EXPERIMENTAL STUDY ON HYSTERETIC DAMPER WITH LOW YIELD STRENGTH STEEL UNDER DYNAMIC LOADING

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SUMMARY

The purpose of this paper is to perform a study on a shear wall assembled with a hysteretic damper unit. Each unit of the shear wall damper is composed of a W-section which is the conventional mild steel structural shape with low yield strength steel, and it is used to control stiffness and resistance of the assembled shear wall damper by changing the number of unit. This kind of hysteretic damper needs high deformation capacity and need to be able to absorb hysteretic energy, because of concentrating cyclic elasto-plastic deformation in low yield strength steel. Recently in Japan, low yield strength steel has been used for hysteretic dampers. Over the past few years a considerable number of studies have been made on utility techniques of low yield strength steel. This steel has two principal mechanical characters as follows: its yield point is one-thirds of that of JIS SN400 (equivalent to ASTM A36), around 100 N/mm^2 (which is called LY100), and its capacity of elongation is over the double of elongation of SN400, over 50 percent. LY100 is suitable to use for the steel damper, because the damper with LY100 ensures yielding and energy dissipation for smaller deformation and large deformation concentrates on the part of LY100 compared with that of conventional mild steel. However, the mechanical characteristics, particularly yield point are influenced by strain rate. Therefore, we conduct examinations for these dampers under dynamic and static loading, to investigate the energy dissipation capacity of the damper under dynamic loading, increasing stress of strain rate at this damper.

INTRODUCTION

After the 1995 Hyogo-ken Nanbu earthquake, structural control has paid much attention to seismic design, with the premise that such control can improve ultimate resisting capacity of structures and reduce their damage under earthquake loading. A hysteretic damper is a type of passive control device which uses the hysteresis of the material of the damper as the source of energy dissipation. A disadvantage of such dampers is that they absorb earthquake energy only when they go through inelastic deformation. To overcome this restriction of hysteretic dampers, low yield strength steel whose nominal yield stress is about 100-140N/mm^2 class, is used as the

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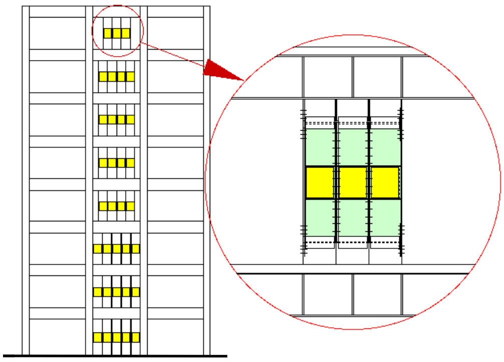


