DEVELOPMENT OF SEISMIC PERFORMANCE FOR REINFORCED CONCRETE MEMBERS WITH EARTHQUAKE - RESISTANT STEEL BAR

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ABSTRACT:

Center for High-Tech Research, Fukuyama University (High-Tech Research Center for Structural and Material Developments) was established in 1999 by the grant from Ministry of Education, Culture, Sports, Science and Technology of Japan. It was researched with the improvements in seismic performance of structures, especially for materials and structures. In 2004, Ministry accepted the continuing project proposal of the center. A group of faculty member of the department of Civil Engineering, Architecture and Mechanical Engineering is now studying on a common theme "Research Project on Improvements in Seismic Performance of Structures" from various aspect of research. In this project, the influence which a few coefficients determine a mechanical performance of main bars do to earthquake energy consumption in formation of the plastic hinge of RC members is considered. Then Earthquake-Resistant Steel was developed in this Center. This paper describes the characteristics of this steel and the application examples in Reinforced Concrete members.

KEYWORDS: Reinforced Concrete，Ultimate Shear Strength，Earthquake-Resistant Steel，Energy Absorption Capacity, Diagonally Reinforcement, Shear Span Ratio

1. INTRODUCTION

In Center for High-Tech Research, Fukuyama University, it was researched with the improvements in seismic performance of full-scale structures, especially for development of exotic materials and application to the structures. Then Earthquake-Resistant Steel (named Fukuyama Low Yield Steel; FLS) was developed in this Center (Yoshimura, H. et al. (2005)).

Authors considered the application of the idea to improve the seismic resistance of short concrete columns, which have repeatedly been pointed out to be greatly affected by shear under earthquake loading, and carried out some basic experiments (Minami, K. et al. (1983)). The results showed that the columns with diagonal reinforcements had considerably superior resistance against seismic loading to those with conventional paralleled reinforcements. Then, the influence of the steel bar do to earthquake energy consumption in formation of the plastic hinge of structural members is considered (Uenoya, M. (2003), Kamiji, K. et al. (2007)). This paper describes the characteristics of FLS and the application examples in Reinforced Concrete members with FLS.

2. MATERIALS

The tensile coupon test results of two materials are obtained as mild steel (SD295A, yield stress of 340 N/mm^2 and tensile strength of 520 N/mm^2) and new low-yield with high tensile strength steel made in Fukuyama University (FLS, nominal 0.2% offset yield stress of 120 N/mm^2 and tensile strength of 465 N/mm^2). The mechanical properties of two materials are summarized in Table 2.

The target for new FLS is to behave as hysteretic dampers to ensure yielding and energy dissipation at the early strain stages and the material strength increases steadily to the ultimate strength of the SS steel in the large strains. Mechanical properties of FLS can lead to the possibility of the development of plastic shear links insert into the framed structures to improve the seismic performance of the structures. The chemical composition of FLS is FE-15% Ni-15% Cr in which carbon content is similar to LY steel.

The stress-strain relationships obtained from the tensile tests are shown in Figure 1. This Figure shows that the tensile stress of FLS (465 N/mm^2) becomes close to the tensile strength of SD (437 N/mm^2) where the strain of FLS (51%) becomes almost 2.5 times of SD (18%).

Table 1—Specimen

Series	Specimens	Concrete Strength	Dimensions		Share Span Ratio	Applied Axial Compression Ratio	Reinforcement			
			Section	Height			Parallel	Diagonal	Shear	
		Fc(N/mm^2)	D×D(mm^2)	h(mm)	h/D					ρ_w(%)
Parallel only	P30F	33.3	300×300	900	3	0	5-φ16	-	D10@75	0.63
	P30S						5-D16			
Mixed Use of Parallel and Diagonal	X30F	35.9		900	3		2-D16	3-φ16	D10@100	0.48
	X30S							3-D16		
	X20F			600	2			3-φ16		
	X20S							3-D16		
	X10F	39.2		300	1		2-D10	4-φ16	D6@50	0.42
	X10S							4-D16		
	X06F			200	0.66			4-φ16		
	X06S							4-D16		
	X03F			100	0.33			4-φ16		
	X03S							4-D16		

