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Effects of loading rate on reinforced concrete shear walls: Part 1 Dynamic properties of large-size rebars

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Abstract

The objectives of this study are to experimentally investigate the effects of loading rate on reinforced concrete shear walls, and to propose material constitutive laws of concrete and rebars accounting for the effects of loading rate.

Part 1 of this study shows the results of high speed tensile loading tests of large-size deformed rebars of 38 mm and 51 mm in diameter with the temperature of test specimens varied. The loading speeds were varied from 0.01 cm/s (static) to 200 cm/s. The temperature of the specimens was set to -20°C, 20°C and 60°C, respectively. The regression curves of the yield strength of large-size rebars accounting for effects of both strain rate and temperature are proposed based on the test results.

1 Introduction

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

It is well known that the yield strength of rebars increases as the strain rate increases by previous experimental researches [e.g. 1),2),3)] However, there are relatively large scatters in obtained dynamic increase factors (DIF) of yield strength depending on kinds of steel, diameters and testing methods. In the present study, the dynamic properties of large-size rebars used in actual nuclear related structures are main concerns even with the variation of atmospheric temperatures. Thus, high speed tensile loading tests of large-size rebars, ranging from 38mm to 51mm in diameter, at the low, normal, and high temperatures were carried out for the purposes. Further, this study presents regression formuli of the dynamic properties of large-size rebars accounting for effects of both strain rate and temperature based on the test results.

2 Outline of the Tests

Unconfined tensile tests were performed using large-size deformed rebars, namely, D38 blast furnace (SD345), D38 electric furnace (SD345), and D51 blast furnace (SD390), of which the nominal yield strength are $345 N/mm^2$ for SD345 and $390 N/mm^2$ for SD390, respectively. In this test, two strain rates of $10^{-2}/s$ and $10^{0}/s$, called low speed and high speed respectively, were chosen. Static loading tests at the strain rate 10^{-4} /s were also performed for the comparison. In addition, the temperatures of specimens, +60℃, +20℃, and -20℃ which are called high, normal, and low temperatures respectively, were selected.

Fig. 1 shows the drawing of a specimen. The length of the specimen is eight times the rebar's nominal diameter with both ends weld-bonded to the loading jigs of diameter twice that of the rebar. Fig. 2 shows a gas hydraulic type dynamic loading apparatus at Sumitomo Metal Technology Inc., which can load at a speed upto 2 m/s. The maximum loading capacity is 1.5 MN, and the maximum stroke is 250 mm. The loads are measured by a strain gauge placed on the loading jig. The strains are obtained by averaging relative displacements at both ends of the specimen measured by a optical displacement meter, and the strain rates are defined by averaging between the starting point of loading and the upper yield point in the strain-time relationship. The elongation after fracture is also measured.

3 Test Results at Normal Temperature

3.1 Stress-strain relationship

The stress-strain relationship of the D38 blast furnace rebars, as an example, is shown with the variation of strain rates in Fig. 3. In all the cases, the yield strength and tensile strength increase as the strain rates increase, and it should be noticed that the fracture elongation increases at the high speed loading.

3.2 Strength properties of rebars

The strain rate effects on the lower and upper yield strength, and the tensile strength of large-size rebars are summarized below.

Fig. 4 shows the dynamic increase factors (DIFs hereafter) of the lower yield strength of D38 blast and electric furnaces, where DIF is defined as the ratio of dynamic strength to static strength. At the strain rate of 10^{-2}/s (low speed), the DIF is about 1.1, and it is about 1.2 at the strain rates of 10^{0}/s (high speed) , and. there are little differences in the rate effects on the strength of the two types, blast and electric furnaces. The regression formula is evaluated for the DIF of the lower yield strength of D38 as a function of strain rate based on the test results as follows.

$$\frac{{}_D f_y}{{}_S f_y} = 1.18 + 0.085\log(\dot{\varepsilon}) + 0.010 \times \log(\dot{\varepsilon})^2 \quad \cdots\cdots (1)$$

(for the lower yield strength of D38)

where, ${}_D f_y$: dynamic yield strength

${}_S f_y$: static yield strength

$\dot{\varepsilon}$: strain rate

Fig. 5 shows a comparison of DIFs of the lower yield strength of D51 blast furnace to the regression curve of D38. The DIFs of D51 show 1.04 and 1.13 at the strain rates of 10^{-2}/s and 10^{0}/s, respectively, and the DIFs of D51 show slightly smaller values compared to that of D38. The regression formula DIF of the lower yield strength of D51 is given by Eq. 2.

$$\frac{{}_D f_y}{{}_S f_y} = 1.12 + 0.060\log(\dot{\varepsilon}) + 0.076 \times \log(\dot{\varepsilon})^2 \quad \cdots\cdots (2)$$

(for the lower yield strength of D51)

Regarding the upper yield strength shown in Table 1, the DIFs for D38 are about 1.1 at low speed and 1.5 to 1.7 at high speed respectively,. For D51 blast furnace, the DIFs are slightly lower than those of D38, that is, 1.07 att low speed, and 1.20, at high speed.

