Overview of Japanese Joint Research Project on Safety-Related Issue of Extremely Thick Steel Plate Applied to Large Container Ships

Sumi, Yoichi
Department of Systems Design for Ocean-Space, Yokohama National University

Yajima, Hiroshi
Graduate School of Engineering, Nagasaki Institute of Applied Science

Toyosada, Masahiro
Kyushu University : Professor Emeritus

Yoshikawa, Takao
Department of Marine Systems Engineering, Kyushu University

他

Overview of Japanese Joint Research Project on Safety-Related Issue of Extremely Thick Steel Plate Applied to Large Container Ships

Yoichi Sumi[1)], Hiroshi Yajima[2)], Masahiro Toyosada[3)], Takao Yoshikawa[4)], Shuji Aihara[5)], Toshiyuki Matsumoto[6)], Kazuhiro Hirota[7)], Hideyuki Hirasawa[8)], Masanobu Toyoda[9)] and Koji Gotoh[4)]

[1)] Department of Systems Design for Ocean-Space, Yokohama National University, Yokohama, Japan
[2)] Graduate School of Engineering, Nagasaki Institute of Applied Science, Nagasaki, Japan
[3)] Professor Emeritus, Kyushu University, Fukuoka, Japan
[4)] Department of Marine Systems Engineering, Kyushu University, Fukuoka, Japan
[5)] Department of Systems Innovation, The University of Tokyo, Tokyo, Japan
[6)] Research Center, Nippon Kaiji Kyokai (ClassNK), Chiba, Japan
[7)] Ship & Ocean Engineering Department, Mitsubishi Heavy Industries, Ltd., Nagasaki, Japan
[8)] System Technology Development Center, Kawasaki Heavy Industries, Ltd., Kobe, Japan
[9)] Ship & Offshore Basic Design Department, IHI Marine United Inc., Tokyo, Japan

Abstract

A national joint research project, which is focusing on the safety-related issue of extremely thick steel plate applied to hull of large container ships, was conducted from April 2007 to March 2009 organized by the Japan Ship Technology Research Association (JSTRA) supported by the Japanese Government in collaboration with universities, research institute, classification societies and relevant industries including shipbuilding, steel manufacturing and shipping.

This project consisted of the three working groups of experts, whose tasks were 1) Study of the arrest design of brittle crack propagation, 2) Study of the fatigue crack growth from embedded flaws in butt welds and the consequent brittle crack initiation, 3) Study of the NDT technology for welding joints of extremely thick plates.

The joint research project made practical recommendations to prevent brittle fracture of hull in large container ships. Overview of the working group activities and the recommendations are presented in this paper.

Keywords

Large container ship; Extremely thick steel plate; Arrest design of brittle crack; Fatigue crack growth; NDT; Structural integrity;

Introduction

The brittle fracture in ship hull structures, which might lead to catastrophic failures, must be prevented as far as reasonably practicable. Recently, with the increase of the size of container ships, extremely thick steel plates have been applied to hatch side coaming, upper deck and other longitudinal structural members in order to maintain the structural integrity of such ships.

The current classification society rules for hull structures have been considered to be valid not only to prevent the brittle crack initiation but also to arrest the brittle crack propagation, regardless of the increase in steel plate thickness. However, a lot of recent researches concerning this issue have suggested the possibility that current classification society rules might not guarantee the structural integrity of the large container ships to which the extremely thick plates are applied.

A national joint research project focusing attention on the safety-related issue of extremely thick steel plate applied to hull of large container ships was conducted from April 2007 to March 2009 organized by the Japan Ship Technology Research Association (JSTRA) supported by the Japanese Government in collaboration with universities, research institute, classification societies and relevant industries including shipbuilding, steel manufacturing and shipping.

This project consisted of the three working groups of experts, whose tasks are as follows.

- Working group 1: Study of the arrest design of brittle crack propagation,

- Working group 2: Study of prevention of brittle crack initiation.

- Working group 3: Study of the NDT technology for welding joints of extremely thick plates.

The joint research project made practical recommendations to prevent brittle fracture in large container ships consisting of two main contents, that is to say;

1. Prevention of brittle crack initiation, which is the first important issue to prevent brittle fracture of hull, and
2. Arrest of brittle crack propagation, which is a backup measure in case of brittle crack initiation by chance.

Overview of the working group activities and the recommendations are presented in this paper.

Proposal of Effective and Practical Recommendations to Prevent Brittle Fracture Accidents

The project has proposed the recommendation for prevention of brittle fracture of large container ships based on the outcomes of the three working groups as described hereinafter, with the following fundamental ideas;

1. To prevent brittle crack initiation is the first important issue for the prevention of brittle fracture of hull
2. To arrest brittle crack propagation at proper locations is also important as a backup measure in case of brittle crack initiation by chance to avoid brittle fracture of hull

The recommendation suppose the ships service area to be North Pacific and service period to be 25 years on fatigue growth of embedded welding flaws, which can be considered to cover the wave-load histories of general large container ships.

On the initiation of brittle crack, the recommendation considers the maximum wave-load expected to be encountered by large container ships in North Atlantic during 25 years period.

To prevent brittle crack initiation, the recommendation proposes the following measures;

(1.) To control embedded flaws of welding joints of extremely thick steel plates by Ultrasonic Testing (UT) during ships construction and after in service in order to avoid the initiation of brittle crack resulting from fatigue growth of embedded welding flaws to the limit size.

