eq.A-7 provided that the center to center of boundary elements is considered as the effective depth of the wall structure. Consistent correlation between the results of finite element analysis and experiment was observed provided that the tensile stress in concrete is properly released after section cracked.

INTRODUCTION

Shear walls are commonly used in reinforced concrete construction to resist the shear force induced by earthquake. To fulfill the functional requirement, the reinforced concrete shear wall may have to contain opening. The stiffness and strength of the wall are reduced by the reduction in concrete area and the discontinuity of the reinforcement due to opening. Further more, the stress concentration may occur around the corner of the opening which in turn induces the crack at early stage of loading process and hence reduces the stiffness and strength of the wall.

In this study, specimens with different size of opening and different reinforcing arrangement around the opening were prepared and tested to illustrate the effect of the design parameters on post-cracking behavior and ultimate strength. Finite element analysis was conducted to compare the analytical and experimental results.

TEST PROGRAM

In this experiment, a total of 13 shear wall panels as shown in Fig. 1 were constructed; instrumented and subsequently tested to failure. The dimension of the specimen is shown in Fig. 2, which represents approximately 2/3 size of prototype shear wall. The detail of specimen and material properties are shown in Table 1. With exception of the size of opening and reinforcing pattern around opening, the overall dimension of boundary element and reinforcement were the same for all wall units. When the rebars were discontinued due to opening, different amounts of reinforcement with different patterns were arranged around the opening as shown in Fig. 1.

