REQUIRED FRACTURE TOUGHNESS OF STEELS TO PREVENT BRITTLE FRACTURE DURING EARTHQUAKES IN STEEL BRIDGE PIERS

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Abstract: During the 1995 Hyogo-ken nanbu earthquake in Japan, brittle cracking accidents were occurred in several steel bridge piers. From the investigations on the cracked structures, deterioration of fracture toughness of steel by the effect of large plastic strain is considered as the dominate cause. This study is aiming to determine the required fracture toughness to prevent brittle fracture during earthquakes in steel bridge piers by discussing on the following objectives. 1) To identify the characteristics of strain history during large earthquakes in steel bridge piers by dynamic FEM analysis, and based on that, 2) to determine patterns of strain history that should be considered by discussing the process of the occurrence of brittle fracture, and 3) to evaluate the extent of deterioration of fracture toughness of steel by various patterns of large plastic strain including reversed patterns by CTOD tests.

1. INTRODUCTION

During the 1995 Hyogo-ken nanbu earthquake in Japan, many civil structures were damaged and also in steel bridge piers. Brittle cracking accidents were occurred in some steel bridge piers (JSCE 1995), which were the first experience in steel bridge piers. Figure 1 shows the cracks occurred during the earthquake. Many investigations have been conducted to prevent local buckling from the viewpoint of structural details and to ensure high ductility of steel columns, and the limitation of the parameters like width-thickness ratio have been suggested for design of new steel piers (T. Usami et al 1995). Also, some investigations (C. Miki et al 1998, 1999, 2000, I. Okura et al 1996, JWES 1999) on the prevention against brittle fracture accidents in bridge piers were conducted and concluded that deterioration of fracture toughness of steel due to effect of introduced large plastic prestrain could be considered as the main cause of brittle fracture. Therefore, in order to prevent brittle fracture, it is necessary to use the steels that have enough fracture toughness even after plastic prestrain experience. However, the required level of fracture toughness of the steel to prevent brittle fracture during earthquakes in steel bridge piers has not been clear until so far. This study is aiming to determine it, and so the followings were considered as the objectives.

1) To identify the characteristics of plastic strain history during earthquakes in steel bridge piers and to determine the patterns of strain history that should be considered by discussing the process of the occurrence of brittle fracture.
2) To evaluate the extent of deterioration of fracture toughness of steel by various patterns of plastic prestrain.

Finally, the discussions for suggesting the required fracture toughness of steel to prevent brittle fracture were made by organizing all the results of fracture toughness tests.

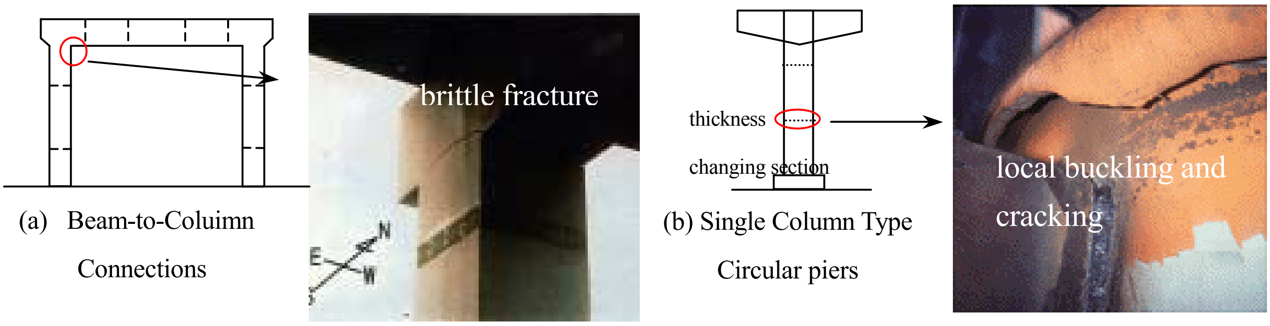
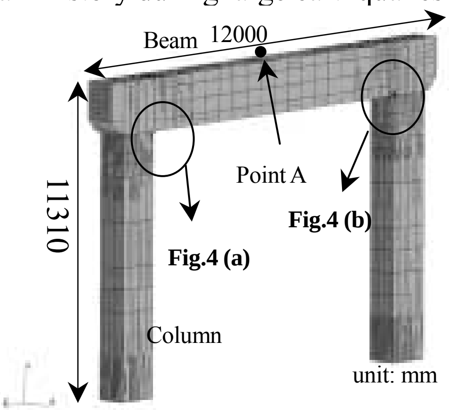