(2.) To control quality of welding joints of extremely thick steel plates so that they are ensured sufficient brittle fracture toughness corresponding to the above UT control.

Adequate variations of measures are accepted in the recommendation under the consideration of differences from the above supposition of ships service areas and higher brittle fracture toughness than the expected. The recommendation shows some examples of these variations as optional measures.

To arrest brittle crack propagation at proper locations and to avoid large-scale brittle fracture of hull, which is called as brittle crack arrest design, the recommendation refers to Guidelines on Brittle Crack Arrest Design published by ClassNK in September 2009, which is based on the outcomes of the working group 1.

The Guidelines specifies the brittle crack arrest design by arranging steel plates with high brittle crack arrest toughness (K_{ca}) at proper locations giving the minimum K_{ca} for the arrest design. Furthermore fundamental procedure to verify the effect of structural discontinuity on the brittle crack arrestability is shown in the Guidelines.

The recommendation consists of the following contents.

1. Application of the recommendation
2. Prevention of brittle fracture of hull

   2.1 Prevention of brittle crack initiation

   - New ship (Ships to which the recommendation is applied during construction)
   - Existing ship (Ships to which the recommendation is not applied during construction)

   2.2 Arrest of brittle crack propagation (Brittle crack arrest design)
3. Construction details

The recommendation considers longitudinal strength members on the strength deck side with the thickness over 50mm as its targets. Special consideration is necessary in case of members' thickness over 75mm.

On the prevention of brittle crack initiation, the recommendation specifies the measures both during construction and after in service for new ships and measures after in service for existing ships as follows in order to confirm no considerable embedded welding flaws exist over the ships lives.

[for new ships]

1. During construction

(1.) Ultrasonic testing on all target butt welding joints (Length of detected flaw to be 25mm or less)

(2.) Brittle fracture toughness (K_c) of target welding joints to be 3,000 N/mm$^{3/2}$ or over (or equivalent toughness)

2. After in service

(1.) Ultrasonic testing on all target butt welding every 10 years

(2.) Visual inspection on target butt welding joints within 3 years intervals (as far as possible)

[for existing ships]

1. After in service

(1.) Ultrasonic testing on all target butt welding 10 years after delivery and every 5 years after that

(2.) Visual inspection on target butt welding joints within 3 years intervals (as far as possible)

Furthermore the recommendation shows the examples of variations considering the different service area from the supposed one or higher brittle fracture toughness than the expected as the following options.

Option 1: In case of higher brittle fracture toughness (K_c ≥5,000 N/mm$^{3/2}$)

Option 2: In case of the service area being exclusively between Europe and Asia

Option 3: In case of the service area being exclusively North Atlantic

On the construction details, the recommendation proposes the butt joint shift on Hatch side coaming joints and Upper deck joints with proper distance or equivalent structure design to the butt joint shift.

Outline of Working Groups Achievements

Working Group 1

The tasks assigned to Working Group1 are the study of arresting of brittle crack propagation and the development of brittle crack arrest design. The tasks were conducted by the Brittle Crack Arrest Design Committee organized by ClassNK (Yamaguchi et al., 2010).

In this regard, previous research concluded that brittle cracks propagate along the welded joint deviate into the base plate due to effects such as weld residual stress and that brittle crack arrest toughness K_{ca} for arresting the propagation of long brittle cracks is at least 4,000 to 6,000 N/mm$^{3/2}$ at the service temperature. These were based on test results for the roughly 35 mm thick steel plates that were used on large ships at that time. However, recent research has shown that for extremely thick steel plates, previous research results related to preventing propagation of brittle cracks is not directly applicable. Fig.1 shows a summary of the results of recent large-scale crack arrest tests on extremely thick steel plates compared with the general understanding of brittle crack arrestability of roughly 35 mm thick steel plates obtained by previous research.

In development of brittle crack arrest design, a steel plate with required brittle crack arrest toughness K_{ca} must be selected. At this moment, temperature gradient type ESSO test is the most popular method for the determination of material brittle crack arrest toughness K_{ca}. However, up until now there has not been either an established code or standardized test method.

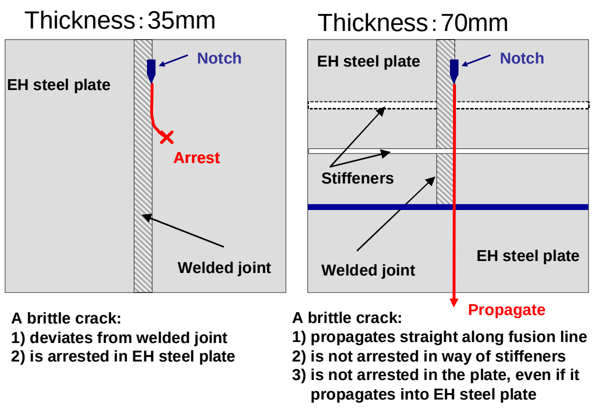


Fig. 1: Summary of brittle crack arrest test results.

Based on the above understanding, the following research was conducted in order to achieve the aim.

1. Development of a minimum brittle crack arrest toughness K_{ca} to arrest brittle cracks in hull structures containing extremely thick steel plates.
2. Development of an appropriate countermeasure for the straight propagation of brittle cracks in welded joints.
3. Development of an efficient test method to evaluate brittle crack arrest toughness K_{ca} of extremely thick steel plates.

