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STUDY ON FLAW ACCEPTANCE STANDARD OF ASME CODE SEC.XI BASED ON FAILURE PROBABILITY

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ABSTRACT

Based on the failure probability, the flaw acceptance standard of ASME Code Sec. XI is examined with some concerns weather the failure probability is uniform for flaws with various aspect ratios and failure frequencies are small enough. In this paper, the results of preliminary case studies are described on the failure probability of reactor pressure vessels (RPVs) with a surface flaw specified in Sec. XI. PFM code PASCAL was used for case studies. A PTS (Pressurized Thermal Shock) transient prescribed by NRC/EPRI PTS Benchmark Study was used as an applied load.

Analysis results showed that the conditional failure probability of a RPV with an initial flaw of acceptable depth depends on the aspect ratio. In the case flaw shapes are close to semi-circular, the failure probability are higher than that of the cases aspect ration are less than 0.6 by one order of magnitude due to the difference of fracture behavior at the surface point. A case study for determining the acceptable flaws based on failure probability was also carried out.

INTRODUCTION

A screening standard of small flaws, detected by ISI (In-Service Inspection), that have no significant influence on the structural integrity of Class 1 components through plant life is prescribed in the flaw acceptance standard of ASME B&PV Code Sec. XI [1]. This standard has been determined based on the postulated crack size in the design requirement for protecting a RPV (Reactor Pressure Vessel) against the non-ductile fracture. The acceptance standard for the RPV of an operating nuclear power plant was determined based on the flaw size of one tenth of the postulated crack size at design. Acceptable flaw depths for various aspect ratios were determined based on the stress intensity factor of each crack under a normal operational load [2].

Recently, on the other hand, a probabilistic methodology based on risk information is being introduced in regulations and codes related to the structural integrity in USA. Some concerns from the viewpoint of probabilistic methodology against the deterministic flaw acceptance standard are weather the failure probability is uniform for each flaw with different aspect ratio, failure frequency is small enough, and how the non-detection probability of inspection compares against acceptable flaws. Furthermore, the use of probabilistic methods in determining failure may provide more rational basis for the acceptable flaws. The failure probability based on the probabilistic approach may be a good index for determining the acceptable flaws.

In order to address the above issues, a study was initiated on the failure probability of a RPV with a surface flaw specified in the flaw acceptance standard of Sec.XI by using the PFM code PASCAL (PFM Analysis of Structural Components in Aging LWR) [3-6]. A PTS (Pressurized Thermal Shock) transient prescribed by NRC/EPRI PTS Benchmark Problem [7] was applied as a transient load. Analyses were performed for flaws with various aspect ratios with the parameter of neutron fluence. An evaluation of RPV with a flaw which has Marshall flaw distribution [8] was also performed to compare the failure probability. In addition, a study was also carried out to construct the acceptable flaws based on the failure probability.

CASE STUDIES ON FAILURE PROBABILITY OF A RPV

(1) Flaw Acceptance Standard of ASME Code Sec.XI

The flaw acceptance standard prescribed by Sec.XI is determined based on the postulated crack size in the design requirement of Sec.III for protecting a RPV against the non-ductile fracture. Specifically, the integrity of a RPV is confirmed using a postulated flaw size of depth equal to one-quarter of the thickness and aspect ratio of 1/3 (a/b, a: flaw depth, b: half surface length) at the service level A and B load, while the acceptable flaw size with aspect ratio of a/b=1/3 for the RPV of an operating plant is determined to be one-tenth of the postulated crack size at the design. For other flaws with different aspect ratios, acceptable depths are determined by making the stress intensity factors even.

It was confirmed that acceptable flaws of this standard give nearly uniform stress intensity factors for all aspect ratios under a normal operating load and that the stress intensity factors at the deepest point is larger than that of the surface point up to aspect ratio a/b=0.8, while the stress intensity factor at the surface point becomes larger than that of deepest point above a/b=0.8 [2].

Figure 1 shows the acceptable flaw depth of ferritic vessels with wall thickness of100mm to 300mm. The acceptable flaw depths are about 2 % to 5 % of wall thickness depending on the aspect ratio. As shown in Fig. 1, the original standard established in 1974ed. was altered to accept deeper flaws in high aspect ratios in the revision of 1983ed.

