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AN INVESTIGATION ON BRITTLE FRACTURE OF STEEL PLATE FOR NUCLEAR REACTOR CONTAINMENT

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SUMMARY

The traditional design of nuclear reactor containments has only considered the service condition of elastic stress range in many cases. Recently, some people claim that in case of accident, a certain amount of stressed condition beyond yield should be taken into account to the reactor containment. Because, with the recent development of numerical analysis techniques using high speed digital computers, it is possible that the precise and reliable stress analysis of structures is accomplished.

On the other hand, the studies about brittle fracture of steel have mostly been concerned with the elastic loading condition up to this time. Experimental studies concerning plastic loading condition with Robertson type test of large specimen have not yet been carried out. Hence, in this study, in order to obtain the basic data for plastic design, the brittle fracture propagation and arresting behaviour in the stressed condition beyond yield was examined by means of the double tension test and ESSO test using ASTM A516 Gr. 70 steel plate which is one of the current typical materials for reactor containment.

Recently, various correlations among large scale tests and industrial small scale tests of brittle fracture have been reported. These correlations will play an important part in the assessment of structures and materials. From this point of view, using A516 Gr. 70 steel, some kinds of tests, i.e. deep notch test, bend test, compact tension (CT) test, dynamic tear (DT) test (NRL type), drop weight tear (DWT) test (Battelle type), Charpy test and drop weight test, were carried out, and the correlation among them were investigated.

The brief results are as follows. The curve of loaded stress vs. crack arresting temperature by double tension test and ESSO test, in these tests specimens had gradient temperature distributions, almost corresponded to the transition curves by DT test and DWT test. In other words, the crack arresting temperature at yield stressed condition almost agreed with the transition temperature at the midpoint of curve by DT test and the temperature of 50% shear fracture appearance by DWT test. Concerned with the brittle fracture initiation, the critical CODs obtained from the deep notch test, the bending test and CT test agreed with each other to some extent, in spite of the difference of their loading methods or specimen shapes and sizes. The Kc values of these three tests showed approximately the same tendency.

Furthermore, the correlations between industrial assessment tests and large scale test were investigated. One of them is between the results of large scale tests and the crack arresting curve or K_{IR} curve based on NDT temperature of drop weight test. Another is between the critical CODs and Charpy transition temperature. From this, it was made clear that the critical CODs of bend test and deep notch test can be estimated by Charpy test.

1. Introduction

At present, steel-made nuclear reactor containments are designed for use within the elastic limit of the material. This design practice results in an excessively large safety factor, but in case of the absence of accurate stress analysis, this is considered to be un-avoidable. If design stress is limited at such low values as within the elastic limit, a huge containment for a large nuclear reactor would have to be made from very thick plate. To over-come this difficulty, some limited local plastic deformation under accident conditions has to be allowed so as to reduce wall thickness and size of containment. Such a plastic design has become possible because of a recent development of precise structural stress analysis technique using computerized numerical methods. This in turn calls for not only knowledge in the tensile strength of the materials used, but also the comprehensive understanding of brittle fracture characteristics under yield stress conditions.

However, most research works about brittle fracture have been limited to the elastic region, there having been no report on large Robertson type tests under yield stress. In this report, to assess the safety against brittle fracture in the range of plastic stress, fracture arresting characteristics near the yield stress of the steel plate for containment have been investigated through double tension test and ESSO test.

There have been many correlations reported in the area of brittle fracture study relating the results obtained with large scale tests and those obtained with small scale tests. Because these correlations play an important part in safety evaluation and in material selection of structures, reexamination of the correlations were made carefully in this study. Using a steel plate for containment, some large, medium and small scale tests have been carried out, and correlations among the results of these tests have been investigated.

2. Tested Material and Test Method

2.1 Steel Plate and Weld Joint Tested

Steel plates of 38mm thickness conforming to ASTM A516 Gr. 70 having the chemical composition and the mechanical properties shown in Table 1, which is widely used for nuclear reactor containment in Japan, were tested. Plate A was used to test the base metal, and plate B was used to the weld joints.

