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Effects of Loading Rate on Reinforced Concrete Shear Walls
Part 3. High speed loading tests of reinforced concrete shearwalls and FE simulation analyses

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Abstract

The objectives of Part 3 of this study are to experimentally investigate the effects of loading rate on the shear strength-deformation relationships of RC shear walls, and to propose a FE simulation method. Lateral high speed loading were applied to the 1/10 scale wall specimens with the loading rate varied from static level up to 1.0 m/s. The tests results showed that as the loading rate increases, not only the shear strength but also the shear strain at the maximum shear strength of specimens increase. Results of FE simulation analyses were also presented, accounting for dynamic properties of both concrete and rebars.

1 Introduction

In recent earthquakes such as Northridge earthquake in 1994 and the Hanshin Awaji Earthquake in 1995, significant peak ground velocities at levels over 100 cm/s were observed. In order to evaluate the responses and safety of reinforced concrete (RC) structures subjected to the rapidly induced severe earthquake loads and/or impact loads, effects of loading rate on RC members should be properly taken into account in the material constitutive laws of an analytical model such as a finite element (FE) method.

The objectives of Part 3 of this study are to experimentally investigate the rate of loading effects on the shear strength-deformation relationships of RC shear walls, especially heavily reinforced squat-type shear walls as seen in nuclear-related structures in Japan, and to propose a FE simulation method, accounting for dynamic properties of both concrete and rebars.

2 Outline of experiments

A total of seven cases of static and lateral high speed loading tests were carried out with the variation of the loading speed and the reinforcement ratios of specimens, as shown in Table 1. Three levels of loading rates were chosen, namely, static (of the order of 10^{-6} m/s), medium speed loading (of the order of 0.1 m/s), and high speed loading (of the order of 1.0 m/s) as the main parameters. The loading rates were set with consideration of significant peak ground velocities at levels of over 100 cm/s observed in recent earthquakes such as Northridge earthquake in 1994 and Hanshin Awaji earthquake in 1995 and a fact that there have been little experimental data of high speed loading of shear walls more than 0.1 m/s.

Fig. 1 shows the drawing of a RC wall test specimen, which is called wp1. The test specimens were approximately 1/10 scale RC wall specimens, which simulate a typical squat-type shear wall with a relatively high reinforcement ratio, as seen in nuclear-related structures in Japan. The dimensions of the wall element are 410 mm in height, 700 mm in length, and 100 mm in thickness. The specimens were designed to have a shear span ratio, 0.8, and a reinforcement ratio, 1.0% each face and each side, as of typical shear walls in nuclear reactor structures. The other type of specimens, called wp2, have the same dimensions but higher reinforcement ratio, namely 2.0 %. The static material properties of concrete and rebars of the specimens were shown in Table 2. Although both types of specimens were designed to fail in shear, 30 mm steel plates were attached to the side surfaces of the RC wall element to constrain the flexural deformation, and 50 mm steel plates were attached on the top and the bottom surfaces of the RC wall element to transfer shear force.

Lateral high speed and static loading tests were performed by using a servo-controlled lateral loading machine at the National Defense Academy, as illustrated in Fig. 2. The maximum capacity of loading, loading stroke, and loading speed are 1 MN, 150 mm, and 3.0 m/s, respectively. The test specimens were anchored to the support slab, and the lateral loading to the specimens were applied through the loading rig set on the test specimens. The load, lateral deformation are the main measurements. The vertical deformation of the specimens were also measured to evaluate the flexural deflections of the specimens.

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3 Results and discussion

3.1 Load - shear strain relationships and failure modes

In Table 3, the test results are summarized, in which the measured loading rates for the medium speed loading and high speed loading were about 0.2 m/s and 1.0m/s, respectively, The failure modes of all the specimens were observed to be shear-compression failures of the compressive struts of concrete in RC wall elements. Accordingly, the difference of the reinforcement ratios between the specimen types, wp1 (1%) and wp2 (2%), does not show the significant effects on the shear strength and the failure modes of the specimens in the experiments.