The objectives of brittle crack arrest design are to arrest a brittle crack at specific locations so that large-scale failure of the hull structure is prevented in the event of an unexpected crack initiation. For this objective, functional requirements were defined as follows;

1. Brittle crack should be arrested at specific locations.
2. Hull girder stress after the arrest should be less than specified yield point of the applied steel plates.
3. Consequently, a brittle crack initiation should not result in large-scale failure of the hull structure.

In order to achieve this objective and fulfill these functional requirements, the basic concept of arrest design should be to ensure that the 'material resistance to brittle crack propagation' is larger than the 'driving force causing brittle crack propagation.' Qualitatively, the following methods may be considered;

(a) Arrange materials so as to have a large resistance to brittle crack propagation, and arrest brittle cracks that penetrate the material. (Material arrest)

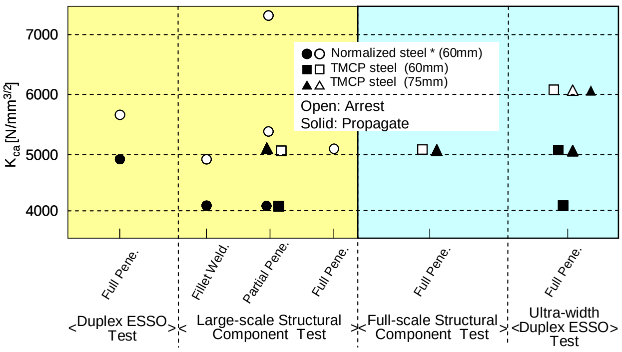
(b) Eliminate continuity of the crack propagation route. (Structural arrest)

(c) Use combination of (a) and (b), i.e. if the driving force can be reduced by structural discontinuity, the brittle crack can be arrested even with reduced material resistance.

In consideration of brittle crack propagation in the joints of the hatch side coaming and the strength deck of large container carriers, arresting a crack in the fillet welded structural part could be expected to yield the combined effects of (a) and (b) above, i.e. (c).

For Development of minimum brittle crack arrest toughness K_{ca}, three kinds of large-scale crack arrest tests were conducted. Firstly, the ultra-wide duplex ESSO tests were conducted for evaluating the K_{ca} required for arresting brittle crack using only the material resistance. This test can be interpreted as a more conservative test than using actual components, because the test piece does not have any large structural discontinuities. Further, in order to understand the effects of structural discontinuity, the large-scale structural component model tests were also conducted. Finally, the full-scale structural component tests were conducted as an evaluation test for simulating the actual structure of a large container ship. The test specimens for the large-scale structural component model tests and the full-scale structural component tests were prepared such that the ends of the hatch side coaming under the butt welded part penetrated the strength deck, similar to the conditions found on actual ships. Applied stress of all tests is hull girder stress.

Fig.2 is a summary of the results of these tests. Brittle crack toughness K_{ca} 6,000 N/mm $^{3/2}$ is considered to be an upper limit for crack propagation in the ultra-wide duplex ESSO tests which evaluate the K_{ca} without considering structural discontinuity. Further, the effectiveness of structural discontinuity was confirmed in the result of duplex test and large-scale structural component test shown in yellow. Therefore, in case of considering the structural discontinuity of actual structures, that value is considered to be safety side for arresting brittle crack and was established as the minimum requirement for typical brittle crack arrest design.



Note : * Test specimen of Normalized steel is heated in order to make its K_{ca} value comparable to that of TMCP steels.

Fig. 2: Test results of large-scale crack arrest tests.

For development of an appropriate countermeasure for the straight propagation of brittle cracks in welded joints, a weld line shift as shown in Fig.3 is the most reliable and practicable measure in present shipbuilding. The butt weld joint of the structural member in which the crack has propagated and the butt welded joint of the structural member which the crack will penetrate should be separated by more than a set distance so that the propagated brittle crack penetrates the base plate. Fig.4 shows an example of a numerical analysis of the brittle crack propagation route conducted under various conditions (Yoshinari, et al., 2009). In this project, 300 mm was in general used as the required weld line shift. This value is on the safe side that encompasses various crack propagation modes, and, therefore, was set as a basic requirement of the guideline.

For development of an efficient test method to evaluate brittle crack arrest toughness K_{ca} of extremely thick steel plates, 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} value were also investigated. Based on these results, a test method that enabled common test results even for different test laboratories was developed. Fig.5 shows the outline of newly developed test method "Brittle crack arrest toughness K_{ca} test method".

These findings of the Committee were summarized in the ClassNK "Guidelines on Brittle Crack Arrest Design" shown in Figs.6 and 7 (Nippon Kaiji Kyokai, 2009). These developed guidelines are the first in the world to set forth clear functional requirements for brittle crack arrest design. The ClassNK and representatives from industries continue the research project to study and investigate issues related to extremely thick plates in large container ships, and are planning to further develop the content of these guidelines, including the development of more rational arrest design by quantitative assessment of structural discontinuities, as well as an assessment method for brittle crack toughness value using smaller scale tests.