Two kinds of weld joints were prepared; submerged arc weld (SAW) joint and manual arc weld (MAW) joint. Welding processes and conditions were chosen so as to simulate the actual case of containment fabrication as much as possible. For SAW, Y-CM wires (4.8mm dia.) and YF-15 flux were used, and for MAW, LB52N (4mm and 5mm dia.) were used. SAW joint was welded in single-V butt joint with broad root faces. Heat input was 39 to 46 KJ/cm approximately. MAW joint was double-V butt joint with heat input of about 24 to 30 KJ/cm. The chemical composition and the tensile properties of the weld metals in these joints are shown in Table 2.

2.2 Brittle Fracture Test Method

The specimens were tested for brittle fracture in the following six test methods, in addition to conventional Charpy test and drop weight test ;

a) Double tension test is a large scale test designed to examine the brittle fracture propagation arresting characteristics. Only the base metal was tested. The shape of the specimen was as shown in Fig. 1. The portion to be tested was machined to 25mm from original 38mm thickness to conduct the test property. The crack initiating portion was cooled to a very low temperature to initiate the brittle crack by an auxiliary load, with the rest of the specimen having temperature gradient. The temperature at the point where the crack was arrested was measured.

b) ESSO test is also a large scale test to examine the arresting characteristics of materials. Only MAW joint specimens were tested. In order to make a brittle crack propagate along the length of the weld, side grooves and other devices were employed as proposed by Miya et al. [11]. Furthermore, to prevent crack from developing under high load before an impact was applied, the portion to be struck was situated outside the parallel portion, as shown in Fig. 2. The temperature distribution was as same as that of double tension test, and the temperature at the point where the crack was arrested was measured.

c) Deep notch test is a large scale test designed to study the fracture initiation characteristics. The base metal was tested with the specimen shape as shown in Fig. 3 (a), and weld joints were tested with that of Fig. 3 (b).

d) Dynamic tear (DT) test has been developed by NRL for obtaining energy transition curves, which are expected to represent the fracture arresting characteristics of materials. The 38mm thick plate was machined to 35mm, the specimen width was 120mm, the bending span was 406mm, and the notch length including the Ti embrittled portion was 44mm. The base metal and MAW joint were tested.

e) Drop weight tear test (DWTT), developed by Battelle Memorial Institute, is designed to obtain the fracture transition temperature, that is also thought to represent the arresting characteristics. Although this test procedure is standardized by ASTM [2] for evaluating pipeline materials, some slight modifications were made in the present study. For testing the base metal, the 38mm thick plate was machined into two types of specimen; 35mm thick one and 15mm thick one. For testing MAW joint, 15mm thick specimens were made from the first quater thickness on the back pass side. All these specimens were made with width of 75mm, bending span of 400mm and pressed notch depth of 5mm.

f) Three point bend test is a test to research the fracture initiation characteristics. The specimens were prepared in conformity to ASTM E399 [1]. Among the specimens of 35mm thickness, some were provided with a fatigue notch as per E399, but others were provided with a machined notch with a tip radius of 0.05mm or 0.1mm.

In all the specimens tested for the weld metal (WM) in any of the above test methods, notches were made at the middle position of WM. As the grooves were in single-V form or double-V form, the fusion line (FL) and the heat affected zone (HAZ) were not perpendicular to the plate surface. Therefore, in the specimens for studying FL or HAZ, the notch was made not only through FL or HAZ, but also through the base metal and WM, and consequently, especially tests for FL not necessarily produced the characteristics of FL only, but often produced mixed characteristics near FL.

3. Brittle Fracture Propagation Arresting Characteristics and Correlation Among Results of Various Tests

3.1 Brittle Fracture Propagation Arresting Characteristics Under High Stress

The arresting characteristics under stresses near yield point were studied by large Robertson type specimens. The relations between the arresting temperatures and the stresses applied for the base metal and MAW joint are shown in Fig. 4. In some MAW joint specimens, the cracks deviated and arrested at the base metal, but these data were eliminated. According to Fig. 4, the arresting temperatures for the base metal and for WM are nearly equal, while corresponding temperatures for FL is approximately 10°C higher. In the specimens under stresses near yield point or above, brittle fracture propagation was not arrested at any temperature below 0°C. In the case of a nuclear reactor containment, even if it is designed with some plastic deformation allowed, the whole containment will not be subjected to such a high stress as the yield point. When such a containment is used at a temperature around 0°C, and if brittle crack initiates at some point where high stress near the yield point is created, the crack will propagate through the high stress area and will be arrested at the low stress area.