Figure 1: Example for frame with dampers

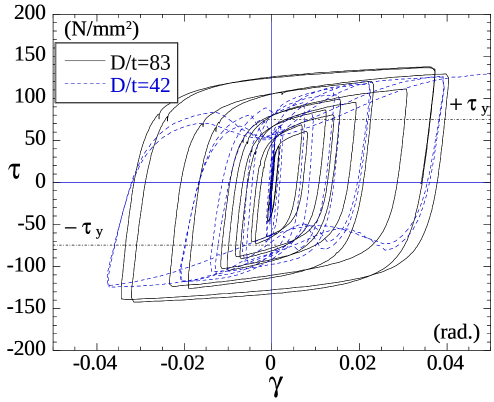


Figure 2: Results of incremental loading test: comparison on D/t

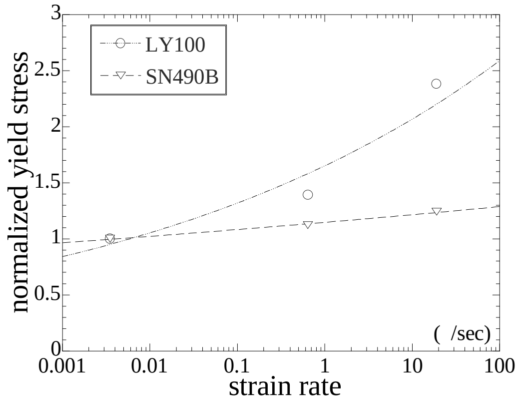


Figure 3: Effects of strain rate

material for hysteretic damper [Nakashima, 1995 and Shimokawa, 1998] in Japan. Use of such low yield strength steel instead of conventional mild steel ensures yielding for a relatively small deformation without changing the dimension of the dampers and stiffness. In this study, low yield strength steel is used as shear panels subjected to in-plane shear force, because yielding of the low yield strength steel can spread over the entire plate in case of a pure-shear deformation, which promises large energy-dissipation capacity. Figure 1 illustrates a prototype building into which hysteretic dampers consisting of shear panels with low yield strength steel (designated LY100 in this paper) are installed. And Figure 2 shows an example of hysteresis loops of a hysteretic dampers (depth-thickness ratio D/t of LY100 plates are 42 and 83) [Hirota, 1997]. Compact shear panel (D/t=42) made of LY100 show stabilized hysteresis loops, and non-compact shear panels (D/t=83) show degradation, in case of more than 0.02 radian shear deformation, in strength, stiffness and energy dissipation which is caused by the growth of out-of-plane deformation after shear buckling. Also strain hardening under cyclic load is conspicuous. Besides, 100 N/mm^2 class low yield strength steel is influenced by strain rate. Figure 3 shows the variation in normalized yield stress due to strain rate. Yield stress may increase by about 50 percent under strain rate which may be 30~60%/sec in hysteric dampers during earthquakes [HOMMA, 1997].

We conduct a study to quantify the increase of the strength and energy dissipation capacity under high-speed cyclic loading, because such quantification is very important for the design of hysteretic dampers with low yield strength steel.

TEST SPECIMEN AND TEST METHOD

Material

Figure 4 indicates σ-ε relation of low yield strength steel (LY100) compared with conventional mild steel (JIS SN400B, equivalent to ASTM A36). Material properties are presented in Table 1. The yield point of LY100 is about half as high as that of conventional

Table 1: Material properties

Test specimen: JIS 5

Material	thickness (mm)	σ_y (N/mm^2)	σ_u (N/mm^2)	EL (%)
LY100	5.9	*129	255	50.9
SN400B	17.1	293	461	46.8

*: 0.2% offset yield stress

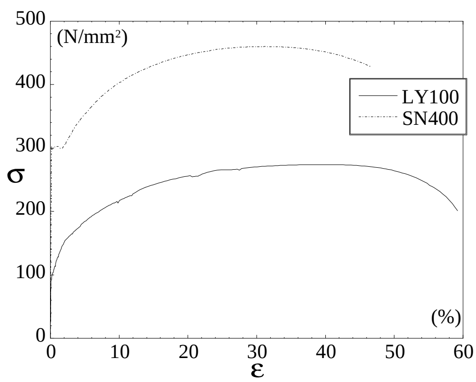


Figure 4: Comparison of σ–ε relationship between low yield strength steel and conventional mild steel

mild steel, and the nominal value of elongation for LY100 is over 50 percent (cf. that of SN400B, over 18-24 percent).

Specimens

To understand the basic behavior of the damper, we examined a unit of resistance element in this paper. Figure 5 shows a specimen, the composition of one unit of the shear wall damper: Using wide flange roll-formed section H-600x200x11x17 (JIS SN400B), a rectangular webbed part is cut out (500x560mm), and welded around a LY100 rectangular plate (6x520x580mm) with fillet welding. D/t of LY100 plate is stiffened by flat bar adjusting D/t=42.

We prepared the six test specimens to investigate the effect of strain rate depending on the parameter conditions attached to the different loading speeds. We planned two patterns of loading history: incremental and earthquake responses, two sorts of seismic wave, JMA Kobe and Yokohama are used.

Table 2: Test specimens

name	D/t-LY100	loading history	speed of loading	
60DDC	42 (t=6mm)	Incremental	dynamic	1Hz/cycle
60DSC			static	0.5mm/sec
60DDK		JMA Kobe	dynamic	real time
60DSK			static	0.5mm/sec
60DDY		Yokohama (artificial)	dynamic	real time
60DSY			static	0.5mm/sec

Table 2 summarizes all of the test specimens and loading speeds.