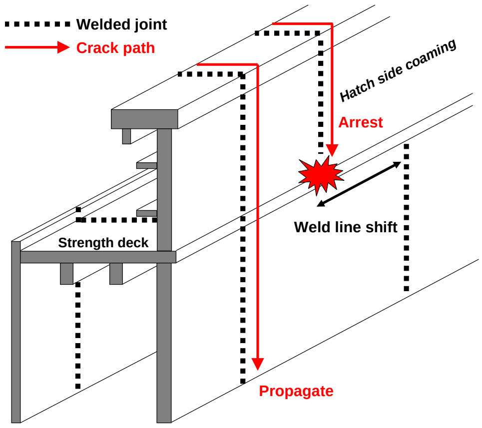


Fig. 3: Concept of weld line shift.

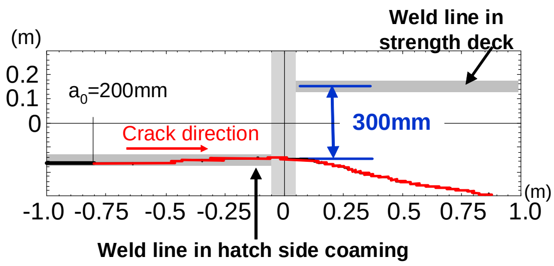


Fig. 4: Example of numerical analysis of the brittle crack propagation route.

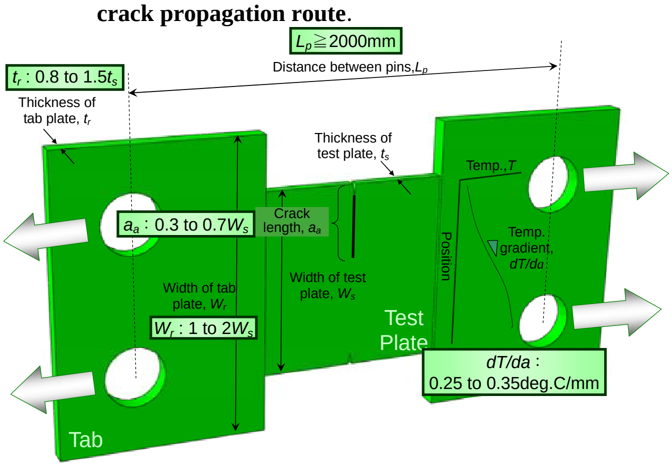


Fig. 5: Major regulations in "brittle crack arrest toughness Kca test method".

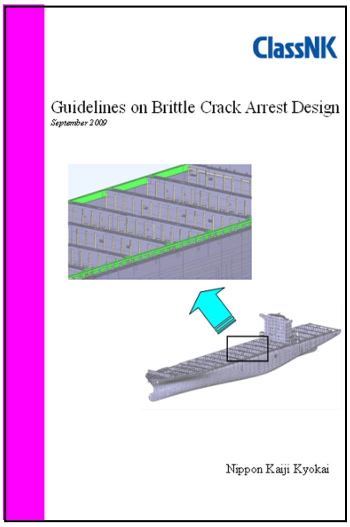


Fig.6: Guidelines on brittle crack arrest design.

Chapter.1 General
1.1 Objectives of brittle crack arrest design
1.2 Applicability
Chapter.2 Basic requirements of brittle crack arrest design
2.1 Functional requirements
2.2 Butt joint shift
Chapter.3 Typical brittle crack arrest designs
3.1 Design against brittle crack initiation in the hatch side coaming
3.2 Design against brittle crack initiation in the strength deck
Chapter.4 Designs other than typical brittle crack arrest design

Annex A Brittle crack arrest toughness K_{ca} test method
Annex B Example of procedure to verify a brittle crack arrest design

Fig.7: Contents of the guideline on brittle crack arrest design

Working Group 2

The tasks assigned to Working Group 2 are the study of prevention of brittle crack initiation. The following research was conducted in order to achieve the aim.

1. Growth analysis of fatigue crack initiated from an embedded initial defect in the butt weld joint of the hatch side coaming.
2. Identification of the critical crack size to prevent the brittle fracture accident in a butt weld joint of the large container ships to which the extremely thick plates are applied.

Initial size of an embedded defect for the fatigue crack growth analysis is assumed by considering the detectability of nondestructive testing which is commonly applied to the hull construction stages.

Numerical fatigue crack growth simulation code FLARP (Toyosada et al., 2004a, 2004b) is applied in order to properly take into account of the loading history effect on the fatigue crack growth behavior. Besides, a practical estimation method of the shape evolution of an embedded defect under fatigue loading is studied.

Preliminary analyses of fatigue crack growth were performed for 12 large container ships, which were selected from the in service built by Japanese shipyards. Based on the results of these preliminary analyses, the representative ship for detailed examination was nominated. Particulars of the subject ship are shown in Table 1.

Table 1: Particulars of the investigated ship

TEU	4200
Steel grade	EH36
Plate thickness of hatch side coaming	50 mm
Still water bending stress	85 MPa
Sagging bending stress	-153 MPa
Hogging bending stress	130 MPa
Working stress range	283 MPa

The following three shipping routes, which are 1) Asia - Europe route, 2) North Pacific route and 3) North Atlantic route, were selected to evaluate the fatigue crack growth. The selections of the routes were based on the actual service records of large container ships and IACS unified rules. Calculation conditions for fatigue crack growth analyses were assumed by considering the long-term prediction of the wave height and the bending moment at mid-ship section for each service route based on wave statistics. The probabilistic distribution of the stress range was assumed as the Weibull distribution. The elastic vibration effect such as whipping on the fatigue crack growth was ignored in these analyses.