A method of estimating the brittle crack arresting temperature from NDT temperature, based on CAT curve proposed by Pellini [6], has been adopted in ASME code [3]. This method is designed to estimate the crack arresting temperature, FTE, under yield stress and corresponding temperature, FTP, under ultimate strength level stress from NDT obtained through convenient drop weight test. Pellini proposed two CAT curves, one for small thickness (5/8″ to 1″) and the other for large thickness (6″ to 12″). In Fig. 5, these curves are compared with the results of large scale tests. NDT temperatures which are the base of this figure were obtained through drop weight test conducted with the base metal, WM and FL. As the specimen thicknesses of large scale tests were 25mm and 38mm, the obtained data should have values close to CAT for small thickness, but there is considerable discrepancy between CAT curve and the test results. NDT temperature, therefore, can not be regarded as a good substitution of large scale tests.

ASME code requires containment material to have NDT temperature 30°F (17°C) below the minimum service temperature. This means that containment will be designed so that brittle fracture is arrested at a half of yield stress, according to CAT curve, but from the results of large scale tests, arresting temperature at this stress level is substantially above this temperature. However, it is not able to conclude immediately that the containment designed in accordance with this code is safe or not, a quantitative evaluation having to be made through the fracture mechanics method which will be described later.

3.2 Comparison Between Results of Large Scale Tests and Those of Medium Scale Tests

Because large scale tests are expensive and time-consuming, they are not practical as a means of evaluating materials. With a view to finding simplier tests that will produce results comparable to those obtained through large scale tests, in this study, DT test and DWTT, classified as medium scale tests, were examined as to their brittle fracture arresting evaluation capability in comparison with large scale tests.

Pellini [6] claims that the middle point temperature (${}_DT_E$) of energy transition curve of DT test corresponds to FTE temperature. Herberling et al. [7] found that 50% fracture appearance transition temperature (FATT) of DWTT corresponds to FTE. To ascertain these propositions, ${}_DT_E$ and 50% FATT were measured with specimens of the base metal and of MAW joint, and they were compared with fracture arresting temperature ($T_{a\sigma Y}$) at yield stress level in Table 3. As can be seen in Table 3, there is a very good correspondence between $T_{a\sigma Y}$ and ${}_DT_E$ for both the base metal and weld joint, but 50% FATT for 35mm thick specimen was only in agreement with $T_{a\sigma Y}$ and that for 15mm thick specimens was substantially lower than $T_{a\sigma Y}$.

As a result, in the case that the thicknesses of specimens of DT test, DWTT and large scale tests are roughly same, their results are expected to agree with each other. If such a result is obtained for other many kinds of steels or joints, DT test and DWTT will be accepted as reliable evaluation tests comparable with large scale tests.

3.3 Correlation Between Large Scale Tests and Industrial Small Scale Tests

It is natural to expect that large scale tests for fracture propagation arresting would produce results more reliable in simulating the fracture phenomena of actual containments than results obtained with small or medium scale tests. However, since large scale tests are too expensive to be performed for every material selection and design situation, it is very important to establish correlations between industrial small scale tests and large scale tests. CAT curve proposed by Pellini is one of such correlations. From the point of view of designing, fracture mechanics approach evaluating fracture for arbitrary combination of stress, temperature and crack size is more convenient than such qualitative approach as CAT. For example, ASME code has employed a fracture mechanics procedure in the recent addenda [4]. However, since this approach of ASME is only applicable where fracture takes place in plane strain condition, it is not applicable for containment where the wall thickness is 40mm or less. Because, unless temperature is extremely low, the plates fracture always in a manner accompanying shear lips.

