FRACTURE MODE TESTS OF DUCTILE CAST IRON FOR CASKS

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ABSTRACT

In case of the holizontal drop accident of cask onto projection, the loading stress on to the surface crack of cask body could be Mode Ⅱ(In-plane Shear Mode) at the bottom of the crack and Mode Ⅲ (Out-of-plane Shear Mode) at the edge of the crack. But, the safety evaluation of Cask material for drop accident is normally used brittle fracture methods only by Mode Ⅰ(Opening Mode). And the fracture toughness values of Mode Ⅱ and Mode Ⅲ of Ductile Cast Iron (DCI) material are not yet obtained. Several fracture mode test of DCI for Casks are conducted under the Mode Ⅰ, Ⅱ and Ⅲ condition using 3 Point Bending (3PB) specimens. The K_{IC}, K_{IIC}, K_{IIIC}, J_{IC}, J_{IIC}, J_{IIIC} values of DCI are obtained and the estimate equations of J_{IIC}, J_{IIIC} values are also proposed from Rice's J integral. Then compared test results with proposed equation. The relations of $K_{IC} < K_{IIC} < K_{IIIC}$, $J_{IC} < J_{IIC} < J_{IIIC}$ are obtained. Also, the influence of plastic restraint force is investigated and the relation of K_{IC} (3PB) $<$ K_{IC}(1TCT) $<$ K_{IC}(Tension) is obtained.

KEYWORDS

Ductile Cast Iron(DCI), Storage Cask, J integral, Fracture Mode, Mode Ⅰ, Mode Ⅱ, Mode Ⅲ, 3 Point Bending, Fracture Toughness, Plastic Restraint Force

INTRODUCTION

During the storage of spent fuel, the material of the storage cask may be subjected to a mechanical impact condition by drop accident. In case of the holizontal drop accident of cask onto projection, the loading stress onto the surface crack of cask body could be not only Mode Ⅰ(Opening Mode) include Bending Mode, but also Mode Ⅱ(In-plane Shear Mode) at the bottom of the crack and Mode Ⅲ (Out-of-plane Shear Mode) at the edge of the crack as shown in Fig.1.

But, the safety evaluation of Cask material for drop accident is normally used brittle fracture methods only by the fracture toughness values (K_{IC}, K_{Id}, J_{IC}, J_{Id}, etc.) of Mode Ⅰ. And the fracture toughness values of Mode Ⅱ and Ⅲ of Ductile Cast Iron(DCI) material are not yet almost obtained.

This paper presents the several fracture mode test's results of DCI for Casks under the Mode Ⅰ, Ⅱ and Ⅲ stress condition using 3 Point Bending(3PB) specimens. And obtained K_{IC}, K_{IIC}, K_{IIIC}, J_{IC}, J_{IIC} and J_{IIIC} values of DCI are discussed.

FRACTURE MODE TESTS IN ELASTIC REGION

Test Materials and Test Pieces

The full scaled test blocks of DCI (JIS G5504(1992) FCD 300LT (Japanese Industrial Standards,1992): the new material code of DCI for casks in Japan)are manufactured and used as a test material.The used cylindrical DCI block with bottom plate,is about 510 mm Thickness(2400mm Outer Diameter×1380mm Inner Diameter)×3690mm Total Length ×600 mm Bottom Plate Thickness and its weight is about 84 Ton.
The test pieces used in this study were taken from this DCI block mechanicaly. The size of used test pieces is 50mm Thickness×100mm Width × 600mm Length. And the fatigue notch (about 5mm length) is added after preparing mechanical notch (about 45mm length). The ratio of a(crack depth)/ W(width of test piece) is aimed about 0.5.

Test Method

Loading Method of each Mode is shown in Fig. 2. Mode I test was conducted by 3PB, and Mode II and III test were by 4 point shearing.Testing temperature was -196,-160,-130 and -100℃. Liquid nitrogen was used for cooling and all tests were conducted staticaly. The displacement value at loading point (d_{LP}) and the displacement value at crack mouth (d_{CM}) were measured by differential transformer and clip gage as shown in Fig.2. After test was ended, the crack propagation length was measured at the point of 1/4, 2/4 and 3/4T(Thickness) on the two sides of fracture surface.

Evaluation of K_{IC}, K_{IIC} ,K_{IIIC}

K_{IC} values by tention test were obtained from applying gross stress obtained from the load(L) − d_{CM} curves, to the equation by W.F.Brown et all.(1966). And K_{IC} values by 3 point bending test were also obtained in accordance with ASTM E399−90(1994). K_{IIC} and K_{IIIC} values were obtained from the equation by A.Ostuka et al.(1984) and K.Thogo et al.(1986) using shear stress values and gross stress as same as K_{IC} estimation.

