AN EXPERIMENTAL STUDY ON MECHANICAL PROPERTIES AND CONSTITUTIVE EQUATION OF SBHS500

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ABSTRACT

“Higher yield strength steel plates for bridges” that is called "SBHS" has been standardized in Japanese Industrial Standards (JIS). However, there are few studies on material properties and stress-strain relationship of SBHS. Moreover, it is necessary to grasp the feature of stress-strain relationship in the plastic range under cyclic loading of SBHS and to develop the constitutive equation in order to evaluate the elasto-plastic behaviour of steel structures made of SBHS under cyclic loading by analysis.

Therefore, the tensile tests and cyclic loading tests of SBHS500 were carried out in order to earn information on the mechanical properties and to grasp the hysteretic behaviour of stress-strain relationship under cyclic loading. On the basis of the test results, the feature of mechanical properties of SBHS500 is examined and the constitutive equation of SBHS500 with high accuracy is proposed.

Keywords: higher yield strength steel plates for bridges, SBHS500, material properties, constitutive equation.

1. INTRODUCTION

“Higher yield strength steel plates for bridges” that is called "SBHS" has been standardized in Japanese Industrial Standards (JIS). The major feature of SBHS is high yield strength and high weldability. Some studies reported the possibility of reduction in construction cost of steel bridges by using SBHS. The Tokyo Gate Bridge is made of SBHS500. However, there are few studies on material properties and stress-strain relationship of SBHS compared with the common rolled steel for welded structures like SM570. Moreover, it is necessary to grasp the feature of stress-strain relationship in the plastic range under cyclic loading of SBHS and to develop the constitutive equation in order to evaluate the elasto-plastic behaviour of steel structures made of SBHS under cyclic loading by analysis.

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This study focuses on SBHS500 as SBHS. The tensile tests and cyclic loading tests of SBHS500 were carried out in order to earn information on the mechanical properties and to grasp the hysteretic behaviour of stress-strain relationship under cyclic loading. On the basis of the test results, the feature of mechanical properties of SBHS500 is examined and the constitutive equation of SBHS500 with high accuracy is proposed.

2. TENSILE TESTS

Table 1 shows the type of test specimens and the number of test specimens. The tensile tests were conducted with the test specimens standardized by JIS. The test specimens were cut along rolling direction (L-specimen) and perpendicularly to rolling direction (R-specimen). The plate thickness of SBHS500 is 9mm and 12mm. The number of L-specimens and R-specimens of SBHS500 whose plate thickness is 9mm and 12mm is 5 respectively. The total number of test specimens is 20.

2.1. Test results and mechanical properties

Table 2 shows the mechanical properties of SBHS500 specified in JIS. Table 3 shows the average value of test results. Figure 1 shows the nominal stress - nominal strain (σ_N - ε_N) relationship gained from the tensile tests. Figures 2, 3, 4 and 5 show the fluctuation of yield stress σ_y, tensile strength σ_B, yield ratio YR (σ_y/σ_B) and elongation, respectively. In these figures, the blue dotted lines (- - -) indicate the minimum yield stress standardized by JIS and the green piece of dashed lines (- · -) show the range of tensile strength standardized by JIS. In figure 5, the red two-dot chain lines (- · · -) show the minimum elongation standardized by JIS. Table 3 shows the average value of test results. The outline of the test results of SBHS500 is as follows.

- The yield stress and tensile strength of R-specimens of 9mm in plate thickness are larger than those of L-specimens of 9mm. On the other hand, the difference of yield stress and tensile strength between R-specimens and L-specimens of 12mm is smaller than that of 9mm.
- The yield plateau is clearly observed in stress - strain relationship of all test results.
- The mean value of the yield ratio of SM570 in the previous study (Minami and Miki 2006) is 86%. The yield ratio of SBHS500 in this study exists between 90% and 95%.
- The elongation of R-specimens and L-specimens of 12mm is larger than that of 9mm.

