Effects of Strain-rate on the Hysteretic behavior of Structural Steels

Y. Shimada
Chiba University, Japan

Y. Jiao
Tokyo University of Science, Japan

J. Kim & S. Yamada
Tokyo Institute of Technology, Japan

SUMMARY:
Dynamic hysteretic characteristics of structural steel components are needed to evaluate of the behavior of steel buildings during earthquakes accurately. Strain-rate is one of these dynamic characteristics. Previous studies of steel have confirmed that high strain-rates increase stress. However, these previous high-speed tests on steel were not enough to judge that strain-rate have no effect on hysteresis. It is because these previous tests are only some high-speed tension-tests or a few limited cyclic loading tests mainly conducted in machine field. Systematic studies of strain-rate are needed to clarify the relationship between hysteretic behavior of steel and strain-rate effect under dynamic cyclic loading.
This paper presents the evaluation of strain-rate dependence in hysteretic behavior by a series of high-speed dynamic cyclic loading tests of structural steel.

Keywords: Strain-rate, Hysteretic Characteristics, Steel, Dynamic Test, Strength

1. INTRODUCTION

Strain-rate is known as one of the elements indices which affect steel hysteresis. Previous experimental studies in steel were already pointed out that strength grows up when strain-rate increases. Especially, the strain-rate effect to the strength of low yield strength steel used in hysteretic damper has been studied to grasp hysteresis characteristics under low cycle loading such as a strong wind. Whereas, general structural steel used in columns and beams ignores strain-rate effect substantially. It is because some previous earthquake damages and some reports show that plastic deformation capacity of general steel is hardly affected at the strain-rate around 0.1-1%/sec. Almost these previous studies of the strain-rate effect in steel was only monotonic loading test or cyclic loading test with limited strain amplitude. The correspondence between stain-rate effect and strength grow under high speed and cyclic load similar to earthquake is not enough examined. Therefore, whether strain-rate effect can be ignored or not is unclear.
This study conducted high-speed cyclic loading test of general structural steel, and evaluated strain-rate effect on steel hysteresis characteristics quantitatively.

2. STEEL HIGH-SPEED CYCLIC LOADING TEST

2.1. Specimen and parameters

Specimen of the test is a steel plate which form is shown as Figure 1. Specimen has a parallel part (its length is 100mm) and two holding part with each six bolts. In this test, the parallel part is test area.

