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An Empirical Study of an Inspection Method for Securing High Reliability of Independent Prismatic Tank Type B

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ABSTRACT

The idea of the independent prismatic tank Type B system for gas carriers was crystallized in 1970's and its design standard was developed while Nippon Kaiji Kyokai (a Classification Society - NK) played an active role. With the design standard thus developed, number of LPG carriers and Ethylene carriers of this system were built with the NK class in the beginning of 1980's. The authors reviewed the tank strength analysis, tank test procedure, design and inspection records of ships in service, and made an empirical research on probability of failure of the tanks. The study concluded that the prevailing design standard for the system were considered quite reasonable and this independent prismatic tank Type B system can be one of the LPG tank systems of high reliability. As the result of the study, this paper descrives highlightely on inspection strategies and methods for securing a high reliability of the tanks.

1. INTRODUCTION

According to information, it is said that construction of LNG carriers using an independent prismatic type B tank (hereafter called "prismatic type B") has been assigned. There have been two reactions of those concerned to this information: the supportive reaction is their recognition that the LNG is the first LNG carrier to be developed purely Japanese techniques, while the conservative reaction is that we must wait until this LNG carrier has proved itself before we make a fair evaluation of the new type of LNG tank. On the other hand, a total of seven fully refrigerated liquefied petroleum gas tankers and ethylene carriers using prismatic type B tanks have been built so far. They have presented no difficulties up to the present and their service records are reportedly satisfactory (mean ship's age about 10 years), but we had no reliable detailed reports.

The base of the design of prismatic type B is the "Design Standard for Independent Prismatic Tank Type B" [1] (hereafter called the "standard") established about 10 years ago. At that time, prismatic tanks were exclusively type A, and design and construction of type B tanks could only be found in revolutional configuration tanks relying on forein techniques. Under these circumstances, the standard was established to obtain for developing prismatic type B tanks as a taken of the joint research [2] made by the Japanese parties concerned.

On these grounds, the authors have studied items which are particularly important factors such as, strength reliability of main girders, support reaction force, and fatigue strength, relating to the strength reliability of prismatic type B tank on the basis of the results of research and expertise obtained through the design and construction of actual ships. And a result of the study was introduced at a lecture meetings [3]. Further, the authors have studied on:

(a) Records of tests and inspection of actual ships, and

(b) Operating records of ships equipped with prismatic tanks type B (including type A).

In this paper, the authors describes in high-light inspection methods and techniques, and evaluation of prismatic type B tanks based on actual inspecting experiences.

2. BASIC DESIGN CONCEPT OF PRISMATIC TANKS TYPE B

If independent tanks are (a)subjected to precise strength analyses using design loads which have been obtained reasonably by direct calculations etc., (b) fatigue fractures of tanks are prevented through detailed fatigue design, and (c) if cracks generated (including through cracks) are detectable with ample time allowance before reaching unstable fracture involving the collapse of tanks with a proof (crack propagation analysis), they are knowledged as type B tanks [4]. These requirements are commonly applicable to both revolutional configuration tanks and prismatic tanks

Table 1 Investigated Ships with Independent Prismatic Tank

	at the end of '79	at 1st quarter of '90
Nos. of ship as type A (*1)	28	42
mean age (year)	10.6	12.9
Nos. of ship as type B (*2)	--	7
mean age (year)	--	9.2

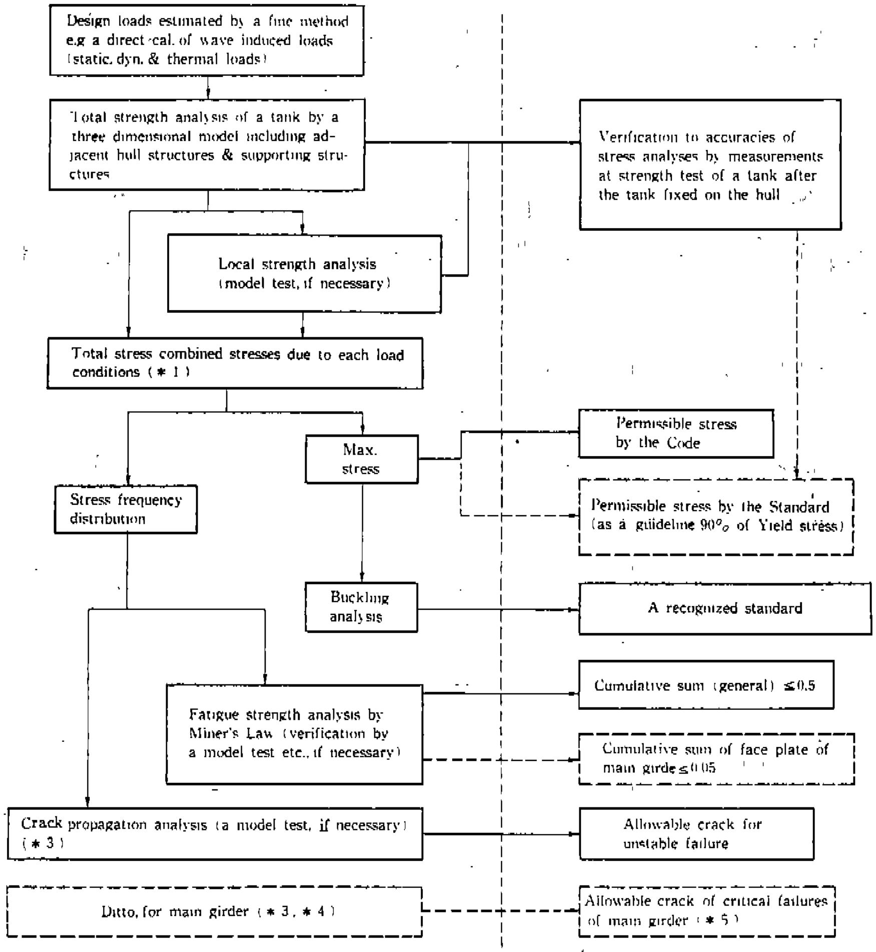
*1) Including 5 ships other than NK's class ships
*2) 3 ships of those are a sister ship i.e. 5 kinds of a design one is provided with a prototype of "IHI SPB Tanks"

According to the operation records of ships with prismatic type A tanks shown in Table 1, prismatic tanks have experienced no critical failures constituting any problems. Prismatic type B tanks are then considered to be built under the same basic structure type with a high degree of structural analysis. If development of structural analysis is taken into account, compliance to the requirements of the Code [4] is considered to be feasible. And characteristic problems for designing the large stiffened plate structures as type B tanks have been studied and introduced [3]. They are summarized as follows;

(1) Main girders

Although the main girders of prismatic tanks are the most important structural members for integrity of the strength, it seems that the requirement of the Code [4] cannot be said to be sufficient on this point. Prismatic tanks are therefore designed so that main girders have a high degree of reliability and no failure likely to impair their effectiveness is assumed to occur as one of the premises to prevent unstable fractures i.e. the girders are to be so designed to be equivalent strength in accordance with the requirements of independent tanks C (= the same level for pressure vessels of the highest grade). Then, analyses are proceeded with an object of local failure. The specific procedure is shown in Fig. 1.

To satisfy the above requirements, it is sufficient to deal only with local cracks in the crack propagation analysis, and the techniques available to us are applicable to this question without posing any difficulties.