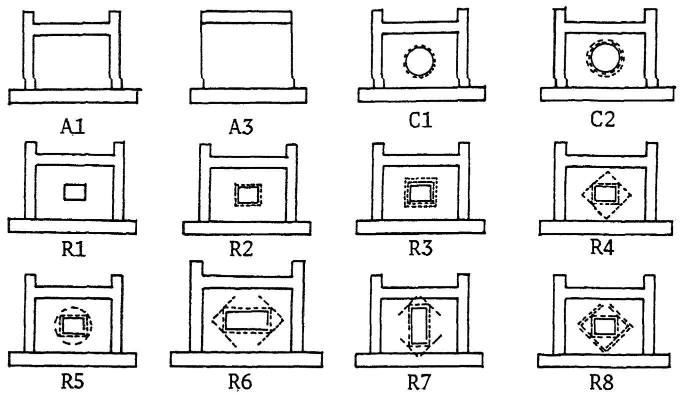

Fig. 1 Test Specimens

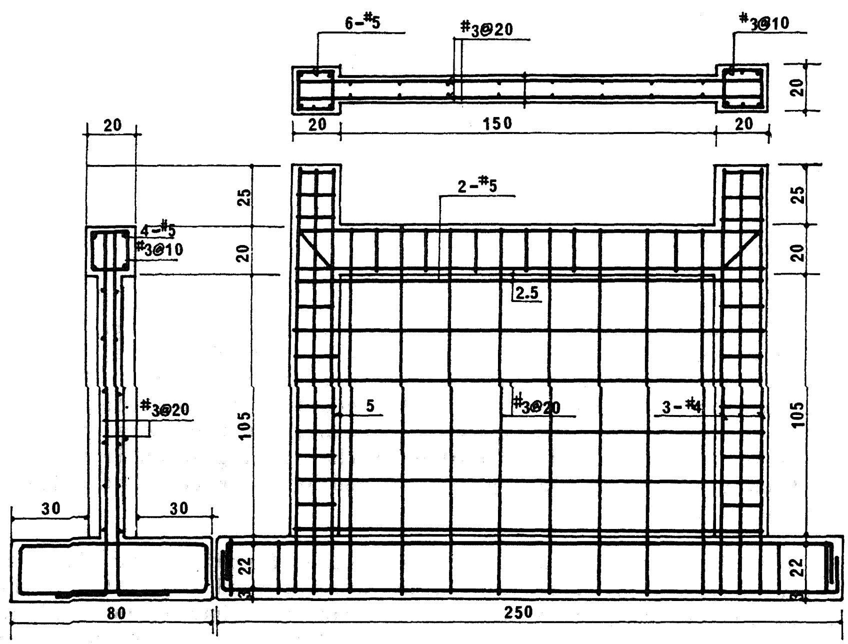

Fig. 2 The dimension of test specimen

To simulate the shear wall structure under seismic action, the lateral load was uniformly applied at top of shear wall through the spread beams, as shown in Fig. 3. Reinforcement within the wall was instrumented with strain gages at critical locations. Readings were taken of the change in strain at all stages of the loading. Mechanical dial gages having 5 cm travel range and 0.025 mm accuracy were used to measure the deflection in lateral and vertical directions during the loading process. The initiation of both flexural and diagonal cracks were carefully observed. The ultimate load, deformation and mode of failure were noted. For specimens subjected to cycle load, the loading was applied progressively at load level 0.6 Pu with an increment of 0.1 Pu until the ultimate load was reached.

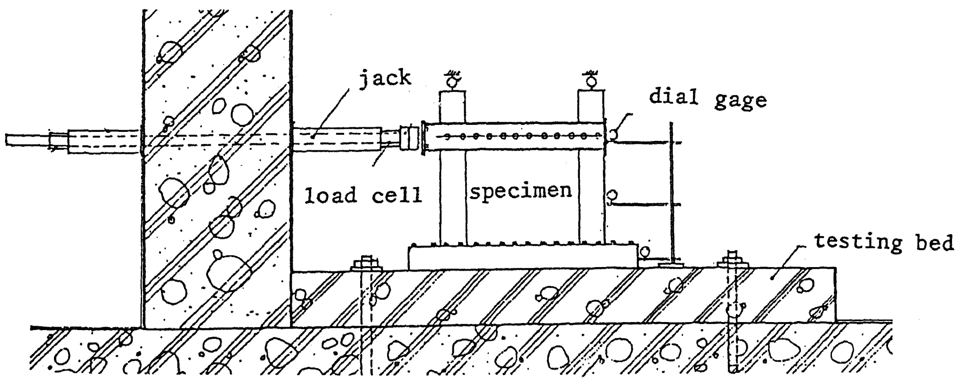

Fig. 3 Test set-up

FINITE ELEMENT ANALYSIS

Finite element analysis was conducted to study the stress distribution within shear wall before crack and to predict the ultimate strength of the wall (4). Before the crack of concrete section or yield of reinforcing steel, the structure was analyzed as linear elastic material. After the concrete tensile stress exceed modulus of rupture or the concrete or reinforcing steel exceeded their elastic limit, the non-linear behavior of material and discrete of element were considered in the analysis. When concrete tensile strain exceeded modulus of rupture ε_{cr}, the stress in concrete was graduatly released to adjacent member (5). The typical stress-strain curve of concrete is shown in Fig. 4. The ultimate strength predicted by finite element analysis is shown in Table 1.

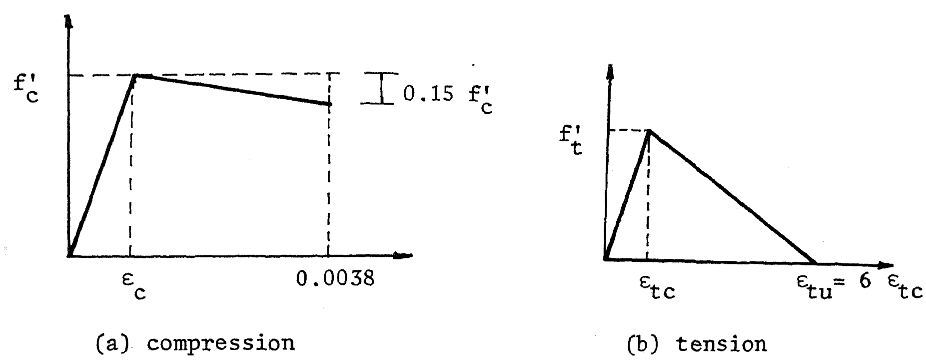

Fig. 4 Stress-strain curves of concrete

RESULTS AND DISCUSSIONS

The test results are summarized in Table 1. The crack patterns and failure modes of the specimen are shown in Fig. 5. Specimen without opening, the crack initiated at bottom corner of the junction of wall and boundary element, while the specimens with opening, the crack initiated at the corner of the opening with relatively low strength. As the applying load increased, the crack propagated outward with an approximate 45° angle as shown in Fig. 5. Specimen fabricated without boundary element, the crack remained almost horizontal until it failed. This indicated that the cracks were mostly generated by flexure.