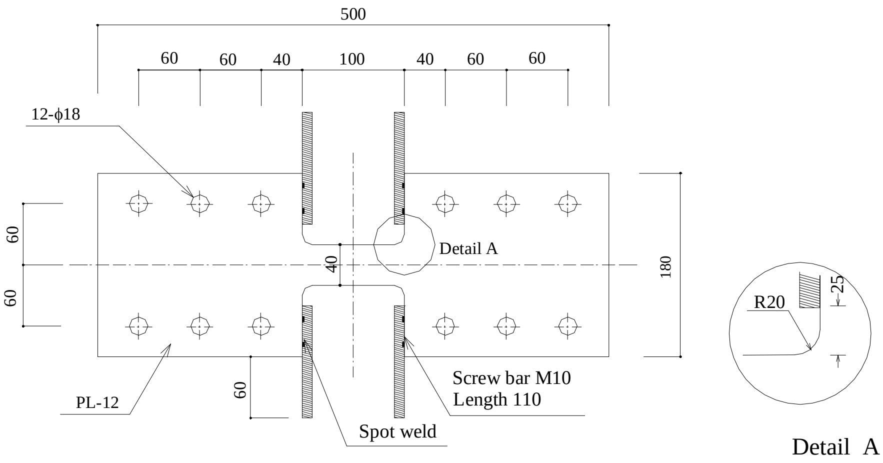


Figure 1. Specimen

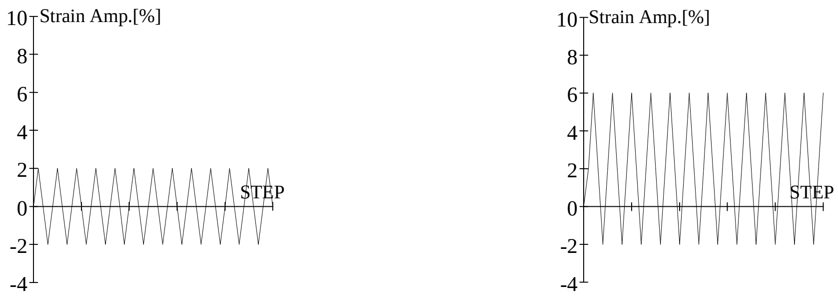
The number of specimens is 28 in total. Table 1 shows specimen list.

Table 1. Specimen list

Series (material)	Specimen Name	Load	Strain-rate [%/sec]	Strain Amp. [%]
SS (SS400)	SS-01	Monotonic	0.1	
	SS-02	Monotonic	10	
	SS-03	cost. Cyclic	0.1	±2
	SS-04	cost. Cyclic	1	±2
	SS-05	cost. Cyclic	10	±2
	SS-06	cost. Cyclic	50	±2
	SS-07	cost. Cyclic	0.1	-2 & +6
	SS-08	cost. Cyclic	1	-2 & +6
	SS-09	cost. Cyclic	10	-2 & +6
	SS-10	cost. Cyclic	50	-2 & +6
SN (SN490)	SN-01	Monotonic	0.1	
	SN-02	Monotonic	10	
	SN-03	cost. Cyclic	0.1	±2
	SN-04	cost. Cyclic	1	±2
	SN-05	cost. Cyclic	10	±2
	SN-06	cost. Cyclic	50	±2
	SN-07	cost. Cyclic	0.1	-2 & +6
	SN-08	cost. Cyclic	10	-2 & +6
BCR (BCR295)	BCR-01	Monotonic	0.1	
	BCR-02	Monotonic	10	
	BCR-03	cost. Cyclic	0.1	±2
	BCR-04	cost. Cyclic	1	±2
	BCR-05	cost. Cyclic	10	±2
	BCR-06	cost. Cyclic	50	±2
	BCR-07	cost. Cyclic	0.1	-2 & +6
	BCR-08	cost. Cyclic	1	-2 & +6
	BCR-09	cost. Cyclic	10	-2 & +6
	BCR-10	cost. Cyclic	50	-2 & +6

Parameters of the test are four; plate materials, strain-rate, strain amplitude, and loading protocol. Plate materials have three types; SS400, SN490 on border to beams, BCR295 on border to columns, both usually used in low-middle rise steel buildings in Japan. Strain-rate is settled a region from semi-static to dynamic. It is based on loading-rate limit of actuators and strain-rate reported in previous earthquake. The maximum of strain-rate of the components damaged in the Northridge earthquake and the Southern Hyogo prefecture earthquake was 1%/sec. Since the larger level earthquake is observed recently, it is possible that the higher strain-rate happens at any components. In this study, strain-rate set four; 0.1%/sec as semi-static, 1%/sec, 10%/sec, and 50%/sec as dynamic.

Loading protocol is monotonic tension load and constant amplitude cyclic load. At cyclic loading, the strain amplitude is settled two. These two cyclic loading pattern shows in figure 2. Here, negative shows tension and positive shows compression in this study. One is both negative and positive 2% which corresponded amplitude area in almost yield strength (in following, it describes ±2% loading), the other is negative 6% which corresponded enough plastic and positive 2% (in following, it describes -2&+6% loading).



(a) ±2% Loading (b) -2&+6% Loading

Figure 2. Loading pattern

Input wave is triangle wave which have constant strain-rate. Loading continued every set till specimen fractured. Single set is 4-50 cycles decided by specimen, and the number of cycles in a set is fixed in principal.

2.2. Set-up and measurement

Figure 3 shows the test set-up. Dynamic actuators in the left side of the figure connected to one side of specimen through a set of parallel move equipment. On the other side of specimen is fixed on the steel rigid jigs. Out-of-plane deformation is protected by a set of buckling protect jig as shown in Figure 4. Volume change of specimen happened by strength change is approved only in a few millimeter of clearance. The clearance is glued by some PTFT sheets.