* 1) Total stress is to be obtained by a properly combining each individual stress due to a load condition for calculations taking into acount its phase

* 2) Stress is to be less than the yield stress taking into acount errors of calculations[1]

* 3) Model test of a bracket toe of a main girder, a tank plate adjacent to a supporting structure[2]

* 4) Surface crack (Propagation for 10 years from depth 15mm × length 5mm or thickness of plate)

* 5) Face plate of Main girder : 5% of sectional area
Bkt toe of M.G. : 25mm
Stiffener of M.G. : not to be propagat to other's members

——— : General requirement of type B[1]

------ : Additional requirement of Prismatic tank type B[1]

Fig. 1 Procedures of Strength Analysis for Prismatic Tank Type B (except those of sloshing, vibration)

Furthermore, a test model to verify the adequacy of the analytical method for preventing unstable fractures involving through cracks of tanks are considered to be within a scale which is practically possible to be implemented. And such a model test was implemented in a joint study at the Shipbuilding Research Association of Japan [2].

(2) Support reaction force

When both the hull and tanks have structural rigidity, interface with each other through supports, whereby a support reaction force is created.

This reaction force is an indeterminate force that varies according to the condition of a ship, which is a particularly intricate phenomenon in the case of prismatic tanks. Therefore, the method of predicting the support reaction force has been pointed out as a very important problem.

Errors involved in predicting this support reaction would generate an excessive concentrated load and cause local failures of support structures and their surrounding structural members. This load has non-linear characteristics in the form of a redistribution of reaction force caused by the change in deflection, and its influence on the integral strength of a tank is insignificant. Furthermore, the support reaction force can be assumed with sufficient accuracy for practical purpose through analyses including the non-linear effects. A full-scale joint experiment was carried out in a joint study project between a shipyard and NK using the first ship equipped with prismatic type B tanks [5].

(3) Fatigue strength

Prismatic tanks with large stiffened plate structures have a number of structural elements and welds that constitute fatigue strength problems, and it has been said that it is difficult to design and construct prismatic tanks of this type having the fatigue strength meeting the requirements of the Code [4].

However, the records given in Table 1 show that there have been no particular fatigue strength problems, and on the basis of expertise obtained through many studies in Japan on the fatigue strength of hull structures as a question of stiffened plate structures, it is considered to be feasible to do a fatigue design of prismatic tanks type B if appropriate studies are made on tank materials.

Table 2 Comparison of QC, inspection & test for Independent tanks
(investigated on 7 shipyards concurrently built tanks & 3 tank makers)

	Type A	Type B	Special requirement to Prismatic Type B (add to the left)	Type C (pressure vessel)
QC, tolerance etc. during fabrication of tank	a standard in accordance with a hull's standard	a standard in accordance with a pressure vessel's of the highest class	–	in accordance with the standard of the highest class ones
[Inspection of weldings]				
Visual inspection	ditto	ditto	–	ditto
X-Ray, UT	all welded joints of tank skin	all welded joints of tank skin	all welded joints of face plates of main girders	all welded joints of tank skin
Surface crack detecting inspection	–	– of main girders	bracket toe etc. openings of tank skin	nozlles and other
Production test	welded joints of tank skin	welded joints of tank skin	welded joints of face plate of main girder	welded joints of tank skin
[Global test]				
strength test	hydro-pneumatic test(*1)	hydro-pneumatic test(*1)	–	pressure test by water pressure(*3)
leak test	concurrently tested by the above or pneumatic test	concurrently tested by the above or pneumatic test	–	after the above pneumatic test(*3)
gas test(*2)	gas detecting test	gas detecting test	–	–

*1 See, Fig.2
*2 Gas trial test using an actual cargo prior to ship's delivery
*3 Strength test = 1.5 times of MARVS, Leak test = 1.25 times of MARVES

3. TEST AND INSPECTION OF PRISMATIC TYPE B TANKS AND RELIABILITY

3.1. Test and Inspection during Construction

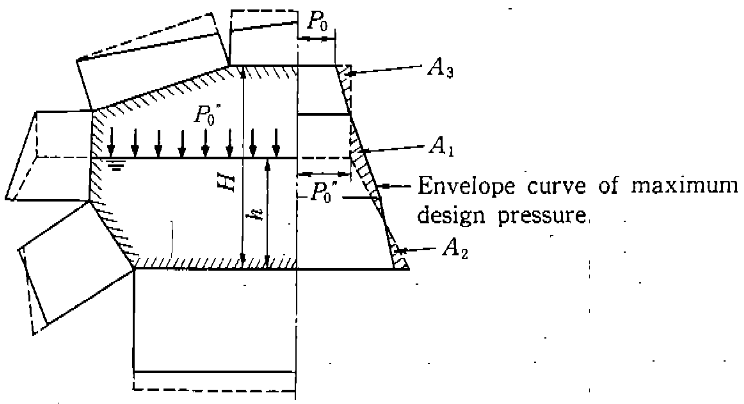
In addition to the requirements of tests and inspection during construction applicable to independent tanks under the provisions of the Code [4) , severe requirements for quality control, test and inspection during construction are imposed on prismatic type B tanks in accordance with the "standard". These requirements are outlined in Fig. 2 and Table 2. Although they are considered to be appropriate for each type of tank, there are some technical problems to be solved. The results of studies on the problems including those to all independent tanks are discussed below.

Test and inspection procedures and latent defects. According to the results of the questionnaire survey conducted by the authors, the views of those who conducted test and inspection on independent tanks, surface defects including cracks to a depth of 0.5 mm , or thereabouts, can be detected through extremely careful visual inspections coupled with surface crack detection tests arranged as appropriate. In the case of a mere visual inspection, there is a possibility of overlooking cracks to a depth of 1.5 mm or so, and care must be taken. On the other hand, the detection of harmful internal defects is considered to be feasible through radiographic test and ultrasonic test. The "standard" specifies the size and geographic features of initial cracks in the crack propagation analysis for prismatic type B tanks are determined taking the test method and other into account. As a reference, 5 mm long surface cracks to a depth of 1.5 mm are assumed, which is considered to be reasonable provided that the severe tests and inspection requirements for prismatic type B tanks are strictly complied with.

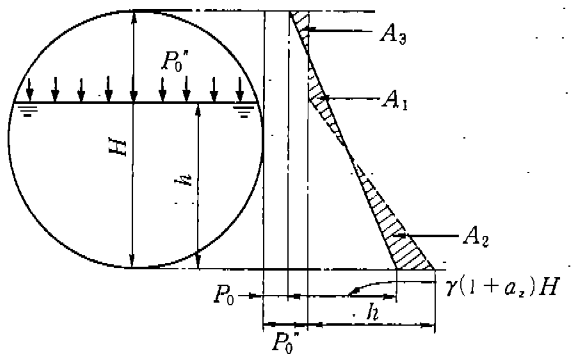
Strength test. The results of the investigation (on the four ships among the seven ships with prismatic type B tank) shown in Table 1 have revealed that the load conditions used for strength tests of independent types A and B tanks shown in Table 2 correspond to about 70 to 90% of the maximum design stress conditions, or the maximum vertical acceleration in tanks and static external pressure conditions under a singular loading condition. This set of load conditions simulates the extremely severe load conditions encountered in actual ship operations, and thus are considered to be effective as a practicable means to verify the strength of these tanks.

Leak test. Leak tests for independent types A and B tanks have been carried out simultaneously with hydrostatic and pneumatic strength tests, or during an air-tightness test (air pressure at $0.3 kgf/cm^2$ or so) which is generally arranged before the hydrostatic and pneumatic tests. Generally, leak tests are carried out by the air-tightness test, but some comments stress that a small defect at leaks which are produced as a consequence of the strength test cannot be detected by such a leak test. The authors, however, are of the view that on the basis of the following reasons there in no particular difference between these two types of leak tests as a means to detect leakage, and selection is left to the discretion of the persons concerned, taking into account the merits involved for work schedule control.

a) If the defects producing a leakage and caused by poor workmanship have a cylindrical shape like blow holes, there is no difference in the detecting ability between a hydrostatic test with a pressure at 2 or 3 kgf/cm^2 and a air-tightness test with a pressure at 1/10 of the hydrostatic test pressure.
b) If a defect producing a leakage have a slit shape, the opening is enlarged at the high stress area during the strength test. If this stress is uniform membrane stress, the limit detectable slit length in the vicinity of the yield stress is 10 to 20 mm (when calculated on assumption that the limit detectable defect diameter is 30 mm for cylindrical defects, and the slit-shape defect has the same flow rate with 100 times the opening area of the cylindrical defect.) In the case of bending stress, it has a greater defect length. Defects of such a size are considered to have been detected by non-destructive test etc. in advance and repaired.



