Mechanical Behaviors of The Low Yield Ratio HT80 as A Structual Steel†

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Abstract

The yield ratio is a index of ductility though it is expressed using stresses. The conventional HT80 has the yield ratio of over 0.9. The low yield ratio HT80, which was developed recently in Japan,has the yield ratio of under 0.9. The low yield ratio HT80 has the superior elongation capacity to the conventional HT80.

This paper reports the behaviors of the low yield ratio HT80 as compared with the conventional HT80.

KEY WORDS: (Yield Ratio) (Elongation Capacity) (Absorbed Energy)

1. Introduction

It is well-known that the uniform elongation decreases in accordance with the yield stress increasing. It is also recognized experientially. There is a tendency to require the elongation capacity for structual members, joints and connections of members from the point of more safety of structures. This philosophy means to enlarge the absorbed energy requirements to fracture of structures by satisfying strength and deformation.

In this connections, there are recently some specifications to order the upper limit of the yield ratio (yield stress/tensile strength)[3]. The many conventional high strength steels of 80kg/mm^2 in tensile strength (hereinafter called HT80A) have the yield ratio of over 0.9. They have smaller in elongation capacity. The high strength steel of 80kg/mm^2 in tensile strength (hereinafter called HT80B) having the yield ratio of under 0.9 was developed recently. Both steels, HT80A and HT80B, have similar chemical compositions, especially the used materials are the same in this study. And they satisfy the yield stress and the tensile strength in specifications. There are difference in heat treatments between HT80A and HT80B.

In this study, Numerical analyses of tensile behaviors are performed on the plate model with center notch and the welded joint model with center crack. The behaviors of HT80B as a structural material are discussed.

2. Numerical Analyses of Notched Plate

2.1 Input data and analytical model

Table 1 and **2** show mechanical properties and chemical compositions of materials. Mechanical properties were obtained from round coupon specimen. As the yield point was not obvious, the proportional limit was used for the yield stress. Gage length was 50mm for elongation measurement. They have the same chemical compositions and the different yield ratio; HT80A is 0.92 and HT80B is 0.86 as shown in Table 1 and 2.

Input data are shown in **Table 3**. In this table, a and n were calculated from σ_Y, ε_Y, σ_B and ε_B. It is worth

Table 1 Mechanical properties

	Y.S. (kg/mm^2)	T.S. (kg/mm^2)	Y.R. (%)	El. (%)	R.A. (%)
HT80A	85.6	93.1	91.9	23.8	67.1
HT80B	70.0	81.7	85.7	26.4	69.7

Table 2 Chemical compositions

	C X100	Si X100	Mn X100	P X1000	S X1000	Cu X100	Ni X100	Cr X100	Mo X100	V X100
HT80A	10	25	80	16	6	19	81	45	40	5
HT80B	10	25	80	16	6	19	81	45	40	5

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Table 3 Input data

	E (kg/mm^2)	ν	σ_Y (kg/mm^2)	ε_Y	σ_B (kg/mm^2)	ε_B	a (kg/mm^2)	n	ε_{max}	H (kg/mm^2)
HT80A	21000	0.3	85.6	0.0041	102.2	0.100	116.1	0.0554	1.11	70.4
HT80B	21000	0.3	70.0	0.0033	93.3	0.109	112.0	0.0824	1.19	75.6

