applied sciences

MDPI

Article

Fracture Assessment of Weld Joints of High-Strength Steel in Pre-Strained Condition

Gyubaek An [1], Jeongung Park [2,*], Mituru Ohata [3] and Fumiyoshi Minami [4]

[1] Department of Naval Architecture and Ocean Engineering, Chosun University, Gwang-ju 61452, Korea; gyubaekan@chosun.ac.kr
[2] Department of Civil Engineering, Chosun University, Gwang-ju 61452, Korea
[3] Graduate School of Engineering, Department of Materials and Manufacturing Science, Osaka University, Osaka 565-0871, Japan; ohata@mapse.eng.osaka-u.ac.jp
[4] Joining & Welding Research Institute Osaka University, Osaka 567-0047, Japan; minami@jwri.osaka-u.ac.jp
* Correspondence: jupark@chosun.ac.kr; Tel.: +82-62-230-7099

Received: 8 March 2019; Accepted: 25 March 2019; Published: 28 March 2019

check for updates

Abstract: Unstable fractures tend to occur after ductile crack initiation or propagation. In most collapsed steel structures, a maximum 15% pre-strain was recorded, at the steel structural connections, during the great earthquake of 1995, in Japan. Almost-unstable fractures were observed in the beam-to-column connections, where geometrical discontinuities existed. Structural collapse and unstable failure occurred after large-scale plastic deformations. Ship structures can also suffer from unstable fractures in the welded joints. The fracture resistance of butt-welded joints subjected to tension in the pre-strained condition was estimated by considering the toughness deterioration, due to pre-strain and toughness correction for constraint loss in a tension specimen. The target specimen for this fracture assessment was a double-edged, through-thickness crack panel, with a crack in the weld joint (heat-affected zone (HAZ)). The critical fracture toughness value (crack tip opening displacement (CTOD)) of a large structure with pre-strain, which was applied to the HAZ region, was estimated from a small-scale, pre-stained, three-point bend specimen. Fracture toughness values, evaluated by a CTOD test, were recently mandated for shipbuilding steel plates. The critical fracture toughness value is a very useful parameter to evaluate the safety of huge ship structures.

Keywords: pre-strain; fracture toughness; brittle fracture; fracture assessment crack tip opening displacement (CTOD); great earthquake; dynamic load; huge ship structure

---

1. Introduction

In general, 600–780 MPa-class high-strength structural steels are developed by a thermomechanical controlled process (TMCP), in steel mills [1]. Recently, the demand for large steel structures has been increasing, and in order to build a large steel structure, the strength must be increased. The application of high-strength steels, such as the 600 MPa-class steel, can be found in recent structures. These steels are used to increase the design stress and reduce transportation cost, owing to their light weight. Steel structure designs generally employ high-strength steel as the structural element. For the safe application of these steels in steel-framed structures, safety during earthquakes (dynamic loading and pre-strain occurrence) and toughness of the weld joint, especially in the heat-affected zone (HAZ), should be ensured. In general, the toughness decreases in the HAZ as the steel undergoes cycles of heat and strain, during multi-pass welding. In multilayer welding, the texture and toughness of the HAZ due to multithermal cycles show very complex distributions. As a result of measuring the toughness change by the crack tip opening displacement (CTOD) test for the multilayer welded HAZ, the decrease in toughness in the HAZ was remarkable [2–4]. The HAZ is characterized by unequal growth of the austenite formed in the dual phase, where C and Mn are not evenly distributed and concentrated on both sides, which thus, remains unstable in the low temperature region, without being decomposed into ferrite at high temperatures. The austenite instead transforms into martensite. This is defined as the M–A (Martensite–Austenite) constituent, which is a very poor phase. From a metallographic viewpoint, the reason why the HAZ is the most vulnerable phase is due to the M–A.

The promotion of a brittle fracture is a very dangerous problem that occurs, owing to dynamic and pre-strain effects. The fracture driving force increased, owing to the dynamic loading effect, and the fracture toughness decreased, owing to the pre-strain effect.

