Development of "Guidelines on Brittle Crack Arrest Design"

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1. INTRODUCTION

In addition to the globalization of markets and the continuous increase in the volume of marine transportation on a global scale, the demand for larger, better performance ships has grown because of the need to reduce both environmental burdens and operating costs. This is especially noticeable with regards to the increased size of container carriers, and ultra large container carriers in the 10,000 TEU class are being constructed worldwide. [1), 2)]

The hull girder longitudinal strength of a container carrier must be ensured using a limited number of longitudinal stiffening members because of the large openings in the strength deck; therefore, thick steel plates have been used in the past for the strength deck structures (hatch side coaming, strength deck, sheer strake, uppermost strake of the longitudinal bulkhead). For this reason, extremely thick plates exceeding 50 mm in thickness are being used in very large container carriers. The most important topic in the use of such extremely thick steel plates is the prevention of brittle fracture leading to large-scale failure.

In order to prevent brittle fractures, current classification rules take both brittle crack arrest and brittle crack prevention into consideration. As a result, even if a brittle crack occurs unexpectedly, the worst condition, including large-scale failure of hull, can be avoided by arresting crack at the appropriate location. [3)]

However, recent research has shown that even for extremely thick plates, past research related to preventing propagation of brittle cracks cannot be directly applied, and further, large-scale model test results show that it may not be possible to arrest crack propagation. This suggests that even if the hull structure using extremely thick steel plates, as in large container carriers, satisfies the steel material grade required by the current Rules for the Survey and Construction of Steel Ships, if a brittle crack occurred unexpectedly, the crack would propagate at a very high speed and could lead to dangerous results, such as a large-scale failure. Establishing technical standards to prevent brittle fracture in the application of extremely thick steel plates in large container carriers is, therefore, an urgent issue.

In response to this situation, ClassNK established the Brittle Crack Arrest Design Committee as part of a Research and Development Project conducted in 2007 and 2008 and studied the behavior of brittle crack propagation of extremely thick steel plates used in large container carriers. This document reports an overview of the "Guidelines on Brittle Crack Arrest Design", which summarizes the findings of the said committee.

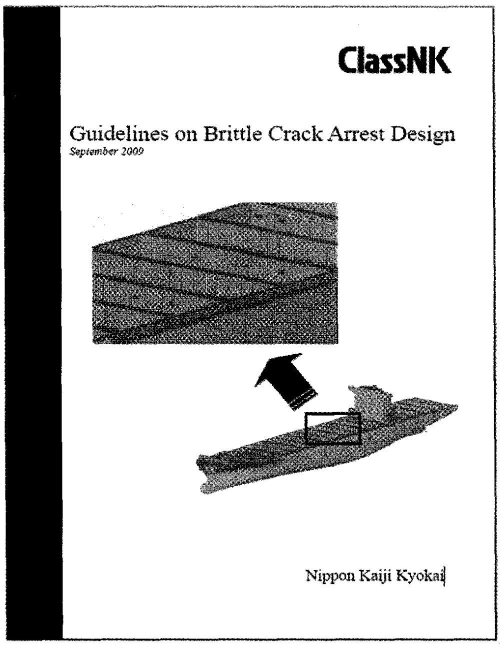

Figure 1 Guidelines on brittle crack arrest design

2. History of development of the "Guidelines on Brittle Crack Arrest Design"

Brittle fracture of the hull structure may lead to large-scale failure and must be strictly prevented. Thus, preventing the initiation of brittle crack is of primary importance if brittle fracture of the ship structure is to be prevented. Currently, separate from the structural strength requirements, classification society rules aim to prevent the initiation of brittle crack by establishing the specification of steel materials to be used, the application of steels (appropriate distribution of material grades with different toughness levels in structural members) and the toughness levels of welded joints.

At the same time, considering the magnitude of accidents to ships caused by brittle fracture and to prepare for the

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unexpected initiation of a brittle crack, the formulation of procedures to arrest propagation of brittle crack at appropriate locations is equally important to the prevention of initiation of brittle crack, and may be thought of as a backup function to prevent large-scale failure of the hull structure.