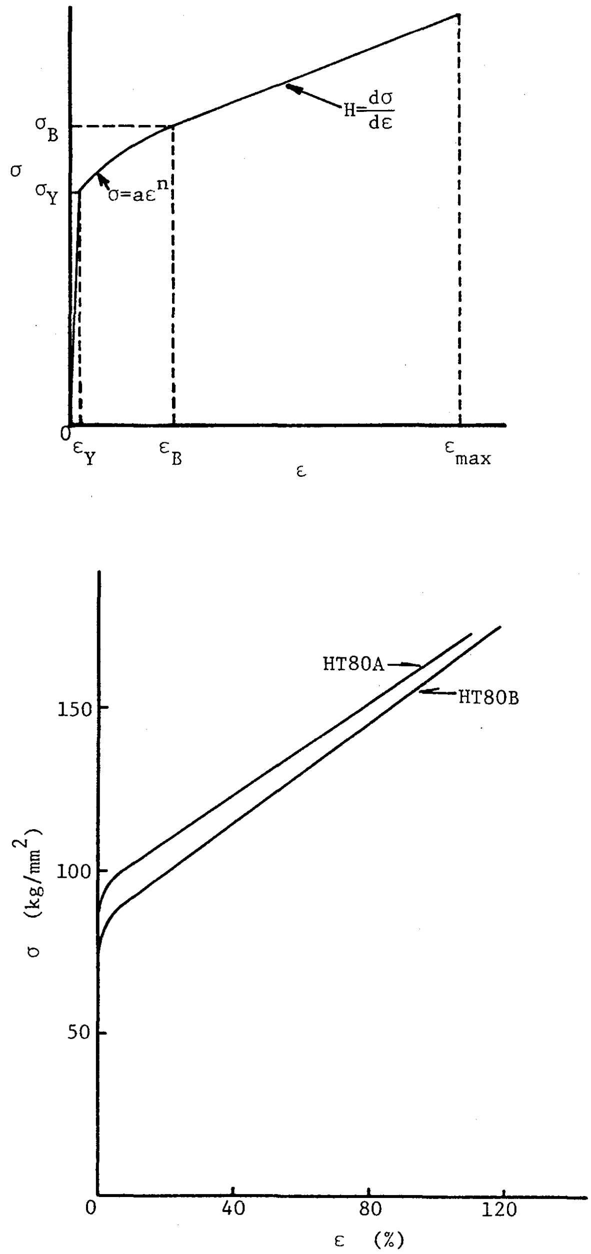

Fig. 1 Stress-strain curves of input data

while to notice the difference in the work hardening exponents. HT80B has about 1.5 times as large as HT80A in the work hardening exponents. It means that the uniform elongation increases on condition of power curve expression. **Figure 1** shows stress–strain curves of the input data. There is little difference in the energy to fracture between HT80A and HT80B.

Figure 2 shows the analytical model. It is a tensile specimen; length l=180mm and width W=60mm. It has a center notch; notch length a=5.0mm and notch root radius ρ =0.5mm. The analysis was performed using finite element method on 1/4 model considering symmetry and plane stress condition. This finite element method is considered deformation.

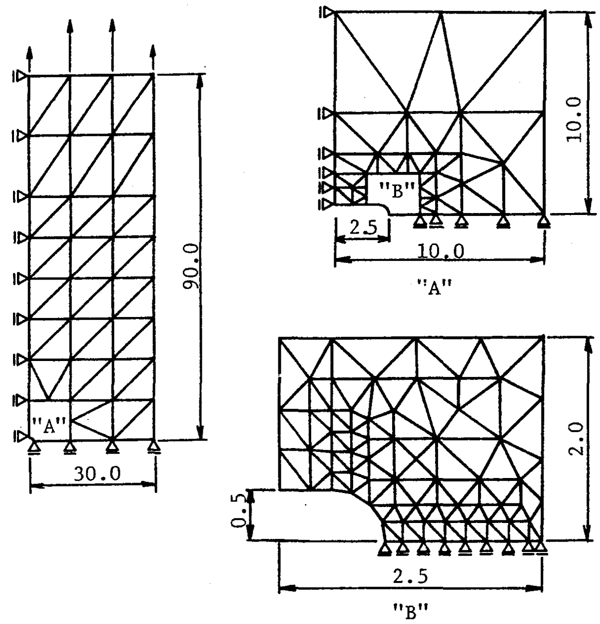

Fig. 2 Analytical model (Unit ; mm)

2.2 Results and discussions

Figure 3(a) and **(b)** show the plastic region at σ_{net} ≒47kg/mm^2. σ_{net} is the nominal stress which is given as (external load)/(area of net section). σ_{net}≒47kg/mm^2 is equivalent to two-third the yield stress of HT80B. It is clear from these figures that HT80B has larger plastic region than HT80A. HT80B has about 1.5 times of HT80A in the size of plastic region. These differences are that σ_{net}≒47kg/mm^2 is equivalent to 55% the yield stress of HT80A. HT80A has smaller plastic region than HT80B in the same stress concentration and external load since HT80A has the higher yield stress than HT80B. Therefore, **Fig. 3(c)** shows the plastic region at σ_{net}≒57kg/mm^2 being equivalent to two-third the yield stress of HT80A.