Figure 1 Cracks occurred in Steel Bridge Piers during the Kobe Great Earthquake

2. CHARACTERISTICS OF THE STRAIN HISTORY DURING EARTHQUAKES IN STEEL BRIDGE PIERS

In order to identify the characteristics of strain history during large earthquakes in steel bridge piers, elasto-plastic dynamic FEM analyses on typical bridge pier structures were carried out. Figure 2 shows the shape and size of the target pier and the FEM mesh of the model. The FEM model was built by half model by assuming symmetry in the direction of out-plane of the frame. The smallest mesh size is around 5mm that is nearly equal to one third of the plate thickness. The steel bridge pier considered here was designed by modifying the parameters of the used stiffened plates of an existing bridge pier according to the limitation for new structures (T. Usami et al 1995). The limitation of the width-thickness ratio of plate elements has been suggested to ensure superior ductility up to the specific displacement level$\delta 95$ beyond δmax. $\delta 95$ is the displacement at which the strength decreases up to 95% of the maximum strength Pmax (at the displacementδmax). Recently, the displacement level of $\delta 95$ has been considered as the level to verify seismic performance of steel bridge piers. In this study, also, $\delta 95$ was taken into consideration as the limit level to ensure the prevention of brittle fracture. Therefore, the strain history during large earthquakes and the strain level at $\delta 95$ are mentioned here.



The Total Number of Elements: about 7000

SECTION	Plate	W	t	n	hs	ts	Rr	γ/γ*	steel
COLUMN	flange	2000	16	4	180	20	0.488	3.01	SS400
COLUMN	web	1500	15	3	175	20	0.488	3.02	SS400
COLUMN	diaphram	-	20	-	-	-	-	-	SS400
BEAM	flange	2000	16	4	182	16	0.488	3.07	SS400
BEAM	web	1800	12	2	122	12	-	3.01	SS400
BEAM	diaphram	-	16	-	-	-	-	-	SS400

W:width, t:thickness, n:number of stiffeners, hs:width of stiffeners, ts:thickness of stiffeners, Rt:width-thickness parameter, γ/γ*:ratio of rigidity

Figure 2 The FEM model of the target steel bridge pier

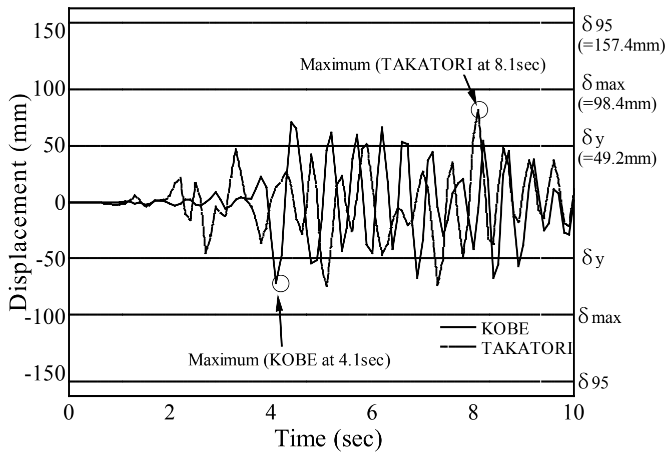


Figure3 Displacement History at the center of the beam

(Point A in Figure 2)

The seismic acceleration waves measured at JR Takatori station and at Kobe Marine Observatory in Hyogo-ken nanbu earthquake were used in the analyses. Figure 3 shows the displacement history at the center of the beam. The values of the yield displacement δy and δ95 in Figure 3 were obtained by the analyses of cyclic static loading under displacement control at point A. Figure 4 illustrates the strain history in direction of component axis near the corner of beam-to-column connections. In both of the cases of Takatori and Kobe, the maximum displacement was in the level over δy and the maximum value of strain during the earthquake was observed at that portion and reached almost 10%. And it can be found that the strain history has the tendency to be one-sided to the region of tension or compression and vary in that region. Finally, according to our previous experimental study (E. Sasaki et al 2001), the measured maximum strain at δ95 near the corner of beam-to-column connections reached less than 10%.