(a) Simulating the internal pressure distribution of Prismatic Tank



(b) Simulating the internal pressure distribution of Spherical Tank

〔N.B〕

——— : maximum loading condition which is predicted to actually encouter

- - - - - : pressure testing condition simulating as far as practicable (P_0'' and h are to be chosen so that $P_0''>P_0$ and $A_2+A_3>A_1$ as far as practicable)

H : depth of tank

h : water head

γ : specific gravity of cargo

a_z : maximum vertical acceleration (non-dimensional)

P_0 : design vapour pressure at ordinary passage

P_0'' : air pressure

Fig.2 Strength Test Methods of Independent Tank Types A & B

c) Even when defects producing a leakage, which cannot be detected by the strength test, are generated, independent types A and B tanks allow detection of leakage by gas detection during gas tests, and therefore there are no problems in verifying structural safety. Should a leakage occur at the time of gas tests, it would pose a serious problem for work schedule control, but such a possibility is extremely low for the reasons given below.

d) The number of cases, in which defects at leakage were detected during the strength test for hull structures, is extremely small (the rate of occurrences is less than 10^{-2} /tank-year), and they were at fillet welds in all cases. In either of independent type A and B tanks, there are no fillet welded structures in the surrounding skins of tanks, and they are subject to severer tests and inspection requirements. It is therefore reasonable to comment that the probability that defects at leakage occur during the strength tests is negligibly low. Needless to say, as far as an investigation carried out by the authors is concerned (109 types A and B tanks, and 119 type C tanks), there were no leakage accidents at all during the strength tests and leak tests after the strength tests (gas tests for tanks types A and B, and air-tightness tests for type C tanks).

An inspection method for IHI SPB tank. It has been reported that a newly designed LNG carriers with a prismatic tank type B shall be constructed in soon. This tank has been so called as "IHI SPB Tank" by its designers. "IHI SPB Tank" has been developed in accordance with the Code [4] and the standard [1], and further an severe inspection method for securing a high reliability of the tank has been proposed [6]. Nippon Kaiji Kyokai (a Classification Society - NK) has throughly reviewed the proposed inspection method at its design approval and has examined in actual application of the inspection techniques by a Classification Survey of a prototype ship of IHI SPB Tank "LEG Carrier M.V. Kayoh Maru".[7] From this experience, we consider that the proposal is of course acceptable as a type B tank and further is available for securing a high reliability of the tank of which its quality is higher than one's expected by the Code [4] and the standard [1].

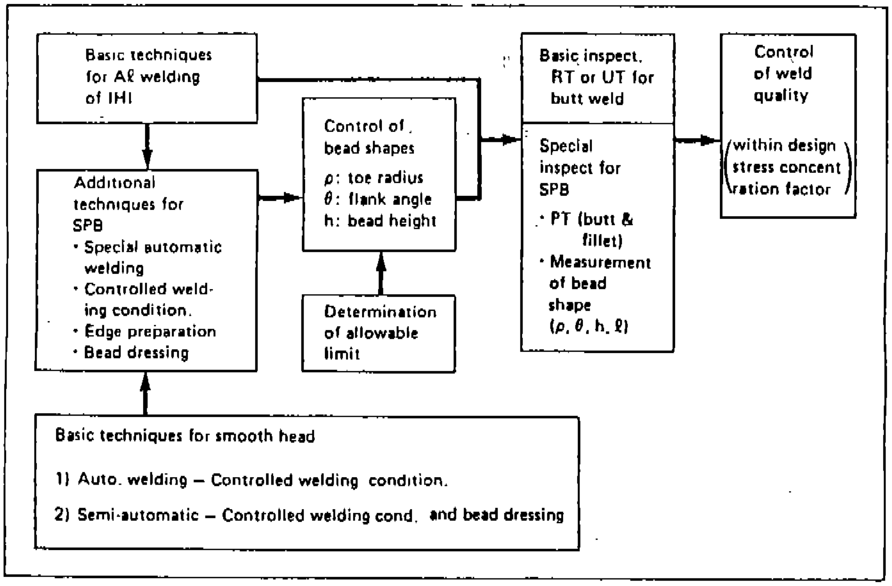


Fig.3 Procedures of Quality Control and Inspection during Construction "IHI SPB TANK" [8]

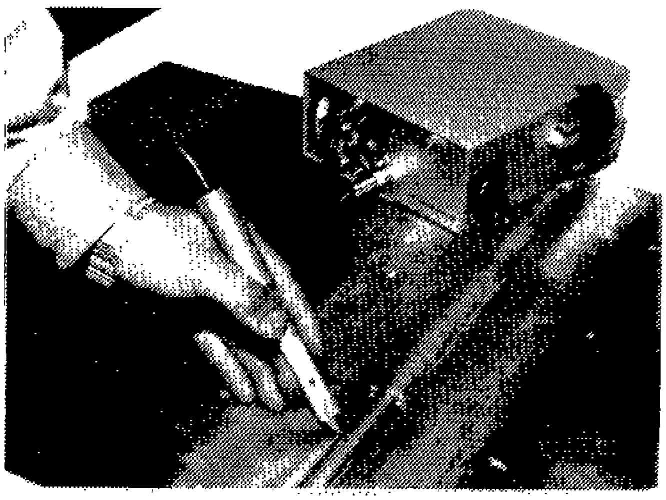


Fig. 4 Pencil Type Sensor

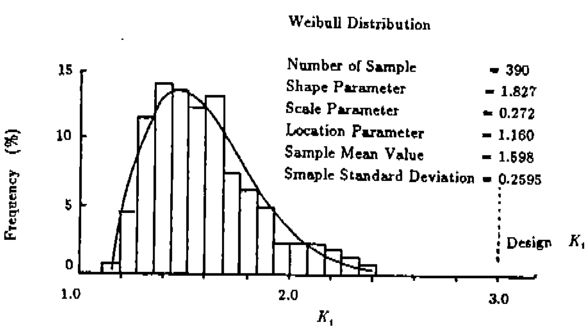


Fig. 5(a) Histogram of Stress Concentration Factor of Welding Shape (Kt)
< IHI SPB-Full Scale Model-LNG(Fillet Weld) [8] >

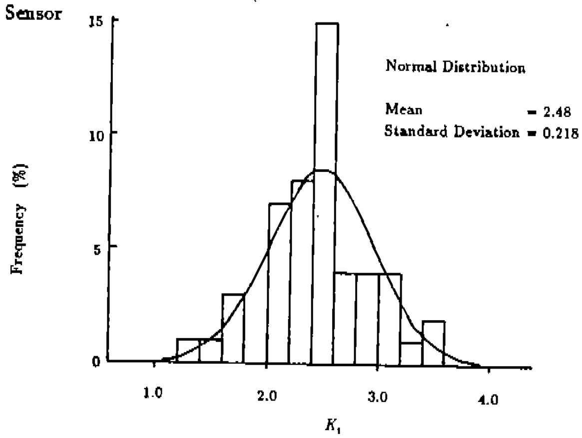


Fig. 5(b) Histogram of Stress Concentration Factor of Welding Shape (Kt)
< Hull Structures(Butt & Fillet Welds) ; Referred from No.92 the Shipbuilding Research Ass. of Japan, Mar. 1980 >

The proposed quality control concept including inspection techniques is outlined in Fig. 3 [8].