Test Results

Test appearance shows in Photo 1 and an example of fracture surface of test pieces shows in Photo 2. Crack was propagated straightly from crack tip in Mode I test. In Mode II test crack was propagated in direction of 45 ∼70 degree to crack line.In Mode III test crack was propagated in direction of 45 degree to crack line at first and then gradually propagated in different direction. As shown in Photo 2,crack was propagated along the vertical plane to the maximum principal stress. (Direction of 45 degree : the plane of the maximum tensile stress, Direction of 71 degree : the plane of the minimum density of strain energy)
An example of the L −d_{CM} relation shows in Fig.3. Mode I test pieces were fractured under low load and small displacement and Mode II test pieces were fractured under high load and small displacement. And Mode III test pieces show the biggest transformation among 3 types. Obtained K values show in Fig.4 with J values that are obtained at next chapter. K_{IC} , K_{IIC} and K_{IIIC} values were increase with test temperature and following relations were obtained.

$$K_{IC} < K_{IIC} < K_{IIIC} \tag{1}$$

But, only Mode I test was obtained valid K values and the estimation by J values should be necessary.
Also, Fig.4 shows K_{IC} values by the other tension test and 3PB test that conducted as Mode I test, in comparison with K_{IC} values by 1TCT (1 inch Thickness Compact Tention) Test specimens of this same DCI block materials. The relation was obtained as follows.

$$K_{IC}\ (3PB) < K_{IC}\ (1TCT) < K_{IC}\ (Tension) \tag{2}$$

And K_{IC} shows smaller values with increasing of plastic restraint force.

FRACTURE MODE TESTS IN PLASTIC-ELASTIC REGION

Test Materials and Test Pieces

The used test material is the same DCI block as used in the above tests in Elastic Region. The test pieces were taken from the DCI block mechanicaly. The size of used test pieces is 50mm Thickness ×100mm Width ×600mm Length,that is same size and configuration as used in the above tests in elastic region. The tests in plastic-elastic region are used 2 type's pre-crack that is mechanical and fatigue notch as below.

1) The mechanical notch :
   Object : to delay the initiation of crack propagation.
   Curvature radius of crack tip : 2 mm
   Length of pre-crack : 2 mm pitch from 42 mm to 58 mm (total 9 types)
   The ratio of a(crack depth)/W(width of test piece): a/W = 0.4∼ 0.6 (a: 2mm pitch)
2) The fatigue notch :
   Length of pre-crack: mechanical notch(46mm length) + fatigue notch(4mm length)
   The ratio of a(crack depth)/ W(width of test piece) : a/W = 0.5

Test Method

Loading method of each Mode is shown in Fig.2. Mode I test was conducted by 3PB, and Mode II and III test were by 4 point shearing.Testing temperature was -100,-40 and 20℃. All tests were conducted staticaly.
The test pieces with mechanical notch were loaded up to near the maximum loading point and then unloaded, in order to measure the gradient of potential energy with crack propagation and also to make key-curve that is used to determine the ductile crack initiation point of the test pieces with fatigue notch.
The test pieces with fatigue notch were loaded to different strain level and then unloaded, in order to vary the length of the ductile crack propagation.
L, d_{LP} and d_{CM} were recorded in both test pieces.

Test Results

1) Estimation of J integral by the potential energy gradient method

J integral value can be obtained as diminution value of the potential energy per unit thickness accompanied with crack propagation. Potential energy(U) can be obtained as an area of L-d_{LP} curve, that is strain energy, in case of the displacement control test. Fig.5 shows an example of the relation between potential energy and a/w ratio in Mode I test, obtained from the L-d_{LP} curve by the test pieces with different length mechanical notch. And the gradient of curve of this Fig.5 shows J integral values as follows.

$$J = -(1/B)(\partial U/\partial a) = -(1/BW)(\partial U/\partial(a/W)) \qquad (3)$$

here, U : Total energy, B : Thickness , W : Width of test piece
Thus one example of obtained $J - d_{LP}$ relation in Mode I test shows in Fig.6.