Assuming the unexpected initiation of a brittle crack, classification rules specify the provision of high toughness steel plates in the sheer strakes and the deck stringer plates, as crack arrestors for arresting the propagation of brittle cracks. Fig. 2 shows the arrangement of crack arrestors (high toughness steel plates having the width requirement) from the application of steel grades to hull structural members specified in IACS Unified Requirement S6. Even if a brittle crack occurs unexpectedly, the crack can be arrested by the high toughness, and worst case scenarios such as large-scale failure of the hull can be avoided.

The classification rules related to arresting brittle crack propagation are based on the systematic research carried out jointly by Japanese universities, shipbuilders, steel mills, research organizations and a classification society. As a result of these research activities, the general findings below were obtained concerning brittle crack arrestability of high tensile plates for the hull with thickness of about 35 mm used in hull structures of large ships at that time and the welded joints of these plates. [4), 5)]

(1) Results of studies by large-scale arrest tests of welded joints showed a high possibility of arresting brittle crack propagated along the welded joint by diverting into the steel plate base metal due to effects such as weld residual stress.

(2) The value for brittle crack arrest toughness K_{ca} required for arresting propagation of long brittle crack that occurs in hull structural members is 4,000 to 6,000 $Nmm^{3/2}$ or greater.

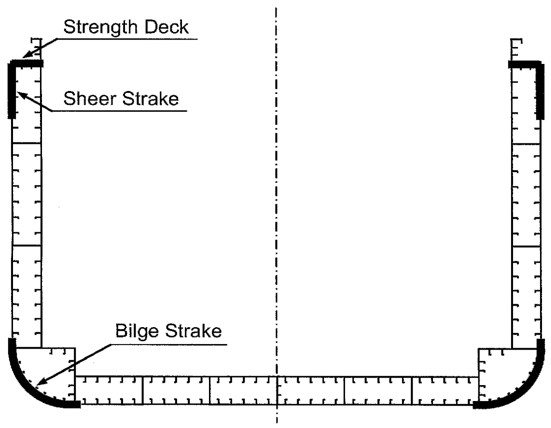


Figure 2 Example of arrangement of crack arrestors (IACS URS6)

In this way, the existing classification rules system is considered to be effective not only in preventing the initiation of brittle cracks but also in arresting the propagation of brittle cracks.

However, recent research has suggested that "the existing rules system cannot be said to guarantee the arrest of brittle crack propagation always for extremely thick steel plates exceeding the record of use until now". More specifically, large scale model test results have reported that "brittle crack that has occurred may propagate straight ahead without arrest even if high toughness EH steel grade that satisfies existing class requirements has been used". This finding differs from conventional knowledge on thicker steel plates used in large container carriers. [6)]

This suggests that even if the hull structure using extremely thick steel plates satisfies the steel grade required by existing rule requirements, if a brittle crack occurs unexpectedly, the crack propagates at high speed, and there is a risk of large-scale failure to occur.

ClassNK established the Brittle Crack Arrest Design Committee made up of members from universities, shipbuilders, steel mills and research organizations as part of the above noted Research and Development Project. This Committee implemented several large-scale tests and numerical analyses, and carried out studies on the behavior of brittle crack propagation of extremely thick steel plates used in very large container carriers. The Committee summarized the results of the studies on very large container carriers using extremely thick steel plates in the hull structure and developed the necessary technical requirements as the "Guidelines on Brittle Crack Arrest Design". This document is the first in the world to specify distinctive, functional, and detailed requirements related to arresting brittle crack propagation, which has not previously been clearly specified in the design of hull structures.

3. Guidelines on brittle crack arrest design and technical background

3.1 Outlines of brittle crack arrest design

(1) Purpose of brittle crack arrest design

The purpose of brittle crack arrest design is "to prevent large-scale failure of the hull structure by arresting the brittle crack at appropriate locations in the hull when such a brittle crack occurs unexpectedly". Consequently, the setting of the "scenario" such as "the location of initiation of brittle crack, and where to arrest that brittle crack" becomes important in brittle crack arrest design.

