Development of Brittle Crack Arrest Toughness K_{ca} Test Method - Brittle Crack Arrest Design for Large Container Ships -2 -*12

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ABSTRACT

Brittle fractures of the hull structure cause serious structural, fatal and environmental damage once they happen. Therefore, ships are basically designed and constructed in such a way to prevent brittle cracks from occurring. Further, if by chance a brittle crack occurs, it is essentially and extremely important that a backup brittle crack arresting function is provided to arrest its propagation and to ensure structural reliability.

As an evaluation method of arrest toughness, several test methods have been developed: Robertson test (1953), ESSO test (1955), Double tension test (1958) and others. At the moment temperature, the gradient type ESSO test is the most popular method for the determination of the arrest toughness of material used because of its convenience. However, there is no code or standard ESSO test despite its long history. In this report, with the goal of developing a standard of ESSO test, effects of testing conditions - that is, thickness of tab plate, width of tab plate, distance between pins, temperature gradient and crack length - on the evaluated K_{ca} values are investigated. Investigation is based on many large scale crack arrest tests with 16, 50 and 80 mm thick low carbon steel plates conducted by four research groups in Japan.

This research has been conducted by the research committee of the Nippon Kaiji Kyokai (ClassNK) and its results have been summarized and incorporated in their "Guidelines on Brittle Crack Arrest Design".

Keywords

Brittle fracture; ESSO test; K_{ca}; Temperature gradient; Crack arrest

1. INTRODUCTION

1.1 Review of wide plate test methods for arrest toughness determination

The two principal philosophies for the avoidance of brittle fracture are (i) to prevent the initiation of cracks and (ii) to select materials which will arrest brittle running cracks following crack initiation. The brittle crack arrest concept in addition to brittle crack initiation control makes it possible to achieve 'double integrity' by preventing both brittle crack initiation and propagation. This concept is effective and essentially important for the integrity of some large structures whose accidental failure may involve significant social damages. The double integrity concept can be applied to the low temperature storage tanks of liquefied gases, such as LNG or LPG, penstocks of hydraulic power plants, large scale ships, etc.

In order to evaluate the arrest toughness of materials, various test methods were developed. In particular, full-scale component testing, the most realistic way of assessing, is, however, neither economic nor practical for most steel constructions. A more practical way is to carry out large-scale, structurally representative, wide plate tests.

The first wide plate crack arrest test was developed by Robertson (1953) at the UK Naval Construction Research Establishment. A typical test method is drawn in Fig.1. The test plate is cooled to the temperature of interest and subject to the maximum design stress. A running crack is then initiated by

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impacting the notched 'ear' of the test plate. The test result is simply a statement whether a running crack is arrested ('no go') or not ('go'). Frequently, gradient temperature tests have been carried out in which an increasing temperature field was imposed on the specimen by cooling one end and heating the other, in this set-up, the crack arrest temperature is defined.

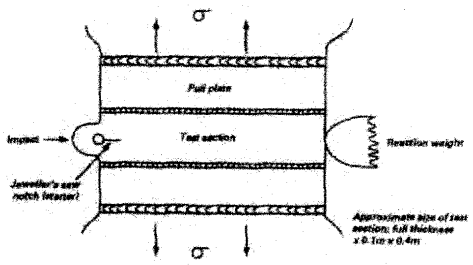


Figure 1 Principle and geometry of Robertson test (Wiesner, 1995)

A second widely used wide plate crack arrest test is the ESSO test, which was developed in the 1950s (Feely et al.,1955) as a modification of the Robertson test following the failure of two storage tanks operated by Standard Oil Development Company (later ESSO). The principle of the test is shown in Fig. 2. The brittle crack is initiated by driving a wedge into a V-shaped slot which has a fine saw cut at its root. A duplex technique is also employed where a brittle crack starter plate is attached to the test material proper which acts as the crack initiator, see Fig. 3. The ESSO test is the most common method of evaluation of arrest toughness at the moment in Japan because of its convenience.

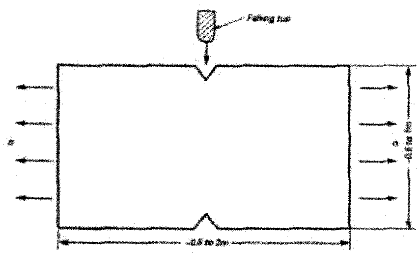


Figure 2 Principle and geometry of ESSO test

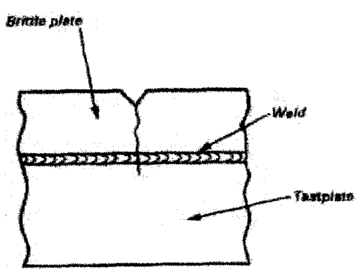


Figure 3 Duplex type wide plate test

The double tension test, which was developed in Japan by Yoshiki and Kanazawa (1958), avoids the complication of the impact blow which is necessary to initiate the brittle crack in Robertson test and ESSO tests. Instead, the crack is initiated by applying a subsidiary load to the edge of the plate via a secondary loading tab, see Fig. 4. As in the Robertson and ESSO tests, the isothermal set-up will lead to a 'go' / 'no go' result and the temperature gradient set-up will result crack arrest temperature.

