Effect of Steel Toughness on Brittle Crack Arrest Behavior of T-weld Joint Structure Using Thick Plates

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Brittle crack arrest properties in ship construction have become more important as shipbuilding steel plates become thicker and stronger. There have been indications that steel toughness can have the effect of arresting brittle crack initiating in a welded joint; however the T-weld joints of an actual large structure have not been well investigated. This report describes how the brittle crack length and steel toughness were found to affect brittle crack arrest behavior. Furthermore, it was suggested that brittle crack could be arrested by using a horizontal plate of K_{ca} that would be sufficient even for the T-weld joint of an actual large structure.

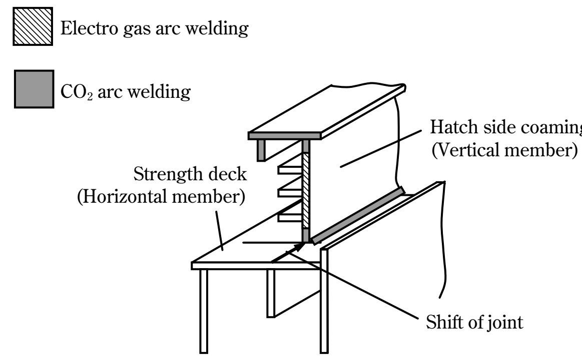


Fig. 1 Construction around hatch coaming

Introduction

The upsizing of container ships not only increases the allowable load and income per passage, but also decreases the number of crossings, which leads to the reduction of CO_2 emissions and contributes to the lessening of the environmental burden. The demand for marine transport is increasing with the recent rapid growth of East Asian economies such as that of China. This upsizing trend is more apparent for transport vessels such as container ships[1)].

A container ship has an upper deck provided with a large opening and employs ultra-thick plates for the longitudinal strength members of its hull. As the ships are upsized, they require steel plates that are stronger and thicker[2)]. According to an experimental result[1)], a brittle crack, initiated in a high-heat-input welded portion of a thick plate, propagates straight along the welded portion. This poses a challenge when adopting thick plates and joining them to hull structures by high-heat-input welding. To satisfy the recent upsizing requirement for container ships while assuring safety, brittle cracks must be arrested without fail before they propagate along the high-heat-input welded portions of thick plates.

As shown in **Fig. 1**, a container ship has an upper deck (strength deck), a hatch side coaming and a T-weld joint that connects the hatch side coaming (a part of the longitudinal stiffening member) with the upper deck. In this construction, a brittle crack propagating straight along a welded portion of the hatch side coaming can be arrested by the base material of the upper deck, if the base material has sufficiently high crack-arresting performance (brittle crack arrestability), and if the positions of welded joints are shifted away from each other in such a way that the crack collides directly with the base material of the deck. Several studies have been conducted on this possibility[3)-6)]. Studies conducted by the authors indicate that brittle cracks can be arrested by constructing the strength deck with a steel plate having a brittle crack arrestability (K_{ca}) exceeding a certain level[5), 6)]. These studies, however, have been conducted on small dimensional scales simulating the actual hull structure, leaving unclear the K_{ca} for steel plates that can arrest the long and large cracks that may occur in actual hull structures.

Hence, large specimens were prepared, each simulating a T joint between a hatch side coaming and strength deck. Brittle fracture tests were performed on these specimens while varying the specimen dimensions and the K_{ca} of the plate simulating the strength decks. The performance of arresting long and large brittle cracks was studied, as reported in this paper.

1. Testing procedure

1.1 Specimen shape

Three types of specimens (specimens 1 - 3, as shown in **Fig. 2** (a)-(c)) were prepared by welding steel plates having a thickness of 60mm. Each specimen had a horizontal member simulating a strength deck and a vertical member simulating a hatch side coaming. Full penetration welding was performed to join the vertical member with the horizontal member to simulate a T joint between a hatch side coaming and strength deck. Experiments