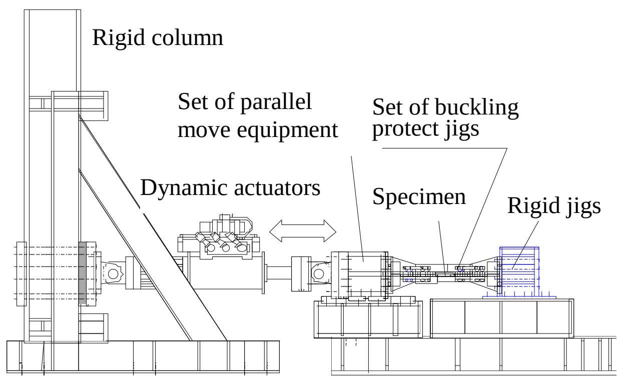


Figure 3. Test set-up

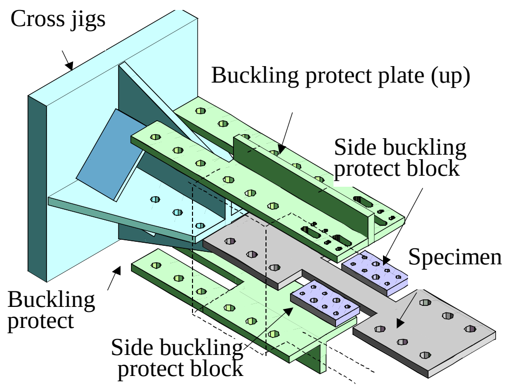


Figure 4. Set of buckling protect jigs

In this test, measurement elements are force and displacement of specimen. Force is measured by load-cells which settled between dynamic actuators and parallel move equipment. Measurement system of displacement is settled as shown in Figure 5. Displacement is measured by four laser displacement transducers; IL-65 and LK-500 (both is made of KEYENCE), and calculated by equation in the figure.

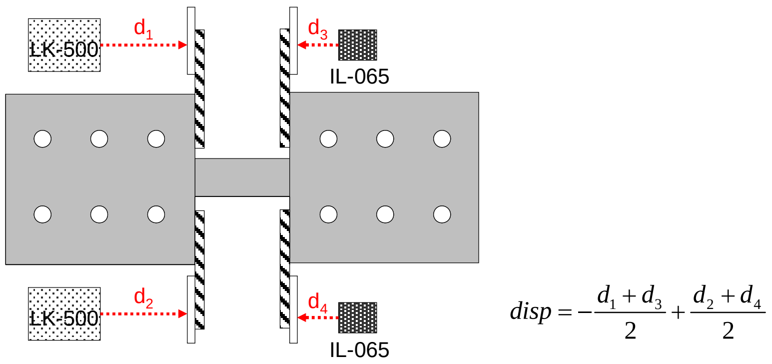


Figure 5. Measurement of displacement

3. TEST RESULTS

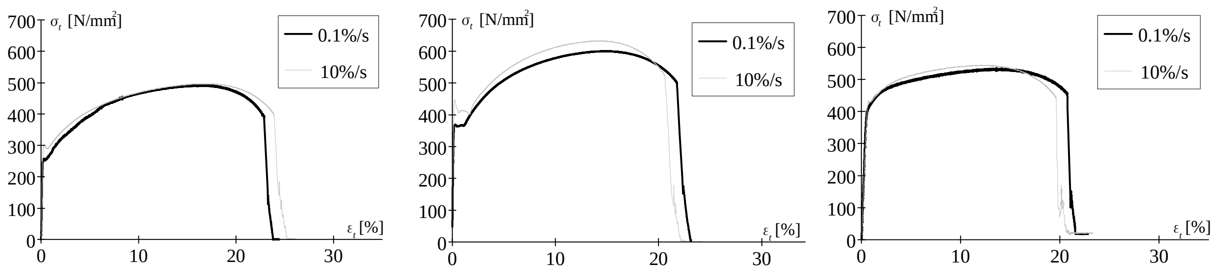
3.1. Stress versus strain relationship (monotonic loading)