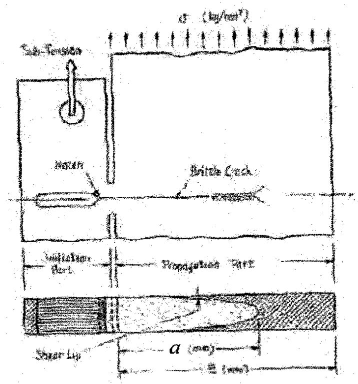


Figure 4 Principle and geometry of double tension test (Koshiga, Imazawa and Takehana, 1963)

In most recent studies, after the work of Yoshiki and Kanazawa (1963), the test results are analyzed not only in terms of a given applied stress but also to calculate the applied stress intensity factor at arrest, i.e. the crack arrest toughness;

$$K_{ca} = \sigma\sqrt{\pi a} \cdot Y \quad (1)$$

Where σ is the applied stress, a the arrested crack length and Y a dimensionless function of plate geometry and crack length.

Also, in the case of the temperature gradient test, K_{ca} is generally represented as an Arrhenius type function of arrest temperature (absolute temperature), T_k, i.e. the crack arrest toughness;

$$K_{ca} = \sigma\sqrt{\pi a} \cdot Y = K_0 \exp(-\frac{T_0}{T_k}) \quad (2)$$

Where K_0, T_0 are the material constants

1.2 Limited scope of testing parameter of wide plate arrest tests

When those wide plate tests are conducted, various testing conditions should be set. Some researchers have pointed out that these testing conditions may influence the test results. Kanazawa et al. (1971) reported one important finding, that is, for longer arrested crack length, a load drop occurred close to the crack path prior to arrest. They proposed scaling the crack arrest toughness value using the ratio of dynamically measured load at arrest to initial load, which improved the applicability in the results. However, large-scale tests should be designed to avoid such complications. Stress waves, which emanate from the propagating crack tip, are reflected at the loading boundaries of the test specimen and may influence a crack arrest event when they return to the crack tip region (Remzi, 1985). Therefore, to ensure structurally representative conditions, the crack arrest event should occur prior to the time t_s, which is needed for the stress waves to travel to the specimen boundaries and back. An estimation of this time has been by Willoughby and Wood (1984):

$$t_s \leq 2L/c \qquad (3)$$

Where L is the distance to the nearest loaded boundary (the reflections from the top and the bottom edge of the test plate are ignored) and c the stress wave velocity (typically 5800 m/s in steel). In order to avoid the stress wave issue, a sufficiently long and wide specimen is required compared with the length of arrested crack. However, practical limitation of specimen dimensions or tab plate dimensions have not been revealed yet.

On the other hand, Aihara et al. (1995) investigated that temperature gradient influences arrest test results very much by the difference of thickness of the side ligament behind the running crack tip. However, practical limitation of temperature gradients has not been revealed yet.

In this brief report, the ESSO test is chosen as the arrest toughness test and arrest toughness data obtained by a lot of ESSO tests is verified with the aim of quantitative definition of experimental limitation of testing conditions.

2. Effect of thickness and width of tab plate on K_{ca} evaluated by a temperature gradient type ESSO test

In most ESSO tests, the specimen is not directly connected to the test rig. Reusable tab plates are usually used between the specimen and test rig for saving the used amount of material tested. However, the connection boundary to tab plate sometimes becomes a resource of reflection of stress wave. In this chapter, the effect of the dimensions of tab plates on arrest toughness evaluations is quantitatively evaluated.

2.1 Steel used

Thickness, chemical compositions and mechanical properties are shown in Tables 1 and 2, respectively. Steel is manufactured by normalizing. Charpy impact value is met in EH grade requirement.

Table 1 Chemical composition of steel used [mass%]

Steel	Thickness [mm]	Chemical compositions				
		C	Si	Mn	P	S
Norma-1	16	0.06	0.13	1.37	0.006	0.0016

Table 2 Mechanical properties of steel used

Steel	Tensile property			Charpy impact property	
	YP [N/mm^2]	*TS* [N/mm^2]	*EL* [%]	vE_{-40} [J]	*vTrs* [deg.C]
Norma-1	321	448	38.8	355	-94

2.2 Testing conditions

Fig. 5 shows the general method of testing. A specimen is connected with a tab plate at both ends by welding. Dynamic change of strain and displacement are measured during crack running. Crack speed is also measured by a crack gauge. Temperature gradient is controlled on the specimen by cooling the start side and heating the other. In order to evaluate the effect of the dimensions of the tab plate, 8 specimens are tested. Thickness of tab plate, t_0 and width of tab plate, B_0, are varied, as shown in Table 3.