Table 2—Material properties of test specimens

Series	Reinforcement	Material	Diameter	σ_y	σ_u	Failure strain
			mm	N/mm^2	N/mm^2	%
Parallel only	hoop	SD295A	D10	328	508	17
	Main bar	SD295A	D16	340	520	18
		FLS	Φ16	120*	465	51
Mixed Use of Parallel and Diagonal	hoop	SD295A	D6	470	559	17
	Main bar	SD295A	D10	337	437	18
		FLS	Φ16	120*	465	51

* 0.2% o set yield stress

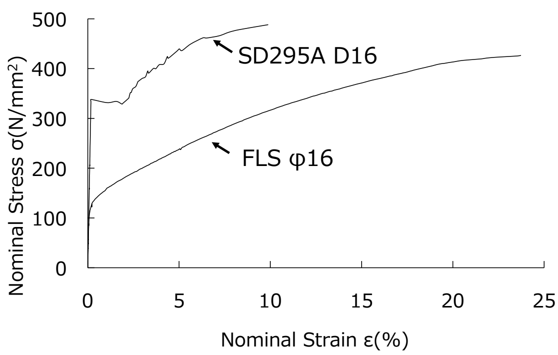


Figure 1—Nominal Stress-Strain Curves of FLS

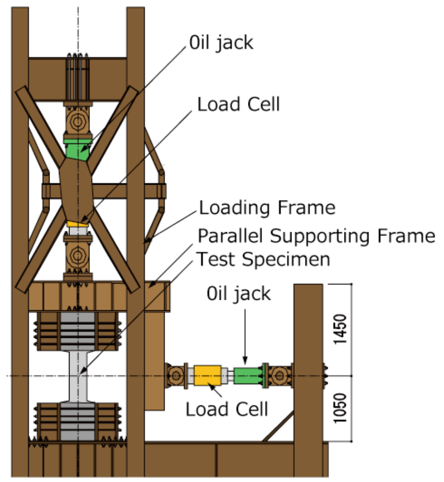
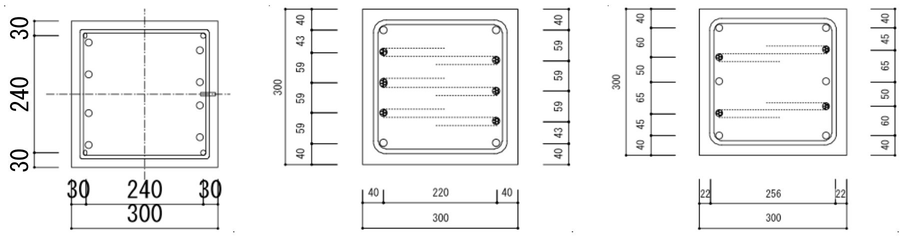


Figure 2—Loading Apparatus

3. TEST SPECIMENS AND TEST SETUP

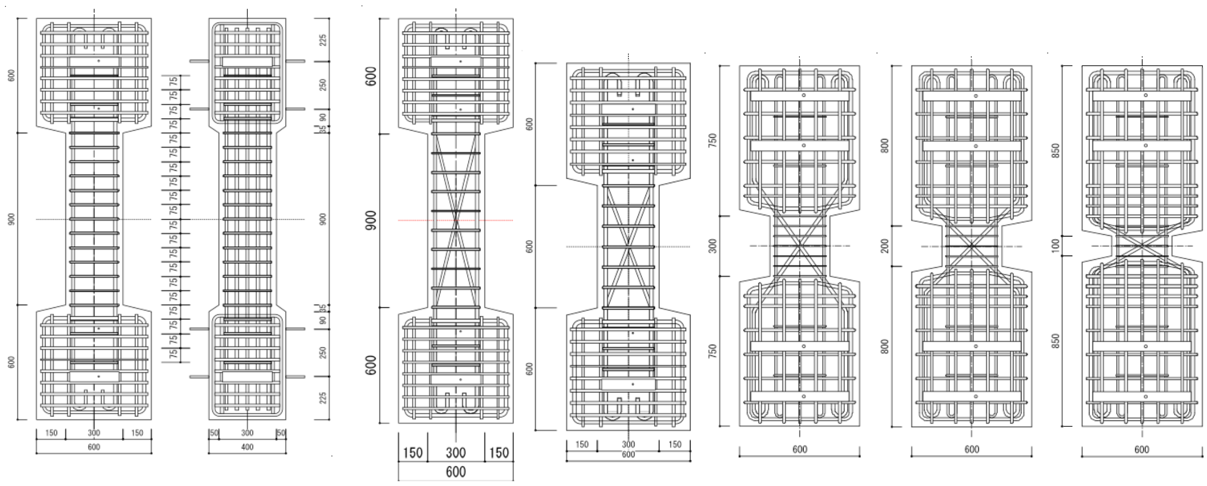
To investigate the seismic behavior of diagonally reinforced members with FLS, a total of 12th specimens are prepared, considering two test parameters: the shear span ratio (h/D=3, 2, 1 0.67 and 0.33) and materials for diagonal reinforcement (SD295A and FLS). The test program is shown in Table 1.