Loading histories for each service route were assumed form a practical point of view, because the loading history has significant influence on the fatigue crack growth behavior. Stress range frequency for each shipping route are divided into the 600 same clustered segments like the storm model (Tomita et al., 1992) and they are repeated during the design lifetime. This treatment is in accordance with the method adopted in the research project by JASNAOE (2007).
At the same time, the effect of loading sequence for fatigue crack growth is investigated by using the storm model based random sequence of clusterd loadings with the mean stress 112MPa and the maximum stress range 262 MPa. The Weibull shape parameter of stress range frequency distribution is assumed as 1.0. Two types of fatigue crack growth model are applied. The one is based on the RPG concept (Toyosada et al., 2004a) to properly simulate the detailed mechanical behavior of the plastic wake during the randomly repeated clusterd loading cycles, while the other is the conventional method based on the modified Paris-Elber's law with the use of Kato's equation (Kato et al., 1983)
An initial embedded crack is located in the middle of plate thickness. Crack depth, width and plate thickness are assumed as 10mm, 50mm and 80mm, respectively.

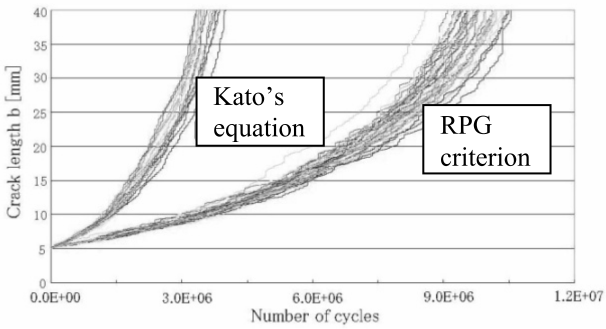
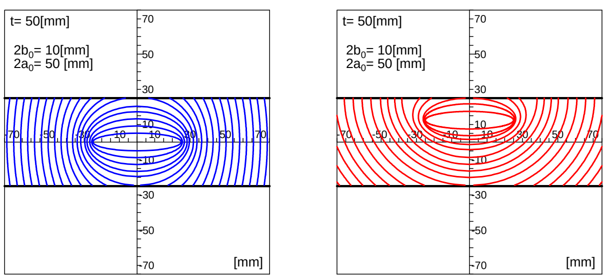


Fig. 8: Fatigue crack growth curves under various loading histories.

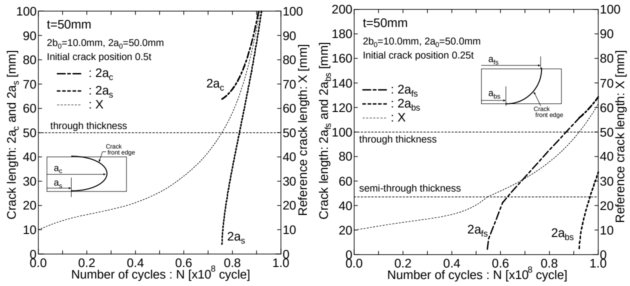
The conventional method gives shorter life than those predicted by the RPG criterion, because the former does not properly take into account of the retardation after a high level of loading. It is interesting to note that the both methods give almost the same crack growth histories when the applied stress range is monotonically increased, that is no retardation effect. Although the standard deviation of lives obtained by RPG criterion is about 2.0-5.9 times larger than those calculated by the conventional method, the coefficient of variance of the curves by RPG criterion is less than 10%. It may be concluded that the scatter of the crack propagation life is not so significant in the present problem. It should also be noted that if the total loading spectrum is divided into 93 clustered loading with the same loading pattern, the result shows a slightly conservative side to those for the random sequence of clustered loading.

In order to investigate the location of an initial embedded defect, we shall consider the two cases, where the center of initial defects locate at 0.5*t* and 0.25*t* (*t*; plate thickness), respectively. Estimated fatigue crack shape evolutions and fatigue crack growth curves are shown in Figs.9 and 10, in which the estimation procedure of an embedded crack shape evolution is established in this research project. Fatigue crack growth analyses are carried out based on the previous work (Toyosada et al., 2004b). From the calculated results, it is clear that the fatigue life at the time of penetration through the thickness is shorter for the condition of initial defect location at 0.5*t* than that at 0.25*t*. Therefore, the initial embedded defects are assumed to locate at 0.5*t* in the following investigations.



a) Initial defect location: 0.5*t* b) Initial defect location: 0.25*t*

Fig.9: Estimated fatigue crack shape evolutions.



a) Initial defect location: 0.5*t* b) Initial defect location: 0.25*t*

Fig. 10: Fatigue crack growth curves.

An allowable initial defect sizes is investigated by choosing various initial defect sizes. The penetration of a crack through the thickness of a plate is considered as a critical condition for the integrity of welded joints. Aspect ratio (crack depth / crack width) of an initial defect is assumed to be 0.2 from experiences of non-destructive testing in hull construction and also from the safety point of view. Fig.10 shows the fatigue crack growth curve of each initial defect condition. In the following figures, the reference crack length means either 1) half crack depth for embedded cracks, or 2) half crack length for through-the-thickness cracks.