2) Determination of the ductile crack initiation point by the key-curve method and estimation of J_{IC} , J_{IIC} and J_{IIIC}

The $L\text{-}d_{LP}$ curve by the test pieces with mechanical notch was regarded as the key-curve, the ductile crack initiation point was obtained as the diverging point of the $L\text{-}d_{LP}$ curve by the test pieces with mechanical notch and by those with fatigue notch, as shown in Fig.7.
J_{IC} , J_{IIC} and J_{IIIC} values are obtained from the d_{LP} and (a/W) values at the ductile crack initiation point, using the $J\text{-}d_{LP}$ relation as shown in Fig.6. Obtained values show in Fig.4 and these relations were obtained in the temperature range of -100～ 20 ℃.

$$J_{IC} < J_{IIC} < J_{IIIC} \qquad (4)$$

3) Comparison with ASTM CODE

J_{IC} values obtained by the potential energy gradient method are compared with those by ASTM E813-81(1981). J_{IC} values obtained by the potential energy gradient method showed good agreement with J_{IC} values by ASTM CODE.

4) Validity of J values

In this study the used condition to Validity of J values are as follows.

$$\text{Mode I} : b_0 \geqq 25(J_{IC} / \sigma_Y) \qquad (5)$$
$$\text{Mode II} : b_0 \geqq 25(J_{IIC} / \tau_Y) \qquad (6)$$
$$\text{Mode III} : b_0 \geqq 25(J_{IIIC} / \tau_Y) \qquad (7)$$

here, b_0 :Initial length of ligament, σ_Y :Valid yield stress(($\sigma_{0.2}$ + σ_{UTS})/2)
τ_Y : Valid shear stress
Equation (5) is according to ASTM E813(1981,1989). τ_Y is defined as Valid shear stress and obtained as $\{\tau_{0.3} + \tau_{UTS})/2\}$ (N.Urabe et al.,1992).

CONVENTIONAL EQUATION OF J_{IIC} AND J_{IIIC}

J.R.Rice et al.(1973) proposed the conventional equations to Mode I transformation of notched material as belows.

For tention load : $$J_I = J_{eI} + (2/Bb)\left[\int_0^{\delta_{PI}} P d\delta_{PI} - P\delta_{PI}/2\right] \qquad (8)$$

For 3 point bending load : $$J_I = J_{eI} + (2/Bb)\int_0^{\delta_{crack}} P d\delta_{crack} \qquad (9)$$

here, P : Loaded Force, δ_{PI}: Plastic element of displacement at loaded point,
δ_{crack} : Displacement at loaded point of crack material,
B : Thickness of test piece, b : Length of ligament
(b = W−a , W : Width of test piece, a : length of crack)

In this chapter the conventional estimate equation of J_{IIC} and J_{IIIC} values of notched material by 4 point shear test is studied. Assumed test piece is as follows.
W : Width of test piece (W=2B), B : Thickness of test piece, a : crack length
Shear stress per unit thickness of test piece is defined as F. And in the condition of constant F, J integral is described as follows correspond to very small crack propagation.

$$J = \partial U/\partial a \qquad (10)$$

here, $\partial U/\partial a$ shows the change ratio of potential energy of notched materials in case of very small crack propagation. And U is equal to complimental energy which is shown in load and displacement curve under the condition of constant load.
In case of 4 point shear test used in this study (l_1=1, l_2=51), F=2P/3.
Then these formula was obtained as the conventional estimate equations of J_{IIC} and J_{IIIC} values.

$$J_{IIC} \text{ or } J_{IIIC} = (4/3Bb)\left[\int_0^{\delta^*} P d\delta - P^* \delta_{PI*}/2\right] \qquad (11)$$

here, P : Loaded Force, δ : Shear displacement at crack tip,
δ_{PI}: Plastic element of δ, * : Initiation point of crack propagation,
B : Thickness of test piece, b : Length of ligament

J_{IIC} and J_{IIIC} values obtained by equations (11) were 12 ～19% bigger than those by the potential energy gradient method. Considerring that J_{IC} values by ASTM E813 that was used same method with equations (11) shows good agreement with J_{IC} values by the potential energy gradient method in Mode I test, it may be said that the different values are caused by influence of rubbing.

CONCLUSIONS

The several fracture mode tests of DCI for Casks are conducted and the obtained results are as follows.

1)The conventional equations of estimating J_{IIC} and J_{IIIC} values are obtained as follows in case of 4 point shear test.

$$J_{IIC} \text{ or } J_{IIIC} = (4/3Bb)\left[\int_0^{\delta^*} P d\delta - P^* \delta_{PI*}/2\right]$$

here, P : Loaded Force, δ : Shear displacement at crack tip,
δ_{PI}: Plastic element of δ, * : Initiation point of crack propagation,
B : Thickness of test piece, b : Length of ligament

2)In the temperature range of −196 ～ 20 ℃, these relations were obtained.
$K_{IC} < K_{IIC} < K_{IIIC}$, $J_{IC} < J_{IIC} < J_{IIIC}$

3)The relation was obtained as follows.
K_{IC} (3PB) < K_{IC} (1TCT) < K_{IC} (Tension)
And K_{IC} shows smaller values with increasing of plastic restraint force.