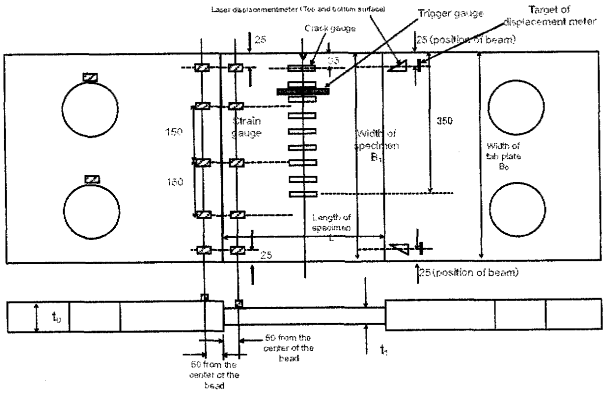


Figure 5 Dimension of specimen and general of dynamic measurement

Table 3 Testing conditions of brittle crack arrest toughness K_{ca} test for evaluation of the effect of thickness and width of tab plate

Mark	Distance between pins L_p [mm]	Thickness of tab plate t_0 [mm]	Width of tab plate B_0 [mm]	Thickness of specimen t_1 [mm]	t_0/t_1 [mm]	Length of specimen L [mm]	Width of specimen B_1 [mm]	Aimed temperature gradient dT/da [deg.C/mm]
TM-N1-1	1500	16	500	16	1.0	500	500	0.25
TM-N1-2	1500	16	500	16	1.0	500	500	0.25
TM-N1-3	1500	**24**	500	16	**1.5**	500	500	0.25
TM-N1-4	1500	**24**	500	16	**1.5**	500	500	0.25
TM-N1-5	1500	**50**	500	16	**3.1**	500	500	0.25
TM-N1-6	1500	**50**	500	16	**3.1**	500	500	0.25
TM-N1-7	1500	**24**	**1000**	16	**1.5**	500	500	0.25
TM-N1-8	1500	**24**	**1000**	16	**1.5**	500	500	0.25

2.3 Test results

Fig. 6 shows the example of the specimen after testing. The arrested crack length is defined as the distance from the edge at start side to the deepest point of brittle fracture surface. Also, the arrested temperature is determined by an interpolative calculation from the temperature record. In the arrest toughness, K_{ca} is calculated by Eq. (4) in which the configuration of the ESSO test specimen is considered.

$$K_{ca} = \sigma\sqrt{\pi a}\sqrt{\frac{2B_1}{\pi c}\tan\frac{\pi a}{2B_1}} = K_0 \exp(-\frac{T_0}{T_k}) \qquad (4)$$

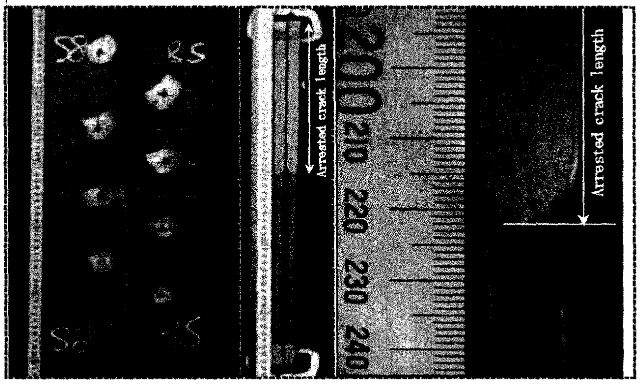


Figure 6 Definition of arrested crack length (ex.TM-N1-4)

ESSO test results are plotted on an Arrhenius relationship in which the horizontal axis is the inverse number of the temperature and thevertical axis is the logarithm number of K_{ca}. It is well known that the test results of each material are linearly plotted on this chart (Eq. (4)). As shown in Fig. 7, results of TM-N1-1~2, 3~4 and 7~8 are located in almost the same band; however, only that the results of TM-N1-5~6 are higher than the other is obvious. This overestimation of TM-N1-5~6 is thought to be caused by unloading stress wave at the boundary between the specimen and tab plate during crack running. This possibly means that evaluation by using a thick tab plate tends to be an inaccurate evaluation. It can be concluded, at least, that thickness of the tab plate is allowed to be increased until 1.5 times the thickness of the specimen. Also, it can be said that to use up to 2 times a wider tab plate than the width of the test plate has little effect on the result.

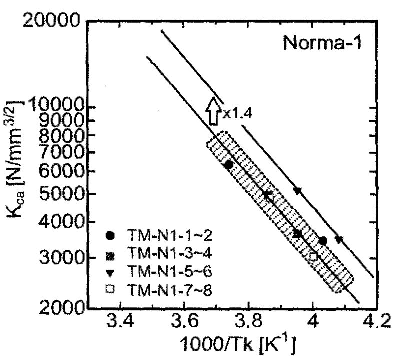


Figure 7 ESSO test result

3. Effect of distance between pins on K_{ca} evaluated by a temperature gradient type ESSO test

During crack running, test rig elastically deforms the specimen at constant displacement through pins. That is, if the distance between pins is very short, an unloading stress wave conveys from crack face to test rig and finally the crack become easy to arrest. In this chapter, the limitation scope of the distance between pins is investigated.