Compare the test results of specimens R3, R4 and R5, which were fabricated with same size of opening but different reinforcing patterns around opening, specimen with diagonal reinforcement has a 15% reduction in strength while a 25%, reduction in strength was observed for specimen with vertical and horizontal reinforcement. In addition to that, smaller distorsion around opening was observed for specimen with diagonal reinforcement. For specimens R6 and R7, which have same size of opening but orientated in different directions, the failure mode was totally different as shown in Fig. 5. However, no significant difference in ultimate strength was observed.

The test results were compared with ultimate capacity calculated by ACI Eq. -A7 (6) and finite element analysis. As shown in Table 1. the ultimate shear capacity was overestimated by ACI. Eq.A7 if the overall width is considered in the calculation. On the other hand, the ultimate shear strength was under estimated, if the boundary elements are excluded in calculation. Reasonable results were obtained by taking center to center of the boundary elements as effective depth in ACI calculation. Compare the test results of specimens R4 and R7, it is observed that the ultimate strength is not only function of the depth of opening, it also highly affected by the width of the opening which is not included in ACI Eq.-A7. The results of finite element analysis were compared with the experimental data. Consistent correlation was observed as shown in Table 1.

Table 1 Specimen properties and test results

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
wall unit	f'_c (kg/cm^2)	opening (cm×cm)	$(V_u)_{Test}$ (ton)	$(V_u)_{ACI}$ Lw=150cm (ton)	$(V_u)_{ACI}$ Lw=190cm (ton)	Finite element analysis (ton)	Loading Pattern
A1	210	None	78.9	60.5	76.6	80.0	Mono.
A2	210	None	71.5	60.5	76.6	80.0	Cyclic
R1	230	30×40	53.9	44.9	61.3		Cyclic
R2	210	30×40	54.2	44.4	60.5	62.0	Cyclic
R3	210	30×40	55.9	44.4	60.5	64.0	Mono.
R4	270	30×40	69.2	46.1	62.8		Cyclic
R5	190	30×40	50.5	43.8	59.7		Cyclic
R6	210	30×80	49.3	28.2	44.4	56.0	Cyclic
R7	210	80×30	45.0	44.4	60.5	54.0	Cyclic
R8	180	30×40	56.0	43.4	59.2		Mono.
C1	240	50ϕ	50.1	41.4	57.5		Cyclic
C2	210	50ϕ	52.9	40.3	56.4		Cyclic