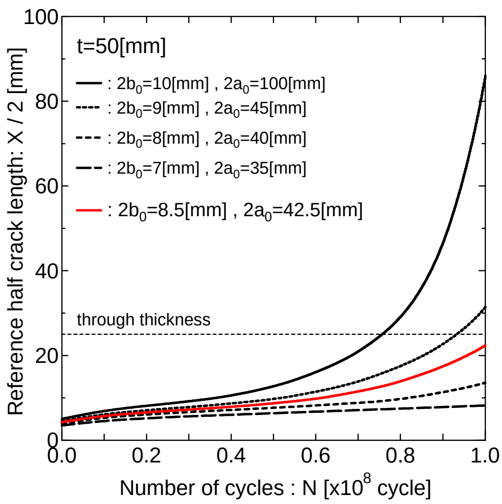


Fig. 11: Fatigue crack growth curves for a container ship with various sizes of initial embedded defects.

From this calculation, we can conclude that the maximum allowable defect size is depth, 8.5mm and width, 42.5mm.

Fig.11 shows the stress intensity factor (K^*) under the maximum design stress combined with the welding residual stress as a function of the reference crack length. The maximum design stress in this research corresponds to the one for high tensile steels of yield strength 400MPa-class. The stress intensity factor, K^*, of the maximum allowable defect attains approximately 2,700N/$mm^{1.5}$ at the penetration.

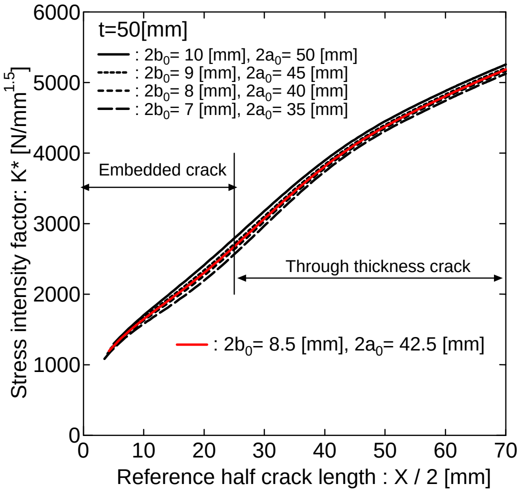


Fig.12: Stress intensity factor under the maximum design stress with the welding residual stress.

Based on the numerical simulations of fatigue crack growth and fracture toughness (K_c) evaluation, working group 2 proposes the following procedures for the prevention of brittle fracture in weld during hull construction and in-service inspection.

1) Hull construction stages.

Fracture toughness (K_c) for a representative welded joint with a fatigue crack, which plate thickness is more than 50mm and applied to large container ships in Japanese shipyards, is more than 4,000 N/mm$^{1.5}$ at -10 Celsius. On the other hand, the required fracture toughness is estimated about 3,000 N/mm$^{1.5}$ by applying the correlation between Charpy energy and K_c value for the plate thickness less than 50mm. It is concluded that the required K_c value for the welded joints must keep higher than 3,000 N/mm$^{1.5}$. To achieve this requirement, allowable initial embedded defect size is lower than 8.5mm depth and 42.5mm width.

2) In-servicer condition

It is expected that the standard quality control procedure of the welded joints in hull structures enables to prevent the fatigue crack growth more than 30 mm depth during 10 years of in-service, because few fatigue crack growth from an embedded crack in welded joints are reported for the merchant ships with hull plate thickness less than 30mm. By considering such practical situations, fatigue crack growth simulations listed below are performed.

- Initial defect: a circle with diameter 30mm located at the midpoint of plate thickness
- Plate thickness: 50mm, 65mm and 80mm
- Shipping route: North pacific

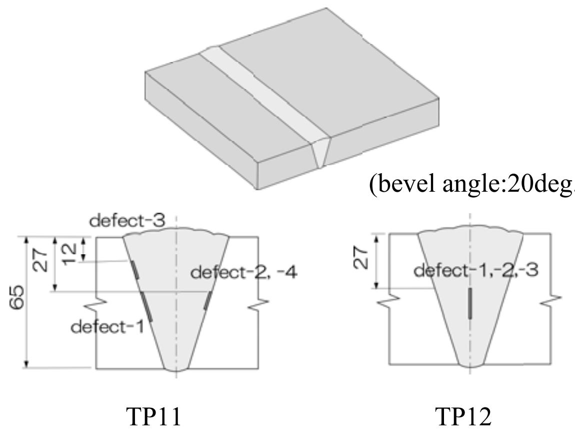
These numerical simulations make clear that it takes more than 10 years that K^* values exceed 3,000N/mm$^{1.5}$. Therefore, the possibility of brittle fracture accident at welded joints is low, if nondestructive tests are performed for the intended butt weld joints in every 10 years and eliminate the defects which the axis length is larger than 30mm.

More serious navigational condition such as encountering heavy storms is also considered to establish the allowable initial defect size.

Working Group 3

Ultrasonic testing (UT) is considered the most effective inspection method of internal defect in the extremely thick plate for practical purposes, but it had not been well discussed the detectablility and the accuracy of smaller internal defect size as mentioned above, especially in practical construction stage. Therefore the authors investigated the detectability and measuring performance among UT techniques using test specimens of thick plate having internal artificial defects in welded joints.

