0822

THE EFFECTS OF LOADING VELOCITY ON ELASTO-PLASTIC BEHAVIOR OF REINFORCED CONCRETE FRAMED SHEAR WALLS WITH AN OPENING

Masayuki ONO[1] And Fumiya EZAKI[2]

SUMMARY

This paper describes an experimental study on the effect of loading velocity on the cracking pattern, the failure mode, the lateral load-displacement relationship and the maximum strength of reinforced concrete (hereafter, referred to as RC) framed shear walls with an opening, and the conformity of the authors' strength reduction factor for estimating their maximum strength.

The effects of loading velocity were not observed in the inclination angle of the inclined cracks in the wall on all test specimens, and similarly in the lateral load-displacement relationship and the failure mode of test specimens with opening ratio above 0.4. However those effects are observed in the crack numbers, the degree of failure and the maximum strength on all test specimens, and, similarly, in the lateral load-displacement relationship of test specimens with opening ratio under 0.4. By using an equation that estimates accurately the maximum strength of RC framed shear wall without opening, and the strength reduction factor r_u as proposed by the authors, the maximum strengths during static and dynamic loading can be calculated with enough accuracy for practical usage.

1: INTRODUCTION

The cracking pattern, failure mode, lateral load-displacement relationship and strength on the members of RC structures generally have been estimated by the results of static loading tests. However, it is necessary to investigate the effect of loading velocity on the mechanical properties and behavior of RC structures, because RC structures are subjected to loading at higher speed during earthquakes, and are deformed with a large strain rate.

UP to now in Japan, experimental studies by Arai, Tanigawa, Mori and Hiraiwa[2], Fukushima, Adachi, Nakanishi, Okuda and Akuzawa[3], Hosoya, Okuda and Kitagawa[5], Iwai, Yoshida, Nakamura and Wakabayashi[6], Nakanishi, Ono, Adachi and Takanashi[8,9], and Shimbo, Murayama, Suda and Ichinomiya [14] have been reported on RC beams, columns, and on the concrete and steel bar under higher speed loading. The effects of loading velocity are gradually becoming clearer by these studies. However, the reports of RC framed shear walls with an opening have apparently not been published yet. Thus, RC framed shear walls with an opening were tested. The specimens used in this test are a scale of about 1/3 the natural size. Their opening ratio is about 0.3 to 0.6. The test specimens were subjected to reversed cyclic lateral load under a constant axial load. The experimental variables included in the test series are the opening ratio and the loading velocity. Two loading velocities, 0.01cm/sec to 0.1cm/sec as the static loading and 1cm/sec as the dynamic loading, were adopted.

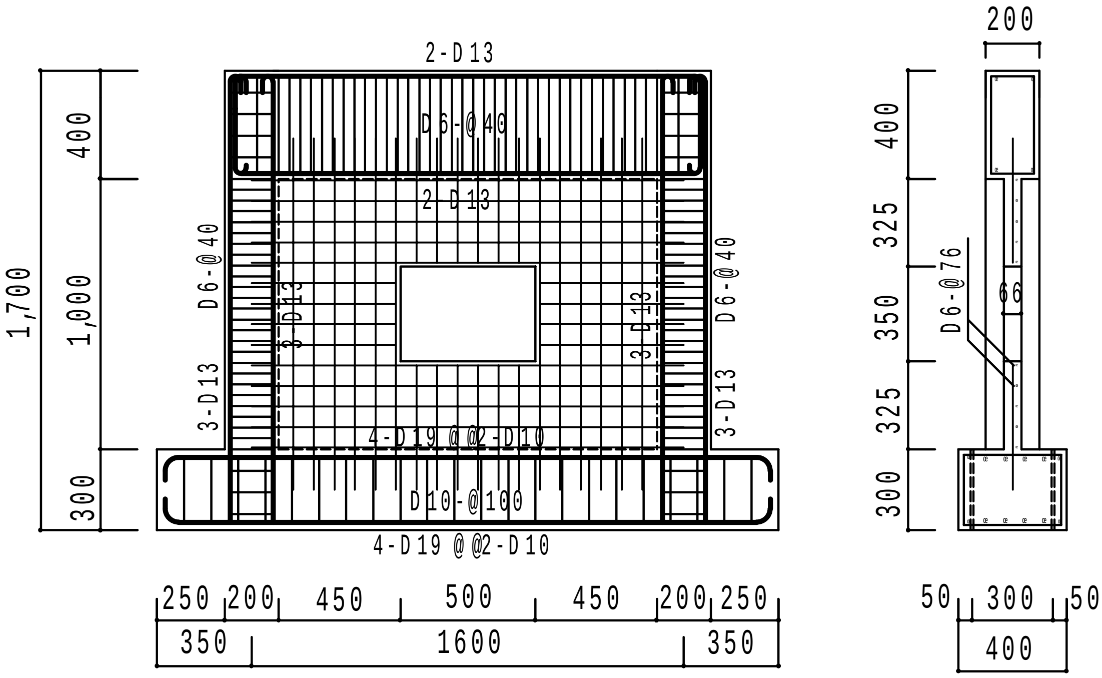
The primary purpose of this paper is to clarify the effects of loading velocity on the cracking pattern, failure mode, lateral load-displacement relationship and maximum strength of RC framed shear walls with an opening. The secondary purpose of this paper is to ascertain the conformity of authors' strength reduction factor for evaluating the maximum strength.