Shown in Figure 3 are the shape, dimensions and reinforcement arrangement of specimens. In the experiments, all the main reinforcements are diagonally placed to intersect at the mid-height of columns in order to clearly observe the basic properties of such members. Test specimens are loaded, making use of the loading apparatus shown in Figure 2, by repeatedly applied anti-symmetric bending moments of equal magnitude at both ends. Horizontal shear is applied under load reversals having gradually increasing amplitude, in which the amplitude is increased after every two cycles. The applied axial compression is zero for all 12th specimens. Mechanical properties of concrete are listed in Table 1 and, reinforcement in Table 2.



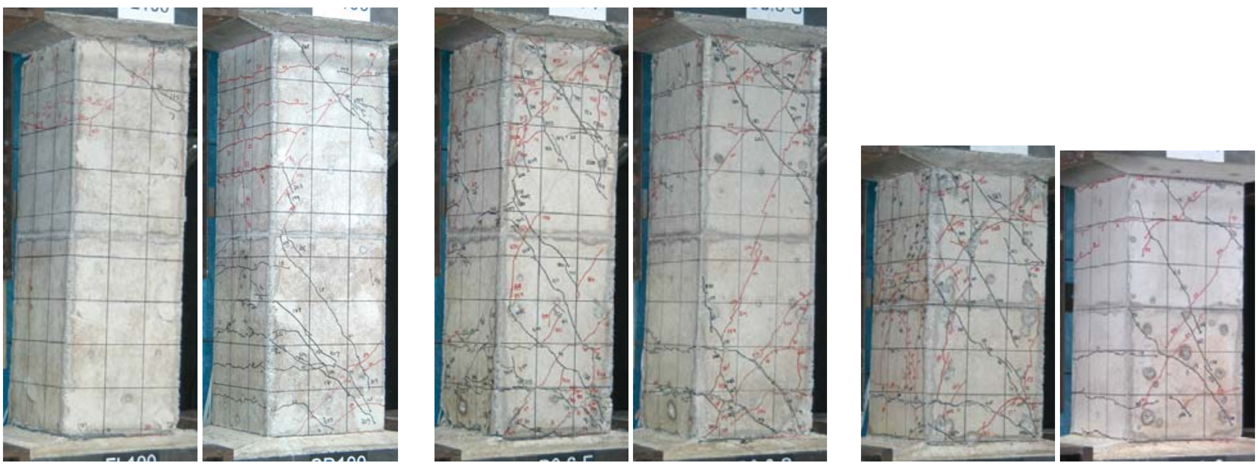
(a) Parallel (b) Diagonal (β_a=0.4) (c) Diagonal (β_a=0.6)

Cross Section for Test Specimens



(a) Parallel (b) Diagonal (h=900, 600, 300, 200, 100mm)