The DIFs of tensile strengths both for the D38 blast and electric furnaces range from 1.05 to 1.06 and from 1.11 to 1.12 at the low and high speeds respectively. For D51 blast furnace, the DIFs of tensile strengths range from 1.04 to 1.08. It should be mentioned that the DIF of tensile strength is slightly smaller than DIF of the yield strength.

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3.3 Elongation after fracture and Young's modulus

The fracture elongation with the variation of strain rates is shown in Fig. 6. The elongation for D51 is smaller than that of D38. As for the strain rate effects, as shown in Table 1, the values stay unchanged at low speeds, but at high speed, the values increase, up to 1.1 to 1.2 times the static values.

As shown in Table 1, Young's modulus shows the slight increase as well as the strain rate increases. The ratios to the static values are from 1.07 to 1.12 at low speed, and 1. 14 to 1.21 at high speed for D38, and for D51, the DIFs of Young's moduli are 1.06 and 1.08 at low and high speeds respectively.

4 Test Results at High and Low Temperatures

4.1 Stress-strain relationship

Fig. 7 shows the stress-strain relationship of D51 at the high speed loading with the variation of the temperatures, as an example. There are common tendencies observed in the stress-strain relationships for the specimens of D38, that is, the yield strength and tensile strength increase as the temperature falls, and no significant influence of temperature is observed on the elongation at fracture.

4.2 Strength properties of rebars (Rate effects at each temperature)

Fig. 8 shows the DIFs of the lower yield strength of D51 with the variation of temperatures. For the results at the normal temperature (+20℃), the regression curve Eq.2 is also plotted. The DIFs at the low (-20℃) and high (+60℃) temperatures slightly exceed the average DIF at the normal temperature. However, the differences in DIF of the lower yield strength due to temperature are not significant.

4.3 Strength properties of rebars (strain rate/temperature dependency)

Fig. 9 shows the DIFs of the lower yield strength of D38 with the variation of both the strain rates and temperatures as well as the evaluated regression formula given by Eq.3.

$$\sigma_y = 243\exp\left(\frac{3631}{R}\right) \quad R = T_k \ln\left(\frac{9.500\times10^8}{\dot{\varepsilon}}\right) \quad \cdots\cdots (3)$$

(for the lower yield strength of D38)

where,

σ_y : lower yield strength (N/mm^2), T_k : atmospheric temperature(K)

$\dot{\varepsilon}$: strain rate (1/s)

Fig. 10 shows the DIFs of the lower yield strength of D51 with the variation of both the strain rates and temperatures as well as the evaluated regression formula given by Eq.4.

$$\sigma_y = 325\exp\left(\frac{2878}{R}\right) \quad R = T_k \ln\left(\frac{4.743\times10^9}{\dot{\varepsilon}}\right) \quad \cdots\cdots (4)$$

(for the lower yield strength of D51)

In Figs.9 and 10, the ranges of the loading speeds and temperatures corresponding to each data are shown. The effects of both strain rate and temperature on the lower yield strength of D38 and D51 are well represented by Eqs.3 and 4.

5 Concluding remarks

The experimental results are summarized as follows.

(1) For D38 and D51, large-size rebars, the effect of strain rate on the material properties at the normal temperature were examined. The lower yield strength of D38 was approximately 1.1 and 1.2 times the value of the static test, and for D51 it was approximately 1.04 and 1.13 times at the strain rate of 10^{-2}/s and 10^{0}/s, respectively. It was also confirmed that there is no difference in the rate dependencies on the strength between the blast and electric furnaces, and that D51 with a larger diameter and higher strength exhibits smaller DIFs of strength than those of D38.

(2) The material properties of large-size rebars were examined with the variation of temperatures as well as strain rates. The results show that the lower yield strength and tensile strength for large-size rebars increase as the temperature falls, and that little influence of temperature on the fracture elongation was found. The DIFs of yield strengths at the low (-20℃) and high (+60℃) temperatures stay the same or increases slightly compared to those at the normal temperature.