[1] *Prof, Dept. of Architecture, Kinki Univ.Japan. Email : ONO@fuk.kindai.ac.jp*
[2] *Prof, Dept. of Architecture, Kyusyu Kyouritu Univ. Japan.*

2. EXPERIMENTAL PROGRAMS

2,1 Test Specimens and Mechanical Properties of Materials :

The test specimens used in this experiment are seven RC framed shear walls with an opening of which the opening ratios are 0.302, 0.436, 0.516 and 0.595 as shown in Figure 1 and Table 1. The opening ratios are calculated using the following formula :$\sqrt{h_0 l_0 / hl}$, where h_0 and l_0 are the clear height and length of the opening, respectively; and h is the distance between the center of upper beam and the upper face of footing beam; and l is the distance from the center to center of the columns. The sectional shape of the boundary frame of each test specimen satisfies the requirements stipulated in clause 18 of the AIJ RC standard[1]. Figure 1 shows the detail of test specimen FW6.6-0.302-S,D, which is the test specimen with an opening reduced to a scale of about 1/3 the natural size.



(FW6.6-0.302-S,D)

Figure 1: Detail of test specimen (unit : mm)

The members of other test specimens have the same dimensions and reinforcement as those of test specimen FW6.6-0.302- S,D. The parameters of the test specimens and the mechanical properties of materials are shown in Table 1. The compressive strength of concrete due to the two types of loading test, $_S\sigma_B$ as the static loading and $_D\sigma_B$ as the dynamic loading, are shown in Table 1 and Figure 2. The average loading times, about 170 sec during static loading and about 50 sec during dynamic loading, are applied. The code of specimen is specified by FWt-ξ-L ; where, F indicates the boundary frame; W, the wall; t, the thickness of wall; ξ, the opening ratio; L, the two types of loading (S : static loading, D : dynamic loading.