As a matter of course, the quality control of the welding is rigidly maintained throughout the construction of the tank by means of radio graphic tests, ultrasonic testing, dye penetrating tests, etc. in accordance with the Code [4] and the standard [1] as shown in Table 2. In addition to these conventional methods, the tank design includes the control of the weld bead shape, as shown in Fig. 3.

Fig. 4 shows one instrument developed in order to check the weld bead shape, the pencil type sensor designed to measure the toe radius of the weld bead: the most influential geometric factor to the stress concentration factor Kt. This handy instrument is designed to be used at the construction site to quickly judge the soundness of the welding.

This concept is that Kt of weld beads is much influenced to fatigue strength, especially such a tank with stiffened plate structures and it should be well controlled by using a high constructing technique with the best inspection methods which are applicable to the actual construction. A histogram of the measured stress concentration factor Kt in the fillet welded joints on the full scale model is shown in Fig. 5(a). This figure shows that the stress concentration factor Kt of the model is well below the design requirement, and is a good shape compared with a conventional structure as shown in Fig. 5(b). NK has ourselves confirmed that the concept could be applicable to the actual prototype tanks "LEG Carrier M.V. Kayoh Maru".

The authors believe that the high inspection techniques are applicable to "IHI SPB tanks" of LNG carriers and they shall be resulted in an extremely few probability of occurrence of any fatigue failure of the tanks.

3.2. In-Service Inspection and Fatigue Reliability

Discussion on basic concept. Discussion was made on stresses to be restricted from the viewpoint of fatigue strength [3], but a quantitative evaluation of the temporal changes in damage probability under the severest conditions is carried out considering three conditions - mean stress to variable stress ratios of 1/2, 1/1 and 2/1 - for each case determined previously, and the effects of the Special Survey are also discussed here.

The values of parameters used in the discussion are given in Table 3, but considerations was given to crack life, dimensions of propagating cracks and discovery rate of cracks as probability factors for respective cases. That is:

a) Crack life was considered in that the logarithmic value of life follow a normal distribution, and the dispersion of the logarithmic value of life is constant irrespective of stress levels, the density function of crack life is substituted with a piecewise constant function by unit time for discretion, whereby the following vectors of crack generation probability were formed:

$$\mathbf{f} = (f_1, f_2, \ldots, f_i, \cdots) \tag{1}$$
$$f_i = f(i\Delta t)\Delta t$$

where

$f()$ is probability density function of crack life

Δt is unit time

b) In discussing the dimensions of propagating cracks, the uncertainty which is relevant to propagating cracks such as material constants governing the rule of crack propagation and form of load relating to stress is complex. However, the ratio of propagation life to reach the damage condition defined [10] to its dispersion is considered to be constant [11] here, and the uncertainty related to crack dimensions in the propagation process is considered with a discrete Markov chain model [11,12,13], whereby the following transition stochastic matrix for crack propagation was formed:

$$\mathbf{T} = (\, t_{ij}\,) \tag{2}$$

$t_{ij} = u_i \quad : i=j,\ i=1,2,\ldots,c-1$

$t_{ij} = v_i \quad : j=i+1,\ i=1,2,\ldots,c-1$

$t_{ij} = 1 \quad : i=j=c$

$t_{ij} = 0 \quad : otherwise$

where

c is defined damage condition

u_i is probability to retain in condition i

v_i is probability to transit from condition i to the next condition

Under the assumption above, the vector for the probability of crack dimensions when unit time n has elapsed can be expressed as shown below

$$\mathbf{A}_n = \sum_{i=1}^{n} \mathbf{f}\,\mathbf{E}_{11}\,\mathbf{T}^{n-1} \tag{3}$$

where

$\mathbf{E}_{11}$ is matrix unit

c) As regards the rate of discovery of cracks at inspection, if the following matrix is formed using the rate of discovery of cracks for each of the conditions of 1 through c referring to literature [14]:

$$\mathbf{D} = (\, D_{ij}\,) \tag{4}$$

$D_{ij} = D(a_i) \quad : i=j,\ i=1,2,\ldots,c$

$D_{ij} = 0 \quad : otherwise$

The probability vectors of crack dimensions $\mathbf{A}_n$ before the $k-th$ inspection at unit time n intervals and $\mathbf{A}'_{kn}$ after inspection can be expressed as shown below

$$\mathbf{A}_{nk} = \sum_{i=1}^{n} \mathbf{f}\,\mathbf{E}_{(k-1)n+1,1}\,\mathbf{T}^{n-1} + \mathbf{A}'_{(k-1)n}\,\mathbf{T}^{n} \tag{5}$$
$$\mathbf{A}'_{kn} = \mathbf{A}_{kn}\mathbf{D}$$

If we consider the effect of repair using a replace model, the following matrix of transitional probability for conditions by inspection history can be formed:

$$\mathbf{Q} = (\, q_{ij}\,) \tag{6}$$

$q_{11} = 1$

$q_{i1} = q_{i-1\,f} \quad : i=2,3,\ldots$

$q_{i2} = q_{i-1\,0} \quad : i=2,3,\ldots$

$q_{ii+2} = q_{i-1\,i} \quad : i=2,3,\ldots$

$q_{ij} = 0 \quad : otherwise$

where

q_{if} is damage probability between $(i-1)-th$ inspection and $i-th$ inspection

q_{i0} is probability of discovery and repair at the $i-th$ inspection

$q_{i\,i+1}$ is probability of unsuccessful discovery of crack at $i-th$ inspection

q_{if} is $c-th$ element of $\mathbf{A}_{in}$

q_{i0} is sum of elements from $1st$ to $(c-1)-th$ order of $\mathbf{A}_{in}\mathbf{D}$

Next, the probability vectors for the results of the inspection are as expressed in (8) if the initial vectors are set as shown below:

$$\mathbf{B}_0 = (0, 1, 0, \ldots) \tag{7}$$

$$\mathbf{B}_k = \mathbf{B}_0\mathbf{Q}^k = (b_f^{(k)}, b_0^{(k)}, b_1^{(k)}, \ldots, b_k^{(k)}, 0, \ldots) \tag{8}$$

where

$b_f^{(k)}$ is probability of having been damaged condition before $k-th$ inspection

$b_0^{(k)}$ is probability of discovery of cracks at $k-th$ inspection

$b_i^{(k)}$ is probability that cracks are not discovered at $k-th$ inspection for the inspection object, which has been used continuously since $(k-i)-th$ inspection

The logarithmic expression of cumulative damage at each time in the past determined by the above-mentioned procedure are shown in Figs. 6, 7, 8, 9 and 10. The broken lines in the figure show the transition of damage probability for a case in which an inspection is not carried out at all, and the solid lines show that for the case in which a detailed inspection is carried out at regular intervals of five years.

It can be seen from these figures that the probability of generating fatigue cracks in the face plates of main girders extremely low, because of the application of the requirements for suppressing the propagation of cracks in preference to the generation of cracks, and therefore they are so reliable that the condition of damage assumed in the "standard" would be hardly reached. In view of the fact that the stress level restricted by the "standard" for the generation of the cracks in the toe of boxing welds for main girder brackets and areas surrounding slots is lower than the stress level required for the face plates of main girder, the probability of generating fatigue cracks is higher than in the case of face plates of main girders, and therefore the probability of reaching the damage assumed in the "standard" is accordingly higher, yet reliability in this case is sufficiently high. Thus, fatigue design should be done in a well-balanced manner, taking both generation and propagation of cracks equally into account, and the same can be said about establishing standards.

Examples of application. When the subject comes to the effects of Special Surveys, which are carried out after ships are commissioned, readers are requested to refer to Figs. 6, 7, 8, 9 and 10 where the solid lines signify changes in cumulative damage when Special Surveys are conducted at regular intervals of five years.