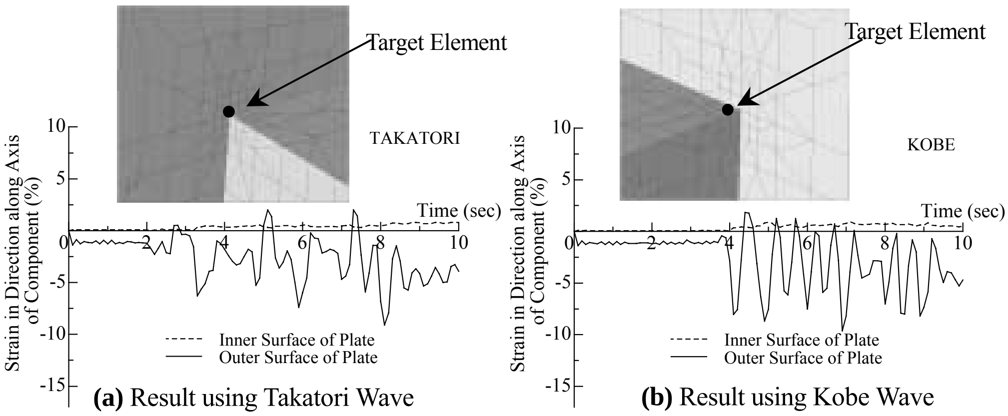


Figure 4 Strain History

3. SCENARIOS OF BRITTLE FRACTURE DURING EARTHQUAKES

As the scenarios of brittle fracture during earthquakes, the following four types shown in Figure 5 were considered. In case of Type I, cracks will be occurred by large compressive plastic train, for example, in the compressive side of local buckling zone (H. Inoue et al 1986). The size of the cracks is small. In case of Type II, cracks are occurred by tensile strain and the following compressive strain makes them sharp. The cracks in Type III and IV occur by fatigue induced by live load like traffic load. Actually, many fatigue cracks were found in steel bents recently (H. Morikawa et al 2002). The deterioration of steels due to plastic strain history, initial cracks and their size and sharpness become our interests.

4. DETERIORATION OF FRACTURE TOUGHNESS OF STEELS BY LARGE PLASTIC PRESTRAIN

The used structural steels were JIS-SM490YB and JIS-SM570Q. They have been commonly used in construction of steel bridge piers. The chemical composition and the mechanical properties of them are shown in Table 1 and Table 2, respectively. Various patterns of plastic prestrain shown in Table 3 were considered and the effects of them on the fracture toughness of steels were evaluated by CTOD