The load-shear strain relationships of the specimens with the reinforcement ratio, 1%, are shown in Fig. 3 with the variation of the loading speeds. The shear strain is obtained by subtracting the horizontal deformation of the bottom of specimen and the influence of the specimen's rotational distortion from the horizontal deformation of the top of the specimen. The influence of loading rate on the load-shear strain relationship is significant, and the maximum load increases as the loading rate increases. Furthermore, it may be pointed out that the shear strain at the maximum load increases as the high speed loading, as well.

3.2 Dynamic increase factor of shear strength

Figure 4 shows the relationship between the dynamic increase factors of the shear strength and the shear strain rates for all the RC wall specimens. The shear strength of a RC wall element is evaluated by subtracting the horizontal loads born by the steel frame, which are computed by FE analysis, from the measured maximum load. The shear strain rate is evaluated by averaging the rates between the time at the half of the maximum load and the maximum load. The dynamic increase factors (DIFs) of the shear strength are approximately 1.3 and 1.5 at the medium speed loading and high speed loading, respectively. In the figure, the solid line is based on the empirical formula for DIF of concrete compressive strength proposed by the authors[2] and the dotted line is a regression curve for shear strength proposed by Kanechika et al[3]. Since the maximum shear strength for all the specimens in the tests are determined by crushing of concrete, the DIFs of the shear strength shows relatively good agreement with DIFs of concrete compressive strength.

4 Simulation analyses

4.1 Outline of FE analyses

Simulation analyses of the static and high speed loading tests of wp1 specimens were conducted based on a finite element method, in which the effects of strain rates on the strength of concrete and rebars are explicitly taken into account. Fig. 5 shows the FE model of the RC wall specimen with the peripheral steel plate frame and the H-shaped loading rig included. Layered shell elements were used for modeling the RC wall. The stress - strain relationships of concrete is defined by the method in reference 4 as shown in Fig. 6. The bi-linear stress-strain relationships is assumed for rebars. For the steel plates, the bi-linear stress and strain relationships with Von Mises' yield criterion are assumed.

The compressive and tensile strength and Young's modulus of concrete, and the yield strength of rebars are defined as functions of strain rates for each element, using the empirical equations proposed in Part 1 and 2 of this study [1, 2]. The constitutive laws of concrete and rebars are reevaluated each time step, depending on the strain rate in the previous time step for each element before the stresses in concrete and rebars exceed the linear limit. If the stresses in concrete and rebars exceed the linear limit, the constitutive laws are assumed to remain constant. As input motions, the lateral displacement time histories of the loading rig, which are obtained by applying a digital filter to the measured displacement time histories to remove the high frequency contents, were applied to the FE model, and the implicit time integration scheme was used to solve the equation of motions.

4.2 Simulated results

Simulated load-deflection curves of wp1 specimens (rebar ratio=1.0 %) under static, medium speed loading, and high speed loading are shown with the comparison of experimetal results in Figs. 7, 8, and 9, respectively. The simulated results for static and the medium speed loading show relatively good agreement with the experimental results. However, there are differences between the analytical and experimental results under the high speed loading, although the maximum loads coincide relatively well. The differences for the high speed loading case may be caused partly by the filtering process of the measured displacement time histories. Table 4 summarizes the comparison of the maximum loads and the DIFs between the analyses and experiments, and the DIFs of material strength in a typical element evaluated by the analyses are shown as well. The analytical results agree relatively well with the experimental results, and the DIFs of the shear strength of the RC wall specimen are shown to be predominantly influenced by the DIF of concrete compressive strength in the analyses. Figs. 10 and 11 show the damage states of concrete and rebars at the maximum loads under static and the high speed loading, respectively. Whereas the region of the concrete softening around the both corners of the concrete struts are similar for both static and high speed loading, the region of rebar yielding of the case of high speed loading is significantly larger than that of the static case. This may be explained by that the larger increase in concrete compressive strength than in the rebar yield strength causes rebar yielding in larger area at the high speed loading.