2.3 Test setup and measurement

Figure 6 shows the loading setup in this test. The test

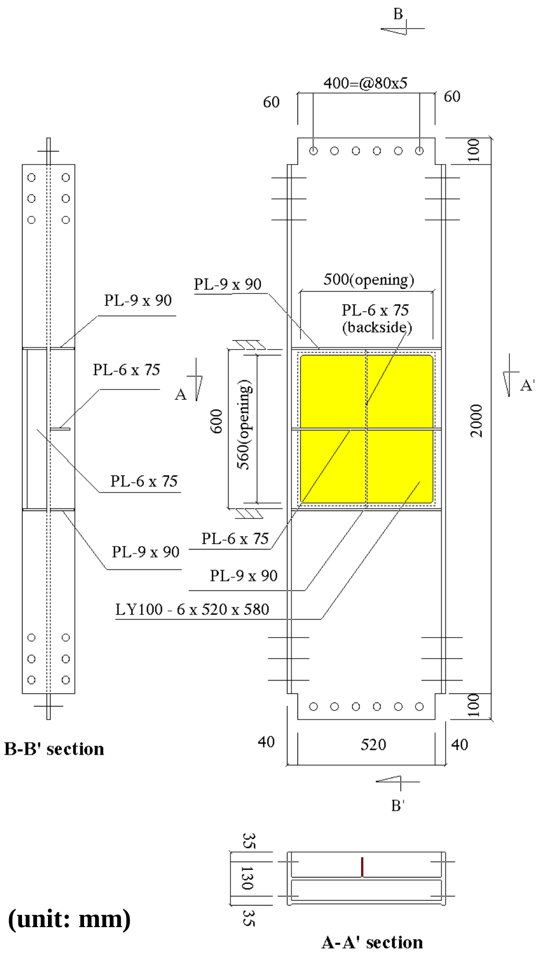


Figure 5: Test specimen

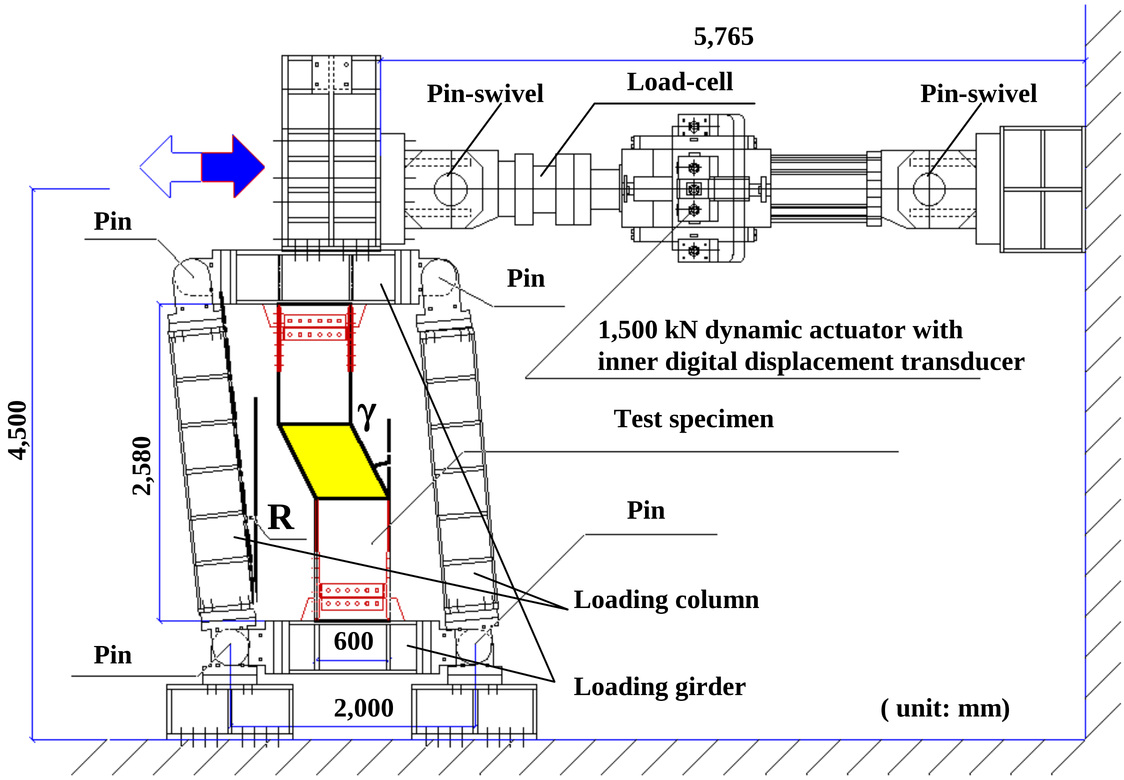


Figure 6: Test setup and definition of drift angles

specimen was installed between loading girders and fastened to them by high-strength bolts. Forced displacement was applied quasi-statically and dynamically to the top of the specimen via the top girder by a horizontally placed actuator. Here, drift angle "R" is defined as horizontal displacement divided by a clear height between the loading girders (2,580mm). This drift angle R was monitored by a digital displacement transducer installed in the actuator. The transducer's signal was continuously fed back to a controller that supervises the actuator ram motion with input displacement history into the controller prior to the test.