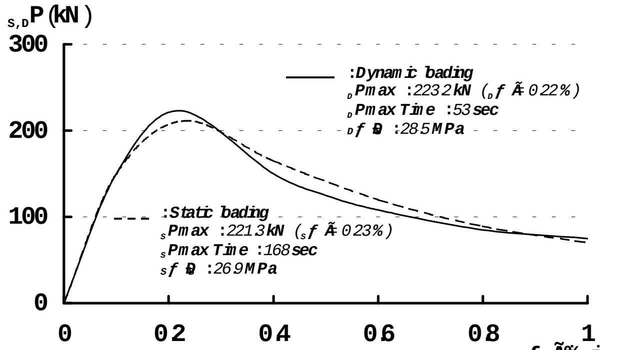


Figure 2 : An example of compressive test for cylindrical concrete

Table 1: Parameters of specimens and mechanical properties of materials

Specimen	Dimension of opening h_0 l_0 (cm em)	Concrete sf Þ		Reinforcement		Common Items
		sf ÞB Df ÞB Mpa	sf Þ, Mpa	sf Þ,M sf Ã,M Mpa	sf Þu Mpa	
FW6.6-0.302-S,D	35 ~50	26.5 28.4	2.46	D6 379.4 0.194	D6 554.0	Column section : B Þ 20 20 (cm) Main reinforcement : 4 - D13 Pg : 1.27 % Pw : 0.8 % (D6 - @40) Beam section : B Þ 20 40 (cm) Main reinforcement : 4 - D13 Pg : 0.63 % Pw : 0.8 % (D6 - @40) Wall thickness : t = 6.6 (cm) Ps : 0.64 % (D6-@76)
FW6.6-0.436-S,D	50 ~73					
FW6.6-0.516-D	58 ~88	27.4 28.8	2.31	D13 337.3 0.182	D13 525.0	
FW6.6-0.595-S,D	66 ~103					

(Notes) Pg : Gross reinforcement ratio of columns and beams; Ps : Shear reinforcement ratio in wall; Pw : Shear reinforcement ratio of stirrups and hoops; sf ÞB : compressive strength; sf Þt : Tensile strength; sf Þy : Yield stress; sf Ãy : Yield Strain; sf Þu : Tensile strength

Loading and Measuring Methods :

Figures 3 and 4 shows the loading apparatus and the measuring apparatus of displacement, respectively. The footing beam of the specimen is fixed on the reaction frame by tightening the high-tension bars. For loading, three actuators are used. First, a constant axial load of 98kN was applied upon the top of both-sides column by the two actuators. And then, the reversed cycle lateral loads were applied with the steel plates tightened by the high-tension bars on both-sides of the upper beam.