Unstable fractures of high-toughness steel structures in weld joints tend to occur after ductile crack initiation or propagation. During the great earthquake, as reported in [2,5,6], damage to steel structures occurred in weld joints after large strain deformation. The pre-strain in the cyclic loading, during the earthquake, occurred at the strain concentration area, like the weld toe in the weld structure. The great earthquake occurred in 1995. In most collapsed steel structures, a maximum of 15% pre-strain was recorded at the steel structure connections [3,4]. An almost-unstable fracture was observed in the beam-to-column connection areas where geometrical discontinuity exists. In the collapsed structures, unstable failures occurred after large-scale plastic deformation. This earthquake was characterized by the brittle fracture of structural steel under high-speed ground motion (104 kines (cm/s)) and large ground displacement (27 cm).

As a complement to the classical, unstable crack-initiation/propagation failure toughness, brittle crack-arrest failure toughness has become an important mechanical property to address material fracture and failure mechanisms, to avoid unstable fractures in structures [7–17].

The objectives of this study are as follows: (i) investigation of the change in the strength and toughness of the TMCP steel welds, with pre-strain and dynamic loading; (ii) development of a fracture assessment procedure for TMCP high-strength steel welds, under seismic conditions; and (iii) verification of the fracture assessment procedure by a large-scale component test. These can establish the procedure for the fracture performance assessment of TMCP high-strength steel welds, under seismic conditions. Attention was focused on the impact of the HAZ softening on structural integrity after pre-straining. The applicability of WES 2808 [18] to 780 MPa TMCP steel and its welds were examined.

2. Manufacturing of the HSB 600 High-Performance Steel Welds

2.1. Material Properties of the Specimens Used

The test specimen was produced by a conventional welding process, namely, submerged arc welding (SAW) [19]. This welding method was selected because SAW applies a relatively large heat input in the construction method of large steel structures, and adversely affects the safety of the welded joints. The mechanical properties and chemical composition of 25 mm-thick, high-strength steel (HSB600 high-performance steel for bridge structures) are listed in Tables 1 and 2, respectively. The tensile test was carried out six times in the rolling direction of the steel plate by ASTM E8 [20], and with round-bar type test specimens, with a strain rate of 0.007 (1/s), at room temperature, (approximately 20 °C). The average yield strength and tensile strength were 604 MPa and 686 MPa, respectively. The Charpy impact energy was carried out by ASTM E23 [21], and the value was 47 J at −5 °C, the temperature required for the test condition of the steel bridge by Korean Industrial Standards (KS D3868) [22]. Figure 1 shows the groove geometry and macro section of the weld joint. The weld joint was made by base metal plates, with the dimensions 1,000 mm in length × 500 mm in width × 25 mm in thickness, with a single bevel groove angle of 17°. The SAW technique was used and the weld joint had a seven-pass welding layer. The general weld joint macro section is shown in Figure 1b. The applied heat input was 50 kJ/cm, which was used in the wide production filed to construct the steel welding structure. The welding conditions are listed in Table 3. The chemical composition of the welding consumable is shown in Table 4 [14] and the used flux was AWS A5.23 F8A4-EA3-G.

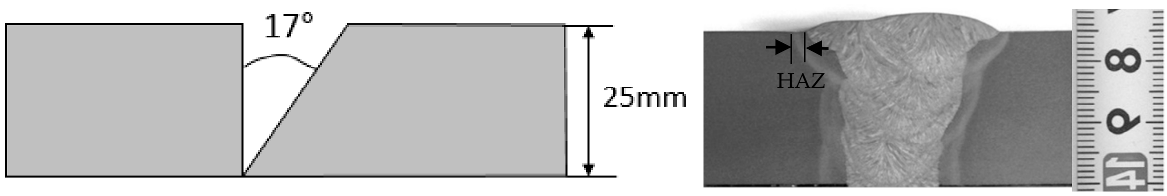
Table 1. Mechanical properties of the HSB600 steel plate used.

Specimen Symbol	Young's Modulus E, (MPa)	Yield Strength YS, (MPa) *	Tensile Strength TS, (MPa)	Yield-to-Tensile Ratio Y/T *
BM*-1	204,600	620	679	0.91
BM-2	207,800	613	693	0.88
BM-3	205,000	632	691	0.91
BM-4	206,700	576	684	0.84
BM-5	205,100	593	680	0.87
BM-6	208,300	589	688	0.86
Average	206,250	604	686	0.88

* BM: base metal, YS: 0.2% proof stress, Y/T= YS/TS.

Table 2. Chemical composition of the HSB600 steel plate used (wt. %).

Steels	C	Si	Mn	P	S	Fe
HSB600 (25 mm)	0.15≤	0.75≤	2.00≤	0.30≤	0.007≤	bal.