(2) PFM analyses on the flaw acceptance standard of ASME Code Sec. XI under a PTS transient

Pressurized Thermal Shock (PTS) is considered to be one of the most severe events for a RPV of PWR. The integrity of a RPV has to be secured even under such events. In this study, analyses of failure probabilities of a RPV with a flaw which meet the acceptance standard was performed under a severe PTS transient which was used by NRC/EPRI PTS benchmark study [7]. This PTS transient is determined by USNRC as representative of PTS events. In addition, the failure probability of a RPV with the flaw depth of Marshall distribution [8] shown in Table 1 is also examined. The frequency of Small Break Loss of Coolant Accident (SBLOCA) was evaluated to be 10^{-4} to 10^{-3} per reactor year by the review of initiating event in USA [9]. The SBLOCA is one of the initiating events of PTS and a postulated pipe break of a small bore piping is applied to assess the integrity of RPV. The frequency of the transient applied in this study, which causes more severe load than that of the SBLOCA, may be around 10^{-4} per reactor year or lower.

Analysis input for the geometry, material properties and other parameters are shown in Table 1. Figure 2 shows the input thermal hydraulic transient of NRC/EPRI PTS transient and the time history of stress distribution along wall thickness obtained by FEM analysis.

PFM code PASCAL [3-6], which has been developed in the flame work of the aging research program at Japan Atomic Energy Research Institute, was used for the analyses of failure probability. Based on Monte Carlo simulation, this code evaluates the conditional probability of crack initiation and failure (through wall crack) of a pressure vessel subjected to a transient loading. The time histories of temperature and stress distribution along the wall thickness were obtained by an input data generator of PASCAL. Figure 3 shows the time history of stress distribution.

Four cases of PFM analyses were performed as shown in Fig.3. In Case 1 and Case 2, the analyses of failure probability of a RPV with initial flaws of the acceptable depths in Sec.XI or a flaw with Marshall distribution[8] were carried out. In Case 1, the incremental crack extension both in the surface and thickness directions are evaluated. As Case 1 analysis exactly follows the crack extension process, a reliable semi-elliptical crack extension behavior can be obtained. On the contrary, in Case 2, the crack initiation at the deepest point of initial surface flaw is evaluated and the initial flaw is replaced by an infinite crack subsequently to the crack initiation at the deepest point. Case 2 simulates the failure analysis in which the crack initiation only at the deepest point is considered and corresponds to the acceptable flaw sizes with aspect ratios 0.0 to 0.8.

For Case 1M and Case 1Mac shown in Fig.4, the analysis of a RPV with an initial flaw of Marshall depth distribution was carried out. In Case 1Mac, the upper truncation of flaw depth was set at the acceptable flaw depth of ASME Sec.XI. Thus the analysis results with upper limit of acceptable flaw depths are compared with the case without upper limit.

In each case, one longitudinal surface flaw is assumed and the failure probabilities were calculated for some fast neutron fluence levels from 0.5 to 5.0 n/cm^2. Maximum fluence of 5.0 n/cm^2 was presumed to correspond to end-of-life-fluence of aged PWR RPVs.

In addition to the above probabilistic analyses, deterministic failure analyses were performed to compare the mean fracture toughness vs. temperature curves for different fluences with loci of stress intensity factors at the deepest point and surface point under the applied transient.

(3) Results of case studies

1) Deterministic analysis

Two cases of deterministic analyses with aspect ratios a/b=0.4 and 0.8 are shown in Fig. 5. In general, the stress intensity factor at the deepest point is larger than that of the surface point if the flaw aspect ratio is small and the stress intensity factor at the surface point increases with aspect ratio. As shown in Fig.5, the locus of stress intensity factor at the surface point for aspect ratio 0.8 is higher than that of the deepest point. On the other hand, the trend of the stress intensity factors are opposite to aspect ratio 0.8 in case of aspect ratio 0.4. Figure 5 also suggests that the neutron fluence about 5×10^{19} n/cm^2 is critical to cause the crack initiation at the surface point for aspect ratio 0.8. For other cases, the crack initiation does not happen deterministically.