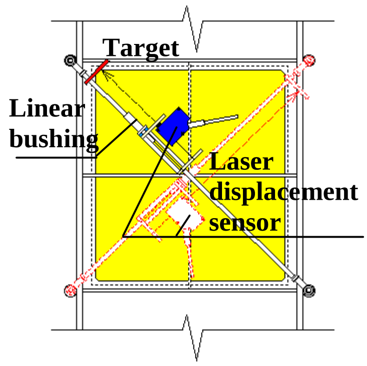


Figure 7: Measurement of deflections

The magnitude of the input load was monitored by a load-cell, installed between actuator and pin swivel. And the term "γ", which can be defined as shear drift angle of LY100 panel, was monitored by laser displacement sensor installed on the upper side of LY100 panel (shown in Figure 7).

Loading programs

For the six specimens, two specimens were loaded cyclically with dynamic (1.0 Hz) and quasi-static speeds (0.5mm/sec), according to the history shown in Figure 8. The ordinate in this figure indicates the horizontal displacement at the top of the specimen relative to its bottom, expressed in term of drift angle R. Two cycles were repeated for each drift angle from 1/800 to 1/50 radian.

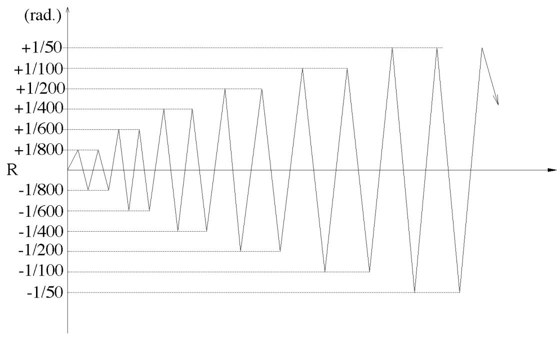
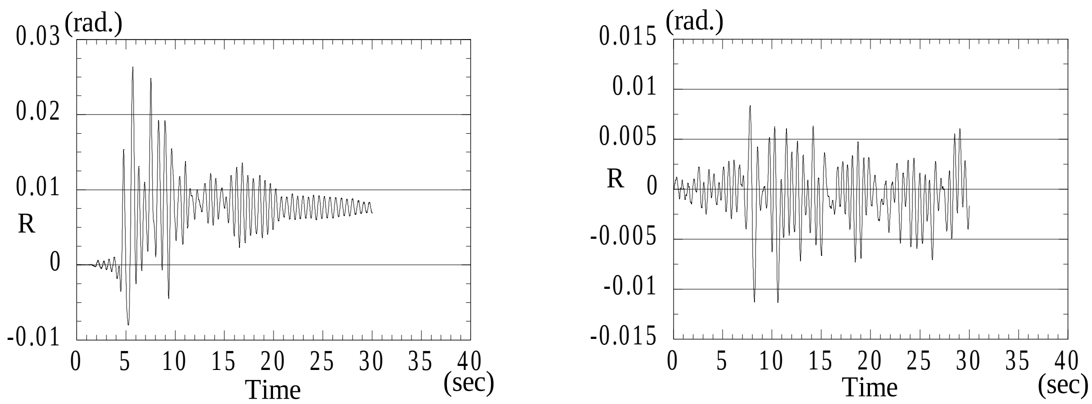


Figure 8: Incremental loading history

The other specimens were loaded randomly with dynamic (real time) and quasi-static (0.5mm/sec) speeds. In these



JMA Kobe, 75kine **Yokohama, 75kine**

Figure 9: Examples for random response of story drift angles

cases, the time histories were the response of story drift of the second story in a 4-story building against JMA Kobe and artificial ground motion Yokohama, shown in Figure 9 respectively. To obtain these time histories, we analyzed the earthquake response of 4-story steel structure with this shear wall type of histeretic