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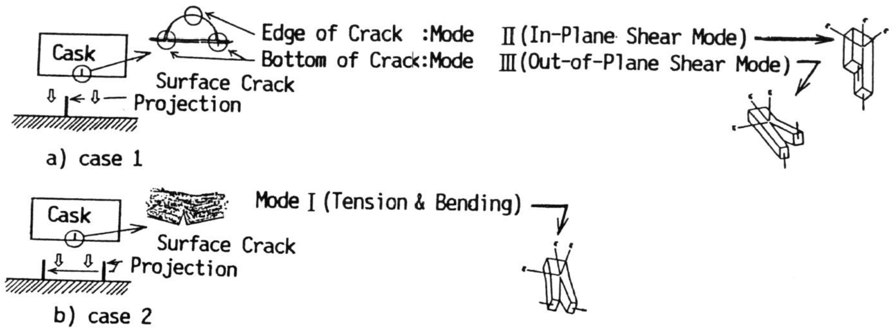
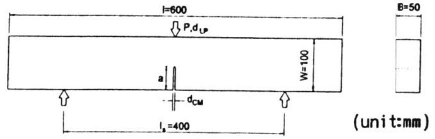
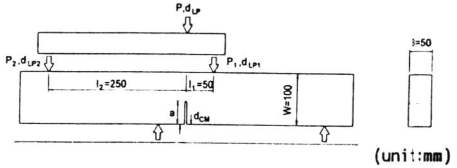


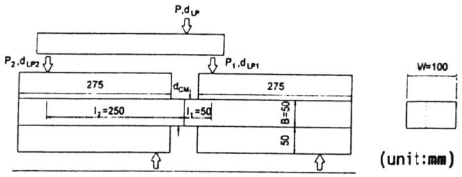
Fig. 1 Relation between the horizontal drop accident of Storage Cask and several Fracture Mode at the surface crack of Cask body.



(a) Mode Ⅰ test(3 Point Bending)



(b) Mode Ⅱ test(4 Point In-plane Shear)



(c) Mode Ⅲ test(4 Point Out-of-plane Shear)

Fig. 2 Test piece and loading method (DCI).

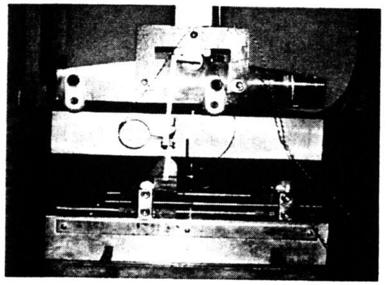
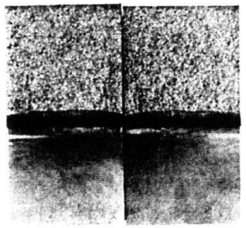
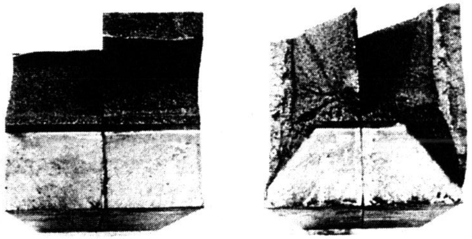


Photo 1 Test appearance of fracture mode test. (Mode Ⅱ test, in the cooling box)



(a) Mode Ⅰ



(b) Mode Ⅱ (c) Mode Ⅲ

Photo 2 An example of fracture surface of test pieces after fracture mode test (DCI).

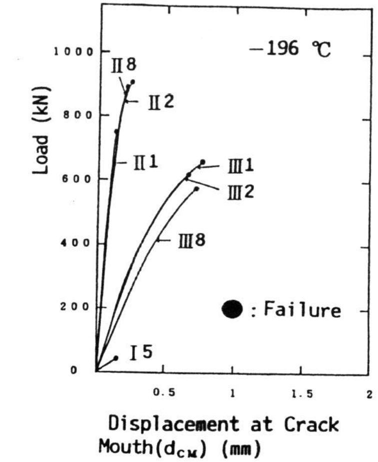


Fig. 3 Relation between Load and Displacement at crack mouth.