2) Failure probability of a RPV with an initial flaw of the acceptance standard by ASME Sec.XI

Figure 6 shows the failure probability of a vessel with an initial flaw of acceptable flaw for various aspect ratios. The failure probabilities scatter about one order of magnitude. This means that even though the stress intensity factors of initial flaws for various aspect ratios against an operational load, failure probabilities are not uniform under a severe PTS event. The failure probabilities for aspect ratio of 0.1 are minimum and those for 0.8 are maximum. The difference between two curves is nearly one order of magnitude in low fluence.

Figure 7 shows the failure probability vs. aspect ratio to determine the dependency on the initial flaw aspect ratio for Case 1 and Case 2. Both cases give identical and reasonably uniform failure probability up to aspect ratio 0.6. On the other hand, above 0.6, the difference in failure probabilities is large. In Case 1, the crack initiation and incremental crack extension analyses both in the surface and wall-thickness direction performed, while the crack initiation at the surface point is not taken into account in Case 2. As Case 1 follows crack initiation and extension conscientiously, Fig. 7 indicates that Case 2 analysis gives an unconservative evaluation of failure probability for aspect ratio above 0.6 under a severe PTS transient. The maximum difference between Case 1 and case 2 is larger more than one order of magnitude.

As described in 2.1 and 2.2, the acceptable flaw depths up to aspect ratios 0.8 are determined by the stress intensity factor at the deepest point under a Service Level A and B, and Case 2 simulates the failure analysis in which the crack initiation only at the deepest point is considered, the discrepancies of failure probabilities at aspect ratios 0.6 to 1.0 as shown in

Fig. 7 reveal that the flaw acceptance standard for surface flaw allows this difference of failure probability under a severe PTS transient. Thus, the discussion by which transient should be applied for determining the acceptable flaw depth should be important, because the determination of acceptable flaw depth depends on applied transient.

A slight dependency on the fluence level can also be seen. This dependency is caused due to the difference of fluences between surface and deepest points.

3) Failure probabilities of a RPV with an initial flaw depth of Marshall distribution

In order to study the influence of flaw depth distribution on the failure probability, a vessel with Marshall flaw distribution was examined. In this study, two cases, i.e., Case 1M and Case 1Mac, were examined. In Case 1M, failure probabilities of a RPV with Marshall distribution was calculated, while in Case 1Mac, Marshall distribution with an upper truncation at the acceptable flaw depth was examined.

The failure probabilities for Case 1M and Case 1Mac are compared in Fig.8. It is seen that the failure probabilities in Case 1Mac are smaller than that of Case 1M by the 1 to 3 orders of magnitude. This means that the standard of Sec.XI allows a flaw which gives the lower failure probability of 1/100 to 1/10 than that by Marshall flaw distribution.

STUDY ON THE CONSTRUCTION OF ACCEPTABLE FLAWS BASED ON FAILURE PROBABILITY

As described above, it was shown that the failure probabilities of a RPV with an initial flaw of the acceptable depth specified in Sec.XI were not uniform under the PTS transient and depended not only on the flaw aspect ratio but analysis algorithm (Case1 or Case2). From the concept of probabilistic methodology, it may be reasonable to define the acceptable flaw against a severe load applied to an aged RPV, because an aged RPV has to secure the integrity under such condition. Based on this premise, a modification of the acceptance standard of Sec.XI is studied as described below.

The mean failure probability at the neutron fluence of 5.0×10^{19} n/cm^2 for initial flaw depths with aspect ratio a/b= 0.0 to 1.0 was used as the target failure probability presuming that the fluence of 5.0 n/cm^2 corresponds to end-of-life-fluence of aged PWR RPVs. The flaw depth for each aspect ratio was determined by sensitivity analyses.

In Fig. 9 the acceptable flaw depth vs. aspect ratio determined by this study are compared with that of Sec.XI. Flaw depths are smaller than those of Sec. XI above aspect ratio 0.7, while deeper flaws than those of Sec.XI can be accepted below 0.6. As the acceptable flaw depth is determined at the fluence level of 5×10^{19} n/cm^2, the dependency of failure probability on neutron fluence is examined as shown in Fig.10. In Fig. 10, the conditional failure probability of a RPV with an acceptable flaw by Sec.XI shown in Fig.7 is also compared. Though failure probabilities are constant for all aspect ratios of fluence 5.0×10^{19} n/cm^2, failure probabilities are not constant and a small deviation from constant value is seen below fluence 5.0×10^{19} n/cm^2. The deviation from a constant failure probability of each fluence depends on fluence level. This deviation becomes slightly larger for lower fluence. A comparative difference exists in neutron irradiation embrittlement, namely fracture toughness, between surface point and deepest point due to attenuation of fluence along vessel wall. This difference in fracture toughness between surface point band deepest point is largest in the case of fluence 0.5 $\times10^{19}$ n/cm^2. Though this situation may result in the above deviation in failure probability, the deviation is not significant because the failure probabilities are reasonably uniform for all fluences.