(**a**) groove geometry (**b**) macro section

Figure 1. Groove geometry and macro section of the weld joint.

Table 3. Welding condition for 25 mm steel plate.

Welding Process	Current (A)	Voltage (V)	Speed (cm/min)	Heat Input (kJ/cm)	Preheat Temp. (°C)	Interpass Temp. (°C)
SAW	700	34	29	50	100	100

Table 4. Chemical composition of the welding consumable (wt. %).

Welding Consumable	C	Si	Mn	P	S	Fe
SAW wire	0.08	0.32	1.67	0.01	0.007≤	bal.

2.2. Double-Edge Through-Thickness Crack Panel within a Crack in the HAZ

The fracture resistance of the butt-welded joints subjected to tension in the pre-strained condition was estimated by considering two effects: (1) toughness deterioration due to pre-strain (ductile-to-brittle transition temperature shifts due to pre-strain), and (2) toughness correction for constraint loss in the target specimen.

The target specimen for fracture assessment was a double-edged, through-thickness crack panel (ETCP) with a crack in the HAZ, as shown in Figure 2. The crack length 2a ranged from 10 mm to 100 mm. It was assumed that 3.0% tensile pre-strain was applied to the HAZ region. The pre-strain amount was measured with line interval lengths near the HAZ area. Lines were drawn at intervals of 3 mm in the loading direction of the specimen, before tensile loading, to measure the pre-strain amount in the HAZ. As the width of the HAZ was 3 mm, an interval of 3 mm was used to measure the pre-stain amount of HAZ. The tensile load applied until the 3 mm interval became 3.09 mm, especially near the HAZ.

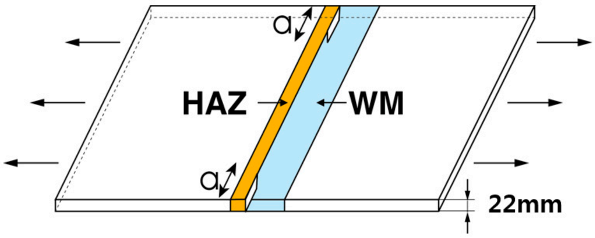


Figure 2. Double-edged through-thickness crack panel with a crack in the heat-affected zone (HAZ).

3. Pre-Strain Effect on Fracture Toughness

3.1. Critical CTOD of 3.0% Pre-strained HAZ Specimen

In order to evaluate the fracture resistance of the 3.0% pre-stained ETCP, toughness deterioration due to the pre-strain should first be estimated. Generally, fracture toughness is required by the CTOD value in the line pipe and the offshore structural steel plate [23]. Therefore, in this study, fracture toughness was evaluated using CTOD. The CTOD fracture toughness of the pre-strained HAZ (fusion line + 1 mm) was measured by a three-point bend (3PB) test. The 3PB tests were conducted to measure the CTOD fracture toughness of 3.0% pre-strained specimens, with full thickness. The thickness of the 3PB specimen, B, was 22 mm, because the specimens should be manufactured by surface finishing in welded joints, which have angular distortion. The 3PB specimen had a deep through-thickness crack; $a/W = 0.5$, where a and W are the crack depth and the specimen width, respectively. The 3PB test temperatures were −60 °C, −40 °C, −20 °C, and 0 °C. The specimen was cooled with liquid nitrogen in a cooling bath. The yield strength of HSB600 steel at the test temperature was used for the calculation of the elastic component of CTOD. The critical CTOD at the fracture was calculated in accordance with ISO12135 [24] and ISO15653 [25]. The fracture toughness results of the pre-strained HAZ are shown in Figure 3. The specific temperature at which the critical CTOD was 0.1 mm, tended to increase with increasing pre-strain. The 3.0% pre-strain shifted the specific transition temperature by approximately 40 °C. These results indicate that the deterioration of the fracture toughness due to pre-strain should be taken into account, during the safety assessment against fracture from the weld HAZ, in the pre-strained condition. Table 5 summarizes the critical CTODs of the 3.0% pre-strained HAZ used in the assessment [19].

