An Experimental Study on Seismic Performance of Hybrid Steel piers with Vertical Ribs Made from SBHS700

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Abstract

Some methods for evaluating the seismic performance of steel bridge piers have been already proposed in the previous studies. Steel bridge piers are sometimes required to have seismic performance that ductility is improved with restraining increase in ultimate strength but it is difficult to fulfill such seismic performance by the proposed methods in previous studies. By the way, "Higher yield strength steel plates for bridges" has been standardized in Japanese industrial Standard (JIS). The major feature of higher yield strength steel plates for bridges, SBHS, is high yield strength and high weldability. Among SBHS, SBHS700 has the highest yield strength and the highest tensile strength. There is possibility of fulfilling the seismic performance of steel bridge piers which has been difficult to gain so far by applying SBHS700 to them. Therefore, the purpose of this study is to investigate material properties of SBHS700 and the seismic performance of hybrid steel bridge piers whose vertical ribs are made from SBHS700.

Introduction

The Kobe Earthquake in 1995 caused the huge damage to highway bridges like never seen before in Japan. The seismic design specifications for highway bridges were revised in 1996 (Japan Road Association. 1996) in consideration of the damage and the ductility design method, which had already been adapted to reinforced concrete bridge piers, was also introduced to steel bridge piers. After that, seismic design specifications were revised in 2002 and 2012(Japan Road Association. 2002, 2012) and more detailed seismic design methods for steel bridge piers have been specified in the 2012 seismic design specifications . Steel bridge piers are often constructed under the condition that the area of construction sites is restricted or the soil condition is not good. The seismic performance that ductility is increased with restraining increase in ultimate strength is one of required or desirable performance. However, it is difficult to fulfill such seismic performance by the proposed methods in previous studies.

By the way, "Higher yield strength steel plates for bridges" has been standardized in Japanese industrial Standard, "JIS" (Japanese Standards Association.2008). The major

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feature of higher yield strength steel plates for bridges, SBHS, is high yield strength and high weldability. Among SBHS, SBHS700 has the highest yield strength and the highest tensile strength. There is possibility of fulfilling the seismic performance of steel bridge piers which has been difficult to gain so far by applying SBHS700 to them. However, information on stress-strain relationship and the mechanical properties like the yield stress, the tensile strength and the elongation of SBHS700 is not sufficient compared with the other rolled steel for welded structure like SM490 and SM570 (Murakoshi et al. 2008). Moreover, little is known about the seismic performance of steel bridge piers made from SBHS700 .

Therefore, this study is intended as an investigation to investigate material properties of SBHS700 and the seismic performance of hybrid steel bridge piers whose vertical ribs are made from SBHS700

Material Properties of SBHS700

(1) Tensile Tests and Mechanical Properties of SBHS700

Table 1 shows the mechanical properties of SBHS700 specified in JIS and those of HT80 specified in Honshu Shikoku Bridge Standards (HBS). HT80 is high strength steel and it was applied to Honshu Shikoku bridges. As shown in Table 1, mechanical properties such as the yield stress and the tensile strength of SBHS700 are almost the same as those of HT80.

Table 2 shows the types of test specimens and the number of test specimens. The tensile tests were conducted with the test specimens made according to specifications in JIS. The test specimens were cut along rolling direction (R-specimen) and perpendicularly to rolling direction (P-specimen). The plate thickness is 9mm and 12mm. The total number of test specimens is 20.

Table 3 shows the average values of test results. Figure 1 shows the nominal stress - nominal strain (σ_N - ε_N) relationship obtained from the tensile tests. Figures 2, 3, 4 and 5 show the fluctuation of yield stress (upper yield stress or proof stress) σ_y, tensile strength σ_u, elongation and yield ratio YR (σ_y/σ_u) , respectively. The blue dotted lines (- - -) in Figures 1 and 2 indicate the minimum yield stress specified in JIS, the green piece of dashed lines (— · —) in Figures 1 and 3 show the range of tensile strength specified in JIS and the red two-dot chain lines (— · · —) in Figure 5 show the minimum elongation specified in JIS. The outline of the mechanical properties of SBHS700 in this study shown in Figures 1～5 is as follows.