CONCLUSION

A preliminary study for establishing the flaw acceptance standard based on failure probability was described. The flaw acceptance standard of ASME Code Sec. XI has been examined from the viewpoint of failure probability under a severe PTS transient by using PFM code PASCAL. The failure probabilities of a vessel with an initial flaw specified by ASME Code Sec. XI and subjected to the same fluence considerably depends on the initial flaw aspect ratio. The result of case studies shows that the crack initiation at the surface point of a semi-elliptical flaw is significant under a PTS load if the flaw aspect ratio is large. Thus, the discussion by which transient should be applied for determining the acceptable flaw depth is important.

The results for the case on a RPV with Marshall flaw distribution suggests that the acceptance standard of Sec.XI allows a flaw which gives the failure probability of 1/100 to 1/10 than that described by Marshall flaw distribution.

A study to construct the acceptable flaw standard based on failure probability was also investigated. In this study, flaw depths with different aspect ratios which gave a constant failure probability were determined under the PTS transient at the neutron fluence of 5×10^{19} n/cm^2.

Though the results obtained by this study suggest that the acceptable flaw can be determined more rationally based on failure probability, following items should be examined as the future works for establishing the revised flaw acceptance standard based on failure probability.

- Study on the role of overlay cladding
- Study on the effect of application of elasto-plastic fracture criterion on the crack arrest behavior in upper shelf temperature.
- Discussion of the applied transient, i.e., Service level A, B or C, D, for determining the acceptable flaw depth

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Table 1 Analysis condition

Geometry of pressure vessel	2286mmID, 228.6 mmT, (Effect of overlay cladding is not considered)
Chemical compositions	Cu content:0.2 wt%, σ=0.02wt% Ni content:1.0 wt%, σ=0.05 wt%
Material properties	Initial RT_{NDT}; -38.92 ℃, σ=9.444 ℃ Evaluation of ΔRT_{NDT}; Eq. By RG1.99, σ=0.0 ℃ Fracture toughness K_{IC}/K_{Ia}; Mean curves by USNRC with σ=15 % of mean value
Evaluation of fluence attenuation	Eq. By USNRC RG1.99, σ=30% of mean value
Initial flaw geometry and distribution	Flaw orientation: longitudinal Flaw depth: Flaw acceptance standard by ASME Code Sec.XI and Marshall flaw depth distribution; Flaw depth density= $\lambda \exp(-\lambda a)$ λ=0.16 mm^{-1}, a: Flaw depth
Transient of PTS	Exponentially decreasing fluid temperature at the inner surface: Initial temperature; 288 ℃, Cooling rate; 0.0025℃/s Pressure: 6.895 MPa(constant)

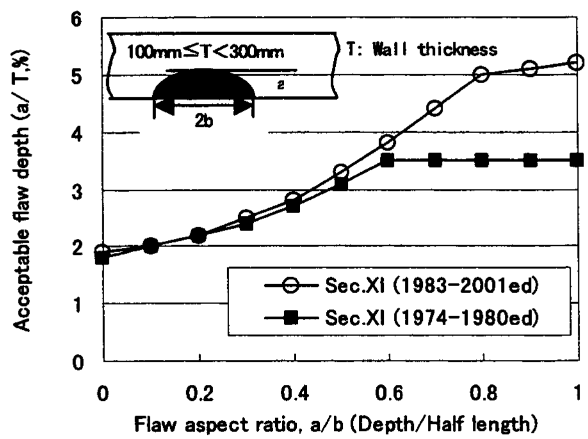


Fig.1 Acceptable surface flaw depth vs. aspect ratio for RPV in ASME Code Sec.XI (1974ed-2001ed)