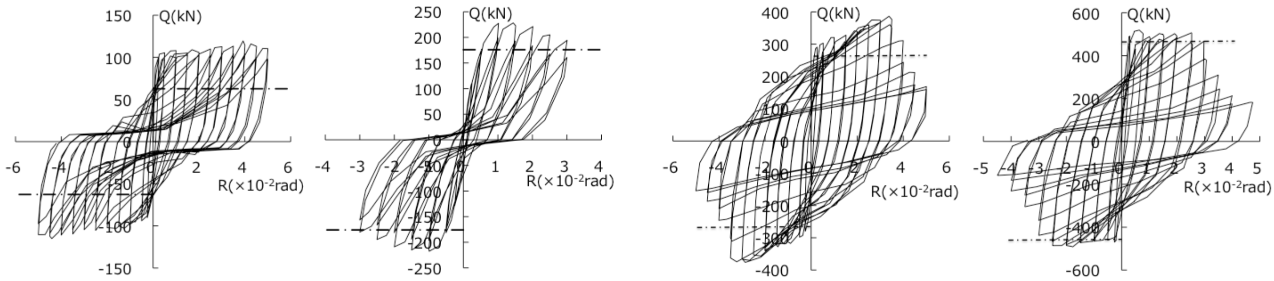
Figure 3—Details of Specimens (Units; mm)



(a)P30F (b)P30S (c)X30F (d)X30S (e)X20F (f)X20S

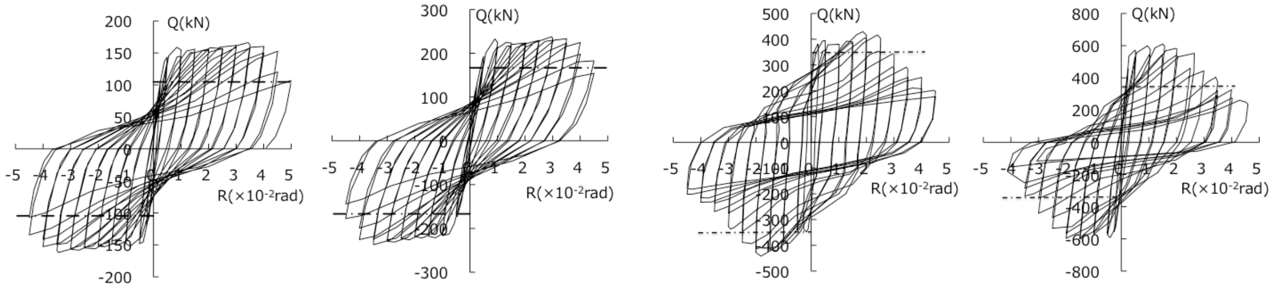
(g) X10F (i) X06F (k) X03F

Photo 1—Failure Modes at the maximum shear strength



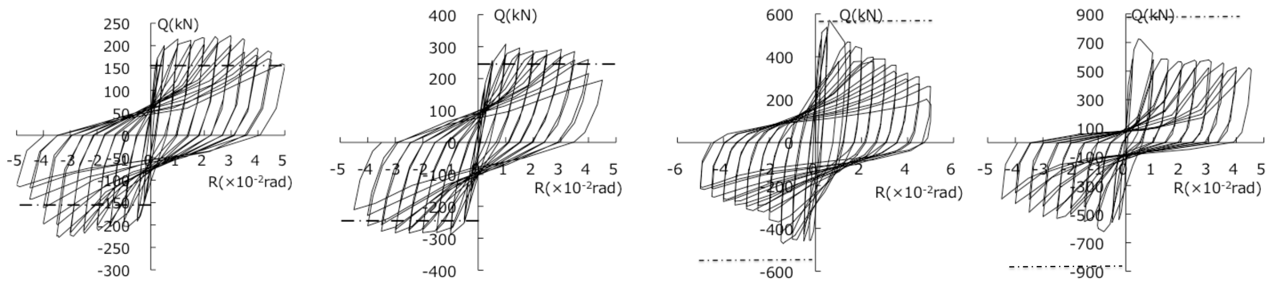
(a) Specimen P30F (b) Specimen P30S
<Parallel reinforcement>

(g) Specimen X10F (h) Specimen X10S
<h=300mm (h/D=1.0)>



(c) Specimen X30F (d) Specimen X30S
<h=900mm (h/D=3.0)>

(i) Specimen X06F (j) Specimen X06S
<h=200mm (h/D=0.67)>



(e) Specimen X20F (f) Specimen X20S
<h=600mm (h/D=2.0)>

(k) Specimen X03F (l) Specimen X03S
<h=100mm (h/D=0.33)>

Figure 4—Hysteretic loops of specimens

4. TEST RESULT AND DISCUSSION

4.1. Failure Mode and Hysteresis Loops

Photo 1 shows the damage at the maximum shear strength. The failure mode of all specimens is flexural failure having some cracks along the diagonal reinforcing bars, except the specimens having longer shear span ratio.