WES standard [10] is known as a fracture evaluation method correlating plane stress fracture arresting toughness K_C, allowing shear lips, to the results of Charpy test. In this method, first, K_C values obtained through large scale tests have been correlated to 50% fracture appearance temperature (${}_PT_C$) obtained through pressed Charpy test, then ${}_PT_C$ has been correlated to 50% fracture appearance temperature (${}_VT_{rs}$) obtained with V-Charpy test, and ${}_VT_{rs}$ has been correlated in turn with temperature ${}_VT_{rE}$ that corresponds to a half of absorbed energy of the upper shelf in V-Charpy test, so that ultimately, K_C has been correlated with ${}_VT_{rE}$. As K_C also depends on plate thickness, a way is provided to produce K_C values for any plate thicknesses. In Fig. 6, K_C values estimated from the results of Charpy test in accordance with this method, and corresponding K_C derived from double tension test or ESSO test are compared. K_C of large scale tests were calculated by the following formula ;

$$K_C = \sigma\sqrt{\pi c}\ \sqrt{(2W/\pi c)\tan(\pi c/2W)} \qquad (1)$$

where σ is applied stress, c is crack length (Figs. 1 and 2), and W is width of specimen. For the base metal, the values derived from ${}_PT_C$ showed best coincidence with the experimental values, and for MAW joint, values derived from ${}_VT_{rE}$

agreed better with the experimental values than those derived from $_vT_{rs}$.

As NDT temperature of the steel studied is -45°C, according to ASME code, its minimum service temperature should be -28°C. According to Fig. 4, to arrest brittle fracture at this temperature, stress must be kept below around 9 kg/mm², which is substantially lower than the stress allowed by CAT curve. On the other hand, extrapolating the experimental results shown in Fig. 6, and evaluating K_c at -28°C to be 200 $kg\sqrt{mm}/mm^2$, for "arrest use" (welded structure in which brittle fracture is especially important) as specified in WES standard, an allowable stress is about 11 kg/mm², and for "general use" (welded structure in which brittle fracture requires general caution), an allowable stress is about 36 kg/mm².

4. Correlation Among Some Tests on Brittle Fracture Initiation Characteristics

4.1 Comparison Between Deep Notch Test and Three Point Bend Test

With regard to brittle fracture initiation characteristics, the deep notch test and the three point bend test were performed and compared. In Fig. 7, the critical COD values (δ_c) obtained from these tests are compared. δ_c for the deep notch test were obtained by converting the measured value by clip gauge into the value at the notch tip through the formula based on B-C-S model. With the bend test, the converting formula as per DD-19 [5] was used. As shown in Fig. 7, for the base metal, the results of the bend test and the deep notch test were in good agreement. On the other hand, for the weld joints, δ_c of the deep notch test was smaller than that of the bend test. However the difference between the values of the two tests decreased with rising temperature. K_c values of these tests also showed the same tendency.

As shown above, despite the different specimen shapes and sizes and the different loading modes, these two tests produced results that were in good agreement for the base metal. Furthermore, δ_c gave wider temperature range in which two test methods agreed than K_c gave. On the other hand, for weld joints, with both δ_c and K_c taken as parameters, the bend test produced less severevalues than the deep notch test. This seems to be caused by the effect of welding residual stress in deep notch specimens.

The fact that, for the base metals of many kinds of steels, the bend test and the deep notch test agree over a wide temperature range in the critical COD has been confirmed [12], so that COD can well be taken as a reliable parameter for evaluating steel structures. However, for weld joints, the bend test can not be used as a means of structure evaluation without some consideration for the effect of welding residual stress. Although Burdekin et al. [9] propose that yield strain can be used as a means of evaluation without regard to service conditions, as shown in Fig. 7, the effect of residual stress is different depending on temperature or stress.

The above comparisons are based on machined notch, but where very sharp defect is expected, the results of bend test with specimens having fatigue notch should be used. Having compared in the bend test between fatigue notch and machined notch, the former has given about 40 to 60°C higher transition temperature range of δ_c than the latter. It is reasonably expected that if deep notch test was made with fatigue notch specimens, considerably severer results than those in Fig. 7 would be obtained. Thus, when the correlation between a large scale test and a medium scale test is obtained with the use of machined notch, and this correlation is applied to the results of medium scale test with fatigue notch for structure evaluation, a high degree of safety and reliability will be secured.

4.2 Correlation Between Fracture Initiation Test and Charpy Test with K-Value Taken as Parameter

If the results of convenient industrial small scale tests such as Charpy test, can be correlated to K_c or K_{IC} of large or medium scale tests, that would be a great benefit to design, even if the correlation is of statistical nature without clear physical meaning, because such a correlation would enable the small scale tests to be used for evaluating interrelations among defect size, allowable stress and service temperature. For example, such a correlation was proposed by Barsom et al. [8]. And Ito et al. [13] have developed Barsom's concept further and converted K_c for FL obtained from the large specimen with surface notch and residual stress, into K_{IC} to correlate with Charpy absorbed energy.