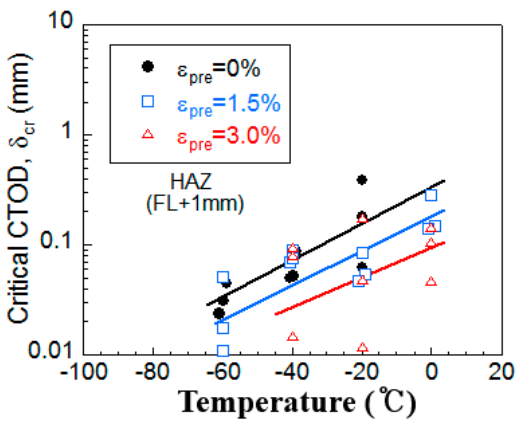


Figure 3. Effect of pre-strain on ductile-to-brittle transition temperature [19].

Table 5. Critical crack tip opening displacement (CTOD) data of 3.0% pre-strained HAZ obtained by the three-point bend test.

Temperature	Critical CTOD (3PB)	
T (°C)	δ_{cr} (mm)	$\delta_{cr\ ave.}$ (mm)
−20	0.012	0.079
−20	0.049	
−20	0.177	
0	0.047	0.1
0	0.108	
0	0.145	

The critical CTOD of the ETCP would be larger than that of the 3PB standard fracture toughness specimen that was subjected to tension, owing to the plastic constraint loss around the crack tip in the ETCP. ISO 27306 [15] provides an engineering method to correct the CTOD toughness for the constraint loss in structural components. The toughness correction ratio, defined as the equivalent CTOD ratio β, was standardized in ISO 27306. Figure 4 shows a monograph of β_0 for an ETCP, including a reference size of the crack. β_0 is a function of YR and m, where YR and m are the yield-to-tensile ratio and the Weibull shape parameter, respectively.

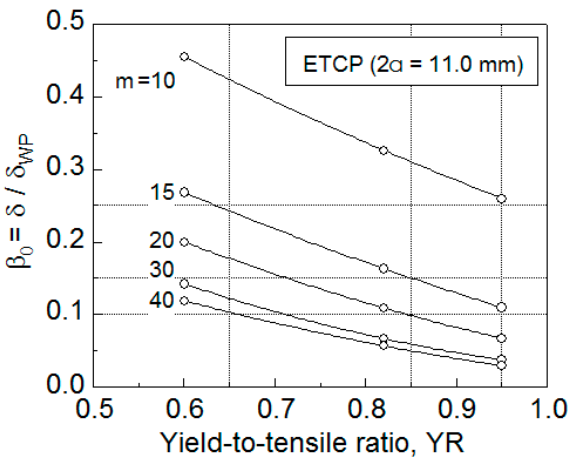


Figure 4. Monographs of equivalent CTOD ratio β_0 for double-edged, through-thickness crack panel (ETCP) with a reference crack length of 2a = 11 mm.

3.2. Estimate of Critical CTOD in Pre-strained ETCP

The equivalent CTOD ratio β_{2a} for the ETCP with crack length 2a was determined using Equation (1) [13].

$$\beta_{2a(ETCP)} = \beta_{0(ETCP)} \cdot (2a/11)^{k_{ETCP}(m,\ YR)},\ k_{ETCP}(m,\ YR) = \frac{-0.57 + 3.1YR - 1.45YR^2}{\exp\{-0.35(m-10)\} + 1} \quad (1)$$

According to ISO 15635 [25], the yield strength used in the calculation of the CTOD—when located in (or is partially in) the transformed HAZ—is higher than the yield strength of the base metal and weld metal (WM) strength applied, as it is difficult to evaluate the strength of the actual HAZ. When under-matched, weld-joint, pre-strain is applied, most of the deformation occurs in the base material, and the strength of the base metal becomes almost similar to that of the WM. Therefore, the yield strength of the base material was used in the CTOD calculation in this study and was estimated from the stress–strain curves of base steel, without the pre-strain, as shown in Figure 5. The yield stress of the pre-strained HAZ σ_Y^{pre} can be obtained using Equation (2) [18].

$$\sigma_Y^{pre} = S_Y(\varepsilon_{pre}) \tag{2}$$

where $S_Y(\varepsilon_{pre})$ is the true stress of the original HAZ at the true pre-strain ε_{pre}. The tensile strength of the pre-strained HAZ σ_T^{pre} can be determined by Equation (3) [18];

$$\sigma_T^{pre} = \sigma_Y \frac{1+\varepsilon_T}{1+(\varepsilon_T - \varepsilon_{pre})} \tag{3}$$

where σ_T and ε_T are the tensile strength and uniform elongation of the original HAZ, respectively. The estimated YR of the 3.0% pre-strained steel was 0.90, where σ_Y^{pre} and σ_T^{pre} are 684 MPa and 759 MPa, respectively. The equivalent CTOD ratio β_0 for the ETCP with YR = 0.90 was 0.08 for m = 20 (Figure 4). The equivalent CTOD ratios β_{2a} for the 3.0% pre-strained ETCP, with different crack lengths $2a$, were calculated using Equation (1); the results are listed in Table 6.