(3) The regression curves of the yield strength of large-size rebars accounting for effects of both strain rate and temperature were proposed. It was also confirmed that the proposed regression formuli gives a good agreement with the test results.

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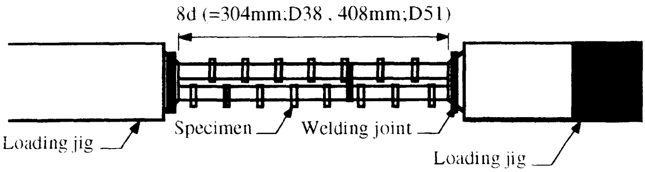

Fig.1 Specimen

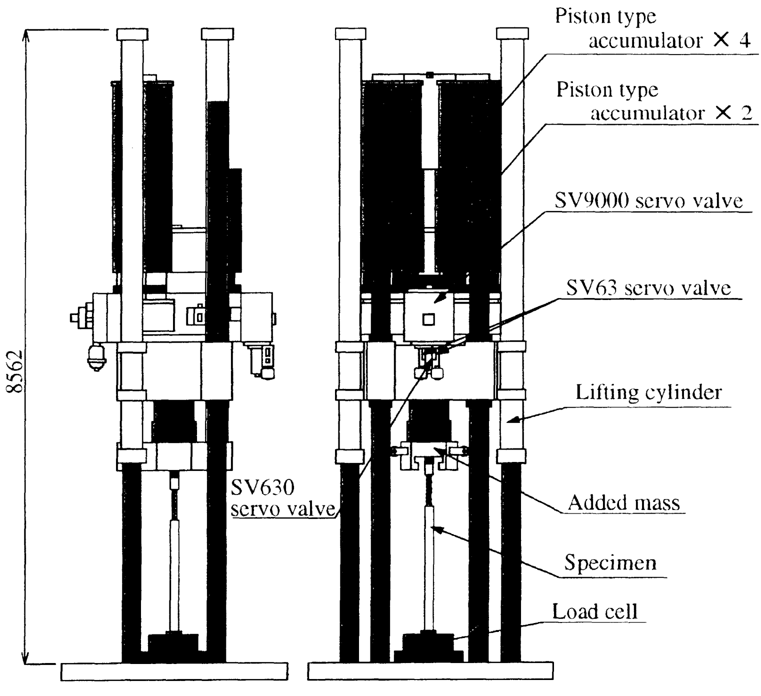

Fig. 2 Dynamic destructive testing machine

Table 1 Specimens and test results

Rebar	Test results										
	Test temperature (℃)	Loading rate (strain rate)	Mean strain rate before yield (/s)	Ratio to Young's modulus of static test	Upper yield point (N/mm²)	Dynamic increase factor :DIF	Lower yield point (N/mm²)	Dynamic increase factor :DIF	Tensile strength (N/mm²)	Dynamic increase factor :DIF	Fracture elongation Δl (%)
D51 Blast furnace SD390	+20℃ Normal temperature	Static	6.1E-5	1.00	449	1.00	446	1.00	655	1.00	17.7
		2cm/s(10^{-2}/s)	8.2E-3	1.06	474	1.06	465	1.04	678	1.04	17.9
		2m/s(10^{0}/s)	1.4E+0	1.08	539	1.20	502	1.13	707	1.08	19.2
	+60℃ High temperature	Static	5.9E-5	1.00	424	1.00	424	1.00	627	1.00	16.5
		2cm/s(10^{-2}/s)	8.4E-3	1.08	453	1.07	446	1.05	650	1.04	17.8
		2m/s(10^{0}/s)	1.0E+0	1.11	493	1.16	482	1.14	680	1.08	18.8
	-20℃ Low temperature	Static	7.3E-5	1.00	466	1.00	461	1.00	682	1.00	16.4
		2cm/s(10^{-2}/s)	8.6E-3	1.06	515	1.11	495	1.07	708	1.04	17.2
		2m/s(10^{0}/s)	1.3E+0	1.14	597	1.28	554	1.20	739	1.08	19.2
D38 Blast furnace SD345	+20℃ Normal temperature	Static	1.0E-4	1.00	375	1.00	374	1.00	545	1.00	24.8
		2cm/s(10^{-2}/s)	1.2E-2	1.07	428	1.14	401	1.07	571	1.05	25.4
		2m/s(10^{0}/s)	1.9E+0	1.21	601	1.60	441	1.18	610	1.12	28.9
	+60℃ High temperature	Static	1.1E-4	1.00	361	1.00	358	1.00	521	1.00	23.5
		2cm/s(10^{-2}/s)	1.1E-2	1.14	398	1.10	379	1.06	544	1.04	25.6
		2m/s(10^{0}/s)	1.1E+0	1.12	479	1.33	392	1.09	573	1.10	26.1
	-20℃ Low temperature	Static	1.1E-4	1.00	402	1.00	386	1.00	567	1.00	25.4
		2cm/s(10^{-2}/s)	1.2E-2	1.16	474	1.18	436	1.13	600	1.06	25.4
		2m/s(10^{0}/s)	1.8E+0	1.19	583	1.45	497	1.29	639	1.13	28.4
D38 Electric furnace SD345	+20℃ Normal temperature	Static	1.1E-4	1.00	374	1.00	367	1.00	542	1.00	22.1
		2cm/s(10^{-2}/s)	1.2E-2	1.12	419	1.12	400	1.09	578	1.07	22.6
		2m/s(10^{0}/s)	1.8E+0	1.14	554	1.48	446	1.22	603	1.11	27.5
	+60℃ High temperature	Static	1.1E-4	1.00	351	1.00	347	1.00	518	1.00	22.6
		2cm/s(10^{-2}/s)	1.1E-2	1.22	387	1.10	373	1.07	540	1.04	24.5
		2m/s(10^{0}/s)	1.9E+0	1.14	523	1.49	426	1.23	578	1.12	25.6
	-20℃ Low temperature	Static	1.1E-4	1.00	398	1.00	394	1.00	570	1.00	22.9
		2cm/s(10^{-2}/s)	1.2E-2	1.01	485	1.22	430	1.09	595	1.04	24.3
		2m/s(10^{0}/s)	1.7E+0	1.01	596	1.50	502	1.27	634	1.11	26.5