Table 3: Maximum story drift angle and angular velocity

level	JMA-Kobe		Yokohama	
	Rmax(rad)	$\dot{R}$ max(rad./sec)	Rmax(rad)	$\dot{R}$ max(rad./sec)
25kine	0.005	0.057	0.004	0.048
50kine-a	0.014	0.101	0.008	0.066
50kine-b	0.018	0.099	0.008	0.058
75kine	0.026	0.151	0.011	0.084

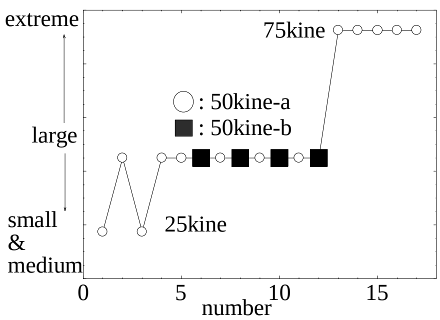


Figure 10: Plan of random loading

damper with LY100 to two ground motions of several intensity levels (25kine, 50kine and 75kine). Figure 10 indicates loading level for each input waves in loading program.

When the input wave is regarded as one set input time history, in total 17 set input time histories were loaded at various levels of input wave. Maximum drift angle and angular velocity of each input level is shown in Table 3.

TEST RESULTS AND DISCUSSION

Results of incremental loading tests

Figure 11 indicates the difference of hysteresis behavior between dynamic and quasi-static loading. The solid line in this figure indicates dynamic loading, and the broken line indicates static loading. Remarkable out-of-plane deformation and crack were not observed in both tests until the end of the tests. Strain hardening was significant in both specimens. The shear stress τ of dynamically loaded specimen, 60DDC, was larger than that of quasi-static loaded specimen, 60DSC at the same shear deformation γ. From the viewpoint of shear stress increase, when the drift angle of whole loading became 0 radian (maximum drift angle speed at each loop became around 40%/sec), the shear stress increase is 20 percent larger than that of static loading. This is caused by the effect of strain rate of LY100, because it is assumed that strain hardening, which consists of kinematic and isotropic hardening, is the same on both dynamic and quasi-static loading. However, the shear stress increase is not significantly large, at most 20 percent shown in Figure 12. It can be seen from the time history of incremental loading in dynamic test traced on sine wave, the angular velocity of shear deformation on the specimens is maximum at γ=0, and minimum at γ = maximum. Although, when the story drift angle reached a maximum (this drift angle speed at each loop became around 0 %/sec), it is only six percent larger than that of static. The shear stress increase for LY100 is mainly caused by strain hardening, on the other hand, shear stress increase by strain rate is not so significant.

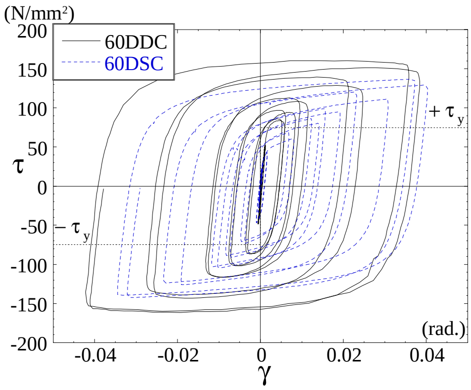


Figure 11: Results of incremental loading test: Comparison on speed of loading

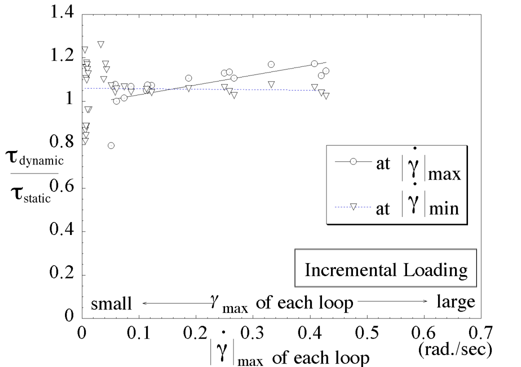
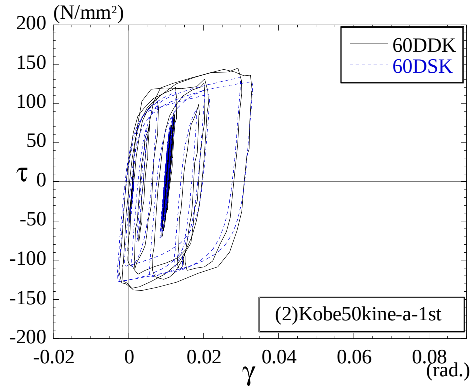