5 Concluding remarks

The experimental and analytical results may be summarized as follows.
(1) For the inelastic behaviors of RC shear walls under rapidly induced lateral loads such as severe earthquake load and impact load, the shear strength of shear walls increase significantly due to the increases of concrete and rebar strength. Furthermore, it may be pointed out that the shear strain at the maximum load increases as the loading rate increases, as well.
(2) Taking into account the dynamic properties of concrete and rebars as a function of strain rate, the inelastic behaviors of shear wall such as load-deformation relationships and the shear strength under high speed loading are well simulated by FE analyses.

Acknowledgments

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References

1. Nakamura, K, J. Mizuno, I. Matsuo, A. Suzuki, and H. Tsubota, "Rate of Loading Effects on Reinforced Concrete Shear Walls, Part 1: Dynamic Properties of Large-size Rebars", Proc. of ERES 99, June 1999
2. Suzuki, A, J. Mizuno, I. Matsuo, A. Kusaka, K. Nakakura and T. Ohno, "Rate of Loading Effects on Reinforced Concrete Shear Walls, Part 2: Dynamic Properties of Concrete", Proc. of ERES 99, June 1999
3. Kanechika, M., K. Igarashi, K. Muroi, and K. Akino, " Nonlinear Analysis Method for Reinforced Concrete Shear Walls of Reactor Buildings Considering the Strain Rate Effects on Skeleton Curves"", Journal of Structural and Construction Engineering, Architectural Institute of Japan, No. 513, pp. 107-114, May 1997
4. Hayami, Y., T. Miyashita, and T. Maeda, "Nonlinear Analysis of Shear Walls subjected to Cyclic In-Plane Shear Walls, 4th International Conf. of Nonlinear Engineering Computations, pp. 299-308, September 1991

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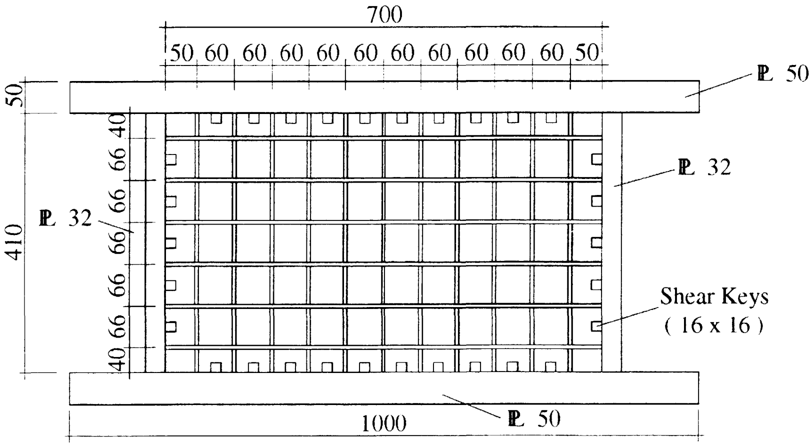

Fig. 1 Test specimen (unit : mm)