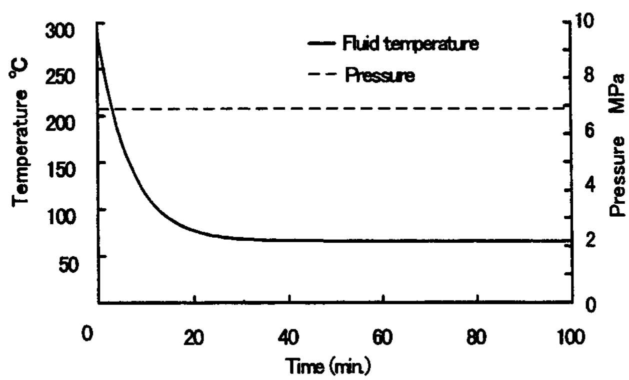


Fig.2 Transient of fluid temperature surface temperature and pressure

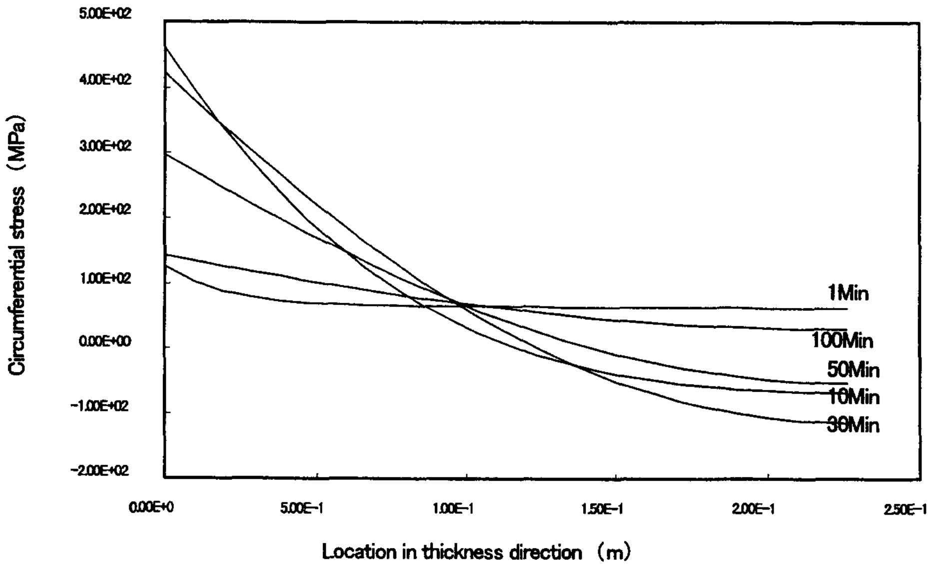
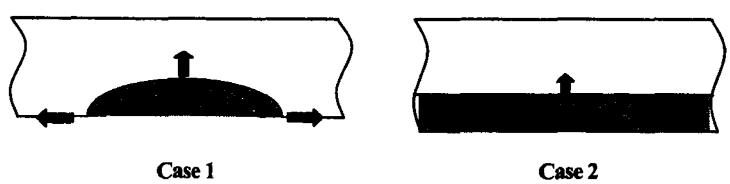


Fig. 3 Stress distribution during the PTS transient



Case 1: Incremental crack extension both to the surface and thickness direction is evaluated. An exact crack extension behavior can be followed.

Case 2: Crack extension only to thickness direction is evaluated. The initial flaw is replaced by an infinite edge crack subsequent to crack initiation. (Simple simulation of failure at deepest point)

Initial flaw for various aspect ratios:

Case 1; Initial flaw with acceptable depth by ASME Sec.IX
Case 1M; Initial flaw depth with Marshall distribution
Case 1Mac; Initial flaw depth with Marshall distribution with an upper truncation at the flaw depth of ASME Sec.XI.
Case 2: Initial flaw with acceptable depth by ASME Sec.XI