(a) The yield stress is much higher than the minimum yield stress in JIS and it is almost the same as the minimum tensile strength in JIS.

(b) The tensile strength is almost the same as the minimum tensile strength in JIS

(c) The yield ratio exists between 92% and 100%. Especially, the mean value of the yield ratio of test results of R-specimen of 12mm is 99%.

Cyclic Loading Tests of Hybrid Steel Bridge Piers

(1) Test specimens

This study employed two test specimens. One of test specimens is a homogeneous test specimen "HO" and its webs, flanges and vertical ribs are made from SM490. The other is a hybrid test specimen "HY". Webs and flanges of "HY" are made from SM490 and vertical ribs are made from SBHS700. Figure 6 indicates the nominal stress - nominal strain relationship of SBHS700 and SM490 which were used in test specimens. As shown in Figure 6, the yield stress and tensile strength of SBHS700 are much higher than those of SM490.

The outline of the configuration of the test specimens is given in Figure 4. The values of the major parameters of the test specimens are listed in Table 4. In Table 4, N_{yN} is the yield axial force, R_{RN} and R_{FN} are the buckling parameters of the plates between longitudinal stiffeners and overall stiffened plates respectively. $\bar{\lambda}_N$ is the slenderness ratio parameter. The definitions of parameters mentioned above are identical to those stipulated in the 2014 seismic design specifications (Japan Road Association. 2014) and are noted below. As for a hybrid test specimen "HY", yield stress σ_{yN} of webs and flanges are different from that of vertical ribs because web and flanges are made from SM490 and vertical ribs are made from SBHS700. It is impossible to calculate N_{yN}, R_{FN} and $\bar{\lambda}_N$ of a hybrid test specimen "HY" according to the following equations (1), (3) and (4) respectively. Therefore, yield stress of SM490 was substituted into equations (1), (3) and (4) in calculating N_{yN}, R_{FN} and $\bar{\lambda}_N$ of "HY".

$$N_{yN} = \sigma_{yN} \times A \tag{1}$$

$$R_{RN} = \frac{b}{t}\sqrt{\frac{\sigma_{yN}}{E}\frac{12(1-\nu^2)}{4\pi^2 n^2}} \tag{2}$$

$$R_{FN} = \frac{b}{t}\sqrt{\frac{\sigma_{yN}}{E}\frac{12(1-\nu^2)}{\pi^2 k_F}} \tag{3}$$

$$\bar{\lambda}_N = \frac{1}{\pi}\sqrt{\frac{\sigma_{yN}}{E}}\frac{2h}{r} \tag{4}$$

where σ_{yN} = nominal yield stress of SM490 specified in JIS (=315N/mm^2); A = sectional area; h = column height (distance from the bottom of the column to the point at which horizontal load is applied); r = radius of gyration of cross section; E = Young's modulus of steel; b = width of flange or web; t = plate thickness of webs and flanges; ν = Poisson's ratio of steel (=0.3); n = number of panels of webs and flanges; k_F = the bucking coefficients.

(2) Loading Conditions

Each test specimen was loaded with hydraulic jacks installed in a stiff frame. In each experiment, the specified compressive axial force shown in Table 7 was first applied to the test specimen using a vertical hydraulic jack. The levels of compressive axial force, N, applied to each test specimen was 15% of yield axial force, N_{yN}, calculated by equation (1) above.

The axial force was kept constant during the cyclic loading experiments. The cyclic loading patterns of horizontal displacement are schematically shown in Figure 8, where δ_{yN} is calculated by the following equation. As for a hybrid test specimen "HY", nominal yield stress of SM490 was substituted into equation (6).

$$P_{yN} = \left(\sigma_{yN} - \frac{N}{A}\right)\frac{Z}{h} \tag{5}$$

$$\delta_{yN} = \frac{P_{yN}h^3}{3EI} \tag{6}$$

where I = moment of inertia and Z = section modulus.