The experiment was carried out by six shipyards in Japan, using test specimens having internal artificial defects. The test specimens (TP11 and TP12) are shown in Fig.13. Their material is EH40 and thickness is 65 mm. The test specimens were made by semiautomatic CO_2 welding, and the artificial defects were processed by electro-discharge machining in weld layers. The defect dimensions are 5 mm - 15 mm in height and 20 mm - 45 mm in length. After the UT experiment, the defect dimensions were confirmed by radiographic testing and cross- section observation.



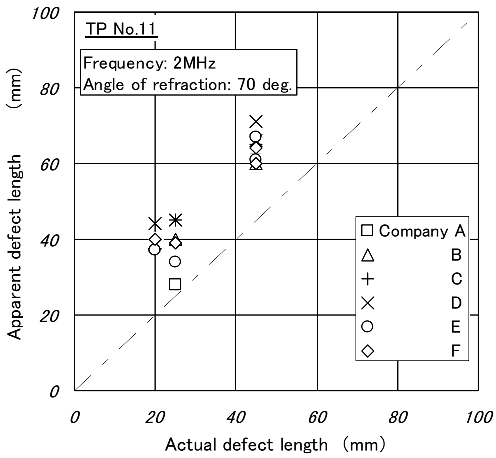
(defect height:5-15 mm , defect length:20-45 mm)

Fig. 13: Geometry of test specimens.

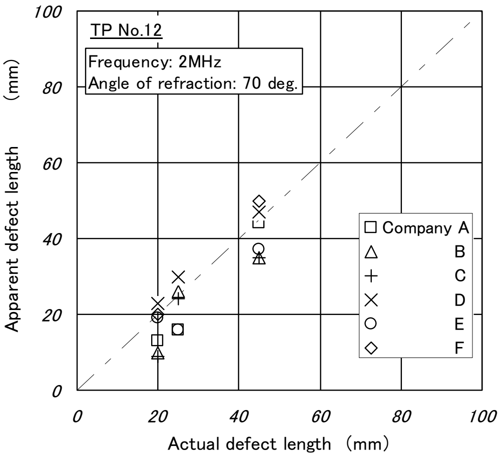
The experiment of detectability was carried out by L-disregard level method in accordance with JIS Z 3060 (2002), and the defect length measuring was done by two methods; L-disregard level method and 6dB-drop method. The test frequency of the probe was 2 MHz and 5 MHz, and the refraction angle was 70 degrees.

The measurement of the defect height was carried out by tip echo technique. The refraction angle of the probe was 45 degrees. Scanning surface and test direction were decided beforehand.

The results of detectability experiment by each shipyard show that they are not so different in the location of defect detected and that the echo amplitude from the defect of TP11 in which the ultrasonic wave is perpendicularly incident on the defect surface is higher than that of TP12 having defects in the thickness direction. In addition, a significant difference was not found in the SN ratio between the frequencies 5 MHz and 2 MHz of the probe. For detecting comparatively large defects, it was confirmed that there is not any significant difference between the probes of 5 MHz and 2 MHz.



(a) TP 11



(b) TP12

Fig. 14: Results of defect length measurement by L-disregard level method.

Example of the results of defect length measurement by the L-disregard level method is shown in Fig.14. From the results by TP11 in which ultrasonic wave is perpendicularly incident on the defect surface, it is seen that either of the evaluated defect lengths with 2 MHz and 5 MHz is conservative enough, and the results by TP12 having an internal artificial defect in the thickness direction show smaller values than TP11.

Table 2: Percentage of underestimating defect length by L-disregard level method.

TP	Frequency	5mm (%)	10mm (%)
11	2MHz	0	0
	5MHz	0	0
12	2MHz	33	17
	5MHz	17	6

Table 2 shows "percentage of underestimating 5 mm or more and 10 mm and more" ("the number of underestimations from 5 mm or 10mm" / "the number of all measurements" x 100 (%)). There was no underestimation tendency in either case of 5 MHz and 2 MHz in TP11, but the percentage of underestimating by 5 MHz was smaller than 2 MHz in TP12. For TP12, 2 MHz is considered harder to underestimate than 5 MHz in the aspect of reflection directivity because it has an artificial internal defects in the thickness direction and the ultrasonic wave is not perpendicularly incident on the defect surface. Which probe is superior cannot be judged here, and further investigation is necessary by such as increasing the number of tests.

Table 3: Percentage of underestimating defect length by 6dB-drop method.

TP	Frequency	5 mm (%)	10 mm (%)
11	2 MHz	10	0
	5 MHz	20	0
12	2 MHz	7	7
	5 MHz	20	20

The percentage of underestimating by 6dB-drop method is shown in Table 3. It is seen that the percentage of underestimating by 2 MHz is lower than 5 MHz. This is because the defect length was overestimated as the directionality is dull and the beam diameter is large in case of 2 MHz. Thus, when applying the 6dB-drop method to measure the defect length, it is considered possible to lower the underestimation possibility by using the probe of 2 MHz.

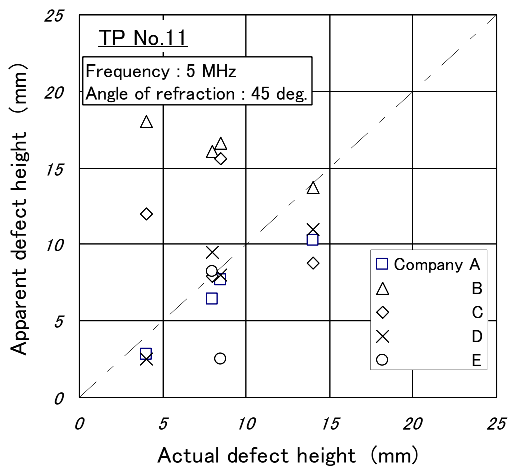


Fig.15: Results of defect height measurement by tip echo technique.