Table 1: Number of test specimens

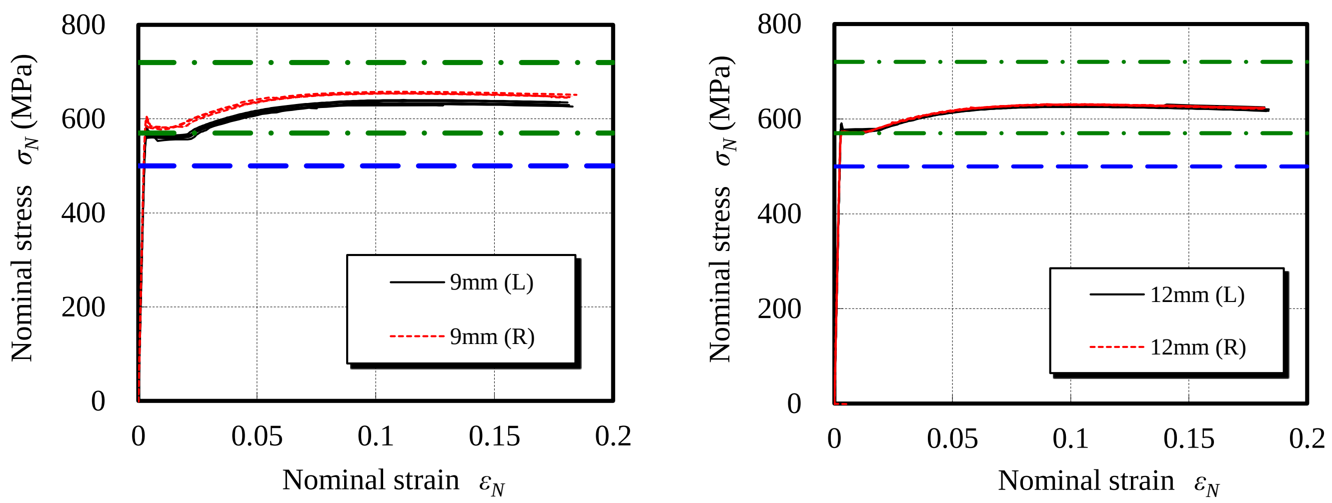
Steel type	Plate thickness	Cut direction	Number
SBHS500	9mm	Rolling (L-specimen)	5
		Perpendicularly (R-specimen)	5
	12mm	Rolling (L-specimen)	5
		Perpendicularly (R-specimen)	5

Table 2: Mechanical property in JIS

	Yield stress (MPa)	Tensile strength (MPa)	Elongation		
			Plate thickness (mm)	Specimens	Elongation (%)
SBHS500	500≦	570~720	6≦t≦16	JIS-5	19≦

Table 3: Results of tensile tests

Steel type	Plate thickness	Cut direction	Yield stress (MPa)	Tensile strength (MPa)	Yield ratio (%)	Elongation (%)
SBHS500	9mm	Rolling	581	636	91	29
		Perpendicularly	605	657	92	27
	12mm	Rolling	589	630	94	33
		Perpendicularly	574	632	91	33