In Fig. 8, the correlation between deep notch test and Charpy test obtained with the use of their method is shown. The correlation of Fig. 8 takes the following form ;

$$(K_{IC}/100)^2 = 1000\ ({}_{V}E/\sigma_Y) \qquad (2)$$

where

$$K_{IC} = (K_C + K_R)/F(t)\ (\mathrm{kg}\sqrt{\mathrm{mm}}/\mathrm{mm}^2),\ F(t) = \begin{cases} 1+0.043\ (t-40) & \text{for } t \leqq 40\ \mathrm{mm} \\ 1 & \text{for } t > 40\ \mathrm{mm}, \end{cases}$$

K_C is deep notch test result, K_R is K-value for welding residual stress, ${}_{V}E$ is V-Charpy absorbed energy (kg-m), σ_Y is yield stress (kg/mm^2) and t is plate thickness. For calculating K_R, actually measured residual stress values, about 23 kg/mm^2 for WM and FL of SAW, about 10 kg/mm^2 for WM of MAW, and about 16 kg/mm^2 for FL of MAW, were used.

The correlation shown in Fig. 8 has a different inclination from that of the formula proposed by Ito et al. This is because their formula is for steels of 60 to 80 kg/mm^2 strength while the steel of the present study is much lower in tensile strength. Thus, it seems that the method employed in Fig. 8 results in substantially different correlation formulae according to the steel grades. To obtain a generally applicable formula, a great deal of data will have to be accumulated.

4.3 Correlation Between Fracture Initiation Test and Charpy Test with COD Taken as Parameter

Burdekin et al. [9] proposed a defect evaluation method based on COD concept, and have presented a design curve. A method like this is very convenient for materials of which δ_C is known. If correlations between δ_C of materials and their Charpy values are known, then from only Charpy test, an evaluation can be made with the use of the proposed design curve. Hagiwara et al. [14] studied the relation between V-Charpy values and COD test results for steel plates ranging from mild steel to 80 kg/mm^2 strength and found statistical correlations. According to them, between the temperature ($T_{0.16}$) at which δ_C is 0.16 mm in bend test with machined notch and ${}_{V}T_{rs}$ of Charpy test, the following relation exists ;

$$T_{0.16} = {}_{V}T_{rs} - (120-\sigma_Y)\ (^\circ\mathrm{C}) \qquad (3)$$

where σ_Y (kg/mm^2) is the value at room temperature. δ_C of 0.16mm is the COD value at the moment of slow crack initiation in advance of brittle fracture. Furthermore, within the transition temperature range, between δ_C (mm) at arbitrary temperature T (°C) and ${}_{V}E$(kg-m) at T+ 120-σ_Y (°C), the following correlation was found ;

$$\delta_C(\text{at } T) = 0.02\ {}_{V}E\ (\text{at } T+120-\sigma_Y) \qquad (4)$$

The correlation of eq. (3) is plotted in Fig. 9. Because between the Charpy results performed with 1/2t and 1/4t positions, the one giving poorer toughness thought to be dominant in the fracture initiation of full thickness specimen, higher ${}_{V}T_{rs}$ value or lower ${}_{V}E$ value was used. In Fig. 9, besides the results of bend test, also results (marked with *) of deep notch test were shown. Although the bend test results are nearly in conformity with eq. (3), they are more scattered than the data presented by Hagiwara et al. The deep notch test results for the base metal are in good conformity with eq. (3), but comparable values for weld joints are substantially in deviation from it. This tendency is comparable with the observation in previous section, i. e., for the base metal, δ_C by deep notch test and bend test are in good agreement, while for weld joints, δ_C by the former are much smaller than those by the latter.

As a result of studying the correlation between critical COD and Charpy energy, the temperature dependence of δ_C for the bend test can be evaluated from ${}_{V}E$ within a certain deviation, using eq. (4). δ_C for deep notch test of the base metal agrees with eq. (4) at arbitrary temperature within the transition range, but for weld joints, a good agreement does not exist because of the effect of residual stress.