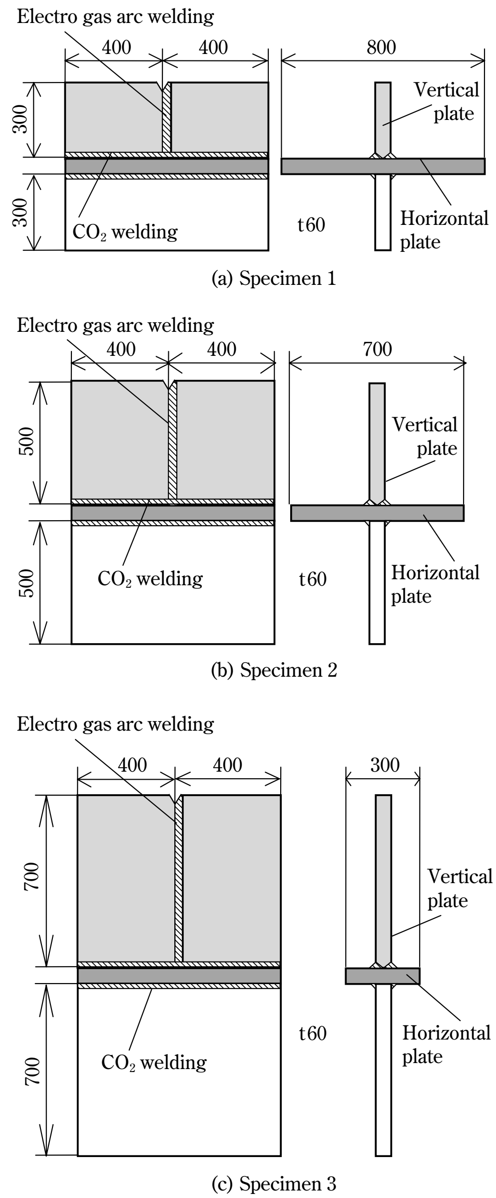


Fig. 2 Dimension of specimens (Unit：mm)

Table 1 Welding condition for specimen 1

Electro gas arc welding	Welding method	Electro gas arc welding
	Welding consumables	DWS-1LG/ ϕ 1.6mm, CO_2
	Welding conditions	Heat input：35kJ/mm
Full penetration welding	Welding method	CO_2 arc welding
	Welding consumables	DW-55E/ ϕ 1.2mm, CO_2
	Welding conditions	Welding current：190～236A Welding voltage ：23～29V Welding speed：18～60cm/min

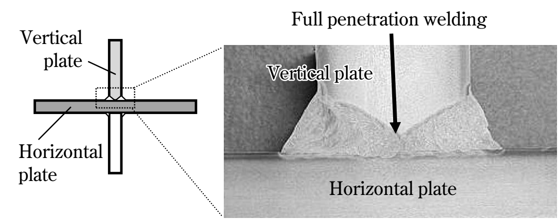


Fig. 3 Cross section of T-weld joint of specimen 1

Table 2 Steels used for the specimen (Steel A was used for vertical plate)

Specimen	Dimension of Specimen	Horizontal plate (Upper deck) K_{ca} at −10℃(N/mm$^{3/2}$) (Material)
1	Fig.2(a)	4,200(N/mm$^{3/2}$) (Steel B)
2−1	Fig.2(b)	
2−2		7,360(N/mm$^{3/2}$) (Steel C)
3	Fig.2(c)	

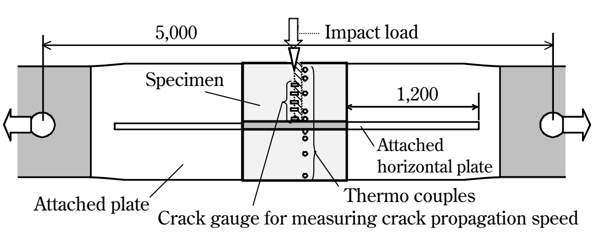


Fig. 4 Schematic illustration of experiment for T-weld specimen

were conducted on these three types of specimens, each having different dimensions, so as to study the effect of crack length reaching the horizontal plate. Each vertical member was made of two steel plates butt-welded by electrogas arc welding (EG welding). The vertical members were welded to the horizontal members by CO_2 welding with full penetration. **Table 1** summarizes the welding conditions, and **Fig. 3** shows a typical cross-sectional macro structure of the full-penetration welded joint.

1.2 Steel plates used for testing

The vertical member was made of the same steel (steel plate A) as reported previously (YS = 520MPa, TS = 619MPa)[6]. In this study, two types of steel plates (Steel plates B and C), having different K_{ca}, were used for horizontal members to study the effect of the K_{ca} values of the horizontal steel plates. The K_{ca} values at -10℃ of the steel plates B and C were 4,200N/mm$^{3/2}$ and 7,360N/mm$^{3/2}$, respectively. Steel plates B and C are both in the same strength class. **Table 2** shows the specimen numbers and the steel plates used for each specimen.