3.1 Steel used

Normalized 16 mm thick steel plate (Tables 1 and 2) is used as well as in the previous chapter.

3.2 Testing conditions

Basic testing condition measurement system is also the same as in the previous chapter, as shown in Fig. 5. Table 4 shows test conditions in which the distance between pins is set to 3500 mm to compare to the 1500 mm in the previous chapter.

3.3 Test results

Fig. 8 shows the ESSO test results. The results of the 3500 mm condition(TM-N1-9~11) are located in almost the same band as that for in the previous chapter's data, except for the 50 mm thick tab plate condition. Furthermore, in Fig. 9, similar arrested crack length conditions of the '1500 mm' and '3500 mm' results are compared. The arrested crack length of both conditions is around 300 mm, which is relatively long. The upper chart is the record of the breaking time of the crack gauge. This record leads to an estimated arresting time. The lower chart shows the dynamic strain change record around pin. No change happens at the time of arresting of crack. That is, 1500mm is a sufficient length for the distance between the pins from the viewpoint of the unloading stress wave effect.

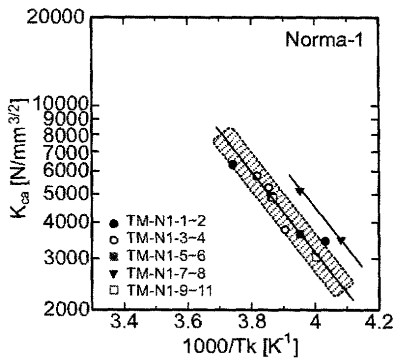
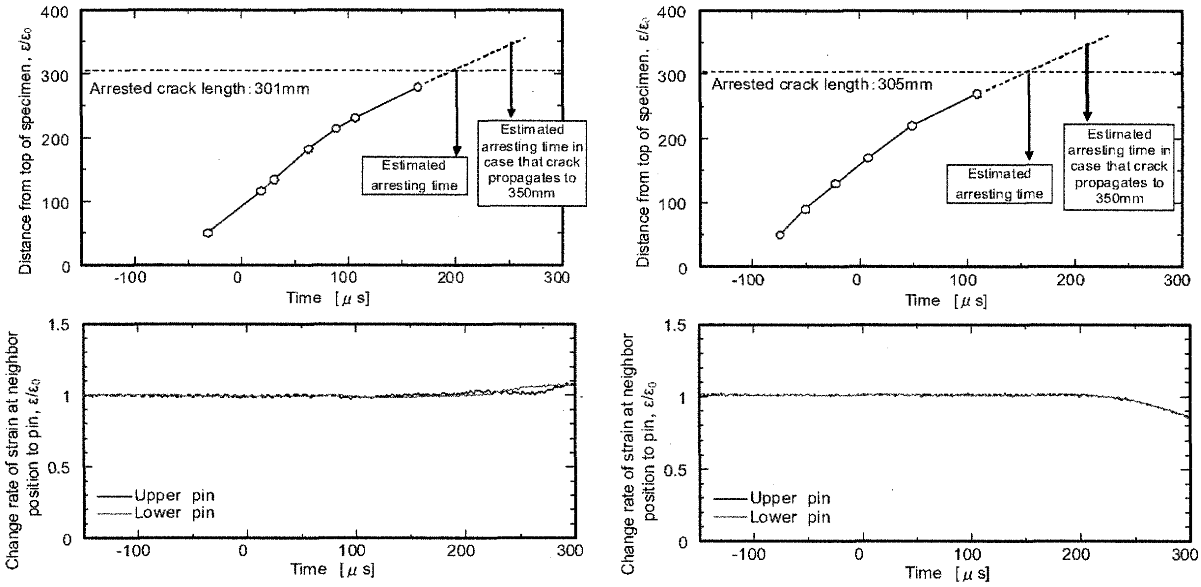


Figure 8 ESSO test result

Table 4 Testing condition of brittle crack arrest toughness K_{ca} test for evaluation of the effect of distance between pins

Mark	Distance between pins L_p [mm]	Thickness of tab plate t_0 [mm]	Width of tab plate B_0 [mm]	Thickness of specimen t_1 [mm]	t_0/t_1 [mm]	Length of specimen L [mm]	Width of specimen B_1 [mm]	Aimed temperature gradient dT/da [deg.C/mm]
TM-N1-9	3500	16	500	16	1.0	500	500	0.25
TM-N1-10	3500	16	500	16	1.0	500	500	0.25
TM-N1-11	3500	16	500	16	1.0	500	500	0.25



TM-N1-2
(Distance between pins : 1500 mm)

TM-N1-10
(Distance between pins : 3500 mm)

Figure 9 Breaking time of crack gauge and strain change around loading pin(TM-N1-2, TM-N1-11)

4. Effect of temperature gradient and crack length on K_{ca} evaluated by a temperature gradient type ESSO test

As described in the introduction, temperature gradient also exercises a major influence over ESSO test results by the difference of development of the side ligament. Fixing a valid range of crack length is also important. Long crack running may lead to stress relaxation by unloading stress wave. In this chapter, using a thicker plate, effect of temperature gradient and crack length are investigated.