(a) t=9mm **(b) t=12mm**

Figure 1: σ_N - ε_N relationship

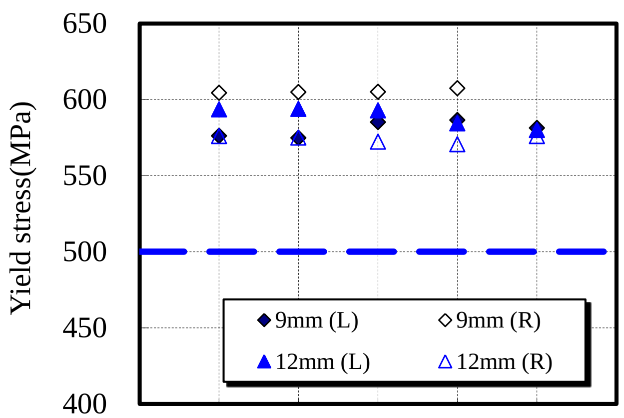


Figure 2: Yield stress

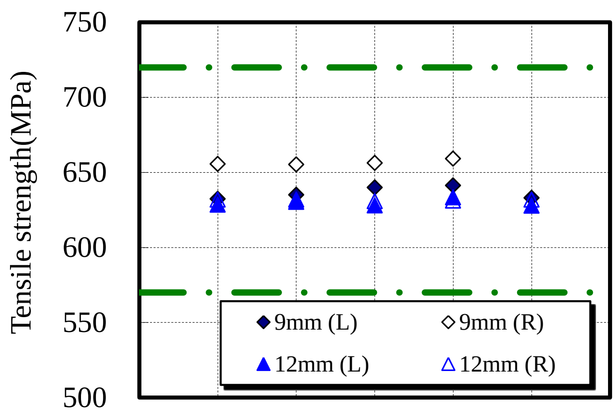


Figure 3: Tensile strength

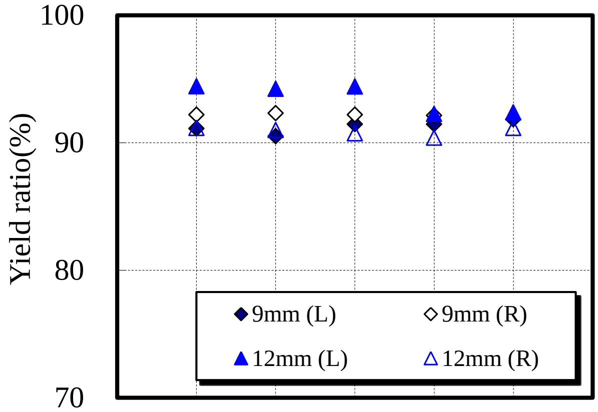


Figure 4: Yield ratio

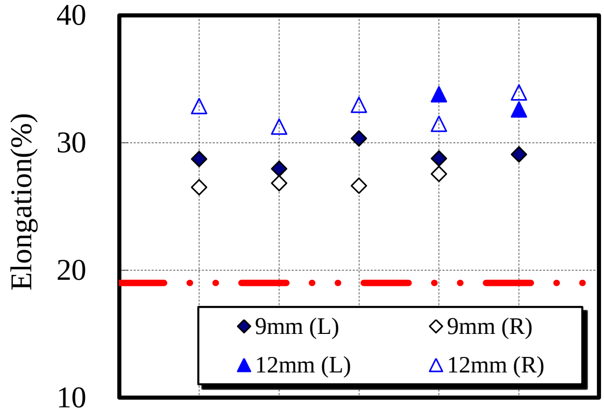
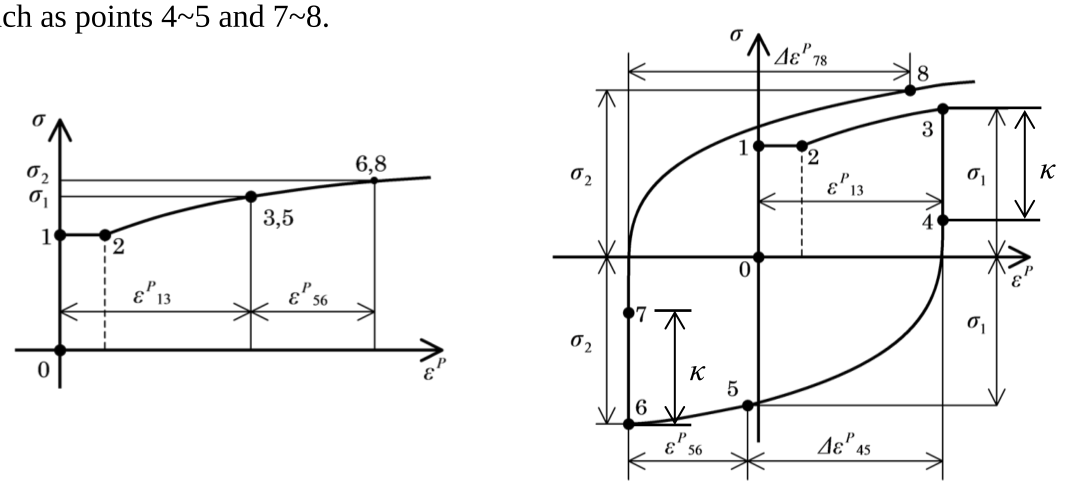


Figure 5: Elongation

3. CONCEPT OF CONSTITUTIVE EQUATION

The constitutive equation for common structural steels like SM490 and SM570 which can express the hysteretic behaviour with good accuracy has been proposed by authors (Nishimura et al. 1995; Suzuki et al. 2003). This study verifies the applicability of the constitutive equation to SBHS500.