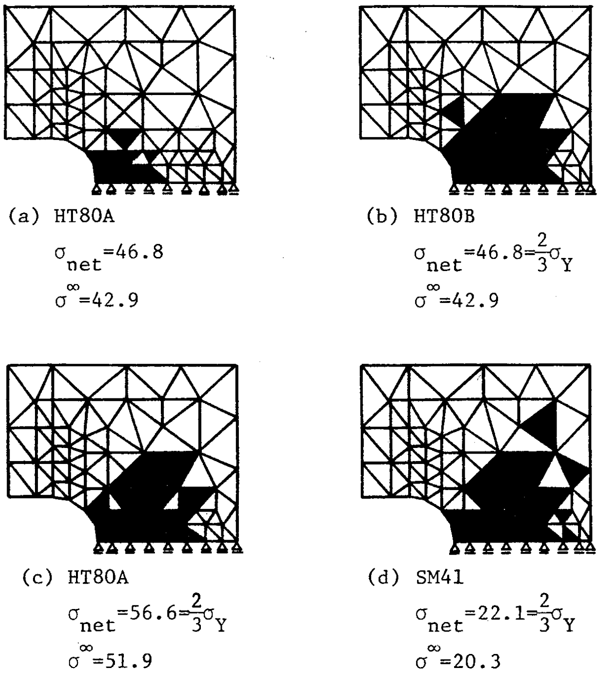

Fig. 3 Plastic region (Unit ; kg/mm²)

For reference, **Fig. 3(d)** shows the plastic region at two-third the yield stress of SM41. There is little difference between HT80A and HT80B. Moreover, even SM41 shows the similar results. The plastic region can be estimated regardless of steel grade using σ_{net}/σ_Y. Post yield stress–strain curves may not have influence on spread of the plastic region.

Figure 4(a) and **(b)** show the plastic region at $\sigma_{net} \fallingdotseq 70kg/mm^2$. This stress is equivalent to the yield stress of HT80B. It is recognized to be the obvious difference in the plastic region between HT80A and HT80B as well as at $\sigma_{net}/\sigma_Y \fallingdotseq 2/3$. HT80B has about 12 times of HT80A in the size of plastic region. The plastic region of HT80A at $\sigma_{net} \fallingdotseq \sigma_Y$ is shown in **Fig. 4(c)**. There is little difference in the plastic region at $\sigma_{net} \fallingdotseq \sigma_Y$. Though σ_{net} is nearly equal to σ_Y in Fig. 4(b) and 4(c), all elements in net section do not yield. The reasons are that yielded elements occur the work hardening following the yield as HT80A and HT80B have not the plastic plateau, and the plastic restraint exists. The plastic region can be estimated using σ_{net}/σ_Y regardless of the yield ratio, the work hardening expornent and so on.

Till now, the behaviors of HT80B as a structual material were discussed using the plastic region while the nominal stress at the net section is under or nearly equal to the yield stress. The yield ratio practically means the uniform elongation (the work hardening exponent) though it is described using the stress. Therefore, the increase of the uniform elongation may have the significant differences in the elongation capacity to fracture. The analytical results to fracture are shown subsequently. In analysis, the following two conditions were defined.

1) The true fracture; The state when maximum plastic strain reached the fracture strain.
2) The unstable fracture; The state of deformation increase without load increment.

The stress-strain curves resulting from analyses are shown in **Fig. 5**. Vertical axis is the nominal stress, which is given as (external load)/(area of net section), normalized by the tensile strength. Horizontal axis is the strain for gage length=150mm. The true fracture occurred in both materials. The nominal stress at net section reaches the tensile stress in both materials. So these two models have the material properties of