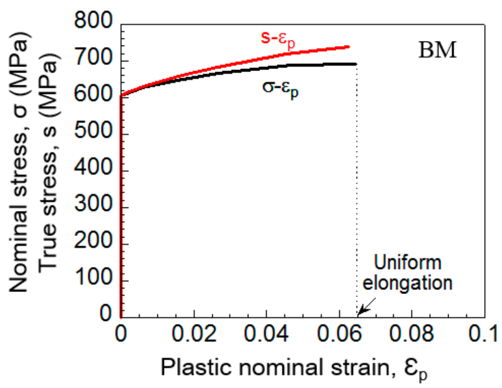


Figure 5. Stress-strain curves for HSB600 steel.

Table 6. Equivalent CTOD ratio β for 3.0% pre-strained ETCP (YR = 0.9, m = 20), as a function of crack length $2a$.

$2a$	$\beta_{0\ (ETCP)}$	$\beta_{2a\ (ETCP)}$
10	0.08	0.07
20	0.08	0.15
30	0.08	0.22
40	0.08	0.30
50	0.08	0.37
60	0.08	0.45
70	0.08	0.52
80	0.08	0.60
90	0.08	0.68
100	0.08	0.75

The critical CTOD $\delta_{cr,ETCP}$ of the 3.0% pre-strained ETCP with the double-edged crack in the HAZ was estimated from the critical CTOD $\delta_{cr,3PB}$ for the 3.0% pre-strained 3PB specimen, given in Table 5, in the form of $\delta_{cr,ETCP} = \delta_{cr,3PB}/\beta_{2a}$. In this estimation, the median of $\delta_{cr,3PB}$ at each temperature was used. Figure 6 presents the estimated critical CTOD for the 3.0% pre-strained ETCP, as a function of the crack length $2a$, at the temperatures 0 °C and −20 °C. The critical CTOD $\delta_{cr,ETCP}$ decreased with the increasing crack length $2a$.

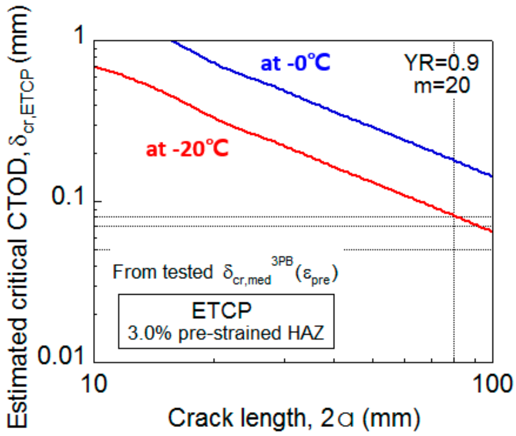


Figure 6. Critical CTODs for the 3.0% pre-strained ETCP estimated from 3.0% pre-strained (three-point bend) 3PB test results.

4. Results and Discussion

In this estimation, the fracture toughness of the pre-strained HAZ obtained by the experiments was employed. WES 2808-2003 [13] provides the estimation method for the pre-strained toughness, as shown in Figure 7. The static fracture toughness of the base metal at the reference temperature of $T - \Delta T_{PD}$ can be used as the fracture toughness in the pre-strain and the dynamic conditions at the service temperature T. The ΔT_{PD} is the temperature shift of the fracture toughness caused by the pre-strain and the dynamic loading. In WES 2808, the temperature shift ΔT_{PD} correlates with the flow stress elevation, $\Delta\sigma_f^{PD} = (\Delta\sigma_Y + \Delta\sigma_T)/2$, by pre-strain and dynamic loading. $\Delta\sigma_Y$ and $\Delta\sigma_T$ are the increase in the yield stress and tensile strength, respectively. The temperature shift ΔT_{PD} is given by Equation (4) [18]. This formula is applicable to the structural steels of 400 to 590 MPa-strength class.