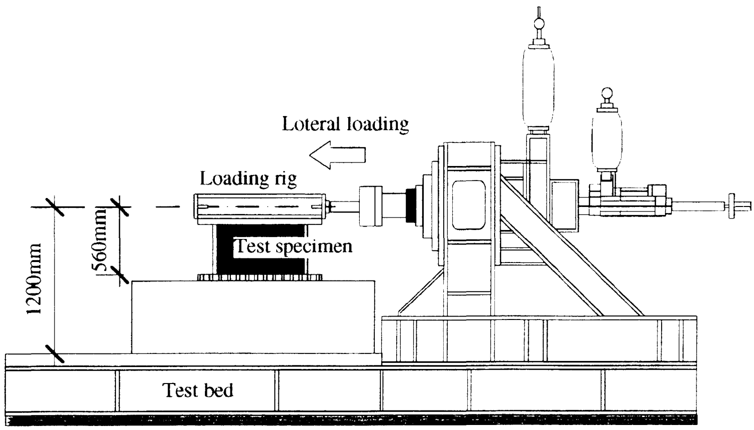

Fig. 2 Loading apparatus

Table 1 Test cases

Specimen	Rebar Ratio		Loading Rate		
	1%	2%	Static (10^{-6}m/s)	Medium Speed (10^{-1}m/s)	High Speed (1.0m/s)
WP1-S	○		○		
WP2-S		○	○		
WP1-M	○			○	
WP2-M		○		○	
WP1-H	○				○
WP2-H1		○			○
WP2-H2		○			○

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Table 2 Material properties (Static)

(N/mm^2)

	Concrete		Rebar		
	Compressive Strength	Split Strength	Yield	Max. Strength	Young's Modulus
Test Values	23.2	2.1	436.9	545.7	197000

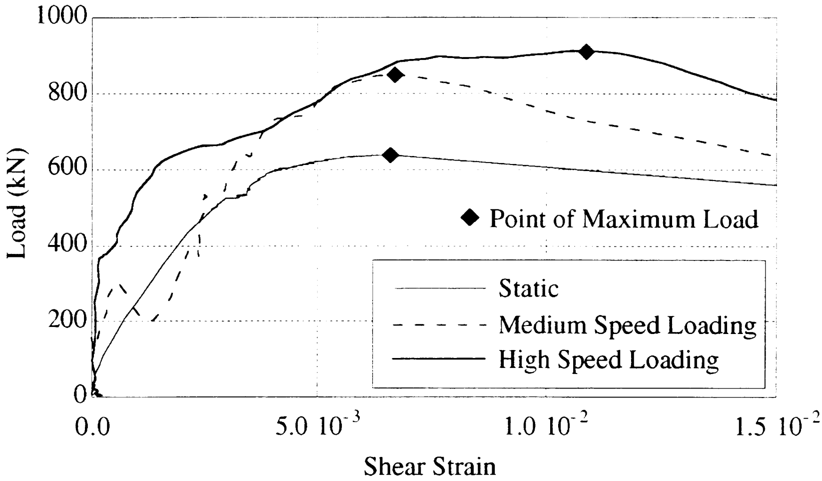

Fig. 3 Load-shear strain relationships
(WP1, rebar ratio = 1.0%)

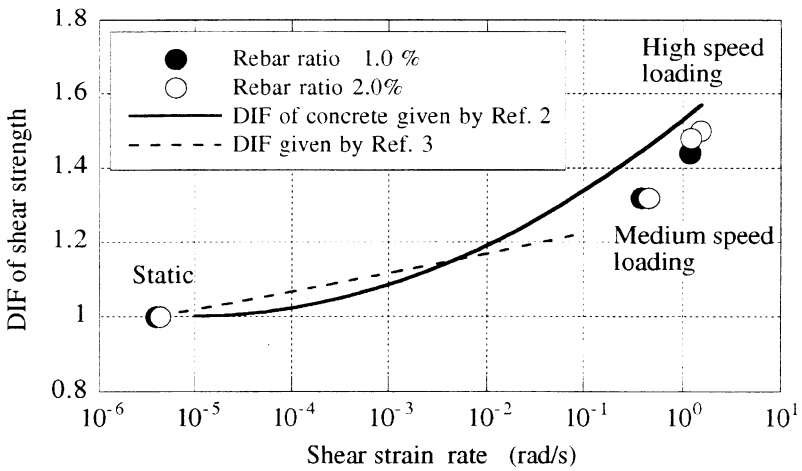

Fig. 4 Dynamic increase factor of shear strength

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Table 3 Experimental results