The results of defect height measurement are shown in Fig.15. The measured values are different among the shipyards. To grasp the tendency of underestimation, the percentage of underestimating where the defect height measured by the tip echo technique is underestimated by 2.5 mm or more and 5 mm or more are shown in Table 4. In addition, the percentage of detecting tip echo ("the number of detecting tip echo " / "the number of all measurements" x 100 (%)) is shown in Table 5. It is apparent that the percentage of detecting tip echo by 5

MHz is high in either TP11 or TP12. That is, while either 2 MHz or 5 MHz is applicable to the defect height measurement by the tip echo technique, the percentage of detecting tip echo can be raised by the use of the probe of 5 MHz than 2 MHz.

Table 4: Percentage of underestimating of defect height by tip echo technique.

TP	Frequency	2.5 mm (%)	5 mm (%)
11	2 MHz	14	0
	5 MHz	11	0
12	2 MHz	0	0
	5 MHz	7	0

Table 5: Percentage of detecting tip echo of defect.

TP	Frequency	Percentage of detecting (%)
11	2 MHz	47
	5 MHz	75
12	2 MHz	33
	5 MHz	81

The detectability and measuring performance of UT was investigated, using test specimens having various kinds of artificial internal defects. The material of test specimen is EH40, thickness is 65 mm and the defects dimensions are 5 mm - 15 mm in height and 20 mm - 45 mm in length. The results are as follows:

- It is confirmed that there is not any significant difference between the probes of 5 MHz and 2 MHz in detecting comparatively large defects.
- When applying the L-disregard level method to measure the defect length, there is case of underestimatation.
- When applying the 6dB-drop method, it is considered possible to lower the underestimation possibility by using the probe of 2 MHz.
- The percentage of detecting tip echo of defect can be raised by using the probe of 5 MHz, while either 2 MHz or 5 MHz is applicable to the defect height measurement by the tip echo technique.

Since the number of test specimens and the number of shipyards participating in this investigation are limited, it is considered difficult to discuss the probability of detecting a defect larger than allowable dimensions to prevent brittle fracture. It is necessary to accumulate data of defect measurement accuracy.

Conclusions

Overview of Japanese joint research project, which is focusing on the safety-related issue of extremely thick steel plate applied to hull of large container ships, is presented in this paper. The joint research project made effective and practical recommendations to prevent brittle fracture accidents in large container ships.

The authors believe the proposed recommendation will contribute to ensuring the structural integrity of ultra large container ships.

Acknowledgement

This research owes much to the thoughtful and helpful activities of the experts from National Maritime Research Institute (NMRI), industry including shipbuilding, steel manufacturing and shipping in Japan and leading members of International Association of Classification Societies (IACS).

This research was carried out under the sponsorship of Ministry of Land, Infrastructure, Transport and Tourism (MLIT), National Maritime Research Institute (NMRI), The Shipbuilders' Association of Japan (SAJ), The Japan Iron and Steel Federation (JISF), Nippon Kaiji Kyokai (ClassNK) and Japan Ship Technology Research Association (JSTRA).

References

JASNAOE. (2007). Project research panel (P-10) report, http://www.jasnaoe.or.jp/research/dl/report_p-10.pdf,[in Japanese]

JIS Z 3060 (2002). "Method for ultrasonic examination for welds of ferritic steel", Japan Industrial Standards.

Kato, A, Kurihara, M and Kawahara, M. (1983). "An Expression of Fatigue Crack Propagation Rates under Wide Ranged Stress Ratios", J. Society of Naval Architects of Japan, Vol 153, pp. 336-343. [in Japanese]

Nippon Kaiji Kyokai (2009). "Guidelines on Brittle Crack Arrest Design"

Tomita, Y., Kawabe, H. and Fukuoka, T.(1992), "Statistical characteristics of long term wave-induced load for fatigue strength analysis for ships", Practical Design of Ships and Mobile Units, PRADS, vol 2, pp 2792-2805

Toyosada, M, Gotoh, K and Niwa, T. (2004a). "Fatigue crack propagation for a through thickness crack", Int. J. Fatigue, Vol 26, No.9, pp. 983-992.

Toyosada, M, Gotoh, K and Niwa, T. (2004b). "Fatigue life assessment for welded structures without initial defects", Int. J. Fatigue, Vol 26, No.9, pp. 993-1002.

Yamaguchi, Y, Yajima, H, Aihara, S, Yoshinari, H, Hirota, K, Toyoda, M, Kiyosue, T, Funatsu, Y, Handa, T, Kawabata, T, and Tani, T (2010). "Development of guidelines on brittle crack arrest design – Brittle crack arrest design for ultra large container ships-1 -", Proceedings of the twentieth International Offshore and Polar Engineering Conference, ISOPE, Beijing [to be published]

Yoshinari, H, and Aihara, S (2009). "Brittle Crack Propagation Behavior at Butt Shifted Welded Joint-Numerical Simulation of Brittle Crack Propagation along Welded Joint (3rd Report) -", Journal of the Japan Society of Naval Architects and Ocean Engineers, No. 9, pp. 177-182 [in Japanese]