(3) Experimental Results and Comments

Figure 9 shows the horizontal load - horizontal displacement relationship (P-δ relationship). Figure 10 shows enveloped curves gained from P-δ relationship in Figure 9. As shown in Figure 10, maximum horizontal load and the ductility (horizontal displacement at maximum horizontal load) of a hybrid specimen "HY" is larger than those of a homogeneous test specimen "HO". However, increasing rate of the ductility is larger than that of the maximum horizontal load. The test results indicate the possibility that hybrid steel bridge piers whose stiffeners are made from SBHS700 may realize the performance that ductility can be increased with restraining increase in ultimate strength. Figure 11 expresses the progress of the out-of-plane deformation of the flange panel in the compression side at the base section. It is found that out-of-plane deformation of "HY" is smaller than that of "HO" at the same cyclic loop. Judging from Figures 6 and 11, the reason why P-δ relationship that ductility can be increased with restraining increase in ultimate strength can be fulfilled is guessed as follows although the detailed has to be conducted in the future works.

・The yield stress of SBHS700 is much larger than that of SM490 as shown in Figure 6.

・The stress level of vertical ribs made from SBHS700 of a hybrid test specimen remains in elastic range and the vertical ribs have enough stiffness for restraining the large out-of-plane deformation of flange panels although the stress level of flange panels made from SM490 is beyond yielding and reaches plastic range.

・The ductility of a hybrid test specimen is increased compared with a homogenous test specimen which corresponds to a conventional type of steel bridge piers because the progress of out-of-plane deformation of flange panels of a hybrid test specimen are slow as compared with a homogeneous test specimen shown in Figure 11.

Conclusions

In this study, the tensile tests of SBHS700 were conducted. Based on results of tensile tests, the information on mechanical properties and stress-strain relationship of SBHS700 is obtained. Furthermore, cyclic loading experiments were conducted with two types of test specimens. One of test specimens is a homogeneous test specimen whose webs, flanges and vertical ribs are made from SM400. The other is a hybrid test specimen whose webs and flanges are made from SM400 and whose vertical ribs are made from SBSH700. The test results indicate the possibility that hybrid steel bridge piers whose stiffeners are made of SBHS700 may realize the performance that ductility can be increased with restraining increase in ultimate strength.

Acknowledgments

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Table 1 Mechanical Properties of SBHS700 and HT 80 Specified in Standard

(a) SBSH700

	Yield stress or Proof stress σ_y (N/mm^2)	Tensile strength σ_u (N/mm^2)	Elongation		
			Plate thickness t (mm)	Test specimen	%
SBHS700	≧700	780～930	$6 \leqq t \leqq 16$	JIS-5	≧16
			$16 < t \leqq 20$	JIS-5	≧24
			$20 < t \leqq 75$	JIS-4	≧16

(b) HT80

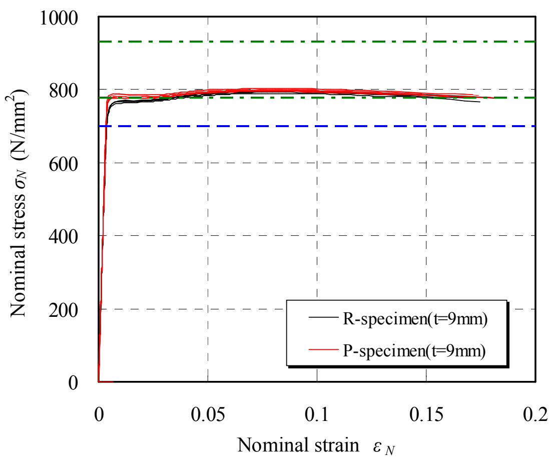
	Plate thickness t (mm)	Yield stress or Proof stress σ_y (kg/mm^2)	Tensile strength σ_u (kg/mm^2)	Elongation		
				Plate thickness t (mm)	Test specimen	%
HT80 (HT780)	$8 \leqq t \leqq 50$	≧70	80～95	$8 \leqq t \leqq 16$	JIS-5	≧16
				$16 < t \leqq 25$	JIS-5	≧22
	$50 < t \leqq 75$	≧68	78～93	$25 < t \leqq 75$	JIS-4	≧16