The concept of the constitutive equation proposed by authors is shown in Figure 6 (a) and in Figure 6 (b). Figure 6 (a) shows the monotonic loading curve expressed in the plastic strain - true stress relationship, and Figure 6 (b) shows the hysteretic curves under cyclic loading expressed in the plastic strain - true stress relationship. The points 0~8 in Figure 6 (b) are respectively equivalent to the points 0~8 (except the points 4 and 7) in Figure 6 (a), and stress level of points 0~8 in Figure 6 (a) is equal to that in Figure 6 (b). In Figure 6 (b), the relationship between the plastic strain and the true stress in the uniaxial stress can be divided into three domains. The parts such as points 0~3, 5~6 and the part after the point 8 are the domain composed of the monotonic loading curve. The parts such as points 3~5 and 6~8 are the transition domain. Furthermore, the transition domain can be divided into the elastic transition domain such as points 3~4 and 6~7 and non-linear transition domain such as points 4~5 and 7~8.



(a) Monotonic loading curve (b) Hysteretic curve under cyclic loading

Figure 6: Concept of constitutive equation

4. NUMERAL FORMULATIONS OF PROPOSED CONSTITUTIVE EQUATION

The numeral formulations of three domains which are the domain composed of the monotonic loading curve, elastic transition domain and the non-linear transition domain are described as follows.

4.1. Domain composed of monotonic loading curve

The monotonic loading curves of several structural steels must be formulated exactly and the formulated monotonic loading curve must stand for characteristics of several structural steels adequately, because the constitutive equation is based on the monotonic loading curve. Therefore, the monotonic loading curve in the hardening region is formulated as follows.

$$\sigma = \frac{E^{P}{}_{st}}{b} e^{a\varepsilon^{P*}{}_{mon}} \ln(1 + b\varepsilon^{P*}{}_{mon}) + \sigma_y \qquad (a \geq 0) \tag{1}$$

Where, $E^{P}{}_{st}$: plastic modulus at the initial hardening.

$\varepsilon^{P*}{}_{mon}$: plastic strain whose origin is the strain at the initial hardening.

σ_y : lower yield stress.

a,b : material properties.

Material properties $E^{P}{}_{st}$, $\varepsilon^{P*}{}_{mon}$, σ_y, a and b in the equation (1) are determined by the tensile tests as shown in Figure 7. Figure 8 shows the comparison between the constitutive equation of SBHS500 expressed by the equation (1) and results of a tensile test.

4.2. Elastic range in transition domain

As to the elastic range in the transition domain such as points 3 ~ 4 and points 6 ~ 7 as shown in Figure 6, it is reported that the elastic range κ in Figure 6 (b) under cyclic loading may diminish in the size form the initial size of the elastic range κ_0 (=2σ_y) because of Bauschinger effects and may converge into the constant size after the structural steel experiences the plastic deformation to a certain degree. Therefore, it is assumed that the reduction of the elastic range can be expressed by the following equation.

$$\frac{\kappa}{\kappa_0} = \frac{1-c}{(\varepsilon^{P}{}_{mon} + 1)^n} + c \tag{2}$$

where, κ : size of the elastic range.

κ_0 : initial size of the elastic range. (=2σ_y)

$\varepsilon^{P}{}_{mon}$: plastic strain of the monotonic loading curve.

c,n : material properties.

Material properties c and n in the equation (2) are given by experiments in order to investigate reduction of elastic range. In the experiment, the loading and the unloading are repeated by small strain intervals. Figure 9 shows the κ/κ_0 - ε^P_{mon} relationship given by the results of the experiments and the curved line expressed by the equation (2).