Fig 4 Analysis cases to determine failure probability

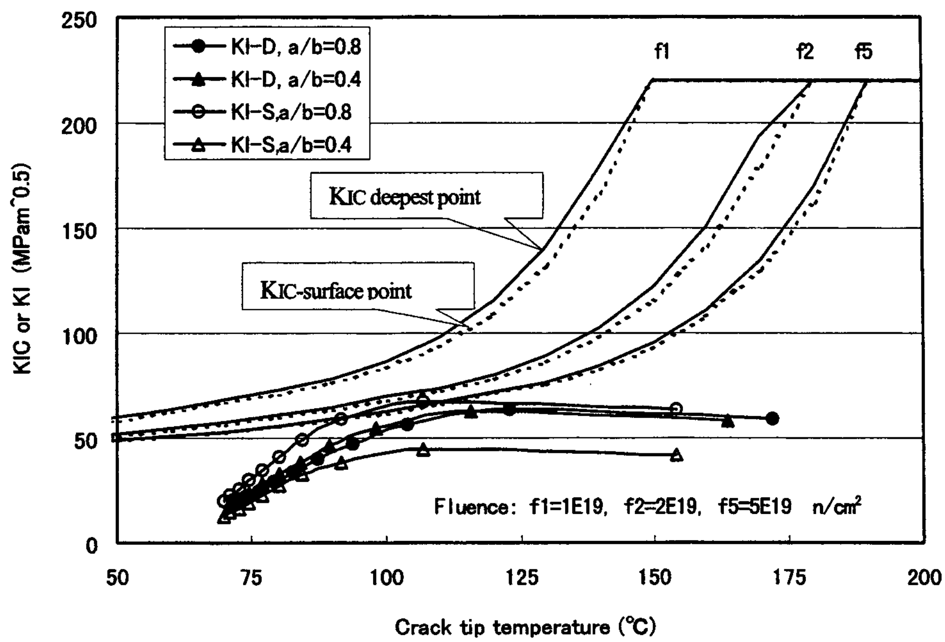


Fig.5 Results of deterministic failure analysis for initial flaws with aspect ratio 0.4 and 0.8

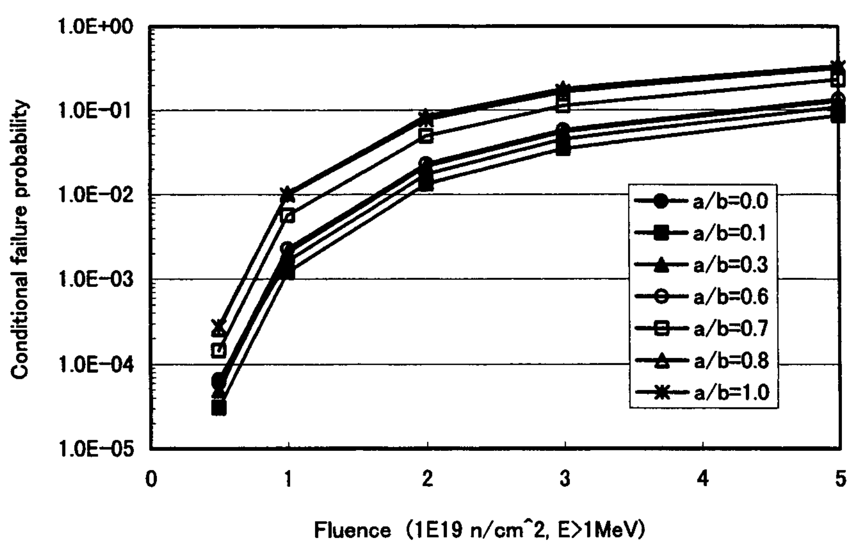


Fig.6 Conditional failure probability (Case 1) of a RPV with an acceptable flaw of ASME Code Sec.XI