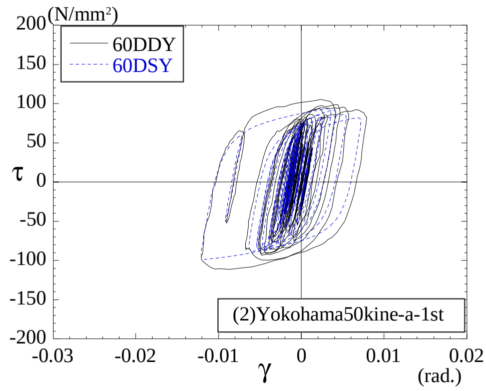
Figure 12: Shear stress increase by strain rate: Incremental loading

Results of random loading tests

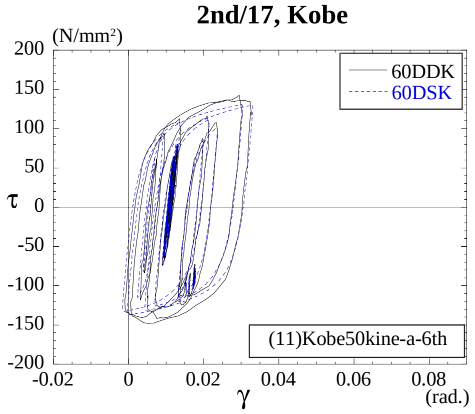
Figure 13 shows several examples of the τ-γ relationship of random loading tests, which are indicated by circles in Figure 14. The solid line in this figure indicates dynamic loading, and the broken line indicates static loading. Figure 14 indicates the variation of maximum loads in each loading set. The photographs at maximum deformation in the 13th set are shown in Figure 15. It is obvious that the maximum shear force is almost constant against the same loading set before occurring crack at LY100 panel, for the 13th set difference between dynamic and quasi-static loading is small. In spite of occurring strain hardening of LY100, shear buckling may contribute to restraining extreme shear stress increase of the damper. The out-of-plane deformation by shear buckling occurred at the 4th and 5th sets in dynamic loading and quasi-static loading respectively in story drift response of Kobe. As the loading test progressed, this deformation gradually increased. Although, the hysteresis loops were not influenced by increasing the deformation before 12th set, under large class seismic waves (50kine). At 15th set (of 60DDK) after maximum loading level from 13th set, which is extremely large class seismic waves (75kine) from this loading set, cracks occurred in three of the four of the divided LY100 panel areas by iteration of shear buckling. The more the number of loading-set, the larger the out-of-plane deformation. Because the stiffener was deformed at the 16th set, loading finished at the 17th loading set. From 13th to 17th loading set, gradually the area of hysteresis loop decreased, because the increasing out-of-plane deformation of LY100-panel and stiffeners occurred at the same time.