4.1 Steel used

Two kinds of steel, 50 and 80 mm thick, are used. Chemical compositions and mechanical properties are shown in Tables 5 and 6, respectively. Steel is manufactured by normalizing. Charpy impact values are met in EH grade requirement.

Table 5 Chemical compositions of steel used [mass%]

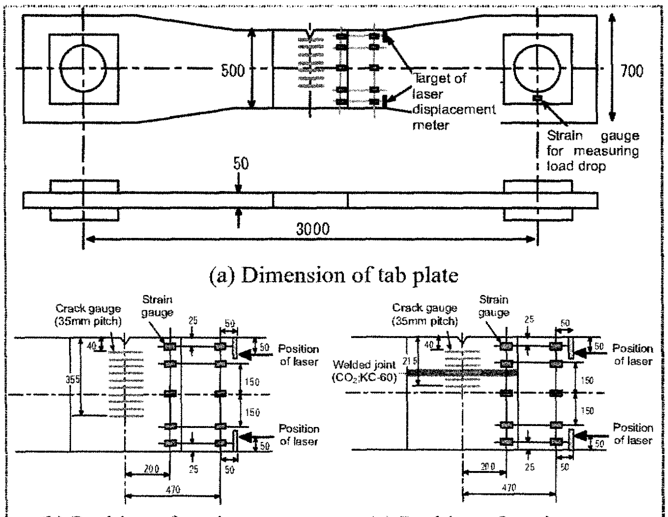
Steel	Thickness [mm]	Chemical compositions				
		C	Si	Mn	P	S
Norma-2	50	0.13	0.40	1.43	0.014	0.003
Norma-4	80	0.16	0.42	1.51	0.011	0.004

Table 6 Mechanical properties of steel used

Steel	Tensile property		Charpy impact property	
	YP [N/mm^2]	TS [N/mm^2]	vE-40 [J]	$vTrs$ [deg.C]
Norma-2	364	514	220	-72
Norma-4	366	532	161	-35

4.2 Testing conditions

ESSO tests were conducted at three different sites in Japan. Testing system and general of dynamic measurement are shown in Figs. 10 to 12, respectively. Testing conditions are shown in Table 7. The duplex ESSO test is also conducted for the condition of temperature gradient '0'. For easily propagation through the running plate and weld metal, suitable embrittled plate and welding consumables are applied for the construction of a duplex ESSO test.



(a) Dimension of tab plate

(b) Position of strain gauge (temperature gradient type)

(c) Position of strain gauge (duplex type)

Figure 10 Dimension of specimen and tab plate and position of dynamic measurement (site A)

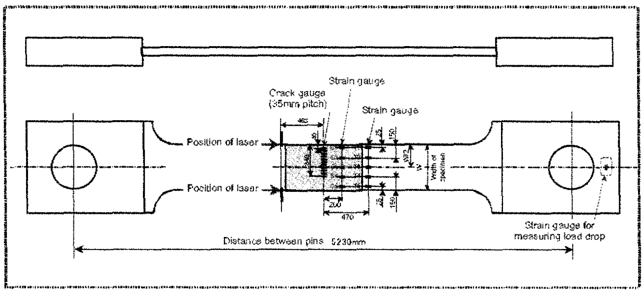
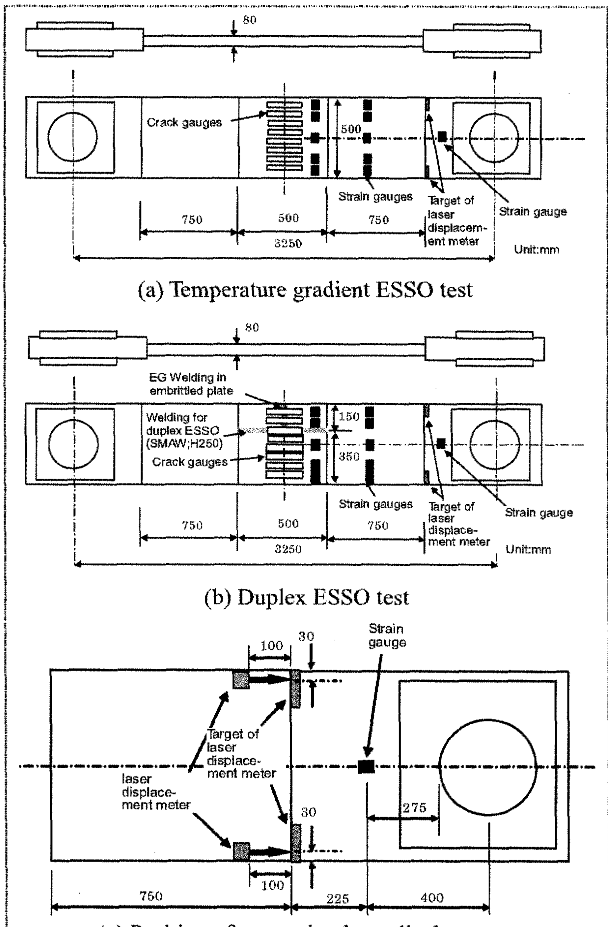