Table 3 Value of Parameters Used for Calculating Cumulative Probability of Failure

	ring face		bracket toe		
	parent plate	butt joint	M.G. face	bracket plate	slot
mean stress	6.2		10.7	15.6	14.6
max. stress amp (kgf/mm^2)	12.4		10.7	7.8	7.3
Std. Dev. of ln(N)	0.4, 0.5 & 0.6				
max. crack length detectable	9.5(*1)		1.25(*2)		
min. crack length 100% detect	12.5(*1)		6.25(*2)		

*1) inspection by X-Rays
*2) inspection by Dye Penetrant

As regards the face plates of main girders, it is practically impossible to find the effects of periodical inspections on improving reliability to any appreciable extent from these figures, because the probability of damage is of an extremely low order. Furthermore, the change in the probability of damage occurring within the range of the service life normally considered is quite insignificant due to the restriction to stress under the crack propagation standard previously discussed: in addition, the propagation speed following the generation of cracks is relatively high. As a result, few effects of improving reliability by periodical inspection are expected. However, quite a high reliability has been established for the face plates of main girders by suppressing the probability of generating fatigue cracks to an extremely low level. This means, it is much effective that the face plates should be closely inspect during construction for securing a high reliability of the tanks. And it seems that inspection strategies and methods which had been applied to the actual tanks were well in accordance with the concept.

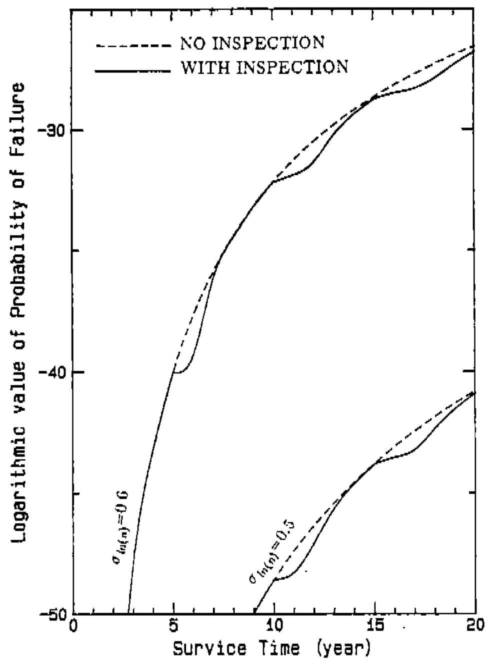


Fig. 6 Cumulative Probability of Failure of Ring Face (Parent Plate)

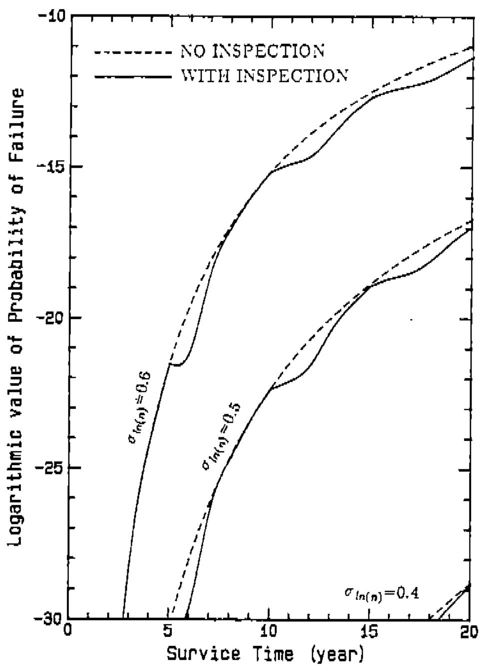


Fig. 7 Cumulative Probability of Failure of Ring Face (Butt Joint)

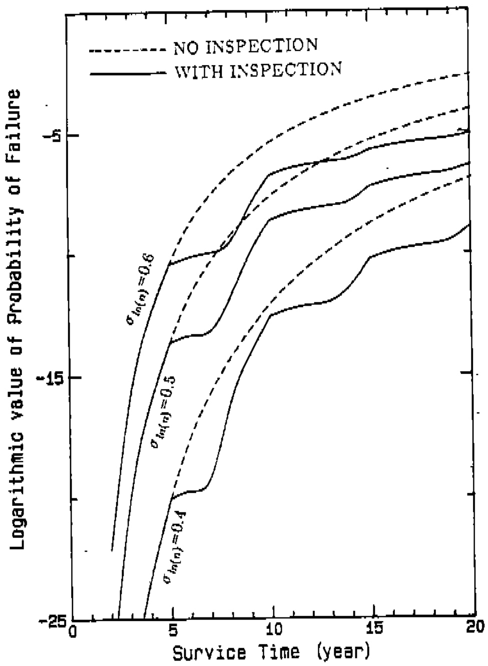


Fig.8 Cumulative Probability of Failure of Face Plate at Bracket Toe

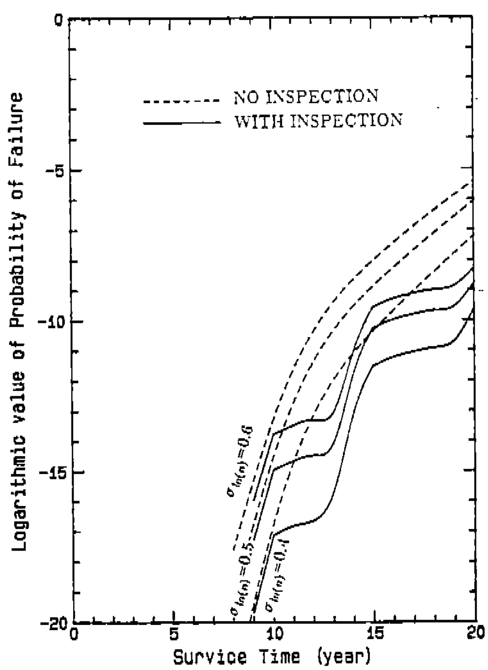


Fig. 9 Cumulative Probability of Failure of Slot

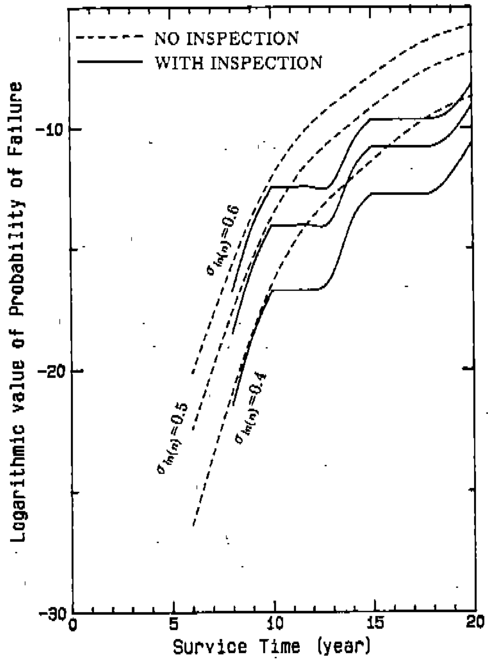


Fig. 10 Cumulative Probability of Failure of Bracket

As regards the generation of cracks at fillet welds of the bracket toes main girders and areas surrounding slots, sufficiently high reliability can be maintained by enforcing early detection of cracks through periodical inspections when the stress levels are kept low in accordance with the standard for generating fatigue cracks as described above. This means it is much effective that these structural elements should be closely inspected at the special surveys for securing a high reliability. Such informations should be given to persons concerned as a inspection guidance by designers of the tanks.

The assessments of the relationships among stress level generated, standard stress levels at each process of generating cracks and their propagation for each structural element, the assumption of reliability using simplified calculation procedures and the evaluation of the effects of inspection are considered to provide a useful guide for to and inspection programme.

Although this discussion focuses on each structural element, studies on an integrated structure formed by these structural elements are considered to be very important for a well balanced ship design if priority research areas are appropriately determined taking into account the degrees of importance of structural members and elements.