4.3. Non-liner transition domain

As to the non-linear transition domain, the domain between points 4 ~ 5 is dealt in this section. Figure 10 shows the non-linear transition domain between points 4 ~ 5. In Figure 10, the beginning point of the non-linear transition domain (the point 4) is assumed to the origin of the coordinate axis. Also the $\overline{X}-\overline{Y}$ axis is defined as shown in Figure 10. Under this condition, arbitrary point P(x, y) of the non-linear transition domain can be formulated as follows.

$$y = E^P{}_0 x + (\Delta\varepsilon^P E^P{}_0 - \Delta\sigma)\left(\frac{x}{\Delta\varepsilon^P}\right)^{m+1}\left\{(1+m)\ln\left(\frac{x}{\Delta\varepsilon^P}\right)-1\right\} \quad (3)$$

$\Delta\varepsilon^P$ and m in equation (3) are formulated as follows.

$$\Delta\varepsilon^P = \frac{e}{d}\sqrt{\left(\varepsilon^P{}_{mon}\right)^2 + 2d\varepsilon^P{}_{mon}} \quad (4)$$

$$m = \frac{f}{\varepsilon^{P*}{}_{mon} + \{1+\exp(g)\}f} - 1 \quad (5)$$

Material properties d, e, f and g in the equations (4) and (5) are given by cyclic loading tests as shown in Figure 11. Figure 12 shows the $\Delta\varepsilon^P$ - ε^P_{mon} relationship gained from the experimental results as shown in Figure 11 and the curved line expressed by the equation (4).