Figure 11 Dimension of specimen and tab plate and position of dynamic measurement (site B)



(a) Temperature gradient ESSO test

(b) Duplex ESSO test

(c) Position of measuring laser displacement and strain gauge in tab plate

Figure 12 Dimension of specimen and tab plate and position of dynamic measurement (site C)

4.3 Test results

Test results are shown in Table 7 and Figs. 13 to 14. K_{ca} values of steep temperature gradient conditions show a lower value than that of a gradual one in both Norma-2 and Norma-4. Also, K_{ca} values of 0.25 deg. C/mm condition and K_{ca} level estimated from results of the duplex test are almost the same. Considering that in an actual structure there is no temperature gradient, 0.50 deg. C/mm condition is too severe to evaluate K_{ca} value.

In order to investigate the effect of crack lengths, results of TM-N2-4 (arrested crack length=340 mm) and -5 (arrested crack length=170 mm) should be compared. These two plots are located on the almost the same line. This means that evaluation under the condition of crack length between these two lengths is constant and valid.

Table 7 Testing conditions and test results

Steel	Mark	Testing method	Testing site	Stress σ [N/mm^2]	Arrested crack length a [mm]	Temperature at arrested point T [deg.C]	K_{ca} [N/mm$^{3/2}$]	Temperature gradient dT/da [deg.C/mm]	Notes
Norma-2	TM-N2-1	Temperature gradient	A	98	238	-23	2984	0.25	
	TM-N2-2			147	271	-6	4967	0.25	
	TM-N2-3			294	228	6	8674	0.25	
	TM-N2-4			196	340	12	8359	0.25	Aiming length of crack:350 mm
	TM-N2-5			132	170	-20	3210	0.25	Aiming length of crack:150 mm
	TM-N2-6			98	273	-10	3332	0.50	
	TM-N2-7			196	255	10	6296	0.50	
	MD-N2-1	Duplex		147	Go	-20	-	0	
	MD-N2-2			123	No Go(203)	-20	2776	0	
Norma-4	TM-N4-1	Temperature gradient	B,C	156	306	19	5848	0.28	
	TM-N4-2			156	300	18	5788	0.26	
	TM-N4-3			120	313	15	4650	0.25	
	TM-N4-4			98	283	7	3440	0.25	
	TM-N4-5			83	311	10	3195	0.25	
	TM-N4-6			98	250	15	3099	0.50	
	TM-N4-7			156	248	25	4902	0.50	
	MD-N4-1	Duplex	C	180	No Go(217)	13	4063	0	
	MD-N4-2			216	No Go(272)	13	4876	0	Large amount of penetration in tested plate
	MD-N4-3			216	No Go(163)	13	4876	0	Pre-loading for residual stress relief

*If fracture surface has multiple arresting positions, first arresting point is identified as 'arrest'.

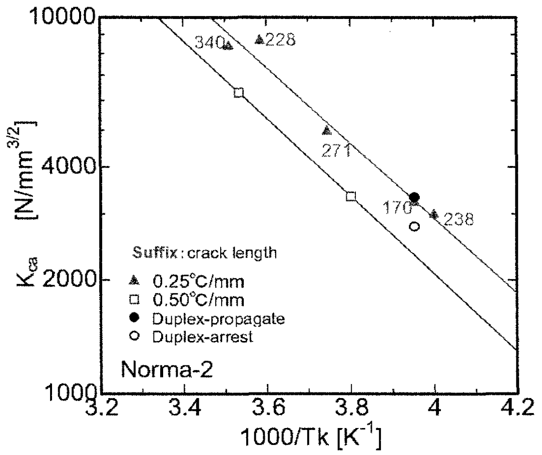


Figure 13 Effect of temperature gradient and crack length on K_{ca} evaluated by ESSO test (Norma-2)

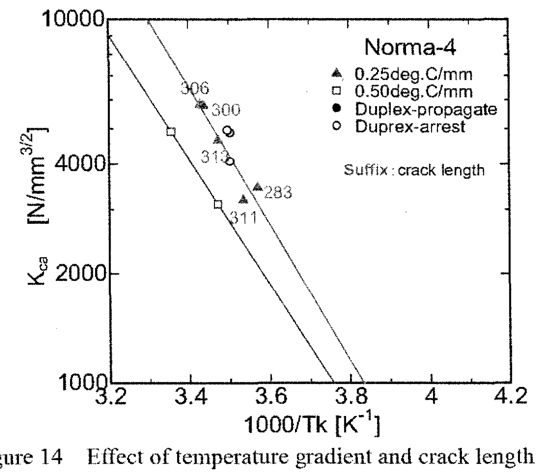


Figure 14 Effect of temperature gradient and crack length on K_{ca} evaluated by ESSO test (Norma-4)