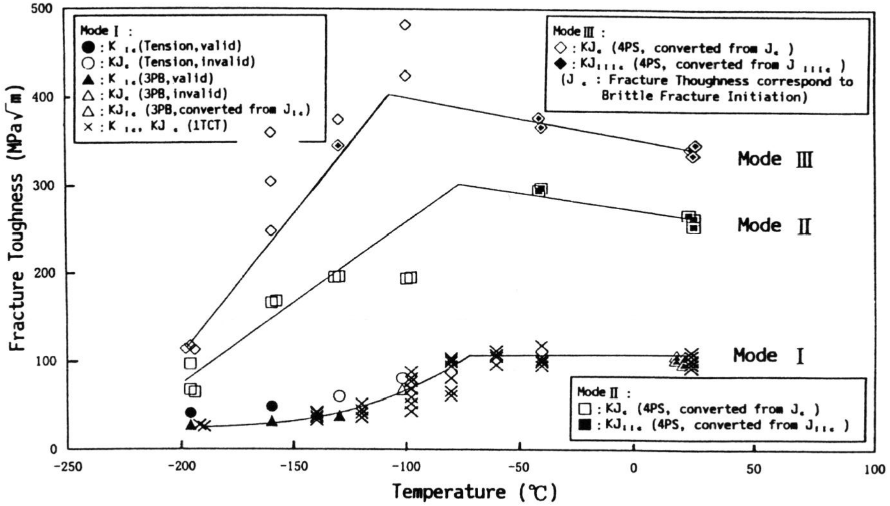


Fig. 4 Fracture toughness of several Mode.

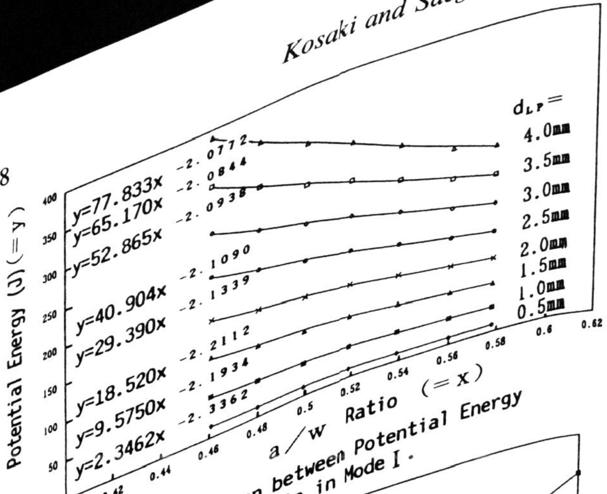


Fig. 5 Relation between Potential Energy and a/W ratio in Mode I.

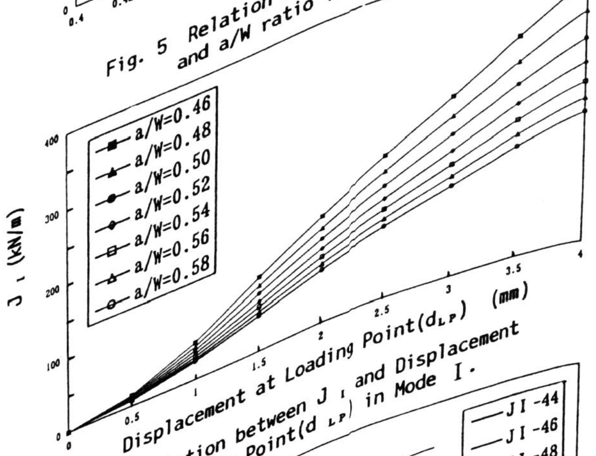


Fig. 6 Relation between J_I and Displacement at Loading Point(d_{LP}) in Mode I.

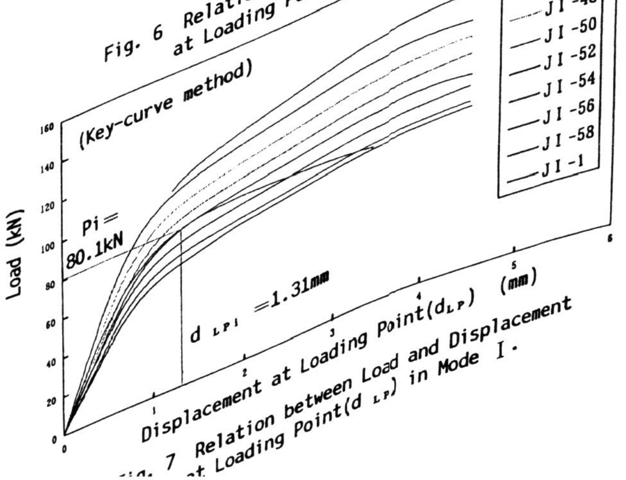


Fig. 7 Relation between Load and Displacement at Loading Point(d_{LP}) in Mode I.