Fig. 3 shows the scenario set in these guidelines. A container carrier with standard structural form was assumed in these guidelines. Two scenarios were considered namely "arrest the brittle crack that has occurred in the hatch side coaming at the strength deck (scenario 1)" and "prevent the propagation of brittle crack that has occurred in the strength deck to the hatch side coaming (scenario 2)".

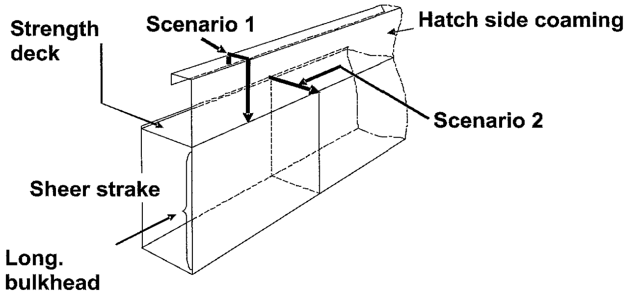


Figure 3 Scenarios for brittle crack initiation and its arrest

(2) Scope of applicability

The members to which these guidelines are applicable were taken as those longitudinal members around the strength deck (hatch side coaming, strength deck, sheer strake, uppermost strake of longitudinal bulkhead) which may be considered for the hull girder strength (hull transverse section modulus) and which exceed plate thickness of 50 mm.

Regarding the thickness of applicability of these guidelines, extremely thick steel plates of thickness exceeding 50 mm were taken to fall within the scope of the guidelines, owing to the reasons mentioned below:

- In existing classification rules, steel material specifications and application of steel grades to hull structural members should differ when plate thickness of 50 mm is taken as the boundary
- For plates of thickness below 50 mm, a number of safety records of usage of the same should exist in hull structure including large ships

For steel plates of thickness below 50 mm also, the requirements of these guidelines can be applied on the safe side. However, considering that brittle fracture accidents have not occurred in ships with service record using steel plates of thickness below 50 mm, excepting special cases such as welding nonconformities in hull extension work of the ship in service, aggressive use of these in arrest design as comprehensive requirements may be limited for the time being only for plates of thickness above 50 mm.

Ships within the scope of applicability in which extremely thick plates of thickness greater than 50 mm are used in the hull structure are mainly very large container carriers. Additionally, container carriers have large hatches; therefore, redundancy against unexpected brittle crack initiation is very small. This is the reason large container carriers were selected as the scope for this guideline.

Furthermore, the purpose of brittle crack arrest design is "to prevent large-scale failure of hull structure by arresting the brittle crack at appropriate locations in the hull", so the strength to be studied was limited to hull girder strength.

However, the effectiveness of existing rules (upper limit of thickness) for arresting brittle crack propagation in steel plates of thickness below 50 mm is one of the issues to be validated.

(3) Assumed applied stress and design temperature

The applied stress assumed at location for arresting brittle crack was considered as 257 N/mm^2, which is the allowable longitudinal bending stress for YP40 steels.

When the location for arresting brittle crack is considered to be the strength deck, the longitudinal bending strength of the hatch side coaming top can also be applied generally to container carriers designed based on YP47 steel.

Compared to the brittle crack velocity greater than 500 m/sec., the cycle of fluctuation of hull girder stress is a few seconds (4 to 5 seconds). For this reason, the change in longitudinal bending stress accompanying the change in the hull transverse section modulus coefficient due to crack propagation is considered not to occur from initiation of brittle crack until its arrest.

The design temperature was taken as -10°C, which is the assumed environment temperature in the existing classification rules system.

3.2 Basic requirements of brittle crack arrest design

(1) Basic concept of brittle crack arrest design

The basic concept of arrest design is ensuring that the "material resistance to brittle crack propagation" is larger than the "driving force of brittle crack propagation".

Qualitatively, the following method and procedure may be considered:

(a) Arrange material with large resistance to brittle crack propagation, and arrest the brittle crack that penetrates the material. (Material arrest)

(b) Ensure that the brittle crack does not propagate by eliminating continuity of the crack propagation route. (Structural discontinuity arrest)

(c) By combining (a) and (b), the brittle crack propagation driving force can be reduced, and consequently, brittle crack can be arrested by small material resistance.