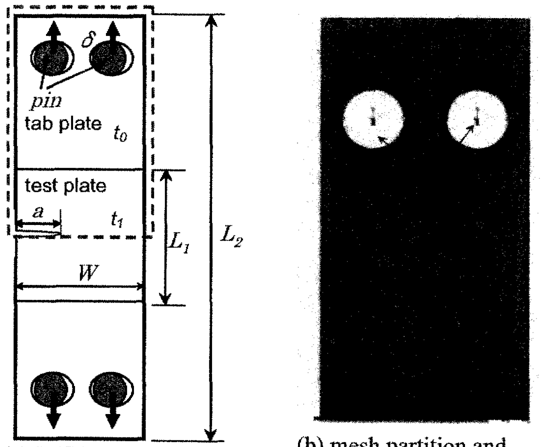
5. Numerical simulation for analysis of stress reflection at tab plate

In the previous chapter, the effects of the dimensions of tab plates on ESSO test results are shown by way of experiment. These effects are caused by stress wave transmission. In this chapter, findings obtained by the experiment are verified by using an analytical approach (details are described in Ando et al., 2009).

5.1 Analysis conditions

In order to simulate an ESSO test system of experiments using Norma-1 steel, a FE-model is created, as shown in Fig. 15. Other analytical conditions are summarized in Table 8. Crack propagation is simulated as the releasing of constraint around nodes arranged on a symmetric face (crack propagation path). By adjusting the rate of releasing of constraint of the nodes, crack velocity can be varied. In this investigation, three patterns of crack velocity are chosen, as shown in Fig. 16. 'V-change' is the schematic line based on typical actual crack velocity data. Generally crack velocity increases in the first step then decreases until arresting. Also constant the velocity conditions, 2000m/s and 1000m/s, are investigated for understanding the trend of effect on crack velocity. Driving force for brittle crack propagation is described as a stress intensity factor as well as an experimental result. K_d is calculated at each step by an average value of stress component during the step time at the position of r distance in front of the tip of the crack and Eq. (5).

$$\log \sigma_{yy} = -\frac{1}{2}\log(2\pi r) + \log K_d \tag{5}$$



(a) ESSO test system (b) mesh partition and boundary conditions

Figure 15 FEM analysis conditions (Actual Model)

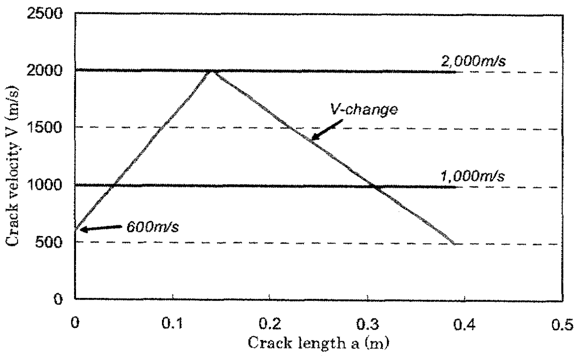


Figure 16 Crack velocity conditions assumed in FEM analysis

5.2 Analysis results

Transition of K_d under conditions of various thicknesses of a tab plate is shown in Fig. 17. In these figures, K_d of single-edge-notched tension panel (SENT: very long dimension for longitudinal direction and no consideration of stress reflection) and some kind of static stress intensity factors are also shown for comparison. The dotted line shows the result of SENT and solid line shows that of the actual ESSO test configuration (Actual Model). K, K_d and a are expressed as the non-dimensional parameters, $K/\sigma\sqrt{W}$, $K_d/\sigma\sqrt{W}$ and a/W. The K_d value of Actual Model is smaller than that of SENT at any crack velocity. According to the results of t_0=t_1=16 mm, there is no difference between different loading boundary conditions. That is, under a condition of 1.5 m of distance between pins, stress reflection does not affect K_d value. Therefore, in other tab plate thickness conditions, stress reflection at the boundary between specimen and tab plate affects a decrease of stress around the crack tip. Viewing 'V-change' condition, as crack velocity is smaller at large a/W region, K_d of the Actual Model becomes remarkably low. This is because when crack velocity is small, duration for crack running becomes longer and there is more stress reflection effect. In the case of the 50mm tab plate, the most notable decrease of K_d is recognized, that is, the decrease rate is 20~30 %.

These analytical results are in excellent agreement with experimental findings described in the previous chapter.