3.3. Comparison of Inspection Strategies and Methods for Prismatic Tanks Type B and Hull Structures

Prismatic tanks as well as hull structures are of a structure consisted of large plates stiffened with internal members such as stiffeners, girders etc. and both of the structures have the same structural properties of the strength for bearing on loads. Therefore a conventional prismatic tank is designed generally in accordance with a design standard of conventional hull structures, and such a tank is defined as type A by the Code [4].

However prismatic tanks type B are designed in accordance with a high class design standard as described in Chapter 2.

Table 4 Comparison of Inspection Strategies and Methods during Construction to Hull Structures and Prismatic Tanks Type B

Items	Conventional Hull Structure	Prismatic Tank Type B $^{N.B.}$
QC, tolerance etc. during construction e.g. (1) tolerance of thickness (2) mis-alignment	a conventional practice approved by Classification Society e.g. J.S.Q.S. [16)] $-0.7\ mm$ 0.15 thickness	a standard developed by a tank's designer being based on the highest class pressure vessel Code $0\ mm$ 0.1 thickness
general inspection during construction	generally, visual inspection at completion of each constructive stage e.g. block inspection, final inspection of a compartment	precise visual inspection at important stages during construction e.g. pre-inspection for important weldings, spot-check of weld bead shapes
X-ray, UT	spot-checks of important butt welds e.g. shell plates, upper deck plates etc.	all butt welds of tank skin and face plates of main girders
Surface crack detecting inspection	arbitrary checks where necessary	all fillet welds at bracket toes of main girders, nozzles and other openings of tank skin if any spot-checks of other welds
procedure test of welds	all welds	all welds
production test	--	all butt welds of tank skin and face plates of main girders
leak test	hose test, water pressure test, air-pressure test	air-pressure test
strength test	spot-check by water pressure test	hydro-pressure test for all tanks
gas test	--	gas detecting test for all tanks
full load test	--	all tanks using actual cargos

N.B. For prismatic tanks type B, inspection methods should be developed for each design of the tanks and approved by Classification Society etc. In this Table, there is shown an example developed as "IHI SPB Tank" [8)]

And the tanks are required to be so constructed and inspected as to have a high quality by the Code [4)] and the Standard [1)] e.g, main girders of the tank should be so inspected as to have a high reliability like as the highest class pressure vessels.

A comparison of inspection strategies and methods of prismatic tanks type B and hull structures is shown in Table 4. From Table 2 and 4, it is found that inspection strategies and methods of prismatic tanks type B is more severe than those of the hull structures. This is one of the bases for ensuring a high reliability of the tanks and it is clearly shown by a record of the seven ships with prismatic type B tanks as described in Chapter 4.

Such high inspection strategies and methods can be also applicable to hull structures in technical. It is of course preferable to be applied such strategies and methods to hull structures, but it is resulted in a high cost of the hull structures. Minimum inspection methods for ensuring safety to the hull structures are given by a recognized standard such as Classification Society Rules. The authors then stress that such a high technique of inspection methods shall be progressively developed to apply to the hull structures being based on a balance of economical efficiency and reliability. To this end, it is the most important that a high reliability ensured by the high inspection strategies and methods is quantitatively assessed, and this paper makes an attempt of such a quantitative assessment of prismatic tanks type B.

4. EVALUATION BY RECORDS OF SHIPS IN OPERATION

4.1. Ships Investigated

This study investigated 49 ships (7 ships with prismatic type B tanks) equipped with prismatic tanks shown in Table 1. In dealing with main girders, where very high levels of reliability, i.e. low rates of damage, are anticipated, as described in Chapter 2, but it was considered to be insufficient to prove if only those liquefied gas carriers given in Table 1 are applicable. Therefore, the main girders of large oil tankers, which can be regarded as having similar structural features, were included in the investigation. However, to eliminate the effects of degraded strength due to corrosion and wear, which are specific to oil tankers, an investigation was carried out on oil tankers aged 10 years or less. Through the comparison of design, tests and inspection methods, the reliability levels of strength for these types of ships can be arranged in descending order as shown in below:

Prismatic type B tanks >

Prismatic type A tanks >

Oil tanker

If we include ships with lower reliability, we can evaluate structural strength on the severe side.

4.2. Rate of Occurrence of Damage

The results of an investigation of rates of occurrence of various types of damage are shown in Table 5 to 8 with supplementary notes given be low:

1) Definitions

Critical failure of tank:

Failure associated with a large spill of cargo, scrapping of a tank, or damage requiring extensive repairs.

Failure of tank:

Failure to tanks other than above.

This includes damage to tank supporting structures, excluding strengthened plywood and supports forming part of the hull.

Critical failure of main girder:

Failure to main girders impairing their effectiveness and involving the risk of collapse when it develops. For example, large cracks running from face plates or bracket toes of the main girders to the web (with a length of 100 mm or more), or large deformations of strut bases. Although seldom occurring, such damage was occurred during the age when it frequently occurred on the main girders of large oil tankers(1965 - 1970).

Failure of main girder:

Failure to main girders other than above.

Failure of supporting structure:

Failure to tank-fitted or hull-fitted supporting structures and supporting members. Displacement stoppers are included.

2) Rate of occurrence of damage λ_F is defined by the following equation equation

$$\lambda_F = r/(N\Delta t) \quad :cases/tank\cdot year \tag{9}$$

where

r is number of cases of occurrence (discovery) of failure per tank. When different types of failure occur to a tank, they are calculated separately.

N is number of tanks observed

Δt is number of years of observations

If the occurrence of failures is random, i.e. the rate of the occurrence of failures per unit time λ_F is assumed to be constant, the interval between failures undergoes an exponential distribution, and hence the relationship can be expressed as below:

$$F(N\Delta t) = 1 - exp(-\lambda_F N\Delta t)$$

Therefore, the upper limit value of λ_F at least lower than the above value at a reliability level can be expressed by the equation below

$$exp(-\lambda_F N\Delta t) = 1 - \beta$$

When the number of failures $r=0$, the rate of occurrence of failure is assumed by

$$\lambda_F < r'/(N\Delta t) = -ln(1-\beta)/(N\Delta t) \tag{10}$$

Since the order of probability of the rate of occurrence of failures is the equation here, $\beta=-0.5(r'=0.7)$ is used.

Table 5 Failure Rate of Prismatic Tank

Kind of failure	No. of cases (r)	No. of obserb. ($N\Delta t$)	failure rate (λ_F)
failure on tank type A	10(*)	2128.5	4.7×10^{-3}
built before 1980	9	1785.0	5.0×10^{-3}
built after 1980	1	343.5	2.9×10^{-3}
failure on tank type B	0	220.8	--
failure on tank type A & B	10	2349.3	4.3×10^{-3}
critical failure on tank type A & B	0	2349.3	--
*) six cases of these resulted in a small gas leakage			

Table 6 Failure Rate on Main Girder(M.G.)