Specimen	Loading Speed (V) (m/s)	Maximum Shear Strain (γmax) ($\times 10^{-3}$)	Shear Strain Rate (γmax) (1/s)	Maximum Load (kN)	Max. Strength of RC wall (kN)	DIF of Shear Strength
WP1-S	2.31E-06	6.60	3.96E-06	638	555	1.00
WP2-S	2.66E-06	7.63	4.36E-06	650	569	1.00
WP1-M	0.20	6.69	3.85E-01	849	768	1.38
WP2-M	0.23	7.55	4.49E-01	828	750	1.32
WP1-H	0.95	10.64	1.17E+00	909	802	1.44
WP2-H1	0.95	8.64	1.52E+00	954	856	1.50
WP2-H2	0.93	6.76	1.20E+00	937	841	1.48

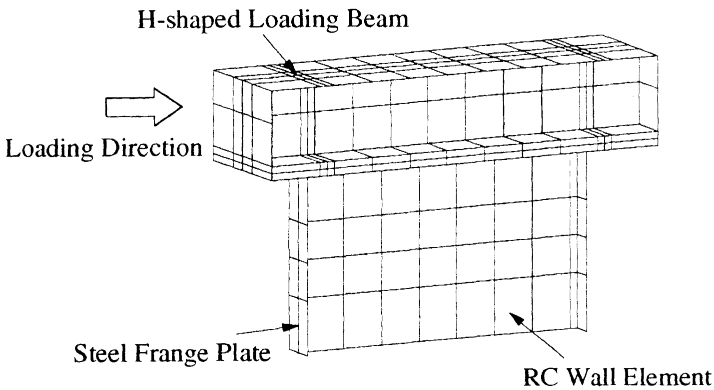

Fig. 5 FE model of test specimen

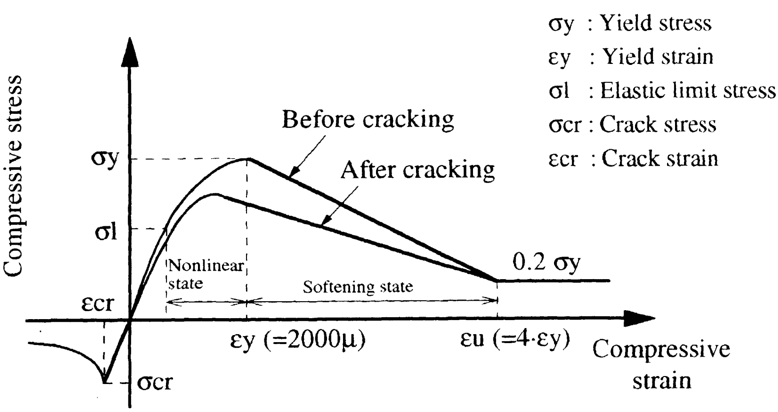

Fig. 6 Stress-strain relationships of concrete

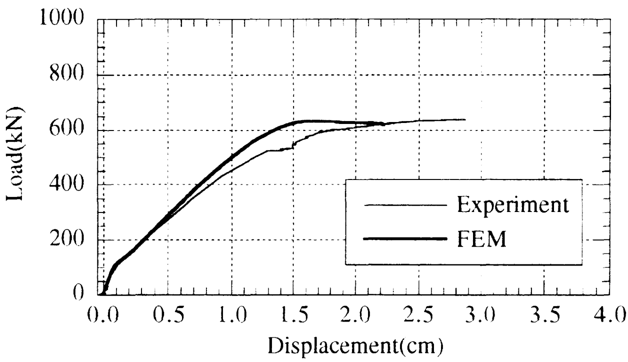

Fig. 7 Load-deflection curve (Static, rebar ratio=1.0%)