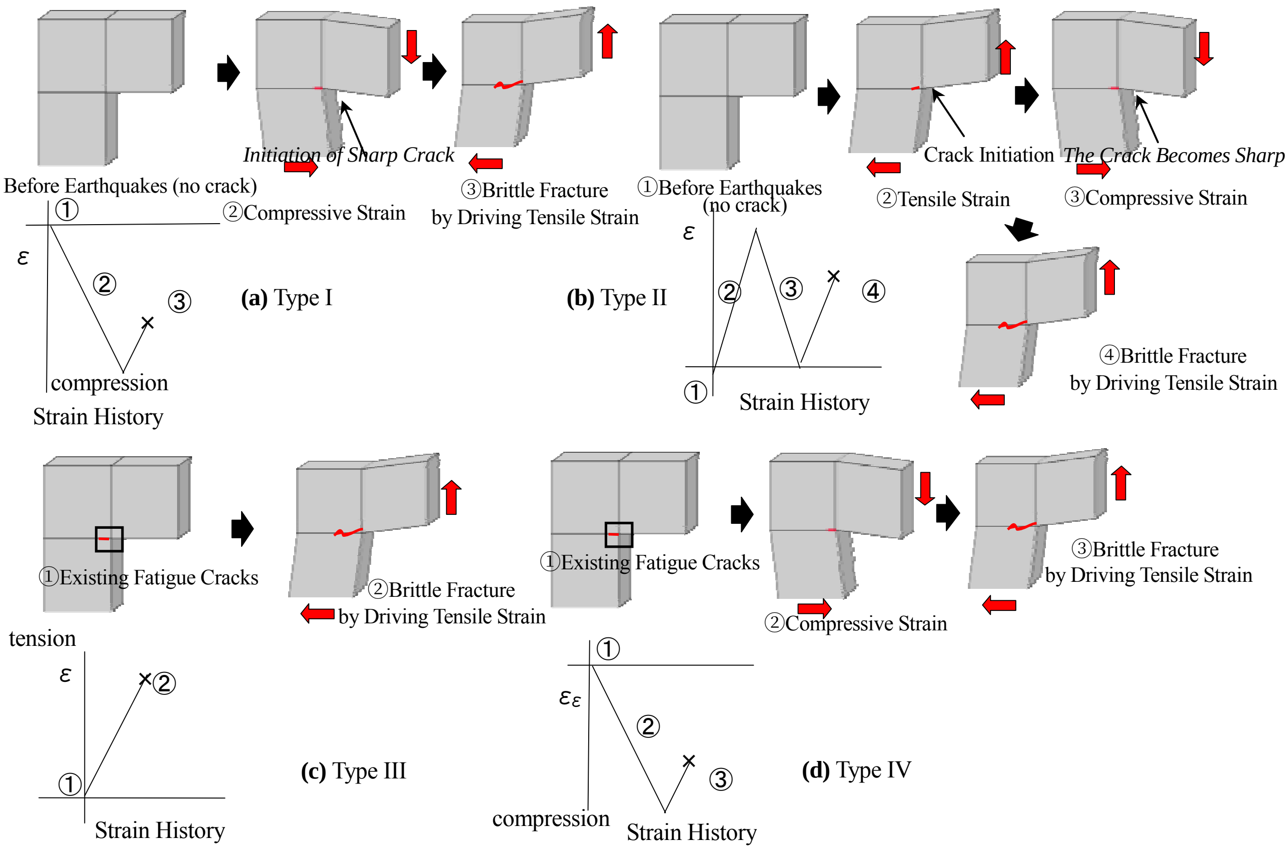


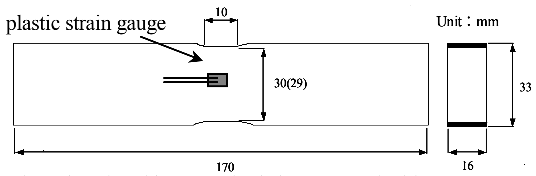
Figure 5 Scenarios of Brittle Fracture

Table 1 Chemical Compositions

Steel	C	Si	Mn	P	S	Cu	Ni	Cr	V
JIS-SM490YB	0.14	0.46	1.56	0.02	0.005	0.01	0.01	0.02	0.04
JIS-SM570Q	0.14	0.23	0.012	0.005	0.005				

Table 2 Mechanical Properties

Steel	Y.P. (MPa)	T.S. (MPa)	Elongation (%)	CVN (Joul)
JIS-SM490YB	407	547	26	154 (0℃)
JIS-SM570Q	560	651	39	299(-5℃)



The value closed by parenthesis is concerned with SM570Q

Figure 6 The Specimen for Introducing of Prestrain

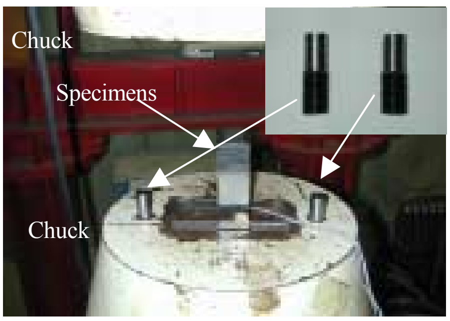


Photo 1 The Fixtures to Prevent Slips Between the Chucks

Table 3 Patterns of Plastic Prestrain

Pattern	Prestrain	Comment
AP0, BP0	0%	no prestrain
AP1, BP1	+10%	uniform tensile prestrain (10%)
AP2, BP2	-10%	uniform compressive prestrain (10%)
AP3, BP3	+10%	cyclic prestrain in tensile region (10%)
AP4, BP4	-10%	cyclic prestrain in compressive region (10%)
AP5, BP5	-5%	uniform compressive prestrain (5%)
AP6, BP6	+5%	cyclic prestrain in tensile region (5%)

*The initial letter of the pattern name shows type of steel.
(A: JIS-SM490YB, B: JIS-SM570Q)

tests. As the levels of prestrain, two levels of 10% and 5% were taken into consideration because reversed patterns of prestrain up to 10% level could be introduced in this study. In order to introduce all the prestrain patterns, the specimens shown in Figure 6 were used to make deformation concentrated at the center. Furthermore, it was needed to invent the fixtures for the direction guides for the chucks in the testing machine shown in Photo 1 to prevent the local buckling of specimens in compressing processes. After the introducing plastic prestrain, bar specimens for tensile tests (Figure 7) and CTOD specimens (Figure 8) were cut from the specimens as shown in Figure 9.