$$\Delta T_{PD}\left(^{\circ}\mathrm{C}\right) = \begin{cases} 0.4\Delta\sigma_f^{PD} & : 0 \leq \sigma_f^{PD} \leq 100\ (MPa) \\ 40 & : 100 \leq \sigma_f^{PD} \leq 300\ (MPa) \end{cases} \tag{4}$$

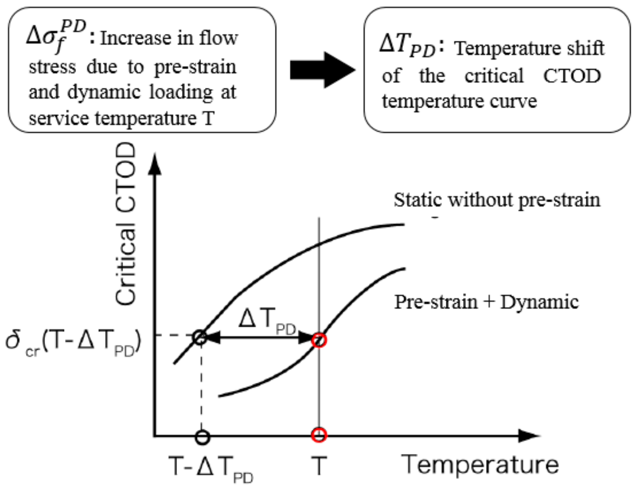


Figure 7. Temperature shift of fracture toughness ΔT_{PD} in pre-strained and dynamic conditions.

According to WES 2808, the fracture toughness of the pre-strained HAZ of HSB600 steel was predicted from the HAZ toughness, without the pre-strain. First, the flow stress of the pre-strained HAZ was estimated under the assumption that the flow stress is the same as that of the pre-strained base steel. The yield stress and tensile strength, as well as the flow stress σ_f^{PD}, of the pre-strained weld HAZ are summarized in Table 7; these were calculated using Equations (2) and (3), on the basis of the stress–strain curve shown in Figure 5. Then, the temperature shift ΔT_{PD} for the pre-strained HAZ was calculated using Equation (4) [13], and the values are shown in Figure 8. The median of the critical CTODs estimated for the 3.0% pre-strained HAZ at −20 °C and 0 °C are listed in Table 8.

Table 7. Mechanical properties of HSB600 steel with and without pre-strain.

BM-2	σ_Y (MPa)	$\sigma_{0.2}$ (MPa)	σ_T (MPa)	σ_f^{PD} (MPa)	YR (=σ_Y/σ_Y)
ε_{pre} = 0%	605	613	693	649	0.87
ε_{pre} = 1.5%	649	–	748	699	0.87
ε_{pre} = 3.0%	684	–	759	722	0.90

σ_Y : Yield stress, $\sigma_{0.2}$: 0.2% proof stress, σ_T : Tensile strength, σ_f^{PD} : (= σ_Y + σ_Y)/2.

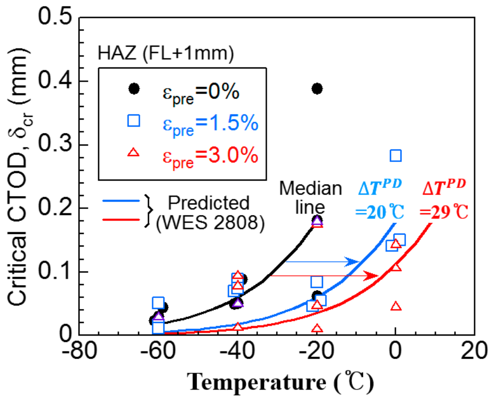


Figure 8. Temperature shift ΔT_{PD} for the pre-strained HAZ predicted with the procedure specified in WES 2808.

Table 8. Critical CTOD for 3.0% pre-strained HAZ obtained by experiment and estimated from δ_c without pre-strain.