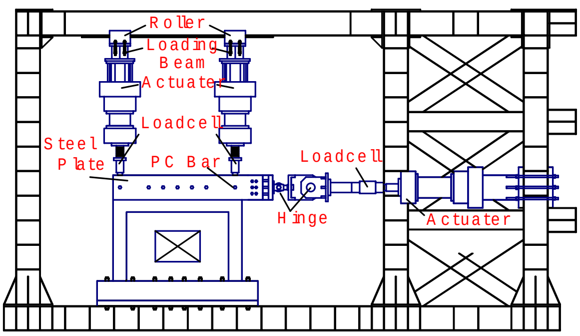


Figure 3: Testing apparatus

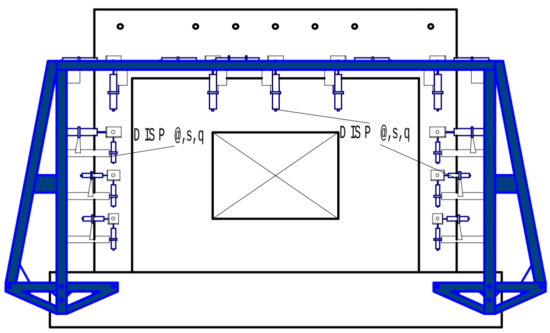


Figure 4: Measuring apparatus of displacement

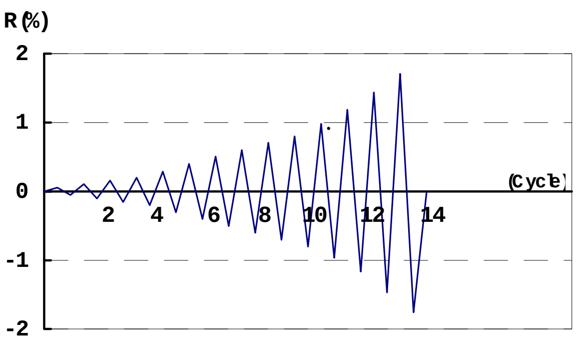


Figure 5: Program of static loading

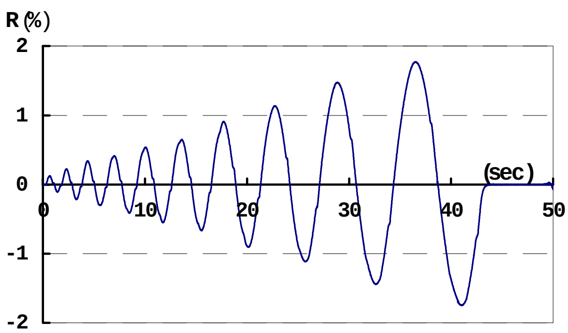


Figure 6: Program of dynamic loading

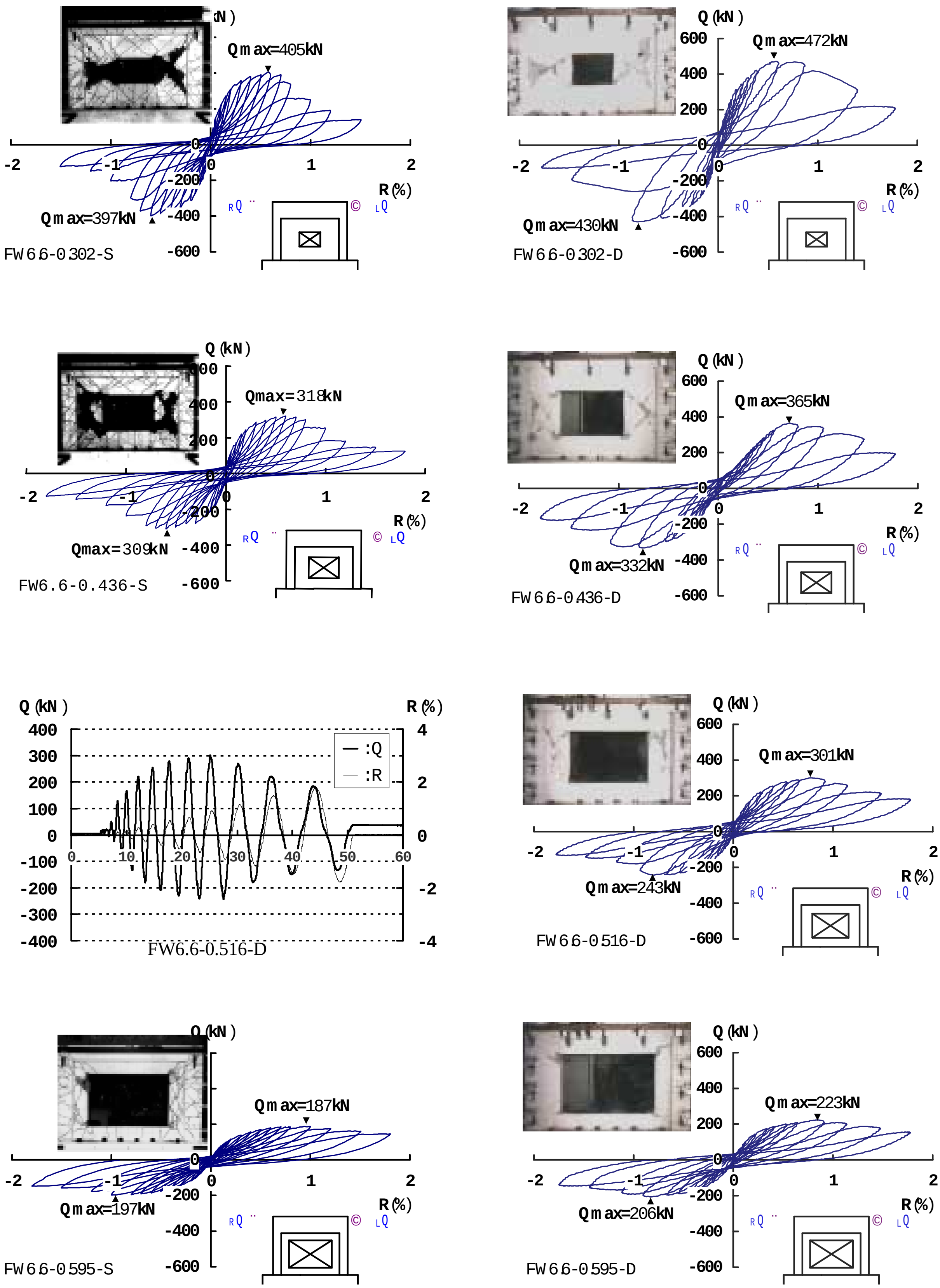


Figure 7: Lateral load-displacement relationships and failure behaviors

The reversed cycle lateral loading method used was displacement-controlled alternating loading with the displacement amplitude increased at each cycle. Two loading velocities, 0.01cm/sec to 0.1cm/sec to simulate static loading, and 1cm/sec to simulate dynamic loading, were adopted.