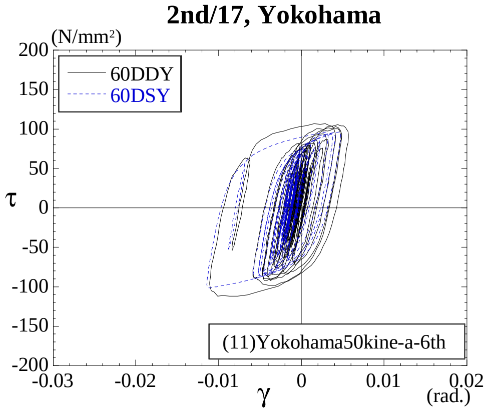
2nd/17, Kobe



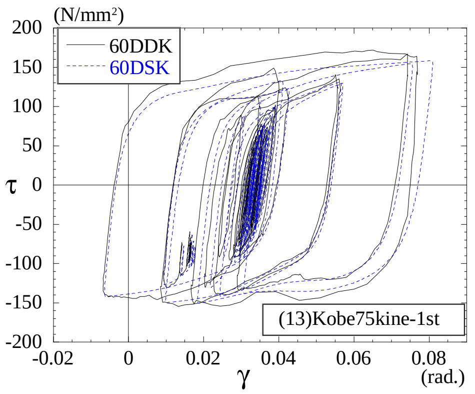
2nd/17, Yokohama



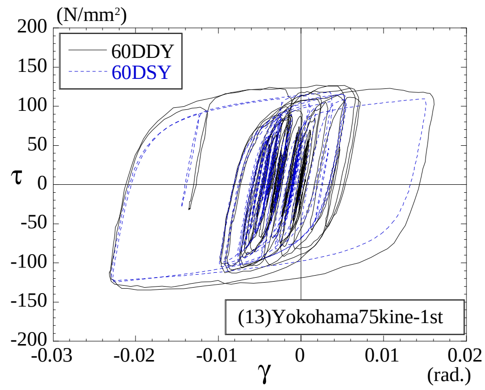
11th/17, Kobe



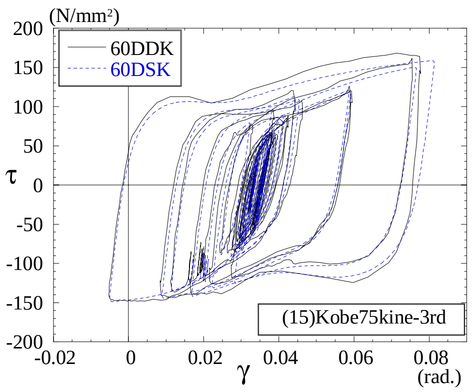
11th/17, Yokohama



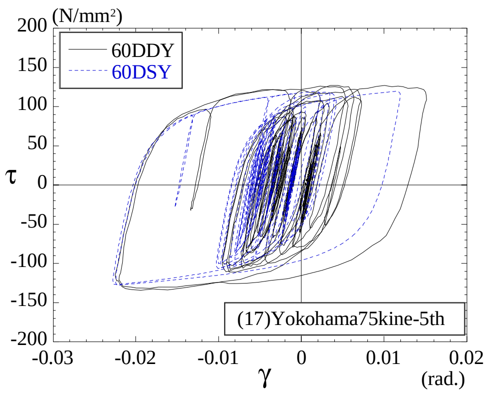
13th/17, Kobe



13th/17, Yokohama



15th/17, Kobe



17th/17, Yokohama

Figure 13: Results of random loading tests

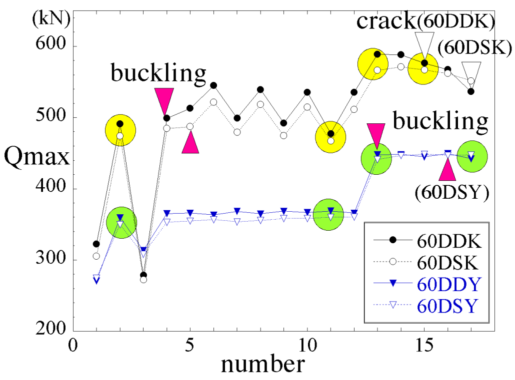
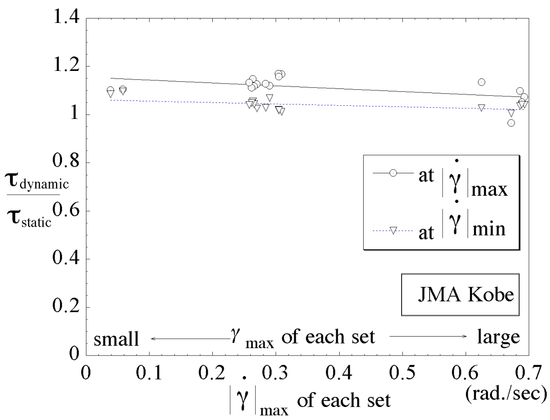