Kind of failure	No. of cases (r)	No. of obserb. ($N\Delta t$)	failure rate (λ_F)
Prismatic tank type A			
failure on M.G.	4	2128.5	1.9×10^{-3}
critical failure on M.G.	0	2128.5	--
Prismatic tank type B			
failure on M.G.	0	220.8	--
critical failure on M.G.	0	220.8	--
Tank of oil tanker*1)			
failure on M.G.	86	33709.0	2.6×10^{-3}
critical failure on M.G.	0	33709.0	$<2.1\times10^{-5}$*2)
Total			
failure on M.G.	90	36058.3	2.5×10^{-3}
critical failure on M.G.	0	36058.3	$<1.9\times10^{-5}$*2)
*1) 232 oil tankers, mean ship's age 8.2 years			
*2) probability assumed by equation (10)			

Table 7 Failure Rate of Supporting Structure(*1)

Kind of failure	No. of cases (r)	failure rate (λ_F)
[for type A]		
supporting structure on tank(*2)		
built before 1980	4(*2)	2.2×10^{-3}
built after 1980	1(*2)	2.9×10^{-3}
supporting structure on hull		
built before 1980	33	1.8×10^{-2}
built after 1980	0	--
bearing materials		
built before 1980	4	2.2×10^{-3}
built after 1980	0	--
[for type B]		
all of the above three components	0	--
*1) Nos. of observation are the same as the table 6		
*2) these failures have been also accounted in the table 6		

Table 8 Reference of Failure Rate

Kind of failure	Failure rate
critical failure on pressure vessel	1.5×10^{-5} / vessel-year
failure on pressure vessel	1.1×10^{-3} / vessel-year
critical failure on pressure vessel for nuclear power	1.0×10^{-5} / vessel-year(*)
*) assumed value for risk assessment	

4.3. Example of Failures

The essential examples of the failures of prismatic tanks and tank supporting structures shown in Table 5,6 and 7 are as follows:

(1) Through cracks in tank plates

Fig. 11 shows examples of through crack in tank plating associated with a gas leakage.

(a) This is an example of cracks generated from the box welding at a scalloped areas of bottom girders developing into through cracks in the tank plating.
Tank end supporting structures are provided in the vicinity of the above, and the excessive support reaction forces and stress concentration due to the welded structure are considered to be the cause of the failure.

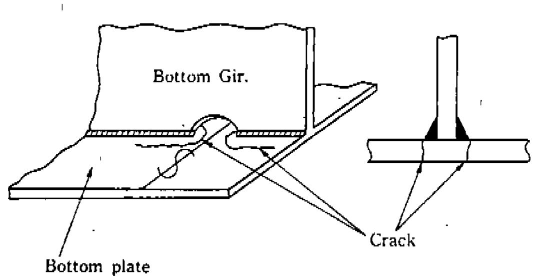


Fig. 11(a) Example of Failure Resulted in a Gas Leakage

(b) This is an extremely rare example of defects in workmanship, which were overlooked.

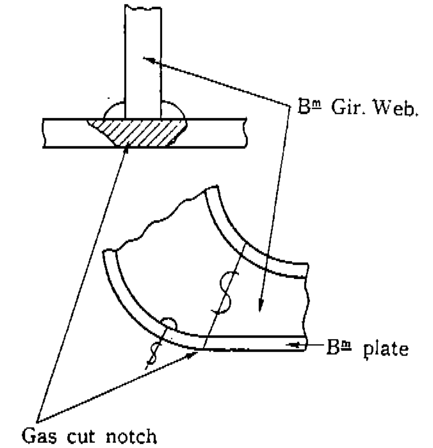


Fig. 11(b) Example of Failure Resulted in a Gas Leakage

(c) This is a failure related to supporting structures, and there are similar examples of failures of this type.

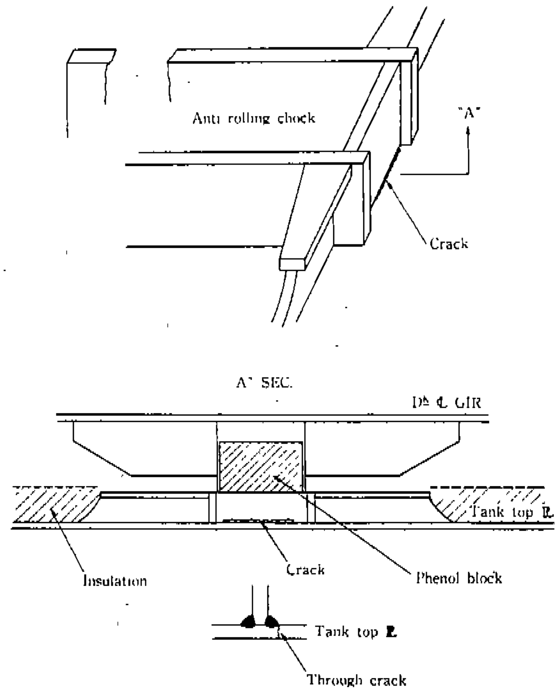


Fig. 11(c) Example of Failure Resulted in a Gas Leakage

To prevent these failures, the following measures are suggested:

(i) to predict support reaction forces adequately

(ii) to design support structures and peripheral structures in which reaction forces are properly dispersed

(iii) to perform proper-weldings and to check them high-stress area (adequate welding configuration and faultless welding)

(2) Failures on main girders

Although no serious failures have occurred in main girders, there are several examples shown in Figs. 12 and 13. It is considered possible to prevent the failure shown in Fig. 12 if an appropriate detail structure (installing collar plates etc.) is employed against high stressed, or if the proof strength of the area is improved. The fracture shown in Fig. 13 can be prevented if it is designed so that support reaction forces disperse properly.

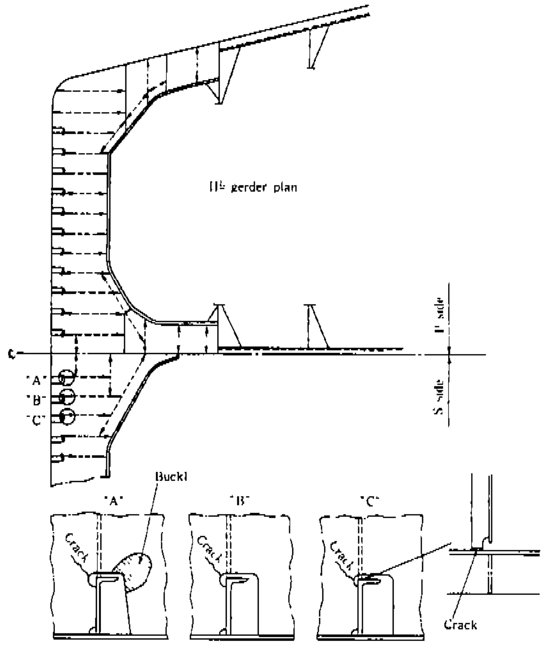


Fig. 12 Failure on Horizontal Girder of a Prismatic Tank

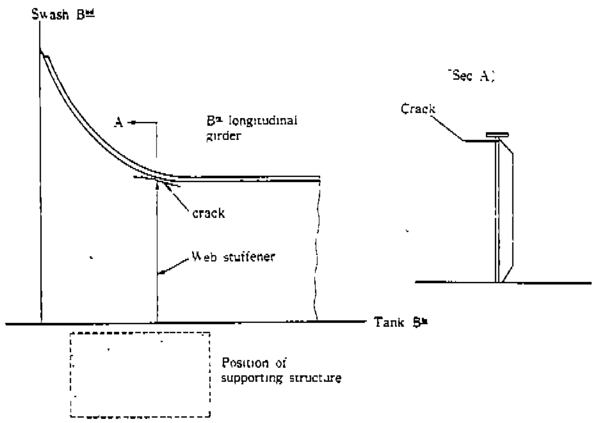


Fig. 13 Failure of Bottom Girder of a Prismatic Tank

(3) Failures of supporting structures

Examples of a failure of supporting structures are shown in Fig. 14. This type of failures have occurred frequently in a relative sense, but it can be prevented if the measures in (1)(c) are taken. Besides the above, failures of tank supporting materials such as strengthened plywood inserted into the space between the tank and supporting structure fitted to the hull occur due to an excessively large load. There are other examples of failures of supporting materials caused by the force created by the relative motions of the tank and hull due to thermal expansion and contraction, as a consequence of the lost clearance in supporting structures of top chocks and resultant loss of relative sliding motions.