Table 8 FEM analysis conditions

Analysis solver	ABAQUS/standard, standard Implicit	
Integral method	Hilber-Hughes-Taylor method	
Elements	Element family	two-dimensional solid element
	Element type	plane strain ,8-node (,or 6-node) biquadratic, reduced integration Pin…analytical rigid surface
Parameter	Young's modulus	206 GPa
	Density	7.8×10^3 kg/m^3
	Poisson ratio	0.3
Mesh	Minimum mesh size	1.0 mm
	Element configuration	Crack propagation area… quadrilateral elements Another area… quadrilateral elements+ triangular elements

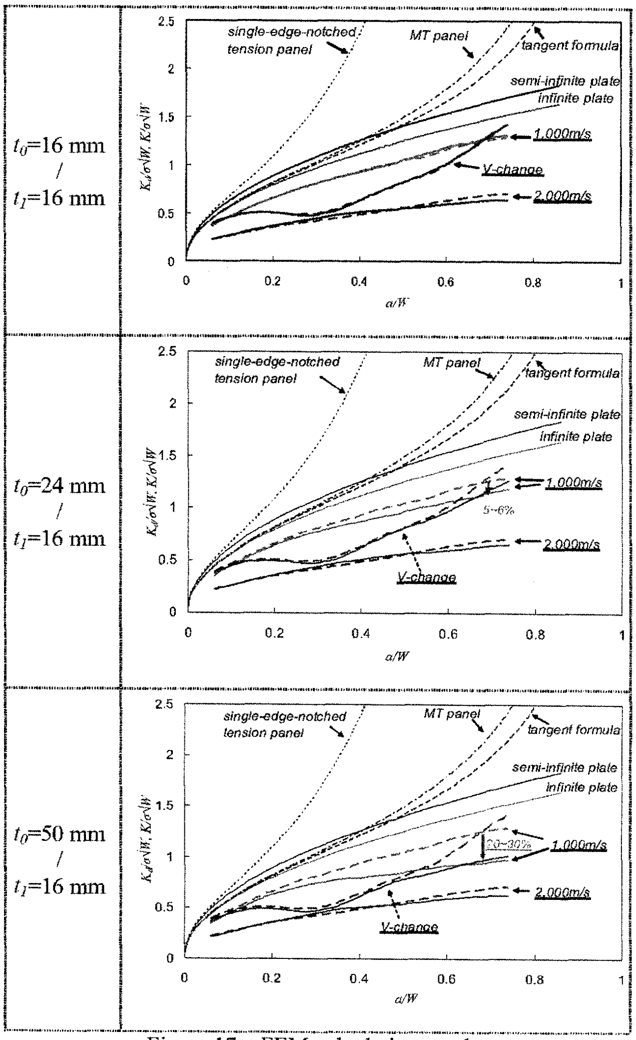


Figure 17 FEM calculation results

6. Establishment of brittle crack arrest toughness K_{ca} test method

ClassNK established the 'Guidelines on Brittle Crack Arrest Design' in September 2009. In this guideline, the 'Brittle Crack Arrest Toughness K_{ca} Test Method' is included as a standard evaluation method of arrest toughness. Major regulations specified in this guideline are shown in Fig. 18, which involves all experimental and analytical results of this time investigation.

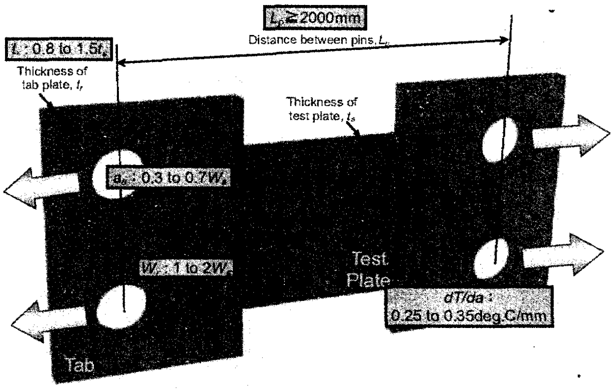


Figure18 Major requirement in "BRITTLE CRACK ARREST TOUGHNESS K_{ca} TEST METHOD"

7. CONCLUSIONS

In this report, with the goal of developing a standard ESSO test, the effects of testing conditions - that is, the thickness of tab plates, width of tab plates, distance between pins, temperature gradient and crack length - on the evaluated K_{ca} values are investigated. Investigation is based on many large scale crack arrest tests with 16, 50 and 80 mm thick low carbon steel plates conducted by four research groups in Japan.

Finally, taking the results of a numerical simulation of a dynamic FEM and each physical meaning into consideration, control ranges of such testing conditions were obtained as follows:

- To use a thicker tab plate than the test plate is qualitatively on the unsafe side of evaluation; however, up to a 1.5 times thicker tab plate than the test plate has little effect on the result.
- To use up to a 2 times wider tab plate than the width of test plate has little effect on the result.
- Short distance between pins tends to bring down load drop at the time of crack arrest, so distance between pins shall be more than 1500 mm for 350 mm of propagated crack length.
- Large amount of temperature gradient gives a smaller K_{ca} evaluation, with the gradient up to 0.25 deg. C/mm condition K_{ca} value nearly equal to that of duplex type test results (no temperature gradient type).

Obtained findings are involved in the newly established standard for evaluation of arrest toughness, 'Brittle Crack Arrest Toughness K_{ca} Test Method'.

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