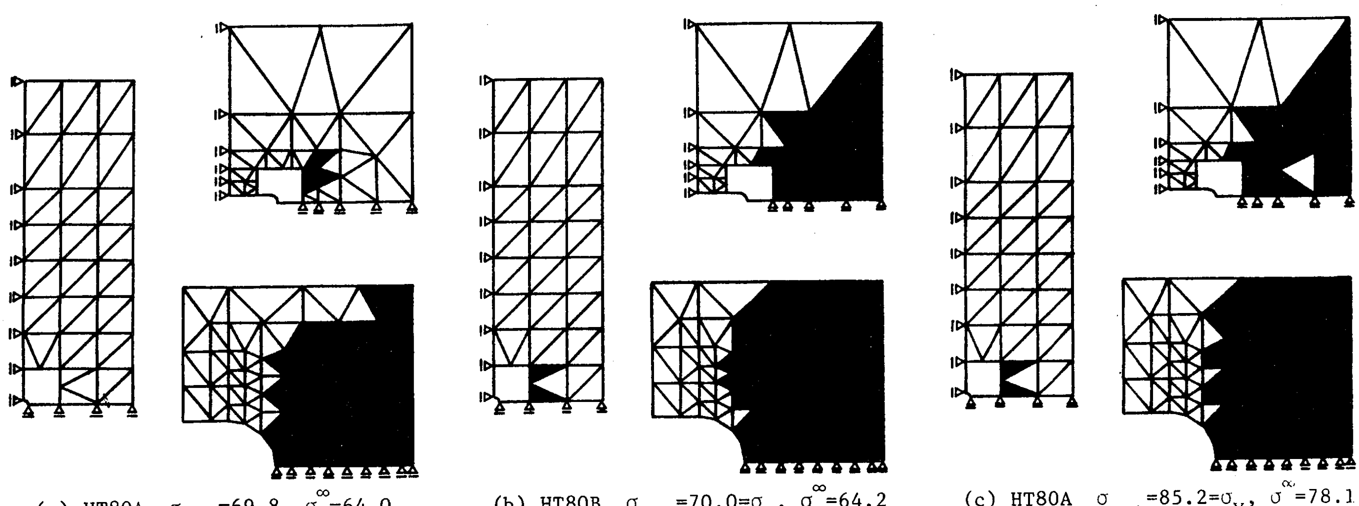

Fig. 4 Plastic region (Unit ; kg/mm²)

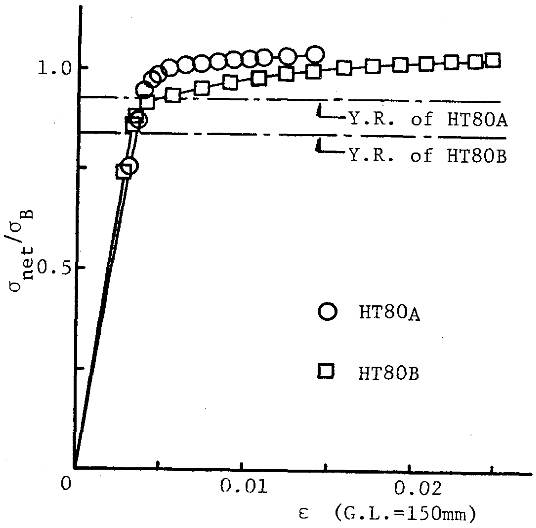

Fig. 5 Stress-strain curves

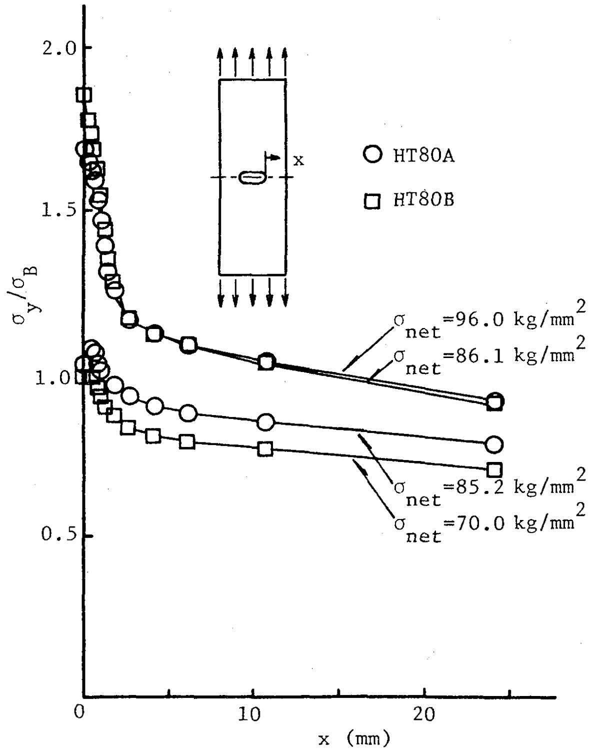

Fig. 6 Stress distributions on net section

coupon test as to stress. As for elongation to fracture, HT80B has about 2 times as large as HT80A. It seems to be the influence of the difference in the work hardening exponent. HT80B is also superior to HT80A in the absorbed energy of notched plate to fracture, in proportion to increase of the elongation. The reason is the difference in the energy absorbed at the other part of notch section. Because there is little difference in ε_{max} of coupon test in two materials and the total elongation of notched member depends on the quantities of the plastic deformation at the other part of notch section.