Note) The values in the table are shown as the average values of three specimens for each test

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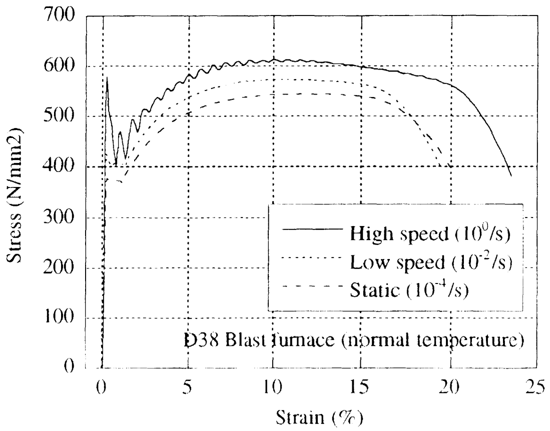

Fig.3 Stress-strain curve (D38 Blast furnace)

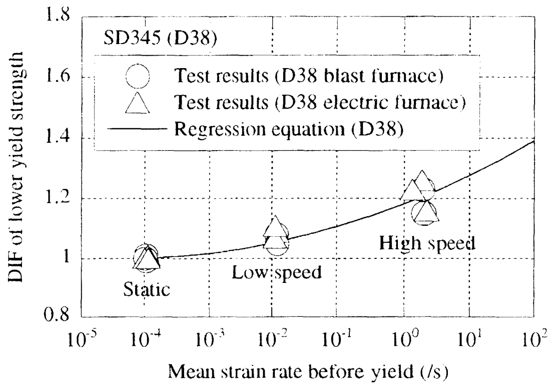

Fig.4 DIF of lower yield strength
(D38 blast furnace and D38 electric furnace)

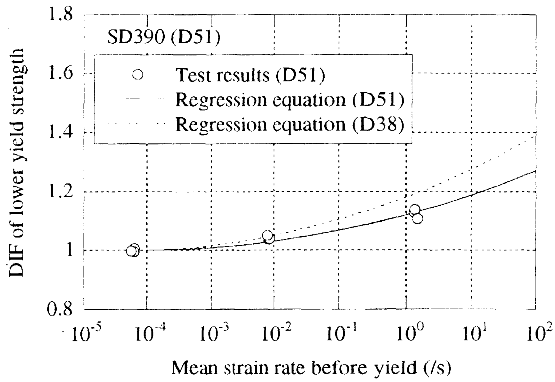

Fig.5 DIF of lower yield strength (D51 blast furnace)