Figure 6 shows stress versus strain relationships of monotonic loading specimen in each series. In following, stress and strain are both real values calculated by equation (1) with engineering stress and engineering strain.

$$\begin{aligned} \varepsilon_t &= \log(1+\varepsilon_n) \\ \sigma_t &= \sigma_n(1+\varepsilon_n) \end{aligned} \quad \textbf{(1)}$$

SS400 series show similar stress-strain curves in both SS-01 (strain-rate:0.1%/sec) and SS-02 (strain-rate:10%/sec). Only SS-02 shows a partial increase of stress near yield point and plastic flow of the specimen is unclear.　In SN490 series, SN-02 also shows a local increase of stress, that increasing tendency is more remarkable than SS-02. And stress of SN-02 decreased rapidly after it has a shorter and unclear plastic flow than SN-01. Fracture strain of SN-02 is slightly small than SN-01 contrary to tendency of fracture strain in SS400 series.

In BCR295 series, stress-strain curve of BCR-02 is similar at the strain hardening region in BCR-01 and BCR-02. Fracture strain of BCR-01 is about 1.1 times than the value of BCR-02.



(a) SS400 (SS-01, SS-02)　(b) SN490（SN-01, SN-02　(c) BCR295（BCR-01, BCR-02）

Figure 6. Stress versus strain relationships (monotonic loading)