The ratio of the strain at fracture to the work hardening exponent is as follows.

$$\text{HT80A;}\ \frac{0.0141}{0.0554}=0.255$$

$$\text{HT80B;}\ \frac{0.0249}{0.0824}=0.302$$

It is concluded from above results that the meaningful difference between HT80A and B is not recognized in decrease of the elongation of notched plate.

Figure 6 shows the distributions of true stress σ_y of load direction on net section. Vertical axis is true stress normalized by the true stress σ_B corresponding to the tensile strength. Horizontal axis is distance from notch root. σ_{net}=96.0kg/mm^2 and 86.1kg/mm^2 are stresses at fracture of HT80A and HT80B, respectively. σ_{net}=85.2kg/mm^2 and 70.0kg/mm^2 are stresses when the nominal stress reaches the yield stress (Refer to Fig. 4(b) and 4(c)). There is a little difference between HT80A and HT80B at near notch root at fracture. However, significant difference is not recognized through the ligament and the stress of almost all elements is over the each tensile strength through the ligament. As for yield state, the stresses of HT80A are higher than those of HT80B from notch root to specimen side. HT80B has a larger residual strength from yield to fracture than HT80A on the basis of the tensile strength. However, HT80A has a larger residual strength than HT80B from the allowable stress state, which means that the nominal stress reaches the allowable stress, to fracture. In Houshu—Shikoku Bridge Authority, the allowable stress is 36kg/mm^2 for HT80[4]. So, σ_a/σ_B is 0.387 for HT80A and 0.441 for HT80B.

The distributions of true stress σ_y on the center line of load direction are shown in **Fig. 7**. Vertical axis is true stress normalized by the tensile strength and horizontal axis is distance from notch side. σ_{net}= 96.0kg/mm^2 etc in this figure are the same as Fig. 6. There is a little difference between HT80A and HT80B in the region from 1mm to 6mm in distance from notch side at fracture. However, difference is not recognized in the region from 6mm to 36mm in distance from notch side and the stress of each element reaches about 90% of the each tensile strength in the same region. The value of 90% corresponds to the ratio of net area to gross area.

$$\frac{\text{Net area}}{\text{Gross area}}=\frac{W-a}{W}=\frac{60-5}{60}=0.92$$

Therefore, it is concluded that the influence of notch length is larger than the influence of notch root radius on the stress in the far distance from notch side.