5. Method of Safety Assessment Against Brittle Fracture of Nuclear Reactor Containment

So far, possible correlations among various brittle fracture tests have been examined for the purpose of obtaining basic data for establishing a method of safety assessment of structures based on industrial small scale tests. However, of course, the data on one steel grade and two weld joints obtained in this study are not sufficient for the purpose and therefore, more generalized study must be conducted in future. Here a conceptual outline of nuclear reactor containment safety assessment method using Charpy test which is a convenient industrial test will be described.

In this study, brittle fracture phenomenon was examined in two phases, fracture initiation and fracture propagation arresting, and the transition temperature for arresting was higher than that for fracture initiation. This means that arresting characteristics are safer criterion to adopt. From this point of view, either arresting or initiation characteristics must be selectively adopted as the safety evaluation criterion depending on the degree of importance of structure or structural element. In Fig. 10, a safety assessment process is proposed. This will be used for evaluation of fracture initiation or fracture arresting as follows ;

(a) For fracture initiation, the size, shape and position of defect must be determined. If reliable prediction on stable crack development caused by fatigue or corrosion is possible (b), or if NDI technique is utilizable (c), they should also be used for this determination. Otherwise, the size and shape of defect with which safety against fracture initiation should be assured are apriori determined and the defect is assumed to exist in the position of the lowest toughness among base metal, HAZ, FL and WM. For fracture arresting, the brittle crack length to propagate is apriori determined first. The longer this length, the higher is safety factor. Also the position where is expected to arrest the crack should be determined. Generally, it is safer to assume that the crack which initiates at weld will propagate along the weld without deviating into the base metal.

(d) The stress at the position determined in (a) under either of the loading conditions of normal operation, abnormal operation, pressure test or accident is calculated. In this computation, such local stresses as welding residual stress, thermal stress and stress concentration should be included.

(e) The temperature in the conditions determined in (a) and (d) is determined.

(f) Under the conditions of (a), (d) and (e), the design K value, K_d, or the design COD, δ_d, is calculated.

(g) V-Charpy test is carried out for the material of the position determined in (a).

(h) If some deterioration of the material is expected during service from radiation embrittlement, hydrogen embrittlement or otherwise, Charpy test results or the toughness value of (j) are correspondingly shifted.

(i) For fracture initiation, an appropriate correlation between large or medium scale initiation tests and Charpy test is selected. If the specimens of large or medium scale test have machined notch, possible difference between machined notch and fatigue notch must be taken into consideration. For fracture arresting, an appropriate correlation between large or medium scale arresting tests and Charpy test is selected.

(j) Using the correlation of (i), fracture toughness value K_c or δ_c under the conditions of (a) and (e) is calculated.

(h) Safety evaluation is done by comparing K_d (or δ_d) with K_c (or δ_c).

6. Conclusion

One of the objectives of this study was to obtain a clear understanding of brittle fracture propagation arresting characteristics under high stress. Robertson type large scale tests were performed on the base metal and weld joints of the steel plate for nuclear reactor containment, and the arresting temperature under yield stress was found to lie above 0°C. This was considerably higher than the temperature derived from CAT curve based on NDT temperature obtained through drop weight test. Rather, the method using Charpy test result as given in WES standard gave better estimation.

Another objective was to obtain basic data required for establishing safety assessment method based on convenient small scale tests, by studying correlations among large, medium and small scale brittle fracture tests. Study on fracture initiation and arresting characteristics revealed that these characteristics can be estimated from Charpy test results within certain deviation ranges. When evaluating the safety of structures utilizing such results as above, the arresting criterion and the initiation criterion are expected to be selectively applied according to the degree of safety requirements. The former, which is higher in safety, should be applied to very important structures.