3.2. Stress versus strain relationship (cyclic loading)

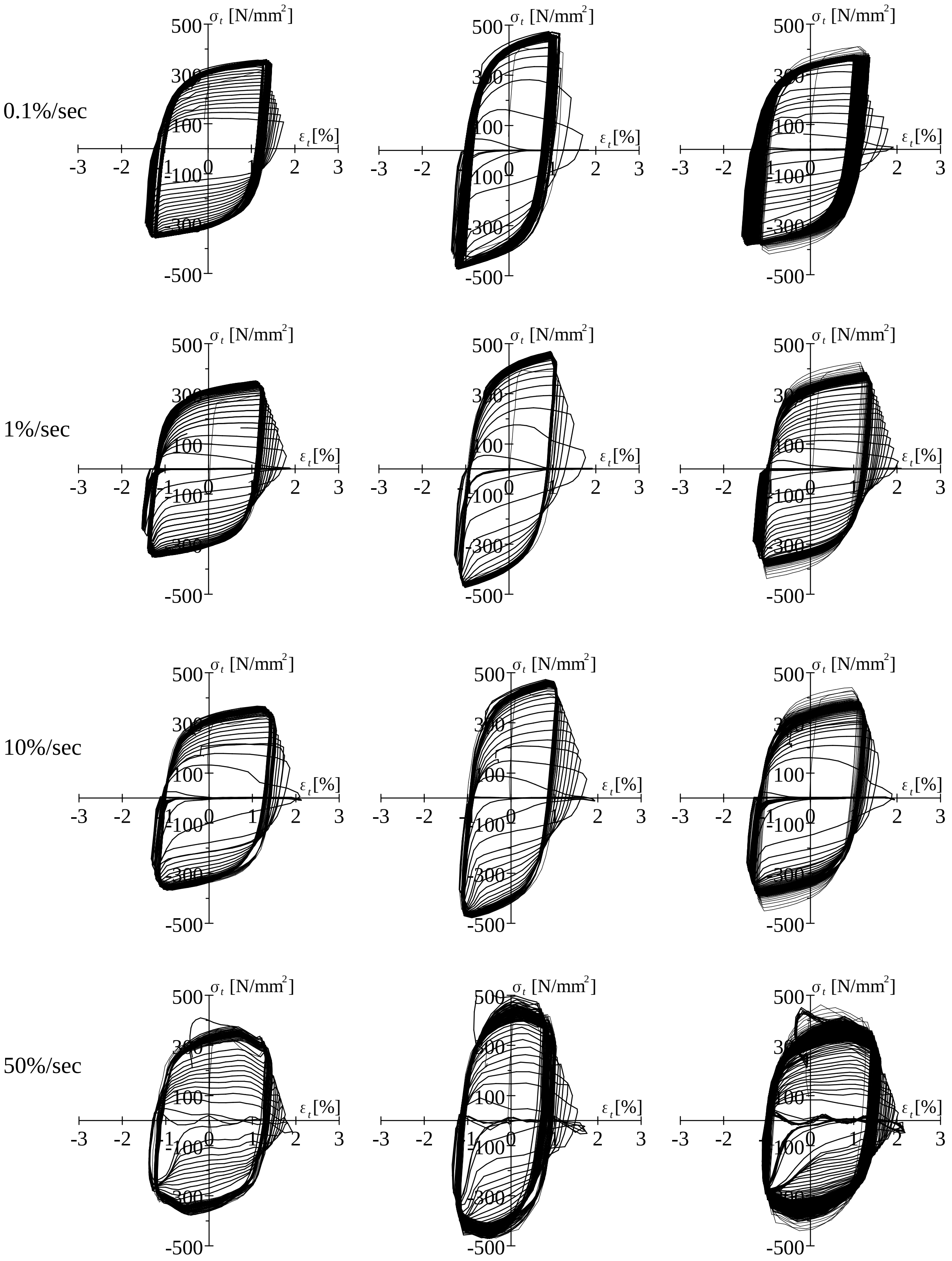
Figure 7 shows stress versus strain relationships of cyclic loading (±2% loading) specimen in each series. Stress and strain in figure 7 are also real stress and real strain. Elastic deformation made the strain amplitude of this hysteresis shorter than setting; 1.5%.
In figure 7, hysteresis in high-speed load is shown so that it goes to below. In all series, all specimens loaded at 0.1%/sec have stationary states with spindle shape. Specimens loaded at high speed; 10%/sec or 50%/sec, have more round and wavelike shape in the hysteresis than specimens at low speed. This tendency is similar to behavior of specimen loaded monotonic at high or low speed. Also this tendency is observed at first half-cycle of every set even if stress whole decrease during cyclic load. Both SS400 and SN490 series have similar shape of hysteresis from yield point to fracture through deteriorating region. While each specimen in BCR295 series have larger stress change than other two series, especially specimens at 10%/sec and 50%/sec are remarkable. One of the reasons which this tendency happened is that BCR295 is cold-formed steel, so that it is possible to generate an extra stress in specimens which cut out from steel pipes.

Figure 8 shows stress versus strain relationships of cyclic loading (-2&+6% loading) specimen in each series. Stress versus stain relationships between ±2% loading and -2&+6% loading specimen have similar tendency even little difference of stress change are there. Therefore, it is possible to regard the hysteresis of steel considered strain-rate as bi-linear model which seldom related to material and strain amplitude. Here, it is applicable that this bi-linear model till about 10%/sec, so that, hysteresis model at more large strain-rate is regarded a full-plastic model, or another index is needed to describe the model.