1.3 Testing method

A tensile testing machine with a maximum load of 30MN was used for the test. **Fig. 4** illustrates the testing method. A jig was disposed between the testing machine and a specimen to apply homogeneous stress to the specimen. The temperature of each specimen was monitored using thermocouples affixed to it at several locations. Each specimen was homogenized at a set temperature of -10℃ for more than 30 minutes before the test. The tensile load was controlled so as to make the average strain, determined by strain gauges affixed to several location of the horizontal plate, become 257MPa (i.e., the design stress of a strength deck).

Under the above conditions of temperature and loading, an impact load was applied to the notched portion on the top of each specimen to initiate a brittle crack.

In a case where the propagation rate of brittle crack is not high enough, the load applied to the specimen may decrease after the initiation of the brittle crack, which affects the test result. Therefore, an additional strain gauge affixed to the jig was used for this test, so that the load behavior after brittle crack initiation could be monitored by measuring the strain on the jig.

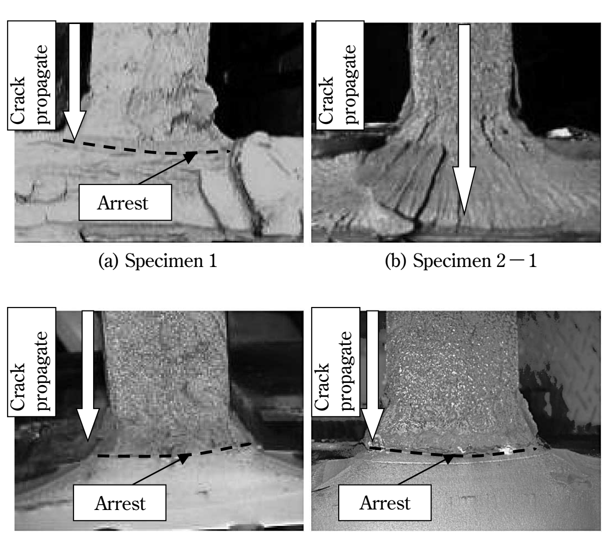
2. Test results

2.1 Brittle crack propagation behavior in vertical member

In all of the above tests, brittle cracks propagated along the EG weld portions immediately after the cracks were initiated. The crack propagation rate, immediately before the brittle cracks reached the T joint, was measured to be 500-700m/s. The strain gauges placed on the jig showed no load reduction that affected crack propagation.

2.2 Brittle crack arrest behavior of horizontal plate

Fig. 5 (a)-(d) shows the fracture surfaces after the tests. It should be noted that, in the case where the horizontal member did not break, it was ductile-fractured forcefully by applying a tensile load after the test.



(a) Specimen 1 (b) Specimen 2－1
(c) Specimen 2－2 (d) Specimen 3

Fig. 5 Test results (fracture surface)

In the case of Specimen 1 (vertical plate height (H)=300mm: horizontal plate, Steel plate B), the brittle crack propagated along the EG weld portion of the vertical plate and propagated further into the horizontal plate via the T joint portion, as shown in Fig. 5(a); however, the extent of the propagation was small compared with the thickness of plate B, showing that the brittle crack was arrested immediately after its propagation into steel plate B.

In the case of Specimen 2-1 (H = 500mm: horizontal plate, Steel plate B), the brittle crack propagated to the end of the horizontal member without being arrested (Fig. 5(b)).

In the case of Specimen 2-2 (H = 500mm: horizontal plate, Steel plate C), the brittle crack propagated about 6~8mm into Steel plate C via the T joint and was arrested (Fig. 5(c)).

In the case of Specimen 3 (H = 700mm, horizontal plate: Steel plate C), the brittle crack propagated about 6~8mm into Steel plate C via the T joint and was arrested (Fig. 5 (d)).

3. Factors affecting brittle crack arrest characteristics

3.1 Discussion on the effect of K_{ca} of steel plate for horizontal plates

Specimen 2-2 arrested the crack, unlike Specimen 2-1, despite the fact that they both have the same shape (H = 500mm). This is attributable to the K_{ca} of the horizontal steel plate of Specimen 2-2 being higher than that of Specimen 2-1. The K_{ca} of the horizontal steel plate significantly affects the brittle crack arrest characteristics at the T joint of the horizontal plate.