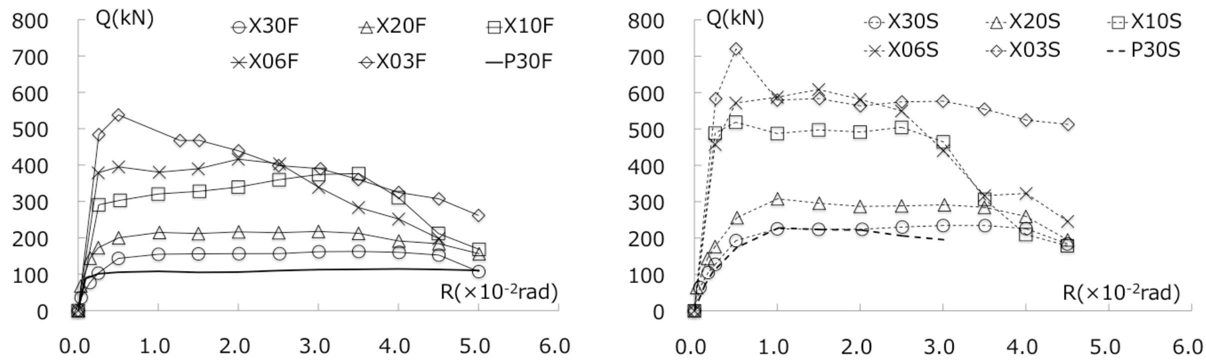
Shown in Figure 4 are the hysteresis loops of all specimens. In the figures, the ordinate represents applied shear Q and abscissa gives the relative slope deflection of columns R. Chain lines in those diagrams denote theoretically obtained ultimate strength. Except the specimen with parallel reinforcement, all the specimens with both FLS and SD showed the deformability up to R=5% rad.

Figure 5 shows the envelope curves obtained in the first cycle of loading for each amplitude level. As the shear span ratio of the specimen becomes small, initial rigidity of members rises gradually regardless of the material of the steel. Note, however, that the strength reduction ratio in the post deflection capacity range is almost constant in the range within the relative slope deflection 2%, except the specimens X03F and X03S, which have the shear span ratio 0.33.

4.2. Energy Dissipation Capacity

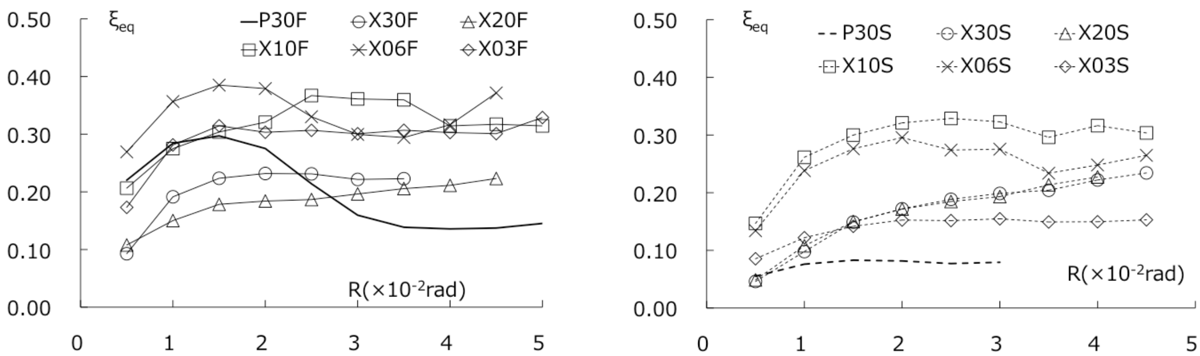
Energy dissipation is an important factor in evaluating the seismic performance of the shear loading. Dissipated energy ξ_{eq} is calculated for each cycle of the hysteretic curves. Figure 6 plots the dissipated energy against the relative slope deflection in each specimen. The energy dissipation of specimens with two steels increases linearly up to the maximum shear capacity, and the energy dissipation capacity of specimens with FLS is nearly 10% more than the values with SD.