As for the distributions of true strain ε_y on net

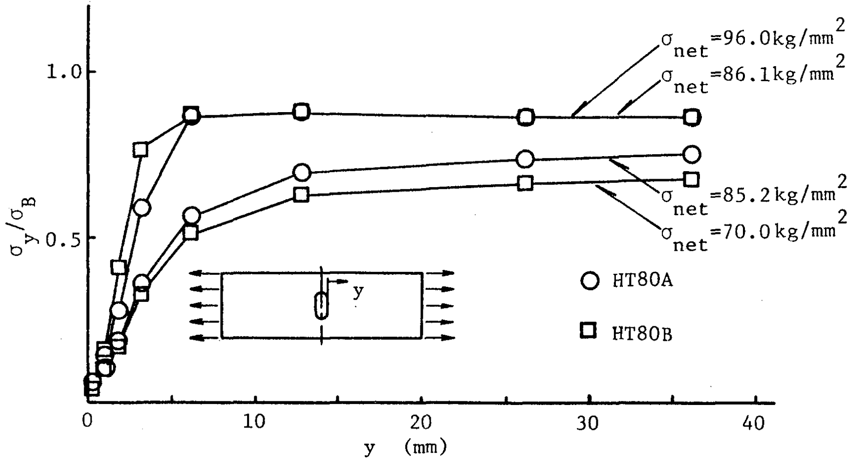

Fig. 7 Stress distributions on load direction

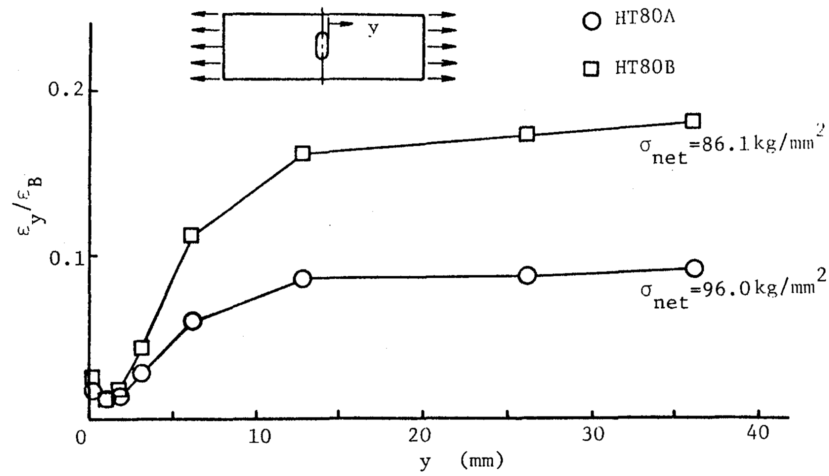

Fig.8 Strain distributions on load direction

section at fracture, significant difference was not recognized in both materials. Strain concentrated at notch root in the same order.

The distributions of true strain ε_y on the center line of load direction at fracture are shown in **Fig. 8.** Vertical axis is true strain normalized by the true strain ε_B corresponding to the tensile strength. Horizontal axis is distance from notch side. Strain of HT80B has about 2 times as large as HT80A in the region from 6mm to 36mm in distance from notch side. As there is little difference in the fracture strain ε_{max} between HT80A and HT80B, above difference is considered as the difference of the yield ratio or the work hardening exponent. HT80B yields easily due to the low yield stress and plastic strain increases in the other part of notch section. As HT80B has about 1.5 times as large as HT80A in the work hardening exponent, the other part of notch section of HT80B can endure larger plastic strain than HT80A. It is concluded from Fig. 5 and 8 that the total elongation depends on the quantities of the plastic deformation at the other part of notch section.

Figure 9 shows relation between crack opening displacement (hereinafter called COD) and the nominal stress in the other part of notch section. COD is difined as the displacement of intersecting point notch side and center line of load direction. Flat part corresponds to the state that the plastic region in net section spreads gradually and COD increases rapidly when the plastic region spreads to all over the notch section. HT80B shows larger COD than HT80A for the same external load. Yield in all over the notch section takes place at low external load in HT80B having the low yield stress after yield at near notch root. Because fracture modes in both materials are the same, the true fracture, and the fracture strain ε_{max} is nearly equal in both materials, it may be considered that COD at fracture is not significant difference between HT80A and HT80B. It is concluded that HT80B can absorb larger energy in member to fracture than HT80A.

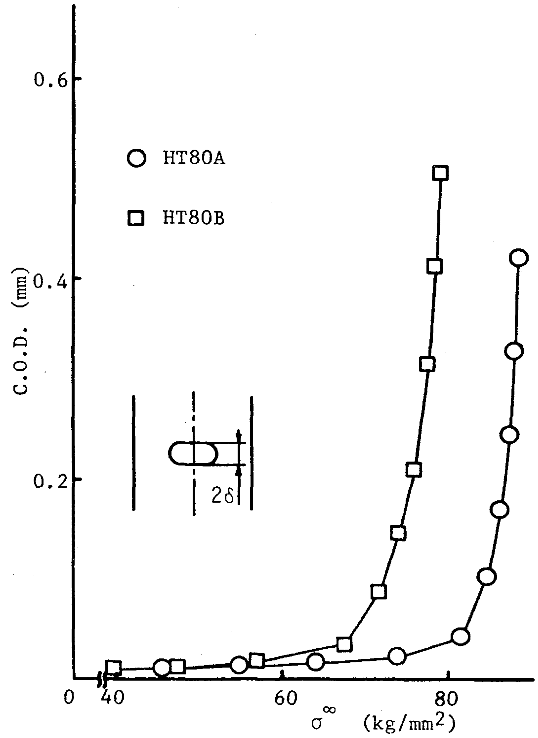

Fig. 9 Relations between crack opening displacement and nominal stress in the other part of notch section