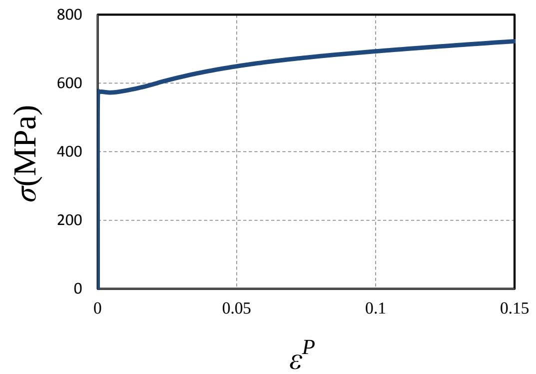


Figure 7: Tensile tests

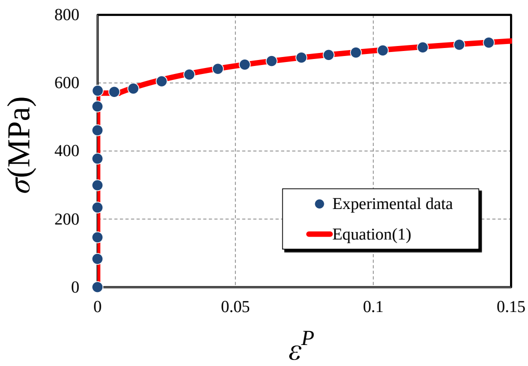


Figure 8: Monotonic loading curve

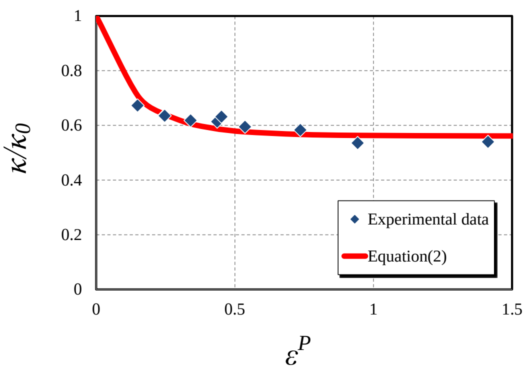


Figure 9: κ/κ_0 - ε^P_{mon} relationship

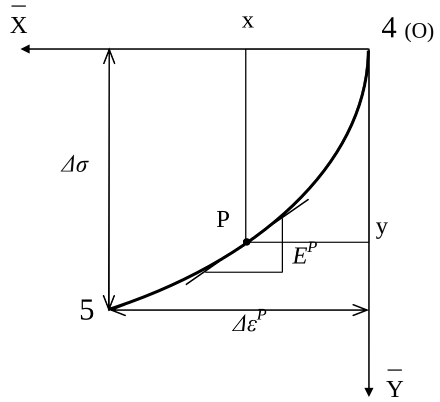


Figure 10: Formulation of non-linear transition domain

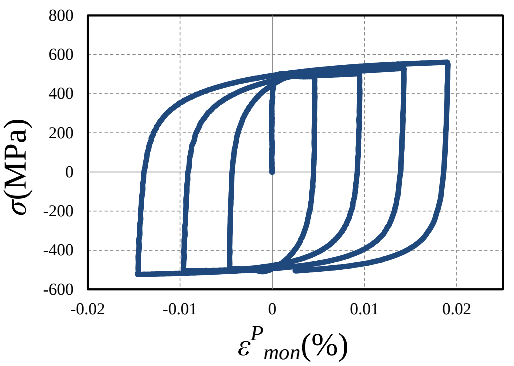


Figure 11: Cyclic loading tests

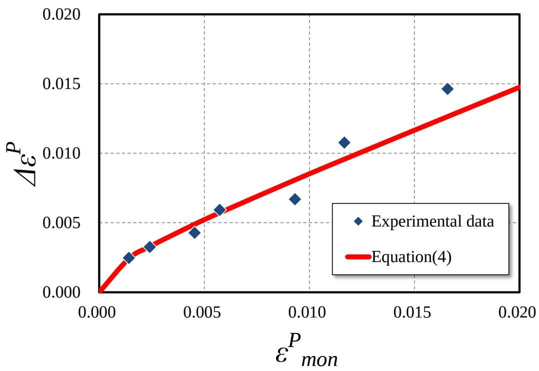


Figure 12: $\Delta\varepsilon^P$ - ε^P_{mon} relationship

5. VERIFICATION OF PROPOSED CONSTITUTIVE EQUATION

In order to confirm the validity of the proposed constitutive equation, comparison between the experimental data and the simulation by the proposed constitutive equation shown in Figure 13 was carried out. In Figure 13, the experimental data are expressed by the points and the simulation by the proposed constitutive equation is expressed by the solid line. According to the comparison in Figure 13, it is found that the proposed constitutive equation can express hysteretic behaviour of SBHS500 under cyclic loading with good accuracy.

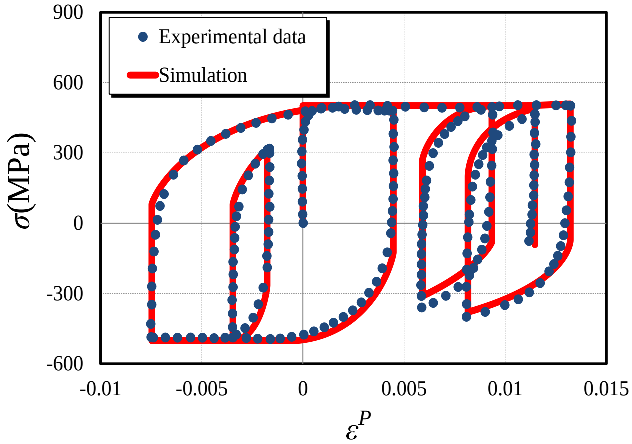


Figure 13: Comparison between experimental data and simulation result

6. CONCLUSIONS

In this study, tensile tests and cyclic loading tests of SBHS500 were carried out. From the tensile tests, information on the mechanical properties of SBHS500, such as yield strength, tensile strength and so on, was earned. From the cyclic loading tests, features of the hysteretic behaviour of SBHS500 under cyclic loading were grasped and the parameters in constitutive equation were determined. Furthermore, in order to confirm the validity of the proposed constitutive equation, comparison between the experimental data and the simulation by the proposed constitutive equation was carried out. According to the comparison, it is found that the proposed constitutive equation can express hysteretic behaviour of SBHS500 under cyclic loading with good accuracy.

ACKNOWLEDGMENTS

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