The programs of static loading and dynamic loading are shown in Figures 5 and 6. The story deflection angle R(%) shown in Figures 5 and 6 is calculated by using the following formula : $R=\delta/h$, where δ are the lateral displacement which were measured at center of upper beam, h(=115cm) is the height between the bottom end of column and the position measuringδon the upper beam. The horizontal line in Figures 5 and 6 represents the cycle numbers and the loading times, respectively.

A load cell mounted to the end of actuator measured the lateral loads. The vertical and lateral displacements of the upper beam and the both-sides column were measured by using high-sensitive displacement transducers as shown in Figure 4. The measured values of the lateral loads and displacements were recorded on a floppy disk using a personal computer. The measured values at the dynamic loading were recorded on a floppy disk at intervals of 0.02sec. The cracking patterns were recorded by sketching through visual inspection, taking photographs and through video camera recording.

TEST RESULTS

The lateral load-displacement relationship and the failure behaviors, after the test was finished, are shown in Figure 7. The vertical and horizontal line of these figures represents the alternating lateral load Q(kN) and the story deflection angle R(%), respectively. The values of R were calculated by dividing the lateral displacement by h=115cm, and Qmax in Figure 7 represents the maximum strength reached while loading the positive load $_{R}Q$ and negative load $_{L}Q$.

Cracking Patterns, Failure Modes and Lateral Load-Displacement:

The behaviors of cracking patterns, failure modes and lateral load-displacement relationship for each test specimens were observed as follows:

[The test specimens of the static loading**]** : The cracks due to the diagonal tensile stress occurred very early at the opening corners. Subsequently, the inclined cracks occurred in the wall at the side of opening, when R was about (0.05~0.25)%. The horizontal cracks occurred in the columns at the position of spandrel wall height, when R was about (0.05~0.15)%. Hereafter, as displacement amplitude increased, many inclined cracks in the wall and the horizontal cracks in the columns increased in number and extended. And then, the inclined cracks in the wall extended into the columns and upper beam. The spread of the inclined cracks width in the wall and the horizontal cracks width in the column, the compressive failures at the opening corners and column base portion occurred, and simultaneously the lateral load reached a maximum at about R=(0.6~1.0)□. As displacement amplitude increased, compressive failure of the wing wall and column base portions became markedly. After the maximum strength was reached, the lateral load-displacement relationship showed a steep decrease in strength, when the opening ratio was less than 0.4. After the maximum strength was reached, the lateral load-displacement relationship showed a gradual decrease in strength, when the opening ratios were larger than 0.4. The test specimen with opening ratio less than 0.4 was in the shearing failure mode. The test specimens with opening ratios larger than 0.4 were in the flexural failure mode.

[The test specimens of the dynamic loading**]** : The observation of the first crack in the wall was difficult owing to the video tape recording .The inclined crack in the wall was observed at about R=(0.1□0.2)%. The cracks of the walls and columns were less than the number of cracks observed during static loading, and these failure behaviors were almost same as the static loading. But these maximum strengths were different due to loading direction. The lateral load-displacement relationship showed a steep decrease in strength when the opening ratio was less than 0.4. The lateral load-displacement relationship showed a gradual decrease in strength when the opening ratio was larger than 0.4. The failure of all test specimens was in the flexural failure mode.

The reinforcements at the columns base portion of all test specimens have been yielded before reaching maximum strength.

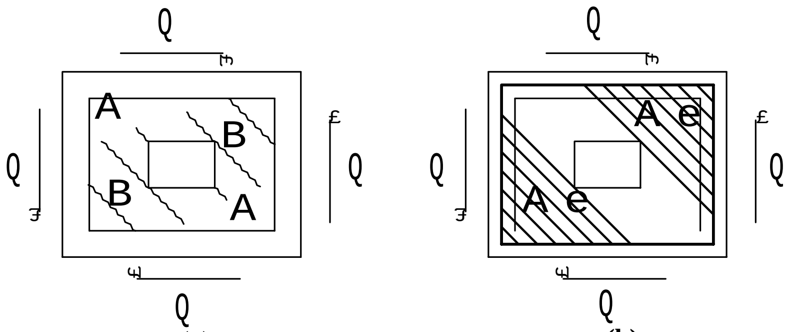
STRENGTH REDUCTION FACTOR DUE TO OPENING