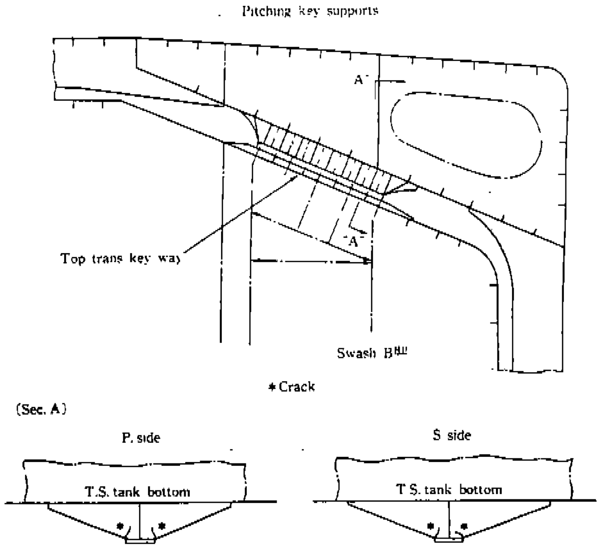


Fig. 14(a) Failure of Supporting Structures (Hull)

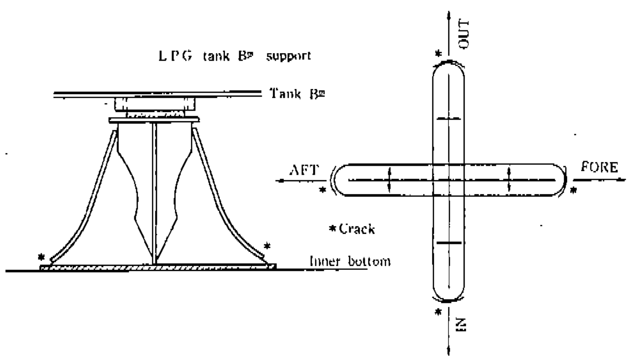


Fig. 14(b) Failure of Supporting Structures (Hull)

(4) Failures of tank stiffeners
As regards tank stiffeners, there is one case of failure involving hair-line cracks, which is mainly caused by defective welding during construction of a ship as shown in Fig. 15. According to information, the failure was discovered soon after commissioning and was repaired with reinforcements made, and there has been no recurrence. Such a failure can be prevented by a precise inspection. No failure of tank stiffeners in other tanks have been reported.

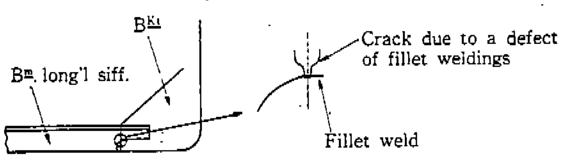


Fig. 15 A Failure on Tank Stiffener

4.4. Discussion

The important items of expertise obtained through the investigation of the records of ships in operation are as follows: .

a) Six among seven ships now in operation provided with prismatic type B tanks are aged about ten years. No failures of tanks and tank supporting structures have occurred in either of these ships.

b) As far as analogical inference is made from those shown in Table 6, the rate of occurrence of failures of main girders is comparable to the level of pressure vessels (critical failure: 10^{-5} /tank-year; other failures: 10^{-3} /tank-year). It is therefore considered that the basic philosophy of the "standard" described in Chapter 2, i.e. "the reliability of the strength of prismatic type B tanks is the same level as the highest grade of pressure vessels", which has been proved by evidence.

c) The overall records of ships equipped with prismatic types A and B tanks show that the rate of occurrence of failure of these tanks is nearly the same as those of pressure vessels (10^{-3} /tank-year, no serious failures at all), and this demonstrates that prismatic tanks have tank structures that are essentially highly reliable.

d) The characteristic facts that can be cited for prismatic type A tanks based on Table 5 or Table 7 are that the frequency of occurrence of failure of tanks and supporting structures has nose-dived since 1980 (14 ships in Table 5). Doubtlessly, this is attributable to each design and general improvement in shipbuilding technology, but we consider that the joint study [2] for establishing techniques to built ships equipped with prismatic type B tanks has had a corresponding contribution to this successful achievement.

e) The failures involving gas leakage shown in Table 5 were detected at an early stage and were repaired. (Four cases of cracks in tank plates in the vicinity of tank support structures, one case of cracks at scallop s of web of girders, and one case of gas cutting notch during construction).

f) Failures of tank supporting structures are more frequent in those fitted to the hull (33 cases), but this was due to the frequent recurrence of the same types of failures in the same ship (29 cases among 33 occurring in two ships).

5. CONCLUDING REMARKS

In this study, the principal strength analysis methods and tests and inspection procedures having important effects on the strength of prismatic type B tanks have been discussed on the basis of the design, inspection and construction records. Furthermore, an extensive investigation has been made on the records of ships in operation. As a result, the very high reliability of prismatic type B tanks has been proved with evidence, and at the same time the rationale of the "standard" serving as a design guidance including inspection strategies has been verified.

(1) In tanks of fully refrigerated liquefied petroleum gas carriers and one ethylene gas carrier (a prototype "IHI SPB tank") equipped with prismatic type B tanks, no failures have occurred. Since prismatic type B tanks are anticipated to be very reliable (i.e. extremely low rate of occurrence of failures), no quantitative evaluation can be made if the above recoeds alone are the basis. The records of other analogous structures were included as materials for evaluation, but it was proved that they have very high level of reliability as shown in Tables 5 and 6.

(2) A variety of design conditions (allowable stress for main girders, allowable values for cumulative damage, tests and inspection procedures for crack propagation analysis conditions) specified in the "standard" were judged to be appropriate as a consequence of our review of examples of applications to real ships, records of ships in operation and theoretical assessments.

(3) In the prospective application of prismatic type B tanks to liquefied natural gas carriers in the near future, it is considered to be feasible to design and build very reliable LNG carriers if they are done on the basis of experience gained with prismatic type A tanks and the philosophy of the "standard", while giving due consideration to the temperature difference with liquefied petroleum gas and ethylene, the difference in materials and large dimensions, etc.. Furthermore, there are many items requiring assessment other than tank strength in the case of LNG carriers, such

as thermal insulation, secondary barriers and related protection systems and others. However, an example of an LNG carrier with IHI SPB tanks now under planning shows that thorough assessments have been carried out on these problems [15). The authors of this paper, therefore, consider that prismatic type B tanks can contribute to the transportation of LNG, as well as to other excellent types of tanks.

The authors wish to acknowledge their deep indebtedness to the shipowners, shipbuilders and many other persons who rendered their assistance or gave valuable comments for this study.

The authors also acknowledge the contributions of shipyards and shipowners who decided to employ prismatic type B tanks.

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APPENDIX

Definition of independent tanks

Independent tanks are self-supporting; they do not form part of the ship's hull and are not essential to the hull strength. The three categories of independent tanks are defined hereunder.

Independent tanks type A:

Independent tanks type A are either prismatic or revolutional configuration tanks designed in accordance with the structural rules primarily using classical ship structural analysis procedures. This type of tanks require the provisions of the secondary barriers to protect the ship's hull to guard against their possible collapse.

Independent tanks type B:

Independent tanks type B are either revolutional configuration tanks or prismatic tanks meeting the design conditions specified in Chapter 2 of this paper. This type of tanks require partial provisions of the secondary barriers assuming possible collapse of tanks in part.

Independent tanks type C:

Independent tanks type C are revolutional configuration tanks meeting pressure vessel criteria designed to a sufficiently high vapour pressure. It is assumed, in design, that no liquid would leak from tanks, and no provisions of the second barriers are required.

R.A. Anderson

I was reading through the report regarding stress concentration factors for brackets and fillet welds. What correlation did you see between the test data and the actual structure?

N. Yamamoto

In general, welding conditions of model structures is considered to be better than the welding of actual structures, so I compare experience of major concentration factors of actual structures. If the issue is actual stress concentration factors of actual stressed welds, by comparison of Figures 5A and A-1, it is possible to achieve good quality control even in the case of actual fractures.