Table 2 Test Specimens of Tensile Tests

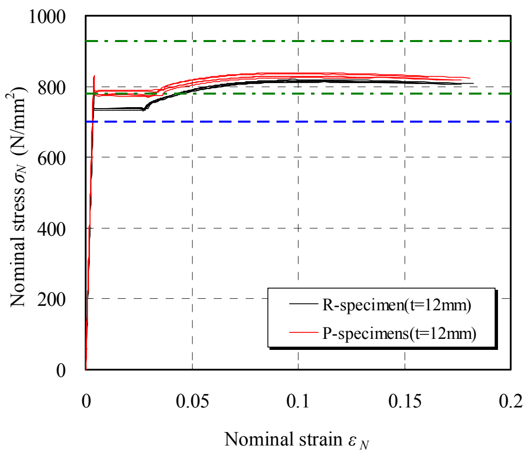
	Plate thickness (mm)	Cut direction	Name	Number of test specimens
SBHS700	9	Rolling	R-specimen	5
		Perpendicularly	P-specimen	5
	12	Rolling	R-specimen	5
		Perpendicularly	P-specimen	5

Table 3 Test Results of Tensile Tests

	Plate thickness (mm)	Cut direction	Yield stress σ_y (N/mm^2)	Tensile strength σ_u (N/mm^2)	Yield ratio YR (%)	Elongation (%)
SBHS700	9	Rolling	770	796	96.7	25
		Perpendicularly	784	802	97.8	24
	12	Rolling	772	818	94.4	30
		Perpendicularly	826	835	99.0	28



(a) t=9mm



(b) t=12mm

Figure 1 Nominal Stress - Nominal Strain Relationship

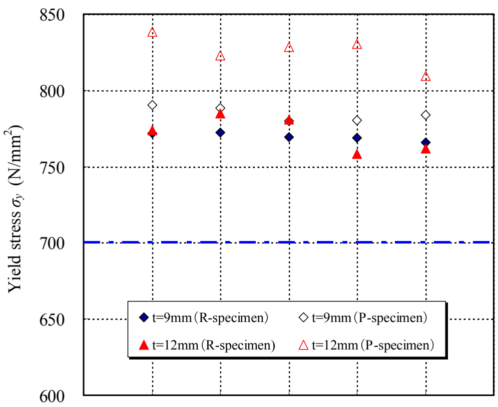


Figure 2 Yield Stress(or proof stress)