Typical examples of (b) include rivet joint and stop hole installation, but these are impractical for use in the hull structures of existing large container carriers. (a) or (c) is considered to be a practical method used in the brittle crack arrest design of large container carriers. For instance, in case of brittle crack propagation and arrest in the fillet welded structural part at the joint of the hatch side coaming and strength deck, (c) can be anticipated to yield the combined effects of (a) and (b) above.

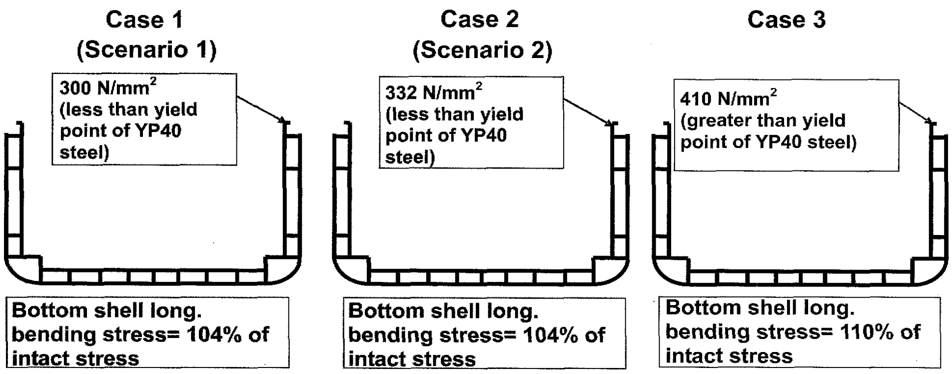
(2) Scenario for brittle crack arrest design

As mentioned above, two scenarios were set for developing these guidelines, namely: "arrest the brittle crack that has occurred in the hatch side coaming at the strength deck (scenario 1)" and "prevent the propagation of brittle crack that has occurred in the strength deck to the hatch side coaming (scenario 2)".

Fig. 4 shows a calculation example of reduction in longitudinal strength corresponding to the failure status of the longitudinal members around the strength deck of an 8,000TEU container carrier. Considering that the probability of brittle crack to generate simultaneously on both sides is extremely low, brittle cracks are assumed to occur only on one side. The reduction in longitudinal strength indicated here is not in the brittle crack propagation state, but it is the reduction in longitudinal strength after the brittle crack propagation has been arrested at a certain location.

As shown in Case 1 (Scenario 1) and Case 2 (Scenario 2) in Fig. 4, if arrest design is carried out to satisfy the two scenarios assumed in these guidelines, the longitudinal bending stress in the hatch side coaming top of the sound side falls becomes less than the specified yield point of the material used, and large-scale failure can be prevented. Here, even if a brittle crack that has occurred in either the strength deck, sheer strake, or the uppermost strake of the longitudinal bulkhead has not been arrested at the butt joint (butt weld joint in the same line), it was considered to be arrested based on findings in the past since the plate thickness becomes smaller than 35 mm below the sheer strake and the uppermost strake of the longitudinal bulkhead and the hull girder stress reduces.

In contrast, as shown in Case 3, when the hatch side coaming, strength deck, sheer strake or the uppermost strake of the longitudinal bulkhead fails, the longitudinal bending stress (maximum design stress) in the hatch side coaming top on the sound side exceeds the specified yield point of the material used. The longitudinal bending stress in the ship's bottom becomes 110% of the intact condition stress, and the buckling of the bottom shell in the hogging condition becomes the cause of concern. In this way, in the condition of Case 3, yield of the member at the deck side, buckling of member in the bottom side occur, leading to risk of large-scale failure of the hull structure.