Temperature	Critical CTOD for 3.0% Pre-Strained HAZ, $\delta_{cr,med}$ (mm)	
T (°C)	Experiment	Estimated from $\delta_{cr,med}$ without Pre-Strain
−20	0.049	0.035
0	0.108	0.11

Then, from the estimated critical CTODs, $\delta_{cr,ETCP}$ for the 3.0% pre-strained ETCP with a crack in the HAZ was estimated with the equivalent CTOD ratio β_{2a}. The β_{2a} used was the same as that listed in Table 6. As shown in Figure 9, the $\delta_{cr,ETCP}$ for the 3.0% pre-strained ETCP, derived from the toughness values estimated on the basis of WES 2808, was almost the same as that estimated from the experimental data of critical CTOD, for the 3.0% pre-strained 3PB specimen (Figure 6).

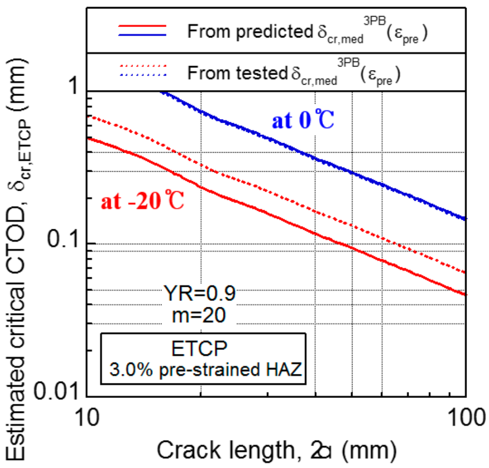


Figure 9. Critical CTOD of the 3.0% pre-strained ETCP estimated from the predicted value.

5. Conclusions

The pre-strain effect on the fracture assessment was determined in 25 mm HSB 600 high-performance steel plate and weld joints. The static fracture toughness of the base metal at a reference temperature of $T - \Delta T_{PD}$ can be used as the fracture toughness in the pre-strain and dynamic conditions at the service temperature T. The ΔT_{PD} was the temperature shift of the fracture toughness caused by pre-strain and dynamic loading. According to the WES 2808, HSB600 steel fracture toughness with pre-strained HAZ was predicted from the HAZ toughness without pre-strain. These results indicate that the prevention of unstable failure owing to pre-strain, should be considered in the failure safety assessment of the weld in the pre-strained HAZ. In addition, the fracture toughness values of large structures with the pre-strain effect can be estimated from small-scale specimens (3PB), despite the high-strength steel plate weld joints.

Author Contributions: G.A., M.O., and F.M. jointly conceived and designed the experiment, performed the experiment and conducted data analysis. G.A., and M.O. analyzed the data and plotted the figures, wrote this paper. J.P. provided scientific guidance.

Funding: This research was supported by the basic science program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (NO. NRF-2017R1D1A1B04029150).

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

δ_{cr}	Critical crack tip opening displacement (CTOD)
ΔT	Temperature shift
a	Crack length
K	Constant
β	Equivalent CTOD ratio
ε_{pre}	True pre-strain
$\sigma_T{}^{pre}$	Tensile strength of the pre-strained HAZ
$\sigma_Y{}^{pre}$	Yield strength of the pre-strained HAZ
m	Weibull shape parameter

References

1. Chae, M.S.; Lee, G.D.; Suh, Y.S.; Lee, K.H.; Kim, Y.S. Mechanical and Forming Characteristics of High-Strength Boron-Alloyed Steel with Hot Forming. *Trans. Mater. Process.* **2009**, *18*, 236–244.
2. Okashita, K.; Ohminami, R.; Michiba, K.; Yamamoto, A.; Tomimatsu, M.; Tanji, Y. Investigation of the brittle fracture at the corner of P75 rigid-frame pier in Kobe harbor highway dur-ing the Hyogoken-Nanbu earthquake. *J. Jpn. Soc. Civ. Eng.* **1998**, *591*, 243–261.