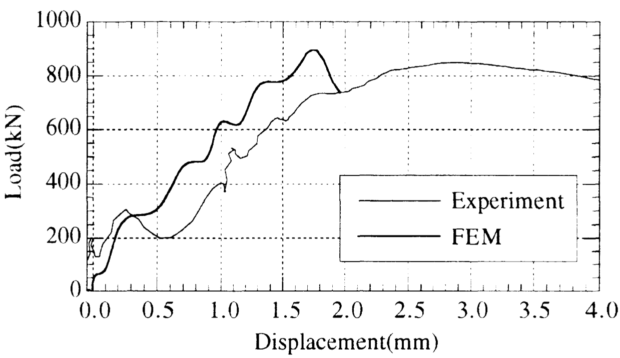

Fig. 8 Load-deflection curve
(Medium speed loading, rebar ratio=1.0%)

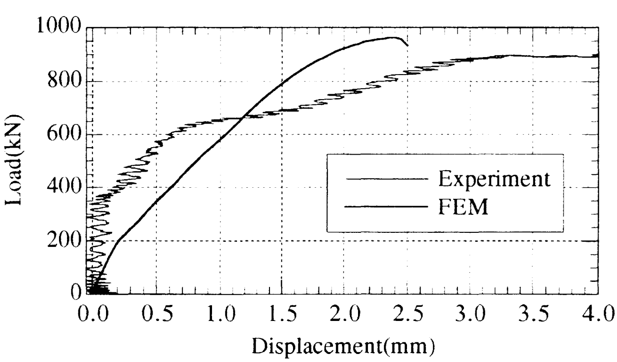

Fig. 9 Load-deflection curve
(High speed loading, rebar ratio=1.0%)

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Table 4 Summary of analytical results

	Maximum Shear Strength (kN)		Ratio of Exp./FEM	Ratio of Max. Shear Strength to Static Strength		DIFs of Material Strength		
	Exp.	FEM		Exp.	FEM	Concrete Compressive Strength	Concrete Tensile Strength	Rebar Yield Strength
Static	638	631	0.99	1.00	1.00	1.00	1.00	1.00
Medium* Speed Loading	849	891	1.05	1.33	1.41	1.32	1.86	1.06
High* Speed Loading	909	958	1.05	1.43	1.52	1.36	1.90	1.07

Notes : Measured loading speed, 0.2 m/s for medium speed loading, 1.0 m/s for high speed loading

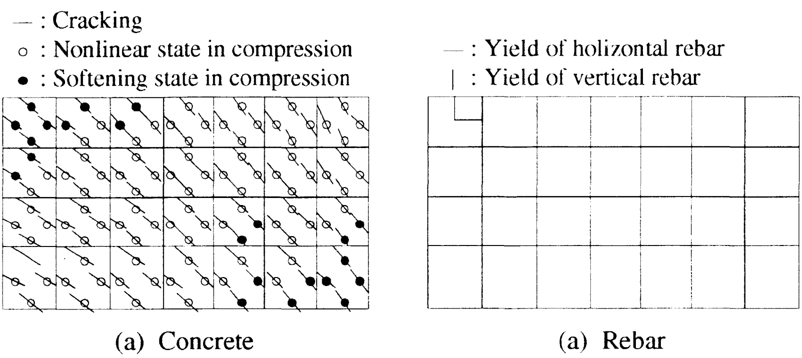

Fig. 10 Damage states of concrete and rebars at maximum load (Static, rebar ratio = 1.0%)

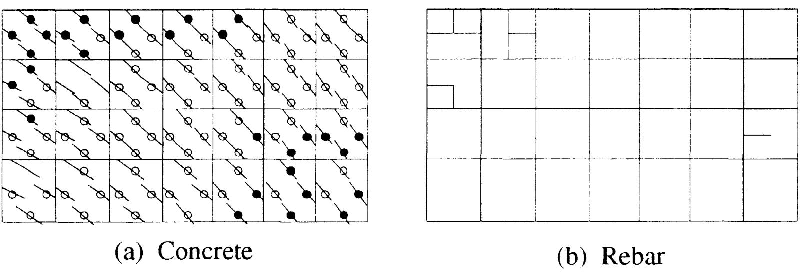

Fig. 11 Damage states of concrete and rebars at maximum load (High speed loading, rebar ratio = 1.0%)