There are two kinds of cracks in RC framed shear walls with an opening as shown in Figure 8(a). The cracks designated A occur firstly at the opening corners due to the diagonal tension. Subsequently, the inclined cracks designated B occur in the wing wall due to the shearing force. These cracks can be seen from failure of past earthquake and experimental results. After the inclined cracks B in the wall occurred, RC framed shear walls with an opening expand due to spreading of the crack width. The compressive stress fields Ae in the wall formed, as shown in Figure 8(b), contributing to the strength of RC framed shear walls with an opening. However, the wall areas outside of the areas Ae do not always contribute to the strength.

According to experimental studies by Ono and Tokuhiro[10,12] and Ono[11] and finite element analysis by satou[13], the inclination angle of the inclined cracks in the wall varies from about 45-degree to 60-degree depending on the opening positions, opening shapes and the effect of vertical loads. It is difficult to define precisely the inclination angle of the inclined cracks, because the opening positions, the opening shapes and the vertical load in actual RC framed shear walls with an opening are quite different. Accordingly, the compressive stress fields areas Ae in this study are defined as shown in Figure 9.

The strength of RC framed shear walls with an opening decreases because of the opening. The decrease of strength is assumed to be affected by the total area ΣAe of the wall where compressive stress fields form. And so, the strength reduction factor due to the presence of an opening proposed by Ono and Tokuhiro[10] as follows:

$$\mathrm{r}_u = \sqrt{\frac{\Sigma Ae}{hl}} \tag{1}$$



(a) (b)

Figure 8: Typical crack patterns and compressive stress field Ae in wall

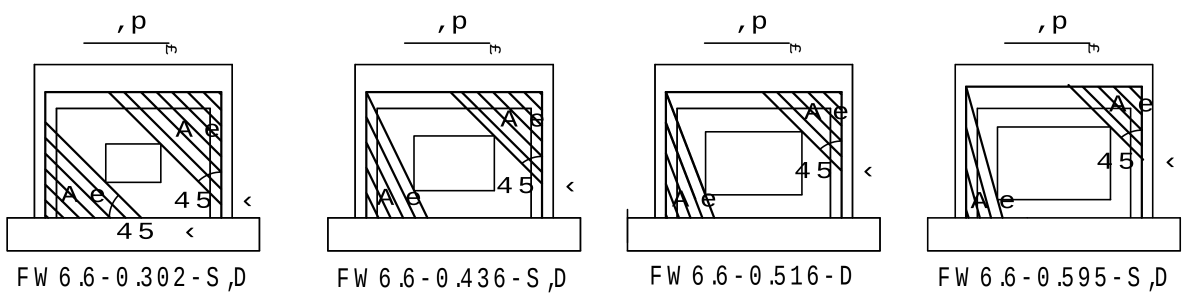


Figure 9: Compressive stress field Ae in wall of test specimen

Table 2 : Comparisons of experimental maximum strength Quex with calculated maximum strength ru Quo and r Quo