3.2 Discussion on the effect of specimen dimensions (brittle crack length)

3.2.1 Comparison of Specimens 1 and 2-1

The brittle crack propagated in Specimen 1 (H = 300mm) was arrested as soon as it collided with the horizontal plate. On the other hand, the brittle crack in Specimen 2-1 (H = 500mm) was not arrested, although its horizontal plate had the same K_{ca} as that of Specimen 1. The difference is considered to be due to the difference in the height H of the vertical plates. Specimen 2-1 had a vertical plate with a larger H, which made the stress intensity factor at the crack tip, K value, larger than that of Specimen 1 when the crack reaches the horizontal plate. The stress intensity factor exceeded the K_{ca} of the horizontal plate, causing the crack to propagate.

3.2.2 Comparison of specimens 2-2 and 3; possibility of arresting even longer and larger brittle crack

In the case of Specimen 3, the crack was arrested despite the fact that the crack, when it reached the horizontal plate, was longer than the crack in Specimen 2 - 2. This is considered to be caused by the K value at the crack tip still being smaller than the K_{ca} of the horizontal plate even under the conditions of the crack in Specimen 3.

According to Machida et al.[7], a rapidly propagating brittle crack suppresses the formation of a plastic region, making the K value almost constant for the increase of the crack length (a saturation phenomenon). If the K value of Specimen 3 is saturated, exhibiting the same saturation phenomenon, there should be no increase in the K value even for longer and larger cracks. If this is the case, cracks should be arrested by using Steel C for the horizontal member. The behavior of the crack in this saturation phenomenon in K value, however, has not been fully understood because of the difficulty in evaluating the K value at the tip of the brittle crack. This study attempts to evaluate this saturation behavior in K value of a brittle crack that propagates in a vertical member during the T joint test. Measurements were conducted using a strain gauge to discuss the characteristics required for a horizontal member arresting a long and large brittle crack.

4. Steel plate characteristics required for arresting long and large brittle cracks

4.1 Study on the saturation behavior of K value

To study the saturation behavior of K value during brittle crack propagation, a strain gauge is affixed in the vicinity of the weld portion (i.e., the crack propagation path) of Specimen 3 to evaluate the strain when the crack passes (**Fig. 6**). The strain distribution in the vicinity of a crack tip is considered to vary corresponding with the K value at the crack tip. So the behavior of the K value is discussed from the aspect of strain behavior.

Fig. 7 shows an example of the values measured by the strain gauge. Also included in this figure is the time period (evaluated by a crack gauge measurement) during which the brittle crack passed right beside the strain gauge. This figure indicates that the strain value reached a maximum immediately before the brittle crack passed right beside the strain gauge. This is considered to be caused by strain that is