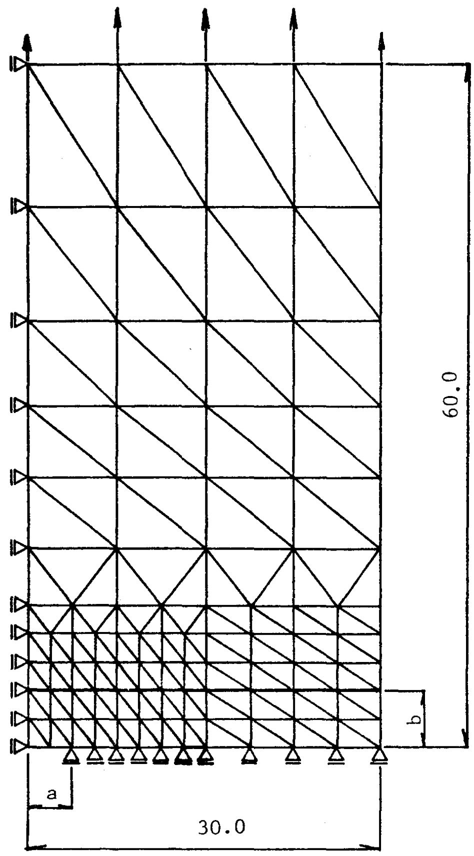

Fig. 10 Analytical model (Unit ; mm)

3. Numerical Analyses of Welded Joint

3.1 Input data and analytical model

Though HT80B has the same chemical compositions as HT80A, HT80B has the yield ratio of under 0.9 by special heat treatments. Therefore, heat affected zone in HT80B welded joint may become the same behaviors as HT80A welded joint for weld heat cycles. The absorbed energy is discussed on welded joint with center crack using the spread of plastic region.

The analytical model is shown in **Fig. 10**; length 2l =120mm, width 2W=60mm, crack length 2a and width of weld metal and heat affected zone 2b having the same behaviors as HT80A. The analysis was performed on 1/4 model considering symmetry and plane stress condition. The analytical cases are shown in **Table 4**. Case 1 is base metal of HT80A with crack, 2a=7.5mm. Case 2 to 4 are welded joints with crack combined by crack length and width of zone having the same behaviors as HT80A. Input data are used the same values in Table 3.

Table 4 Analytical cases

	2a	2b
1	7.5	0.0
2	"	10.0
3	"	15.0
4	15.0	10.0

3.2 Results and discussions

Plastic region of every cases are shown in **Fig. 11.** These are the plastic regions when the nominal stress at net section reaches about 90% of the yield stress. In case 1, plastic region only exists at near crack tip at $\sigma_{net}/\sigma_Y \fallingdotseq 0.9$. In the others, plastic regions exist at HT80B on the boundary of base metal and HAZ, and at crack tip. Case 2, which has short crack and narrow width of zone having the same behaviors as HT80A, shows the largest plastic region in these cases, Fig.11(b) to (d). The plastic region of HT80B shows the tendency to decrease when the joint has longer crack and/or wider width of zone having the same behaviors as HT80A. Crack tip is considered to become blunt by yielding. Plastic region is considered to be formed at HT80B having the low yield stress by the structual discontinuity. It is obvious from above discussions that the spread of plastic region differs by the interaction of the stress concentrations of crack and structual discontinuity. Fracture stress may be increase because weld metal and HAZ become the multi–stress state by forming the plastic region at base metal. As plastic region is formed at HT80B having a larger elongation capacity than HT80A,