Specimen	Quex (kN)	Quo1 (kN)	Quo2 (kN)	Quo3 (kN)	ru	r (r1,r2)	Quex / ru Quo1	Quex / r Quo1	Quex / ru Quo2	Quex / r Quo2	Quex / ru Quo3	Quex / r Quo3
FW6.6-0.302-S	+ 405	634	525	479	0.707	0.688*1	0.904	0.928	1.090	1.119	1.196	1.227
	- 397						0.886	0.91	1.069	1.097	1.173	1.204
FW6.6-0.302-D	+ 472	649	541	484			1.029	1.056	1.233	1.265	1.379	1.415
	- 430						0.938	0.963	1.124	1.154	1.258	1.291
FW6.6-0.436-S	+ 318	634	525	479	0.613	0.544*1	0.843	0.95	1.017	1.146	1.116	1.257
	- 309						0.795	0.896	0.956	1.081	1.052	1.186
FW6.6-0.436-D	+ 365	649	541	484			0.919	1.035	1.101	1.240	1.231	1.387
	- 332						0.835	0.941	1.000	1.128	1.119	1.261
FW6.6-0.516-D	+ 301	651	549	486	0.539	0.450*1	0.856	1.026	1.017	1.218	1.148	1.375
	- 243						0.691	0.828	0.820	0.983	0.926	1.109
FW6.6-0.595-S	+ 187	640	533	481	0.431	0.356*1	0.678	0.821	0.816	0.988	0.903	1.093
	- 197						0.714	0.865	0.859	1.040	0.950	1.151
FW6.6-0.595-D	+ 223	651	544	485			0.794	0.962	0.951	1.152	1.068	1.293
	- 206						0.736	0.891	0.881	1.067	0.989	1.198
The results on statistical study included both positive and negative maximum strength.						A	0.830	0.934	0.995	1.120	1.108	1.246
						SD	0.099	0.070	0.119	0.083	0.132	0.096
						CV	0.119	0.075	0.119	0.074	0.119	0.077
The results on statistical study of small maximun strength in the positive and negative muximum strength.						A	0.794	0.893	0.952	1.071	1.060	1.192
						SD	0.091	0.049	0.111	0.060	0.121	0.067
						CV	0.115	0.055	0.116	0.056	0.114	0.056

Note j + : Positive loading |: Negative loading ru = ă Ae/hl

hl : Area of wall Ae : compressive stress field in wall

r = mini (1 l0 /l, 1 | ă l0h0 / hl) *1 : r1 = 1 l0/l

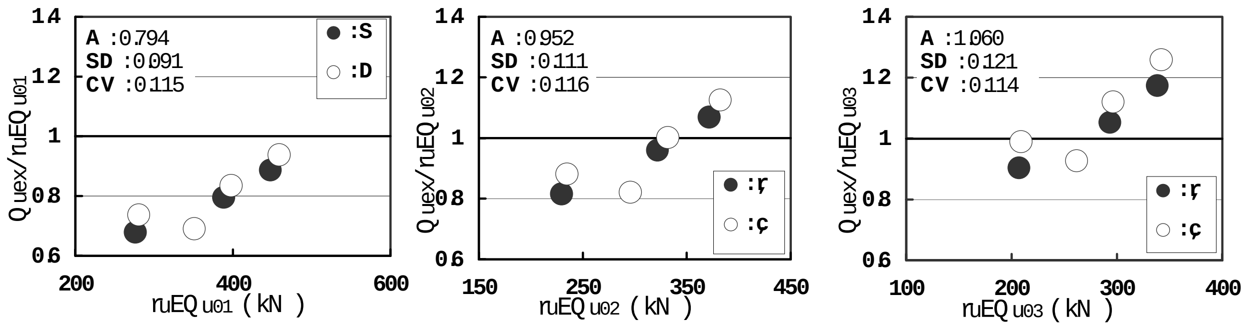


Figure 10: Relationship between experimental maximum strength Quex and calculated one ru Qu01, ru Qu02, ru Qu03

INVESTIGATION OF MAXIMUM STRENGTH

The equation proposed by Tomii & Ezaki [15], Hirosawa [4] and Mochizuki [7] were used to calculate the maximum strength Quo (Quo1, Quo2, Quo3) of RC framed shear walls without opening; where, Quo1, Tomii &Ezaki; Quo2, Hirosawa; Quo3, Mochizuki. By using Quo, ru of Eq.(1) and the strength reduction factor r of the AIJ RC standard, the comparisons of experimental maximum strength Quex with calculated maximum strength ru□Quo and r□Quo for each specimen are shown in Table 2 and Figure 10. Furthermore, the average A , standard deviation SD and coefficient of variation CV are shown in Table 2 and Figure 10. According to the values of A, SD and CV, the maximum strengths calculated using ru and r of each specimens agrees well with its experimental maximum strengths.