3.3. Yield point and maximum stress at each strain-rate

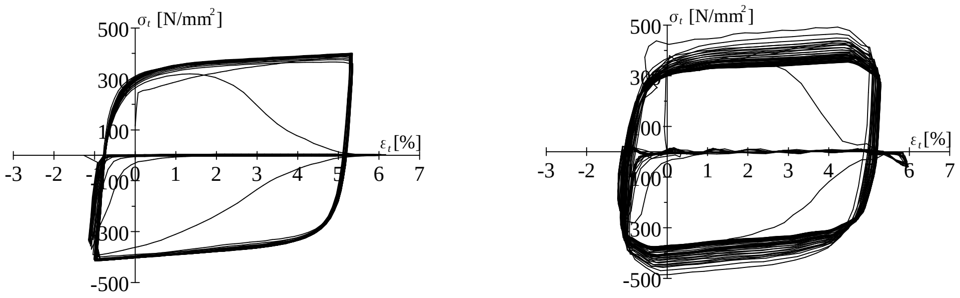
In following consideration, yield point of cyclic loading specimen defines the 0.2% offset stress obtained in the first tension half cycle because plastic flow and upper or lower yield point are unclear in hysteresis.
Figure 9 shows yield point of cyclic loading specimen in each strain-rate. In all steel material, yield point increased according to growing of strain-rate. Yield point at 10%/sec loading is about 1.0-1.2 times than the value at 0.1%/sec loading. As yield point at 50%/sec, SS400 series is almost 1.5 time and SN490 series and BCR295 series are 1.1-1.3 times than the value at 0.1%/sec loading, although yield point at 1%/sec hardly changed compared with the value of 0.1%/sec. This reason is that yield point obtained at a range of locally increasing of stress in the first cycle of high speed loading. The trend of increase by strain-rate is hardly changed by strain amplitude.

In this paper, the maximum of stress in each hysteresis defines ‘maximum strength’. Figure 10 shows maximum strength of cyclic loading specimen in each strain-rate. In all steel material, maximum strength lower increased than yield point according to growing of strain-rate. As shown in figure 10, maximum strength at 50%/sec loading is about 1.1 times than the value at 0.1%/sec loading. This reason is that the number of cycle obtained maximum strength differs to each specimen. In SS400 and SN490 series, the number of cycle when maximum strength happened is large at low-speed loading. While, in BCR295 series, the number which maximum strength obtained hardly differs along each strain-rate. Specimens at -2&+6% loading in all steel materials have comparatively cycle for obtaining maximum strength
Hysteresis characteristics are affected by stress glow, the number of cycle and strain-rate. So that, to grasp how to glow stress in each cyclic behavior is needed.



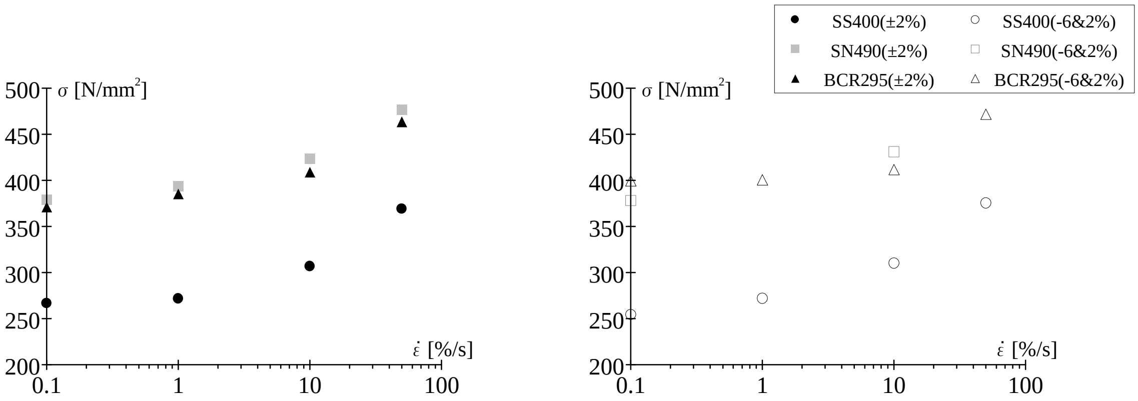
(a) SS400 (SS-03～SS-06)　　(b) SN490（SN-03～SN-06）　　(c) BCR295（BCR-03～BCR-06）

Figure 7. Stress versus strain relationships (±2% cyclic loading)