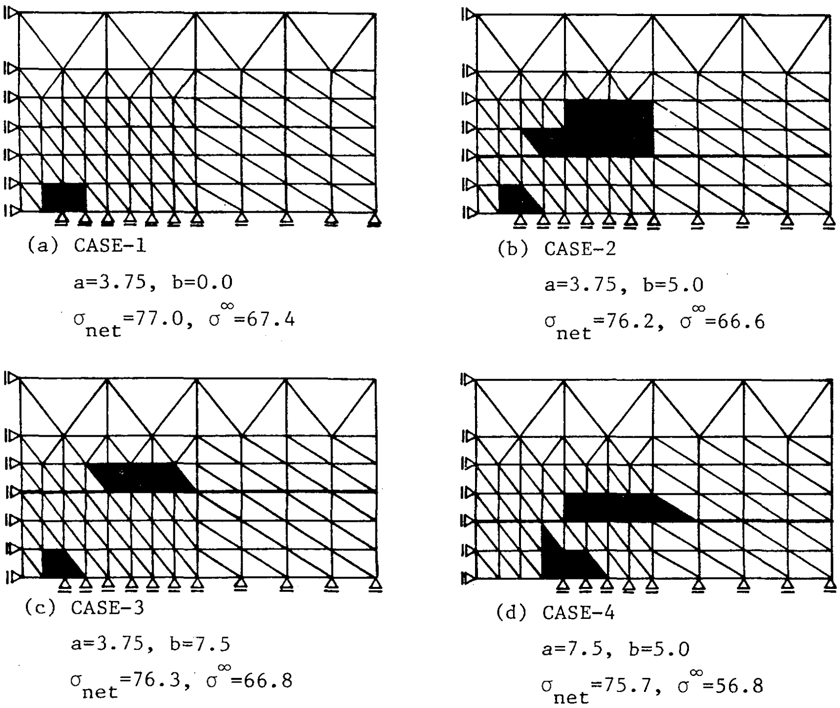

Fig. 11 Plastic region (Unit ; mm, kg/mm²)

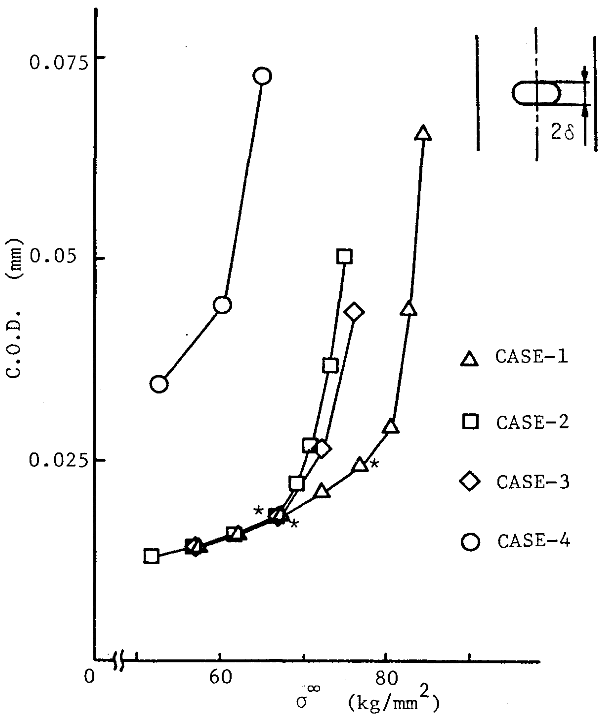

Fig. 12 Relations between crack opening displacement and nominal stress at the other part of crack section.

HT80B welded joint has a superior elongation capacity to HT80A welded joint.

Relations between COD and the nominal stress at the other part of crack section are shown in **Fig. 12.** Case 4 shows large COD as it has a long crack. On survey of the spread of plastic region at the marked points, almost all elements on crack section yielded in case 1, and some elements at crack tip and almost all elements in base metal yielded in case 2 and 3. Rapid increase in COD is considered to be shown due to relaxation of restriction at near crack tip because yield takes place in base metal. HT80B welded joint can absorb larger energy than HT80A welded joint at the same stress level.

4. Conclusions

Numerical analyses of tensile behaviors were performed on the plate model with center notch and the welded joint model with center crack for the purpose of the study on the behaviors of HT80B. The following conclusions were obtained.

1) The low yield ratio virtually means the increase of the uniform elongation though the yield ratio is expressed using the stress. HT80B is superior to HT80A in the elongation capacity and the absorbed energy to fracture.
2) The influence of the yield ratio on the behavior of notched member is not recognized on the basis of the yield stress until the nominal stress at net section reaches the yield stress.
3) In HT80B welded joint, the plastic region is formed at HT80B on the boundary of base metal and HAZ after crack tip yielding. HT80B welded joint has a superior behavior to HT80A welded joint in the absorbed evergy to fracture.
4) Whether HT80A or HT80B is selected for the

structual materials is considered to be the design philosophy. It is that structual members shall have large safety factor on strength or deformation.

5) HT80B is an effective material to the members requiring the deformation capacity, such as corner connections in rigid frames and nodal point of offshore structures.

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