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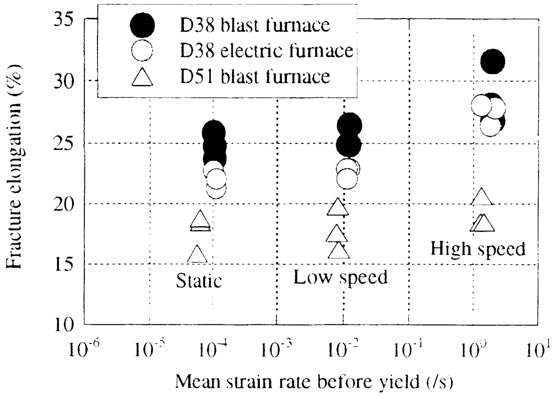

Fig.6 Elongation after fracture (D38 and D51)

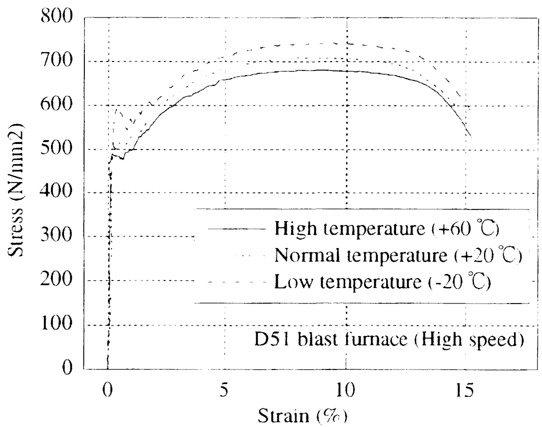

Fig.7 Stress-strain curve of test results with the variation of atmospheric temperatures (D51 high speed)

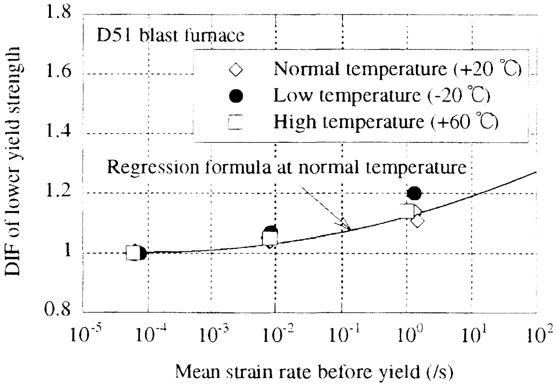

Fig.8 DIF of lower yield strength (D51)

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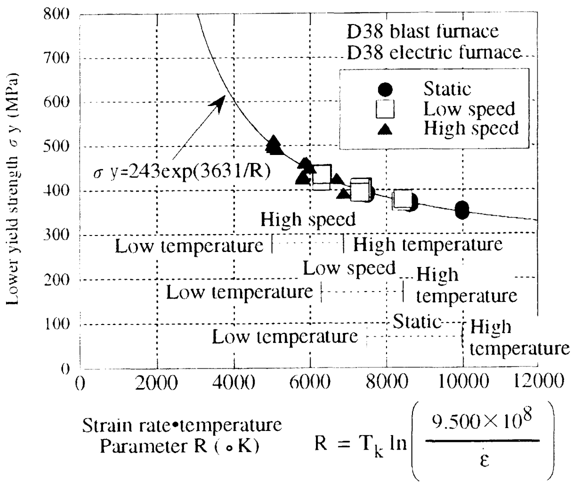

Fig.9 Lower yield strength with the variation of both strain rates and atmospheric temperature (D38)

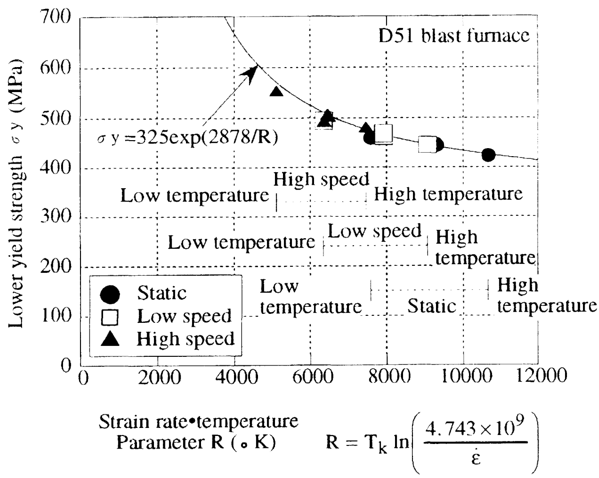

Fig.10 Lower yield strength with the variation of both strain rates and atmospheric temperature (D51)