Case 1: Only hatchside coaming failed (one side)
Case 2: Strength deck, sheer strake, uppermost strake of longitudinal bulkhead failed (one side)
Case 3: Hatchside coaming, strength deck, sheer strake, uppermost strake of longitudinal bulkhead failed (one side)

Figure 4 Study of scenarios of brittle crack arrest design (Study example of 8,000TEU container carrier)

That is, to prevent large-scale failure of the hull structure, the propagation of the brittle crack that has occurred in the hatch side coaming should be arrested at least at the strength deck (Scenario 1), and propagation of the brittle crack that has occurred in the strength deck should be arrested at least at the hatch side coaming (Scenario 2).

In view of the above, arrest design according to the guidelines requires that the following two scenarios be satisfied: "brittle crack that has occurred at the hatch side coaming should be arrested at the strength deck (Scenario 1)" and "propagation of the brittle crack that has occurred at the strength deck to the hatch side coaming should be prevented (Scenario 2)".

(3) Weldline shift

The guidelines consider arrest design by "brittle crack arrestability of material (material resistance that arrests brittle crack propagation)" or "combination of structural discontinuity effects and brittle crack arrestability of material". Accordingly, as shown in Fig. 5, at locations where brittle crack is to be arrested, the propagated brittle crack should be penetrated by the base metal; for this reason, the "butt weld joint of member to which the crack has propagated" and the "butt welded joint of member which the crack is trying to penetrate" should be separated by more than a specified distance. (Weldline shift)

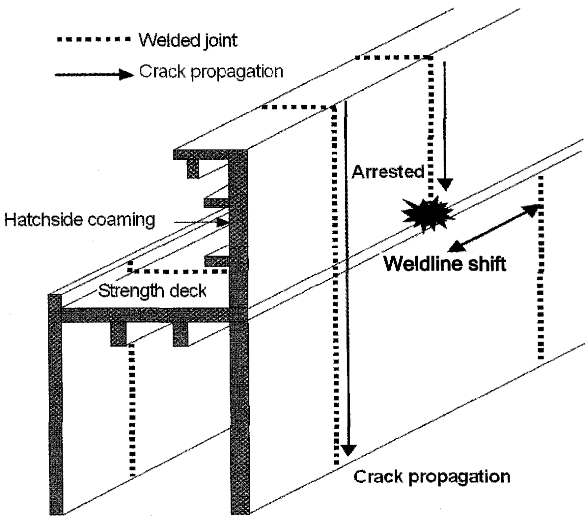


Figure 5 Example of weldline shift in strength deck structure

A standard value of 300 mm was used as the required weldline shift as a result of performing numerical analysis of the brittle crack propagation route under various conditions. [7] This is the value on the safe side that encompasses various crack propagation modes, and is therefore, taken as "Rule Principle" in these guidelines. When confirming the validity of joint arrangement in each design, such as in large-scale fracture tests, this weldine shift value need not be taken.

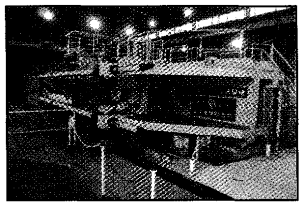
3.3 Typical brittle crack arrest design

(1) Brittle crack arrest design of plate thickness greater than 50 mm and not more than 75 mm

The value for brittle crack arrest toughness K_{ca} required for arresting propagation of long brittle crack that occurs in hull structural members is known to be 4,000 to 6,000 $Nmm^{3/2}$ or greater at the service temperature, according to past research results. These are based on test results for steel plates of thickness of about 35 mm that were used on large ships at that time. In the development of these guidelines, the K_{ca} required for extremely thick steel plates exceeding 50 mm in thickness and used in large container carriers, needs to be clearly defined.

The longer brittle cracks become, the more the crack driving force responsible for propagate the brittle crack increases. For this reason, implementation of large brittle fracture tests that can be carried out on test specimens of size closer to those on actual ships is necessary to understand the propagation and arrest behavior when the crack propagation distance becomes large (long crack) as in actual ships. Fig. 6 shows the large test equipment used by the research committee.