CONCLUSIONS

The effects of loading velocity were not observed in the inclination angle of the inclined cracks in the wall.The effects of loading velocity were observed in the crack numbers and the degrees of failure. The degree of failure in the wall and columns during static loading was more pronounced than the dynamic loading.When the opening ratio is under 0.4, the effects of loading velocity can be observed in lateral load-displacement relationship and the failure mode. The effects of loading velocity can be observed in through the strength of the test specimens. In the case of dynamic loading, the maximum strengths of positive loading became about (10~20)% larger than ones of the negative loading. Moreover, maximum strengths during negative loading were almost equal to ones during static loading.By using the equation to calculate accurately the maximum strength of RC framed shear wall without opening and the strength reduction factor r_u proposed by the authors, those maximum strengths during static and dynamic loading can be estimated with enough accuracy for practical usage.

REFERENCES

Architectural Institute of Japan. (1979), “AIJ Standard for Structural Calculation of Reinforced Concrete Structures.”.

Arai, M. , Tanigawa, Y. ,Mori, H. , and Hiraiwa, T. (1996), “Dynamic properties of concrete under high-speed compressive loading, Proceeding of JCI, vol.18, No.1, pp549-554.

Fukushima, T. , Adachi, H. , Nakanishi, M. , Okuda, A. and Akuzawa, M. (1995) "Study on effect of loading rate on ultimate strength of reinforced concrete columns (Part1. Effect of loading rate on material behavior)",Summaries of Technical Papers Annual meeting of AIJ, Aug, PP409-410.

Hirosawa, M. (1975), Past experimental results on reinforced concrete shear wall and analyses on them (in Japan), Kenchiku Kenkyu Shiryo, 6, pp61□63.

Hosoya, H. , Abe, I. , Okada, T. and Kitagawa, H. (1993),“A study of the effect of strain rate on strength and mode of failure of reinforced concrete (RC) members –Material tests and horizontal loading tests of column members under the high axial load –”, Concrete Research and Technology , Vol.4,No.2,July,PP43-56.

Iwai, S. , Yoshida, N. , Nakamura, T. and Wakabayashi, M. (1992), "Effects of loading rate on the performance of structural elements (Part 1 Effects the strain rate on stress- strain relationships of concrete and steel)", Transactions of AIJ, Apr, pp102-111.

Mochizuki, M. , Takehara, M. and Onozato, N. (1990), “Analyses of the Maximum Strength of Multi-Story Famed Shear Walls with an Opening Using Macro Model” Proceeding of JCI, Vol.12, No.2, pp569-574.

Nakanishi, M. , Ono, A. , Adachi, H. and Takanashi, S. (1988),“Experimental verification of similitude law and loading rate in dynamic model testing”, Proceeding of JCI vol.10, No.3, pp473-478.

Nakanishi, M. , Takanashi, S. , Adachi, H. and Ono, A. (1989), “ Effect of loading rate on mechanical properties of reinforced concrete columns failing in shear”, Proceeding of JCI,Vol.11,No.2,PP235-240.

Ono, M. and Tokuhiro, I. (1992), “A proposal of Reducing Rate for Strength due to Opening Effect of Reinforced Concrete Framed Shear Walls”, Journal of Struc. Constar. Engng, AIJ, No. 435,May, pp119-129.

Ono, M. (1995), “Experimental study on Elasto-Plastic behavior of Reinforced Concrete Frame Shear Walls with a large opening ”, Transactions of JCI, Vol. 17 pp381-388.

Ono, M. and Tokuhiro, I. (1996), “Study on Estimate of the Shear Strength of Reinforced Concrete Framed Shear Walls with Opening”, Concrete Research and Technology, JCI, Vol.7, No.2, July, pp53-64.

Satou, M. Shirai, N. and Seki, N. (1986), “Study on Elasto-Plastic Behavior of Reinforced Concrete Shear wall Structures (Part 28. Evaluation of Ultimate Strength of Shear walls by FEm)” Summaries of Technical Papers of Annual Meeting of AIJ, Aug, pp289-290

Shimbo, H. , Murayama, Y. , Suda, K. and Ichinomiya, T. (1995),“Rate of loading effects on P-δ relationship of RC members”, Proceeding of JCI, vol.17, No.2, pp469-474.

Tomii,M. and Ezaki, F. (1981), “Study on Lateral Shear Capacity of Reinforced Concrete Framed Shear Wall (Part 1.Lateral Shear Capacity Controled by Slip Shear Failure of Wall) ” , Summaries of Technical Papers of Annual Meeting of AIJ, Sept, pp1587-1588.