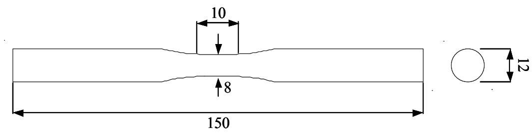
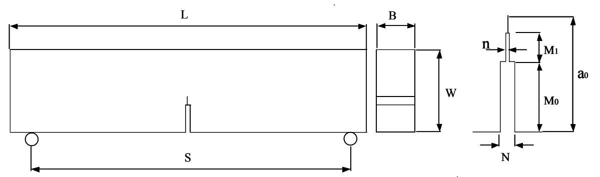


Figure 7 Bar Specimen For Tensile Test



Unit: mm

B	W	S	L	a_0	n	N	M_1	M_0
14.0	28.0	112.0	126.0	0.5W	0.15	1.8	9.0	3.0

Figure 8 CTOD Specimen

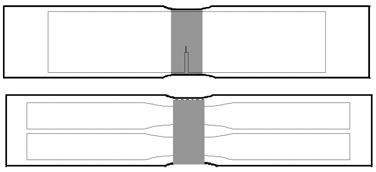


Figure 9 Cutting Techniques

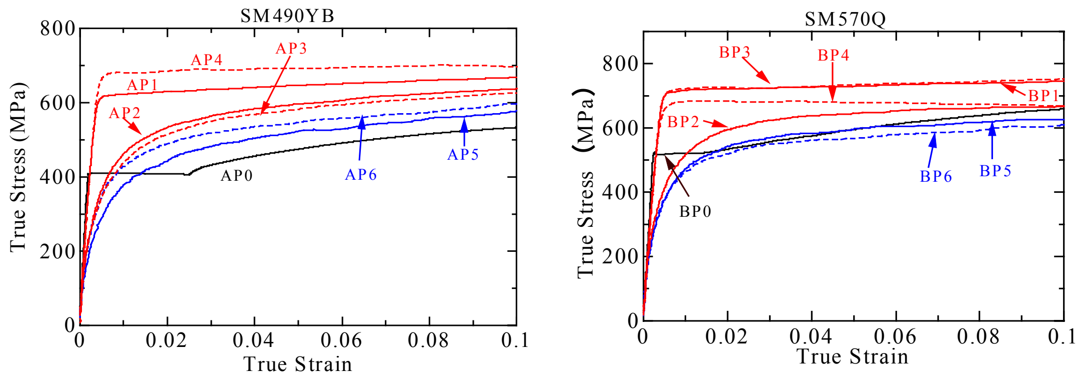
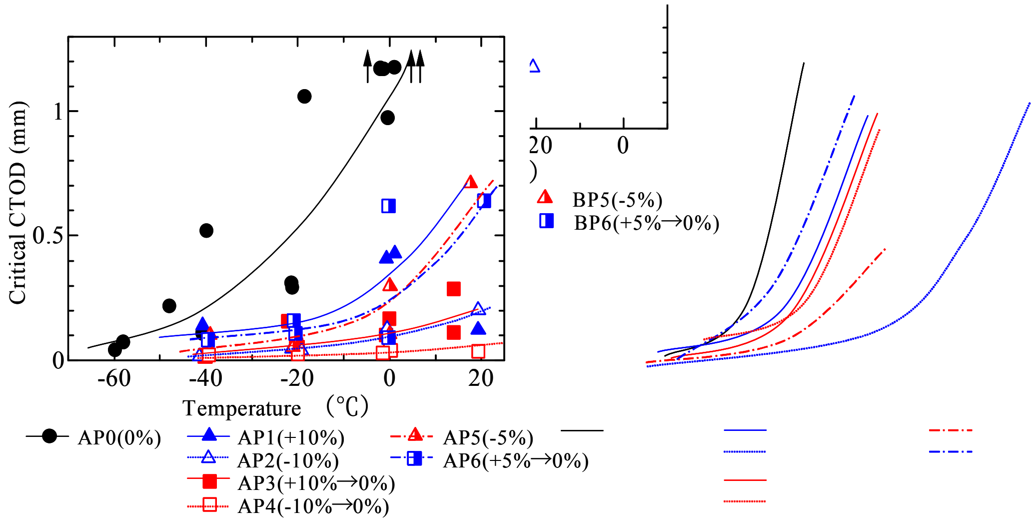


Figure 10 Stress-Strain Relationship

Figure 10 shows the stress-strain relationship after introduction of prestrain for both of the steels. The stress-strain relationship changed by the effect of the prestrain, and so the yield point also varied with the patterns of prestrain.