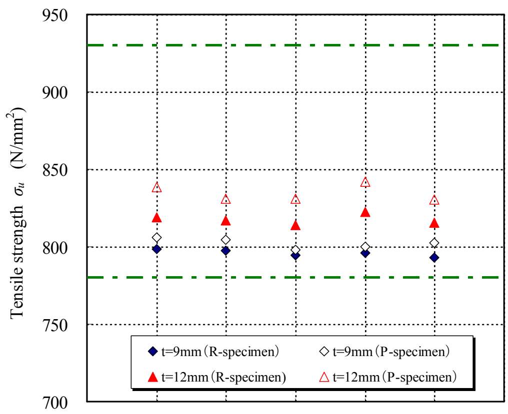


Figure 3 Tensile Strength

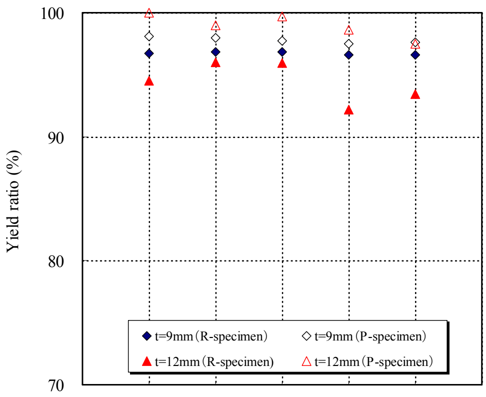


Figure 4 Yield Ratio

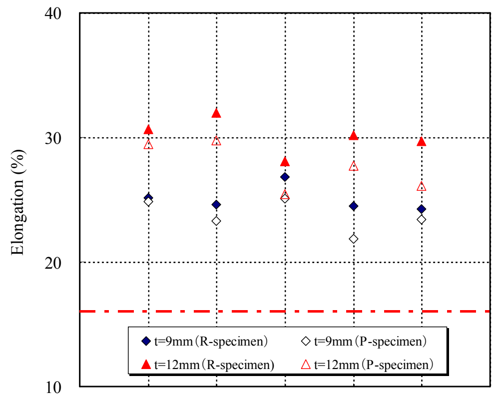


Figure 5 Elongation

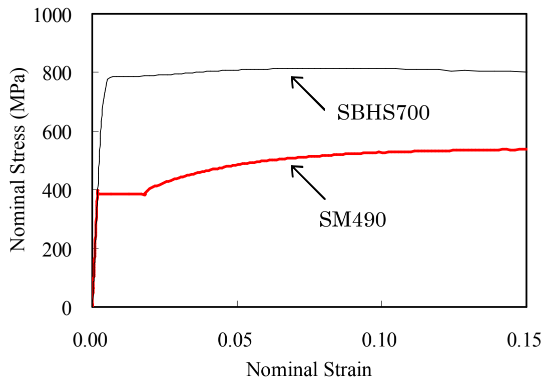
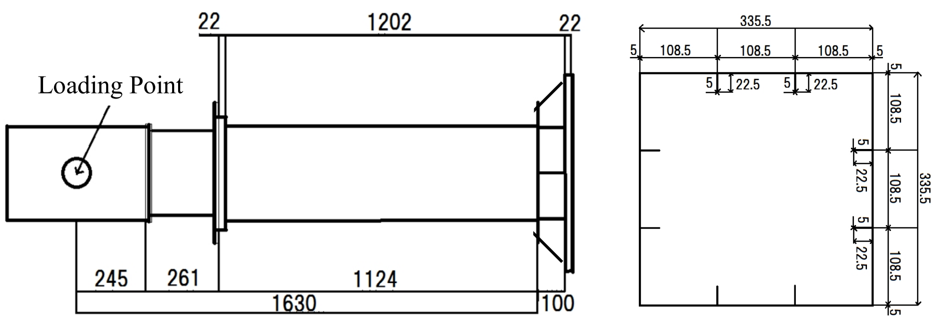


Figure 6 Nominal Stress - Nominal Strain Relationship of SM490 and SBHS700



(a) Side View (b) Cross Section

Figure 7 Configuration of Test Specimen

Table 4 Major Parameters of Test Specimens

		HO	HY
N/N_{yN}		0.15	
λ_N		0.32	
R_{RN}		0.49	
R_{FN}		0.44	
Steel grade	Flanges, Webs	SM490	SM490
	Vertical ribs	SM490	SBHS700