Capability of energy consumption of all specimens is given in Figure 7. The ordinate gives the cumulative dissipated energy absorbed by the member calculated from the hysteresis loops, and the abscissa represents the number of loading. There is no appreciable discrepancy between the parallel reinforcement and the diagonally reinforcement in the range of all amplitude of deflection. Specimen X06F provides the largest energy dissipation capacity.



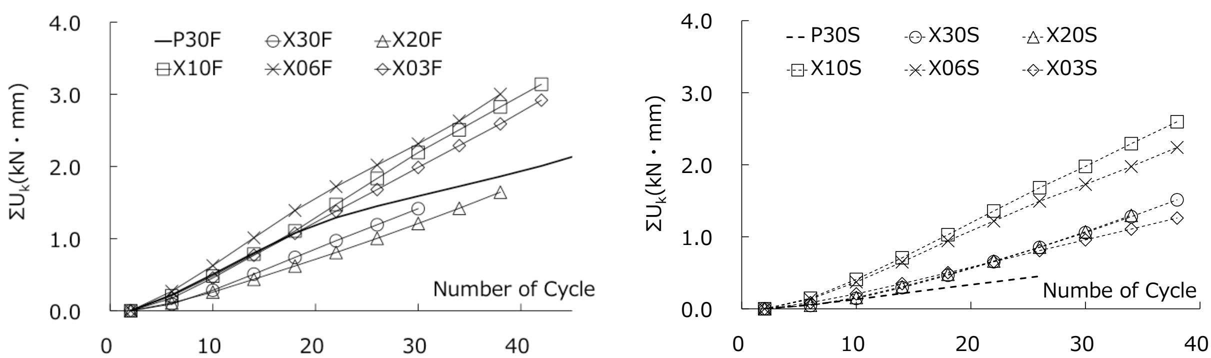
(a) FLS (b) SD

Figure 5—Envelopes of load-rotation curves in positive direction at the first cycle



(a) FLS (b) SD

Figure 6—Transition of equivalent damping factor



(a) FLS (b) SD

Figure 7—Relationships between Accumulative Energy Absorption and Number of Cycles

Table 3—Comparison of measured and calculated strength

Specimens	Calculated Strength Q_{cal}(kN)	Measured Strength Q_{exp}(kN)		Q_{exp}/Q_{cal}	
		Positive Loading	Negative Loading	Positive Loading	Negative Loading
P30S	184	229	218	1.24	1.18
P30F	88	119	115	1.35	1.30
X30F	133	166	162	1.25	1.22
X30S	196	239	238	1.22	1.21
X20F	195	222	228	1.14	1.17
X20S	289	308	289	1.07	1.00
X10F	264	386	376	1.46	1.42
X10S	461	519	491	1.13	1.07
X06F	348	429	442	1.23	1.27
X06S	348	610	600	1.75	1.72
X03F	584	571	471	0.98	0.81
X03S	887	726	623	0.82	0.70

4.3. Ultimate Shear Strength of Columns with Diagonal Reinforcements

The ultimate shear strength Q_{cal} of a reinforced concrete member is calculated by the extended concept of adding component strength of concrete and reinforcements. A summary of results for ultimate shear strength Q_{exp} and the calculated strength Q_{cal} are given in Table 3, where the magnitudes of Q_{exp}/Q_{cal} are calculated from each the positive strengths and the negative ones in each cycle. The value of Q_{exp}/Q_{cal} scatters between 0.70 and 1.75 with its average value of 1.22 at the positive loading. Computed strengths are in good agreement with the test results except for a few specimens.

5. CONCLUSION

Authors consider that the influence of the material do to earthquake energy consumption in formation of the plastic hinge of structural members. Then Earthquake-Resistant Steel (FLS) was developed in our laboratory. This paper describes the mechanical characteristics of FLS and the application examples in Reinforced Concrete members with FLS. The following conclusions are drawn from the results obtained in this study.

1. As the shear span ratio of the specimen becomes small, initial rigidity of specimens rises gradually and the capability of energy consumption of specimen increases up regardless of the material of the steel.
2. The energy dissipation capacity of specimen with FLS is more efficient than those with SD in any range of the relative slope deflection R. Specimen X06F provides the largest energy dissipation capacity.

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