Figure 11 shows the relationship between test temperature and critical CTOD values. The significant and characteristic deterioration behaviors of the two types of steels were demonstrated. On SM490YB steel, the patterns of prestrain in compression region and the reversed patterns caused more deterioration of fracture toughness than those in tensile region and the uniform patterns, respectively. Also, the difference of the level of prestrain, the extent of deterioration of fracture toughness in case of 10% is larger than that in case of 5%. However, in SM570Q steel, no remarkable changes of fracture toughness were observed in most patterns of prestrain, and only in case of uniform compressive, much deterioration of fracture toughness occurred. From these results, among the patterns showed in the process of brittle fracture, uniform compressive prestrain can be considered as the critical pattern to fracture toughness of steel. As mentioned here, the extent of deterioration of fracture toughness depends on the types of steel and the patterns of prestrain.



(a) SM490YB (b) SM570Q

Figure 11 The Critical CTOD Curves

5. DISCUSSIONS ON THE REQUIRED FRACTURE TOUGHNESS TO PREVENT BRITTLE FRACTURE

Figure 12 shows the relationship between prestrain and the amount of temperature shift of CTOD curves by the prestrain. Figure 12 includes all the results for the various types of steel including the results of this study and our previous studies [2]. The temperature shift was defined at the critical CTOD value of 0.1mm and it shows quantitatively how much extent of deterioration of fracture toughness occurred. The results of the reversed patterns of prestrain were plotted on the same position in the value of prestrain. Let us consider 10% level of prestrain corresponding to the displacement levelδ95. In Figure 12, it can be found that the temperature shift reaches at most 50 degrees of Celsius in 10% level of prestrains with considering all kinds of steels. For that reason, it can be said that in order to prevent brittle fracture in steel bridge piers up to the displacement level δ95, the used steel has to have enough fracture toughness even after the temperature shift of 50 degrees of Celsius.

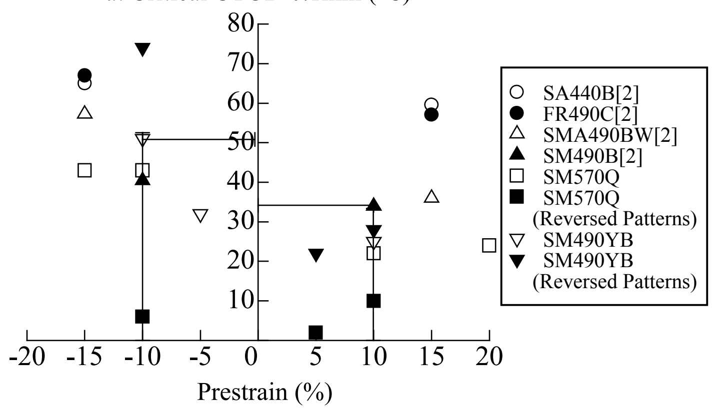


Figure 12 Relationship between Prestrain and Temperature Shift of CTOD Curves

6. CONCLUSIONS

The conclusions of this study can be summarized as follows.

1) By the elasto-plastic dynamic FEM analysis, the strain histories in steel bridge piers during large earthquakes were investigated. The strain histories have the tendency of being one-sided to the region of tension or compression and varying in that region.
2) The plastic strain patterns that should be considered were explained by discussing the processes of brittle fracture, and the effects of the various patterns of plastic prestrain including them on fracture toughness of steels were investigated by CTOD tests. The extent of deterioration of fracture toughness depends on the types of steel and the patterns of prestrain. On SM490YB steel, compressive prestrain and reversed prestrain make fracture toughness more deteriorated than tensile prestrain and uniform prestrain, respectively, and the deterioration of fracture toughness by prestrain in 10% level was more than that by prestrain in 5% level. On SM570 steel, in all the prestrains but uniform compressive prestrain in 10% level, no remarkable deterioration of fracture toughness were not observed.
3) By arranging all the results of this study and our previous investigations concerned with the effects of plastic prestrain, the temperature shift of 50 degrees of Celsius was suggested as the extent of deterioration of fracture toughness of steels due to the effects of plastic prestrain that should be considered in determination of the required fracture toughness of steels to prevent brittle fracture in steel bridge piers to the displacement level δ95.

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