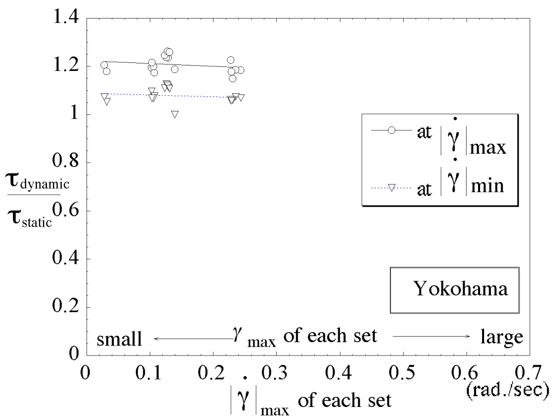
Figure 14: Variations of maximum load

By comparing the shear stress increase under JMA Kobe and Yokohama, the latter is smaller than the former shown in Figure 16. In the random loading tests, the difference of shear stress increase between dynamic and quasi-static tests is about 20 percent as well as the difference observing in incremental loading tests. And both shear stress increase of dynamic and quasi-static maintained almost the same level in spite of increasing angular velocity of shear deformation. This indicates that the effect of the strain rate becomes smaller, as strain hardening becomes larger.

Figure 15: Photograph at maximum deformation



JMA Kobe



Yokohama

Figure 16: Shear stress increase by strain rate: Random loading

Capacity of absorbing hysteretic damping

Figure 17 illustrates definition of cumulative ductility factor η, which is defined as an area of hysteresis loop divided by the product of yield shear force Q_y and yield shear strain γ_y. Figure 18 indicates variations of η for each loading-set. In this figure, the third earthquake is the result of cumulative ductility factor against small earthquake (25kine) after one large earthquake (50kine). In spite of the strain hardening of LY100, the value of η for third earthquake is almost the same as η of first earthquake: level of third earthquake is also 25kine.

According to the study on earthquake response analysis for a 4-story building with this damper, it was revealed that the required cumulative ductility factor is 100 to 200 on cumulative ductility factor against ground motion of JMA Kobe [Kashima, 1998]. As Table 4 indicates, the value of cumulative ductility factor of each specimen is more than requirement. Unequal signs indicate that the specimen had not failed until 17th set loading. Comparing dynamic with quasi-static on cumulative ductility factor for the same ground motion, η of dynamic loading is slightly larger than that of static loading (shown in Figure 18). This is caused by the increase of shear resistance by the effect of the strain rate.

Table 4: Cumulative ductility factor

name	η
60DDC	>1063
60DSC	>1028
60DDK	7262 (*5651)
60DSK	6828 (*6828)
60DDY	>3072
60DSY	>2399

*: by crack occurred

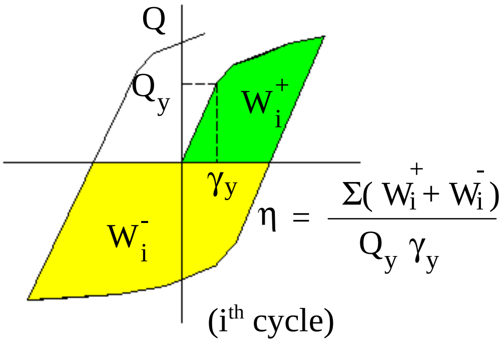


Figure 17: Definition of cumulative ductility factor η

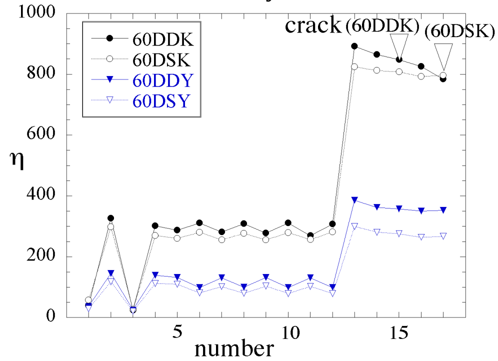


Figure 18: Variations of η

CONCLUSION

The results of this study lead to the following conclusions:

1. The shear stress increase of the shear wall damper (with LY100 which D/t is 42) is mainly caused by strain hardening: though it is also caused by strain rate, its contribution is 20 percent at most, and no more than 6 percent even when the drift angle γ reaches maximum.
2. The shear stress increase of this damper (with LY100 which D/t is 42) is not so much as that of material test of LY100, because shear buckling may contribute to restraining extreme shear stress increase of the damper.
3. The cumulative ductility factor η of the damper is more than five thousand for JMA Kobe ground motion. According to the amount of deformation capacity, the damper can resist large earthquakes several times.
4. Total energy dissipation capacity under dynamic loading is larger than that of static loading, because shear resistance under dynamic loading increases by the effect of strain rate.

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