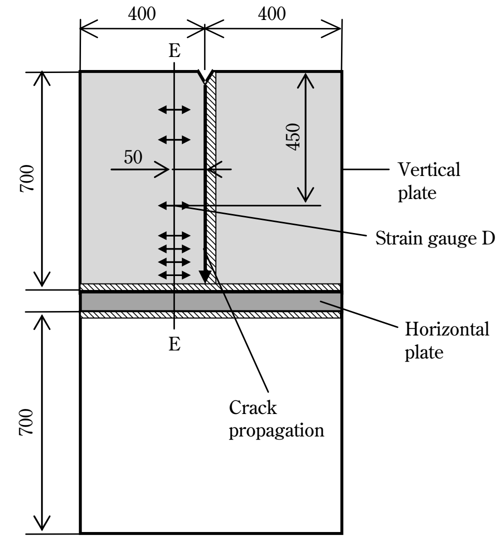


Fig. 6 Schematic illustration of strain gauge measurement along crack path

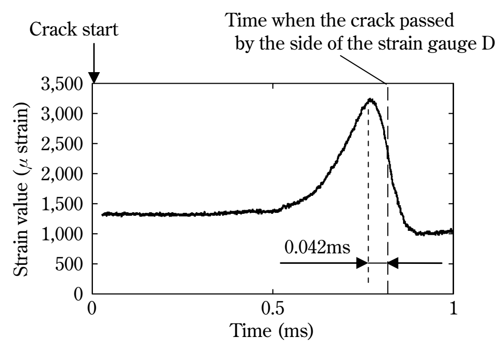


Fig. 7 Strain behavior of strain gauge D in Fig.6

higher diagonally in front, rather than right beside, the crack in the vicinity of a crack tip. As shown in Fig. 7, the difference between the time when the strain reached a maximum and the time when the crack passed right beside the strain gauge was about 0.042ms, which corresponds to a crack propagation length of 26.7mm, considering the crack propagation rate (636m/s for an equivalent crack length) measured simultaneously. The distance between the crack tip and the position where the strain maximizes is calculated, according to the linear fracture mechanics, to be 20mm in the crack propagation direction, assuming the positional relationship of this study (i.e., the strain measured at a point 50mm from the side of the crack path). This calculated value is essentially the same as the measurement result, verifying the validity of the evaluation, using strain measurement, of the strain distribution in the vicinity of a crack tip.

Here, the maximum strain value was first determined from the values measured by the strain gauges, then, the crack length which gives the maximum strain was estimated from the strain propagation rate to establish the relationship between the maximum strain and crack length.

4.2 Results of strain measurement

Fig. 8 shows the relationship between the maximum strain measured and the crack length. Fig. 8 shows a tendency for the maximum strain measured to become almost constant when the crack length exceeds about 500mm. Also shown is a phenomenon in which the strain drops rapidly at a point right before (about 50mm before) the crack reaches the horizontal plate.

These measured results were compared with a finite element method (FEM) analysis performed on Specimen 3. **Fig. 9** shows the analysis model. Here, a 1/2 (half) structure in z-direction was modeled using solid elements. The horizontal plate was divided into three elements, and the vertical plate into six elements, in the plate thickness direction. The adjacent area of the crack propagation was segmented with meshes as small as 5mm at the minimum, to improve the accuracy of the calculation. A model crack (crack length, 0-700mm: crack tip, linear) was introduced, penetrating the plate thickness at the upper end of the vertical plate.

It should be noted that brittle cracks propagate at high velocities (maximum 700m/s in Specimen 3), making the materials through which the cracks propagate deform very rapidly. As a result, the yield strength of the material surrounding a crack tip becomes very high due to the effect of strain rate dependence, and the crack opening becomes very small. To statically simulate this condition, in many cases the original single-edge cracked specimen is converted into a center-cracked specimen for elastic calculation. In this study, a static elastic analysis was conducted on the specimen converted into a center-cracked one with the symmetry boundary condition at the F portion in Fig. 9 (corresponding to the upper end of the specimen). This calculation assumes that a constant load is applied in the arrow direction at the end of the analysis model as shown in the figure, such that the nominal stress becomes 257MPa. The specimen length in the load direction was 5,000mm, which matches the distance between the loading points at the time of experiment illustrated in Fig 4. An analysis solver, ABAQUS6.5 [8], was used.