(a) 8,000-ton tensile test equipment (Nippon Steel Corporation)



(b) 8,000-ton tensile test equipment (JFE Steel Corporation)

Figure 6 Test equipment used in large model tests

This research, in consideration of the actual application and the current manufacturing ability of extremely thick steel plates, conducted the duplex ESSO test for evaluating the K_{ca} required for arresting brittle crack and the medium-scale cruciform structural model tests for evaluating those using both the brittle crack arrestability of material and the effects of structural discontinuities. Moreover, the ultra-large construction model ESSO tests conducted modeling the actual structure as demonstration tests, are illustrated in Fig. 7, together with the shape of the model test specimens of mega structures and the welding assembly sequence. The test specimens were prepared such that the lower ends of the butt welded part of the hatch side coaming is penetrated to the strength deck, similar to the conditions of actual ships.

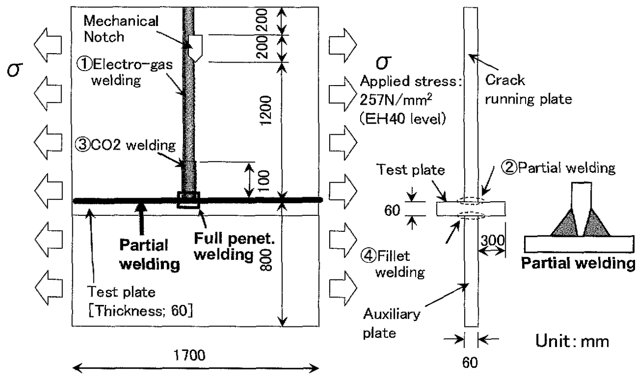


Figure 7 ultra-large construction model ESSO tests conducted modeling the actual structure (Welding consequence :① to ④)

The results showed that in both Scenario 1 (brittle crack that has occurred at the hatch side coaming should be arrested at the strength deck) and Scenario 2 (propagation of the brittle crack that has occurred at the strength deck to the hatch side coaming should be prevented), the material resistance (brittle crack arrest toughness K_{ca} value) required for arresting long brittle crack after considering structural discontinuities was 6,000 $N/mm^{3/2}$.

(2) Brittle crack arrest design of plate thickness greater than 75 mm

The use of steel plates exceeding 75 mm in thickness in the hull structure of container carriers is not common, so the arrest design for steel plates exceeding 75 mm in thickness is an isolated case and it was decided to perform validation by individual large-scale fracture tests.

3.4 Validation of brittle crack arrest designs other than the typical arrest design

As mentioned above, the requirements related to typical brittle crack arrest design assign solutions on the comprehensive safety side considering the practicality of the guidelines. For this reason, when implementing brittle crack arrest designs other than the typical arrest design in these guidelines, "the validity of the arrest design must also be verified by large scale brittle fracture tests of an appropriate size". This is because validation by large scale brittle fracture tests of an appropriate size is essential for evaluating the propagation and arrest behavior of the long brittle cracks anticipated to occur in actual ships.

3.5 Standard test method for assessment of brittle crack toughness (K_{ca} test method)

The guidelines specify minimum brittle crack arrest toughness value (K_{ca} value) as a requirement for typical brittle crack arrest design. Therefore, the material with required K_{ca} value must be selected, but a standardized test method for assessing the K_{ca} value does not currently exist.

Studies and fact-finding inquiry were implemented on the brittle crack propagation arrest tests conducted by various organizations on the effects of test results (K_{ca} value) corresponding to changes in different types of test conditions. Based on the results, a test method that enabled common test results even for different test machinery was standardized, and was incorporated as annex as the "Brittle crack arrest toughness K_{ca} test method".

4. CONCLUSION

The development of a means to arrest brittle crack propagation (brittle crack arrest design) aggressively for large container carriers using extremely thick steel plates based on these guidelines, in addition to measures for preventing brittle crack initiation ensures double safety, is considered to enhance the safety of large container carriers against brittle fracture.

These guidelines may be considered the first in the world to set forth clear functional requirements and comprehensive requirements related to arresting brittle crack propagation.

ClassNK continues to study and investigate issues related to extremely thick plates in large container carriers, and is planning to further develop the content of these guidelines such as more rational arrest design by quantitative assessment of structural discontinuities, assessment method for brittle crack toughness value by smaller tests.

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