3. APD Committee. *Strength and Fracture Toughness of Weld Connections in Steel Framed Structures*; JWES-IS-9701; APD Committee: Singapore, 1997; pp. 47–192.
4. Hemmericha, E.; Rolfeb, B.; Hodgsona, P.; Weissa, M. The effect of Pre-strain on the Material Behav-iour and the Bauschinger Effect in the Bending of Hot Rolled and Aged Steel. *Mater. Sci. Eng.* **2001**, *528*, 3302–3309. [CrossRef]
5. Kinki, A.I. *Reconnaissance Re-Port on Damage of Steel Building Structures Observed from the 1995 Hyogoken-Nanbu (Hanshin/Awaji) Earthquake*; Steel Committee of Kinki Branch: Osaka, Japan, 1995.
6. Toyoda, M. How steel structures fared in Japan great earthquake. *Weld. J.* **1995**, *74*, 132–136.
7. Yamaguchi, Y.; Matsumoto, T. *Technical Requirements to Ensure Structural Reliability for Mega Container Ships-Application of New Higher Strength Hull Structure Steel Plates of Heavy Thick-Ness*; Design & Operation of Container Ships: London, UK, 2006; pp. 43–50.
8. Nakano, Y. Fracture toughness of steels (III) fracture tough-ness and its control factors. *Q. J. Jpn. Weld. Soc.* **1992**, *1*, 6–13.
9. Bezensek, B.; Hancock, J.W. The toughness of laser welded joints in the ductile–brittle transition. *Eng. Fract. Mech.* **2007**, *74*, 2395–2419. [CrossRef]
10. Hajjaj, M.; Berdin, C.; Bompard, P.; Bugat, S. Analyses of cleavage crack arrest experiments: Influence of specimen vi-bration. *Eng. Fract. Mech.* **2008**, *75*, 1156–1170. [CrossRef]
11. Ripling, E.J.; Crosley, P.B. Crack arrest fracture toughness of a structural steel (A36). *Eng. Fract. Mech.* **2008**, *75*, 2984–3009.
12. Masubuchi, K. *Analysis of Welded Structures-Fracture Toughness*, 1st ed.; Pergamon: New York, NY, USA, 1980; pp. 336–399.
13. ISO 27306. *Metallic Materials—Method of Constraint Loss Correction of CTOD Fracture Toughness for Fracture Assessment of Steel Components*; International Organization for Standardization: Geneva, Switzerland, 2009.
14. Kim, T.J.; Jang, B.S.; Kang, S.W. Welding deformation analysis based on improved equivalent strain method considering the effect of temperature gradients. *Int. J. Naval Archit. Ocean Eng.* **2015**, *7*, 157–173. [CrossRef]
15. An, G.B.; Woo, W.C.; Park, J.U. Brittle crack-arrest fracture toughness in a high heat-input thick steel weld. *Int. J. Fract.* **2014**, *185*, 179–185. [CrossRef]
16. Okido, S.; Hayashi, M.; Tanaka, K.; Akinawa, Y.; Minakawa, N.; Mori, Y. Measurement of residual stress in textured Al alloy by neutron diffraction method. In Proceedings of the 7th International Conference on Nuclear Engineering (ICONE), Tokyo, Japan, 19–23 April 1999; pp. 19–23.
17. Woo, W.; An, G.B.; Kingston, E.J.; DeWald, A.T.; Smith, D.J.; Hill, M.R. Through-thickness distributions of residual stresses in two extreme heat-input thick welds: A neutron diffraction, contour method and deep hole drilling study. *Acta Mater.* **2000**, *61*, 3564–3574. [CrossRef]
18. WES 2808. *Method of Assessing Brittle Fracture in Steel Weldments Subjected to Large Cyclic and Dynamic Strain*; The Japan Welding Engineering Society: Tokyo, Japan, 2008.
19. An, G.B.; Park, J.U.; Ohata, M.; Minami, F. Pre-strain effect of on fracture performance of high-strength steel welds. *J. Mech. Sci. Technol.* **2018**, *32*, 3145–3151. [CrossRef]
20. ASTM E8. *Standard Test Methods for Tension Testing of Metallic Materials*; American Society for Testing and Materials: West Conshohocken, PA, USA, 2001.
21. ASTM E23. *Standard Test Methods for Notched Bar Impact Testing of Metallic Materials*; American Society for Testing and Materials: West Conshohocken, PA, USA, 2008.
22. KS D3868. *Rolled Steels for Bridge Structures*; Korean Industrial Standards: Seoul, Korea, 2018.
23. API RP 2Z. *Recommended Practice for Preroduction Qualification for Steel Plates for Offshore Structures*; American Petroleum Institute: Washington, DC, USA, 1998.
24. ISO 12135. *Metallic Materials-Unified Method of Test for the Determination of Quasistatic Fracture Toughness*; International Organization for Standardization: Geneva, Switzerland, 2016.
25. ISO 15653. *Metallic Materials—Method of Test for the Determination of Quasistatic Fracture Toughness of Welds*; International Organization for Standardization: Geneva, Switzerland, 2016.