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Table 1 Chemical composition and tensile properties of the steel plate A516 Gr.70

plate	chemical composition (%)					tensile properties		
	C	Si	Mn	P	S	yield point (kg/mm²)	tensile strength (kg/mm²)	elongation (%)
A	0.18	0.27	1.15	0.005	0.004	38	53	33
B	0.17	0.27	1.17	0.008	0.003	36	53	33

Table 2 Chemical composition and tensile properties of the weld metals

joint	chemical composition (%)							tensile properties		
	C	Si	Mn	P	S	Mo	Ni	yield point (kg/mm²)	tensile strength (kg/mm²)	elongation (%)
SAW	0.04	0.41	1.23	0.022	0.024	0.47		52	60	26
MAW	0.07	0.39	1.39	0.011	0.011		0.47	50	60	26

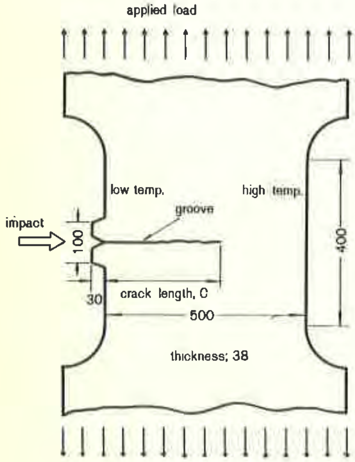


Fig.2 Modified ESSO test specimen for weld joint (unit; mm)

Table 3 Comparison of transition temperatures with the three test methods

kind of test / material	double tension or ESSO test $T_{a\sigma Y}$ (°C)	DT test $_{D}T_{E}$ (°C)	DWTT 50%FATT (°C)	
			35mm thick	15mm thich
base metal	6	3	5	−5
weld metal	23	20		−15
fusion line	17	18		−11

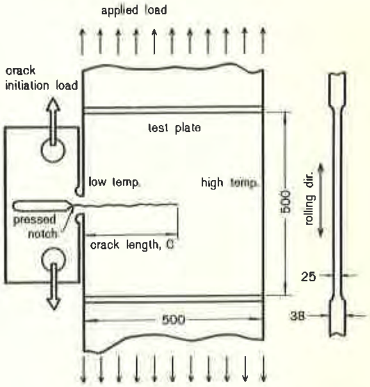
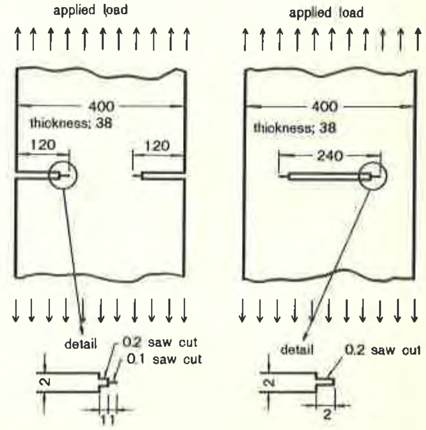


Fig.1 Double tension test specimen for base metal (unit; mm)



(a) for base metal (b) for welded joint

Fig.3 Deep notch test specimen (unit; mm)