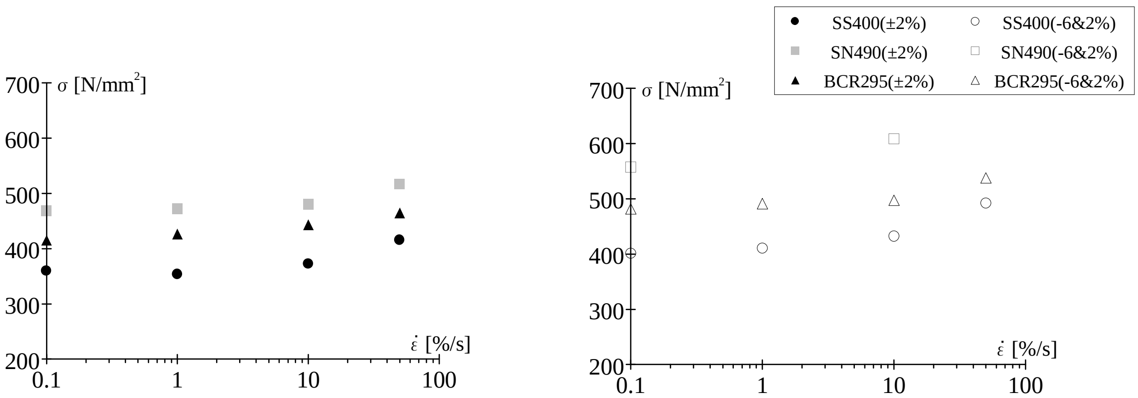
0.1%/sec 50%/sec

Figure 8. Stress versus strain relationships (-2&+6% cyclic loading)



(a) ±2% cyclic loading (b) -2&+6% cyclic loading

Figure 9. Yield point at each strain-rate



(a) ±2% cyclic loading (b) -2&+6% cyclic loading

Figure 10. Maximum strength at each strain-rate

4. STRESSES DURING CYCLIC BEHAVIOR

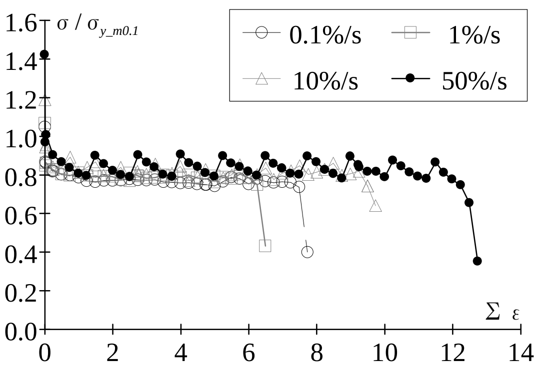
In each specimen, yield point is 0.2% offset strength at the first half cycle, maximum strength is the top strength during all cycle. These two are not considered hysteretic behavior toward fracture. This chapter describes the change of stresses during cyclic behavior.

4.1. 0.2% offset strength

The rate of increase in 0.2% offset strength is defined a division 0.2% offset stress in each cycle by yield point at monotonic and 0.1%/sec loading ($\sigma_{y\_m0.1}$). Figure 10 shows the relationships between a rate of increase in 0.2% offset strength and cumulative strain. In following, the rate of increase shows the first three cycle and every 0.25 cumulative strain since it is complicated.

At ±2% cyclic loading, the rate of increase in 0.2% offset strength at the first cycle has largest value. The rate of increase in 0.2% offset strength at following cycle decrease step by step, and finally it takes almost constant value. The rate of increase during constant area of each specimen slightly up at high speed loading. It is because that strain-rate increases when high speed loading test starts. The rate of increase during constant area in each strain-rate is 0.8 on average; 0.77 at 0.1%/sec, 0.79 at 1%/sec, 0.81 at 10%/sec, 0.83 at 50%/sec.

Figure 11 shows the relationships between a rate of increase in 0.2% offset strength and cumulative strain at -2&+6% cyclic loading. The rate of increase in 0.2% offset strength at 1%/sec is uneven, the value during constant area is also 0.8 on average. Consequently, value of 0.2% offset strength is almost constant except for the first cycle which the 0.2% offset strength is remarkably affect by strain-rate.