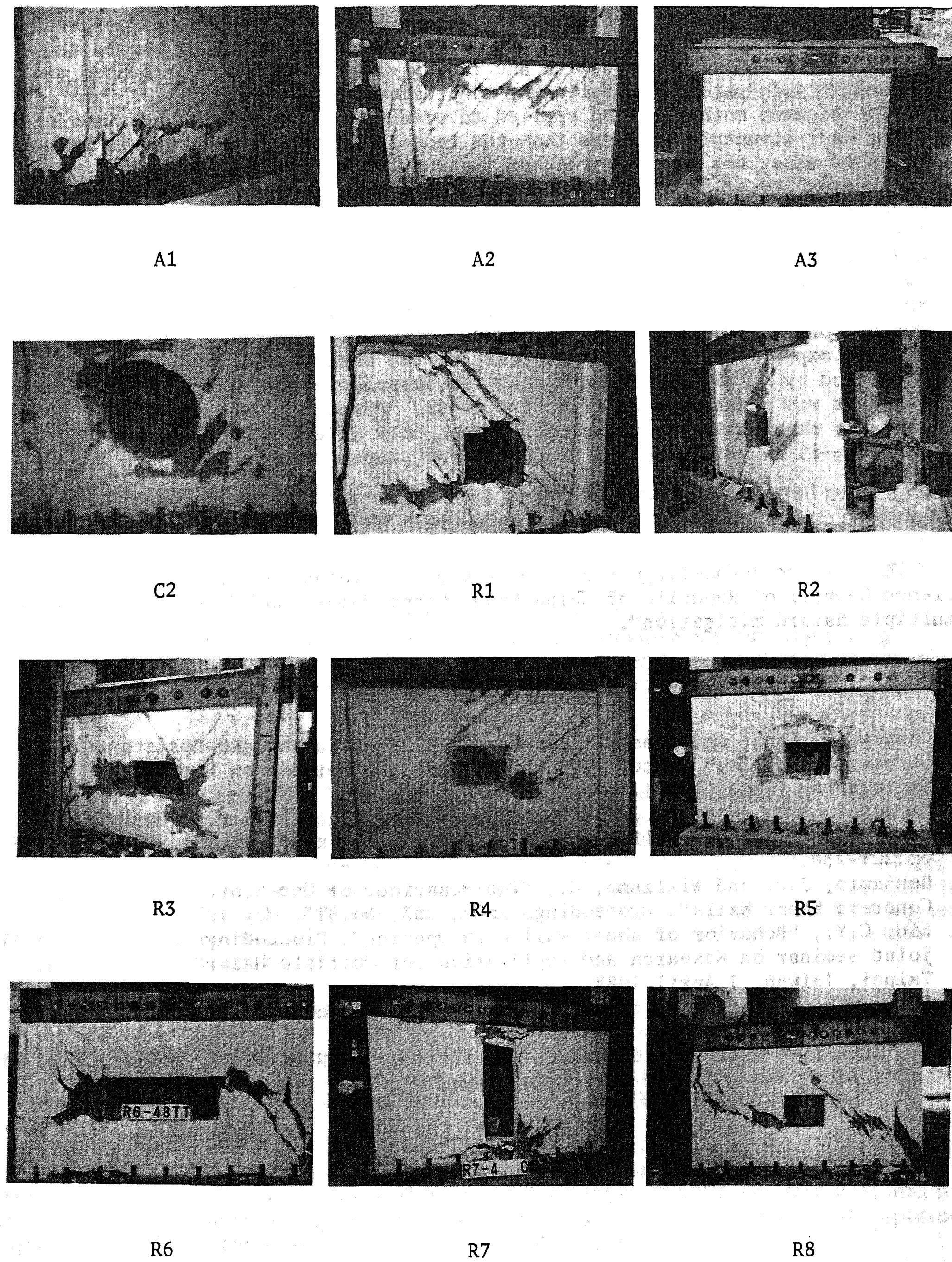

Fig.5 Failure modes

CONCLUSIONS

This test program demonstrated the shear behavior of reinforced concrete walls contain different sizes of opening and reinforcing patterns around the opening. Based on the test results and finite element analysis presented and discussed in this paper, the following conclusions may be made:

1. Finite element method can be applied to predict the post-crack behavior of shear wall structure provides that the tensile stress in concrete is properly released after the concrete reached its modulus of rupture.
2. Shear capacity of shear wall subjected to reverse load is about 90% of that when it subjected to monotonic loading.
3. The ductility and shear strength of the shear wall with opening is highly affected by the reinforcement around opening. The shear capacity contributed by the diagonal reinforcement reached 40% of its yield strength, while the shear capacity contributed by the vertical and horizontal reinforcement reached only 20% of its yield strength.
4. In this experiment, the shear capacity of the shear wall with opening was well predicted by ACI Eq.A7 provided that the distance between center of boundary elements was considered as effective depth. However it should also be noted that the shear capacity of section is not only affected by the width of the opening, it is also affected by depth of the opening as well.

ACKNOWLEDGMENTS

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