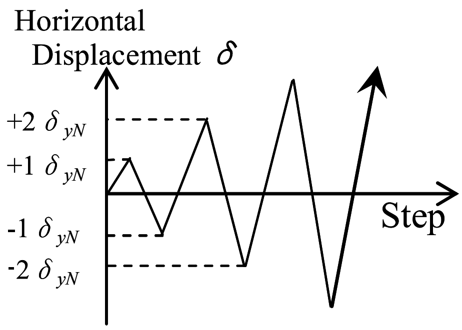
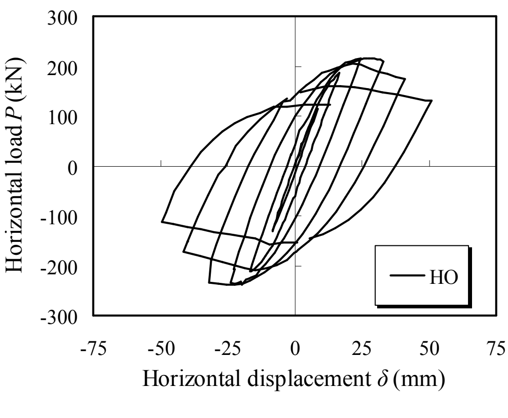
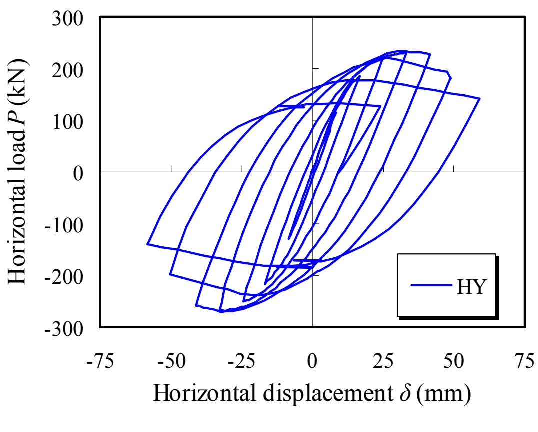


Figure 8 Cyclic Loading Patterns



(a) HO (Homogeneous Specimen)



(b) HY (Hybrid Specimen)

Figure 9 Horizontal Load - Horizontal Displacement Relationship

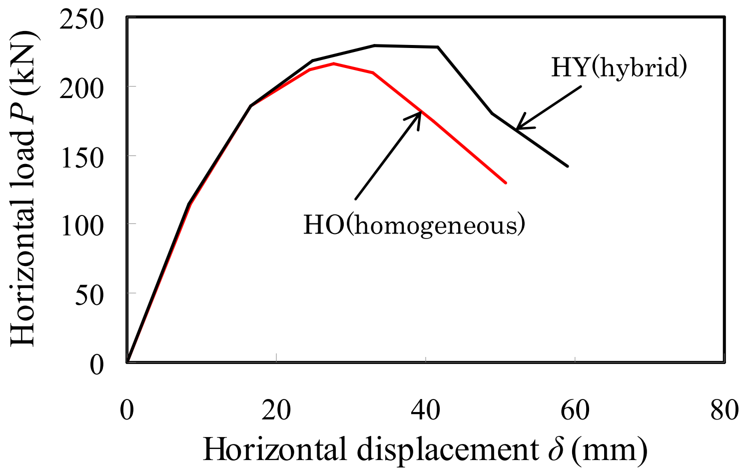


Figure 10 Comparison of Enveloped Curves

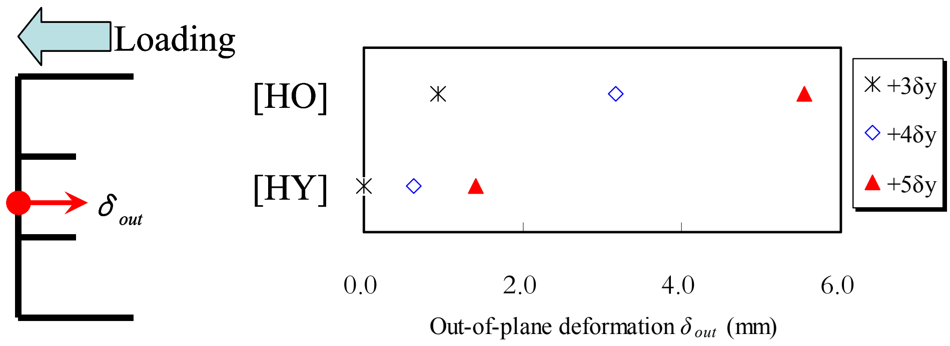


Figure 11 Progress of Out-of-plane Deformation of Flange Panel