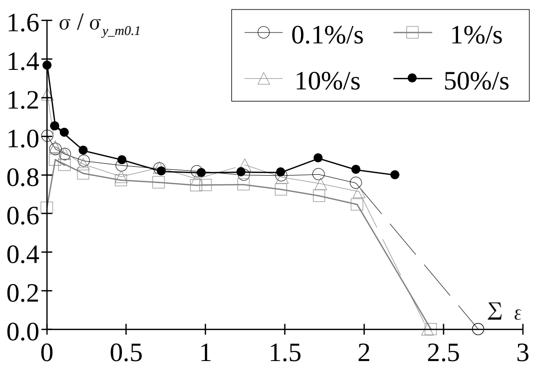


Figure 10. 0.2% offset strength (±2% cyclic loading) **Figure 11.** 0.2% offset strength (-2&+6% cyclic loading)

4.2. Stress versus strain relationship (cyclic loading)

The rate of increase in peak strength is defined a division maximum strength in each cycle by the maximum stress at monotonic and 0.1%/sec loading ($\sigma_{u\_m0.1}$). Figure 12 shows the relationships between a rate of increase in peak strength and cumulative strain.

At ±2% cyclic loading, the rate of increase in peak strength at the first cycle is smaller than the following cycles when strain-rate is 0.1%/sec, 1%/sec, and 10%/sec. And the rate of increase in peak strength at following cycle takes almost constant; 0.7.

When strain rate is 50%/sec, the rate of increase in peak strength at the first cycle has larger than following cycles. And the rate of increase in peak strength at following cycle takes almost constant; 0.66. These trends have slightly deference between steel materials.

Figure 13 shows the relationships between a rate of increase in peak strength and cumulative strain at -2&+6% cyclic loading. The rate of increase in peak strength during constant area is larger than the value at ±2% cyclic loading. Consequently, value of peak strength is also almost constant except for the first cycle. Therefore, it is possible that hysteretic behavior considered strain-rate define as almost bi-linear model. However, the hysteretic model at the first cycle needs specially consideration.

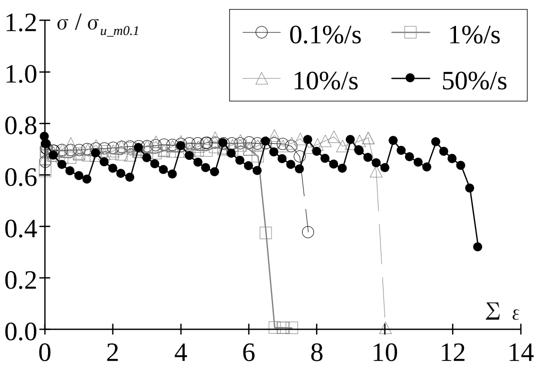


Figure 12. Peak strength (±2% cyclic loading)

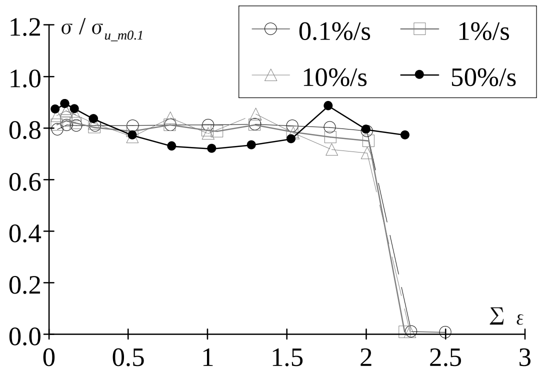


Figure 13. Peak strength (-2&+6% cyclic loading)

5. CONCLUSION

In order to clarify the strain-rate effect in structural steel, this study conducted high-speed cyclic loading test. Obtained results showed that strain-rate affects not only yield point and maximum stress, but also hysteresis and fracture strain.

Both 0.2% offset strength corresponding to the changing point of stiffness, and peak strength corresponding to the maximum point in each cycle kept the constant value by yield point or maximum point in semi-static tension load. Therefore, it is possible to model hysteresis characteristics through all cycle up to fracture considering strain-rate and other parameters as bi-linear. However, more detailed tendency of strength is needed to clarify with other parameters such as temperature, real strain-rate, and stiffness through cyclic behaviors.

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