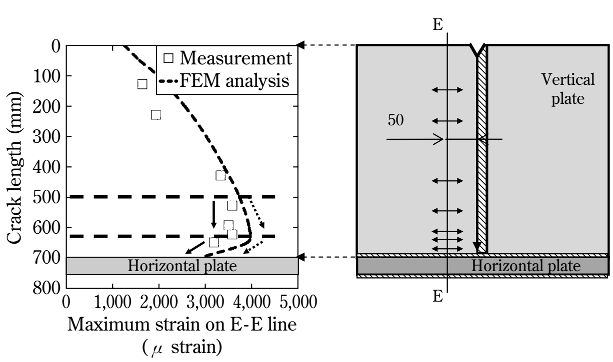


Fig. 8 Relationship between crack length and maximum strain on E-E line in Fig.6

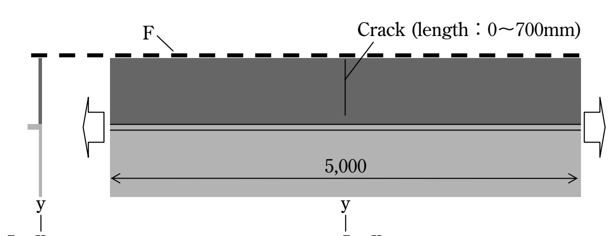


Fig. 9 FEM analysis model for specimen 3

The maximum values for strain in the x direction at each point / position corresponding to the location where a strain gauge was affixed (on the line E-E in Fig 6) were determined from the analysis result in order to examine their relationship with the crack length. The results are shown by the dashed line in Fig 8. As described previously, this study conducted a static elastic analysis for a high speed deformation behavior, and the analysis result did not quantitatively match the measured result. However, the analysis is considered to allow a qualitative comparison with the measured result. As shown in Fig. 8, the analysis result shows a rapid decrease in strain immediately before (about 50mm before) the crack reaches the horizontal plate, the same decrease as measured, indicating that the rigidity in front of the crack tip is increased by the horizontal plate. On the other hand, no strain saturation phenomenon, as observed in the actual experiment, exists in the simulated result in the crack length range of 500mm or longer.

The strain distribution at a crack tip is significantly affected not only by crack length, but also by the crack propagation rate. The strain saturation behavior observed in this study might also have been affected by the rapid crack propagation. To clarify the effect of the propagation rate of a brittle crack, the relation between the brittle crack propagation rate (measured by a crack gauge) and crack length in Specimen 3 is summarized in **Fig.10**. This figure indicates that a brittle crack longer than about 200mm propagates stably at a high rate of about 630-720m/s. In Fig. 8, the measured strain value becomes almost constant in the crack length range of about 500-620mm. In Fig.10, no significant change in the crack propagation rate is observed in the same crack length range, indicating no significant change occurring in the crack propagation behavior itself. In Fig.10, the crack propagation rate increases by about 50m/s for a crack length of 630mm, implying some effect on the periphery of the crack tip, however, no significant

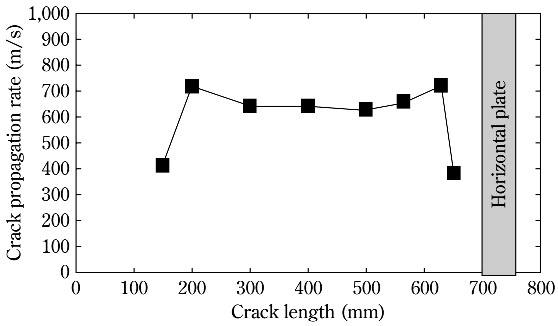


Fig.10 Relationship between brittle crack propagation rate and crack length

increase in the crack propagation rate is observed for the a crack length of 566mm. As shown in Fig. 8, strain saturation behavior is observed for a crack length of 500mm-620mm. The change in the crack propagation rate, observed in the same region in Fig.10, is not considered to affect the strain saturation behavior.

4.3 Saturation behavior of *K* value and the characteristics required for steel

From the previous results, it can be concluded that the strain saturation phenomenon observed in the actual measurements does not correlate with the change in the brittle crack propagation rate and has no link to brittle crack propagation behavior. Kinetic effect, which cannot be taken into account in FEM static elastic analysis, is considered to have affected the result. As described above, the strain distribution in the vicinity of a crack correlates well with the K value of the crack tip, and thus the K of the crack tip in Specimen 3 may also have been saturated. Assuming that this agrees with the above mentioned comment by Machida, K values will saturate to the same value for longer and larger cracks, meaning that brittle cracks can be arrested by using Steel plate C for the horizontal plate (e.g., strength deck) as in the case of Specimen 3.

Conclusions

A study was conducted using large joint specimens, each simulating a joint between a hatch side coaming and strength deck. The focus was put on the effect of the properties of a horizontal plate (simulating a strength deck) on the arrest characteristics of brittle cracks generated in the weld portion of a vertical plate (simulating a hatch side coaming), taking into account the size of the specimen.

The following describes the knowledge obtained:

- For the horizontal steel plate, K_{ca} and specimen dimension (brittle crack length) significantly affect the crack arrest performance. Steel C (K_{ca} = 7,360N/mm$^{3/2}$) exhibits crack arrest even for the largest specimen used in this study.
- A strain measurement conducted during the testing of Specimen 3 confirmed that the strain in the vicinity of a crack tip crack becomes saturated during crack propagation once the crack reaches a certain length.
- The strain in the vicinity of crack tip is considered to correlate with the K value. The brittle crack propagation test conducted on Specimen 3 indicates that the K value can possibly be saturated during crack propagation.
- From the above, cracks longer and larger than the ones studied this time can possibly be arrested by a horizontal plate (e.g., strength deck) made of a steel having adequate brittle crack arrest characteristics.

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