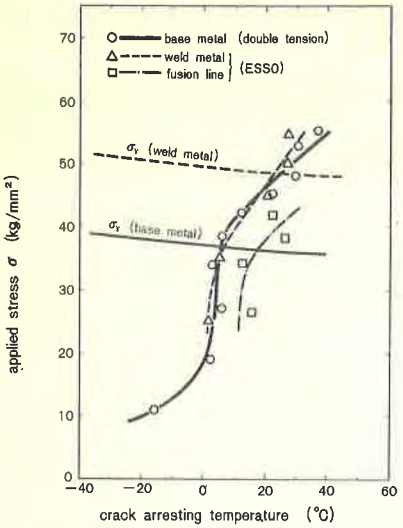


Fig.4 Crack arresting temperature of base metal and MAW joint

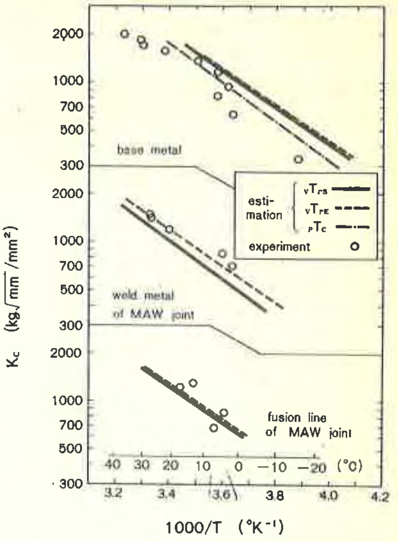


Fig.6 Comparison of K_c estimated from Charpy test with experimental result

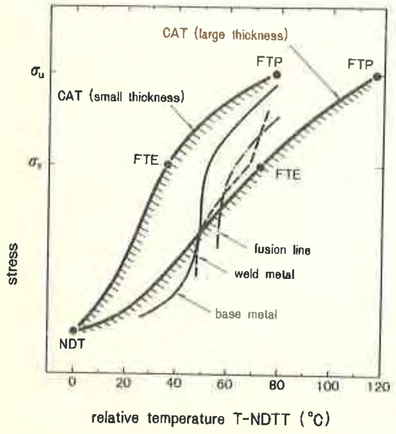


Fig.5 Comparison of estimated CAT curve with experimental result

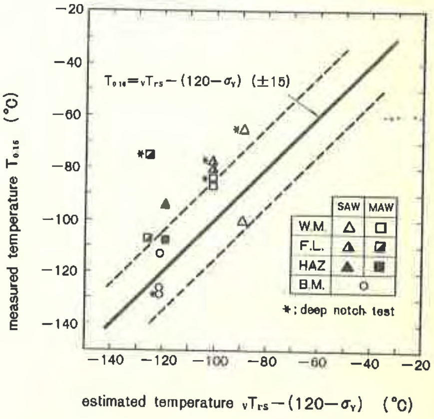


Fig.9 Correlation between critical COD and Charpy transition temperature

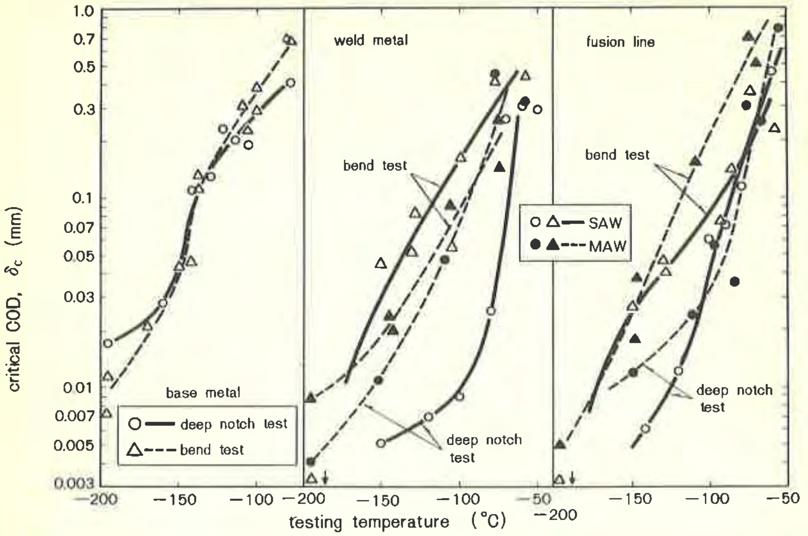


Fig.7 Comparison of critical COD by three point bend test and deep notch test

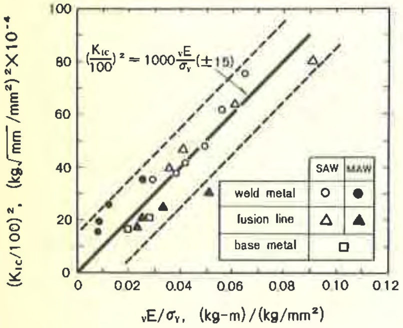


Fig.8 Correlation between K_{IC} and Charpy absorbed energy

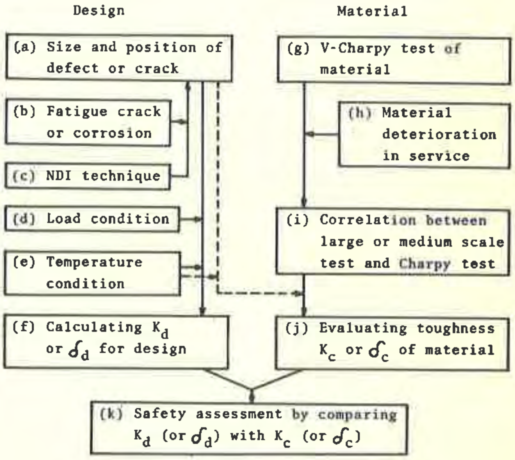


Fig.10 Safety assessment process against brittle fracture of nuclear reactor containment