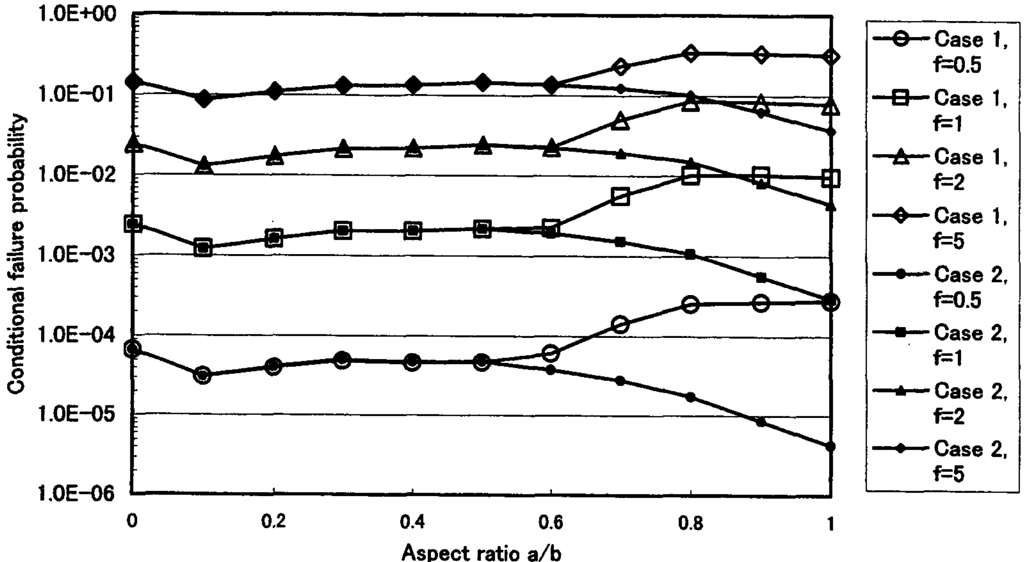


Fig.7 Comparison of failure probabilities between Case 1 and Case 2

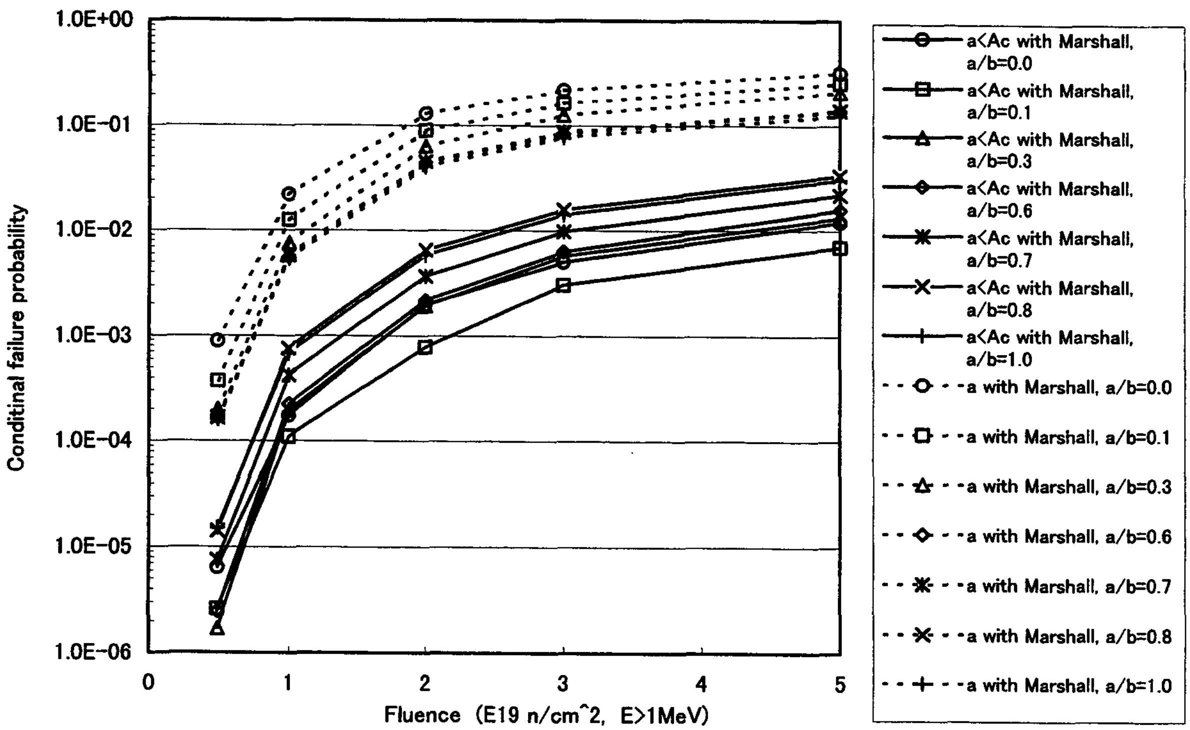


Fig. 8 Comparison of failure probabilities between Case 1M and Case 1Mac

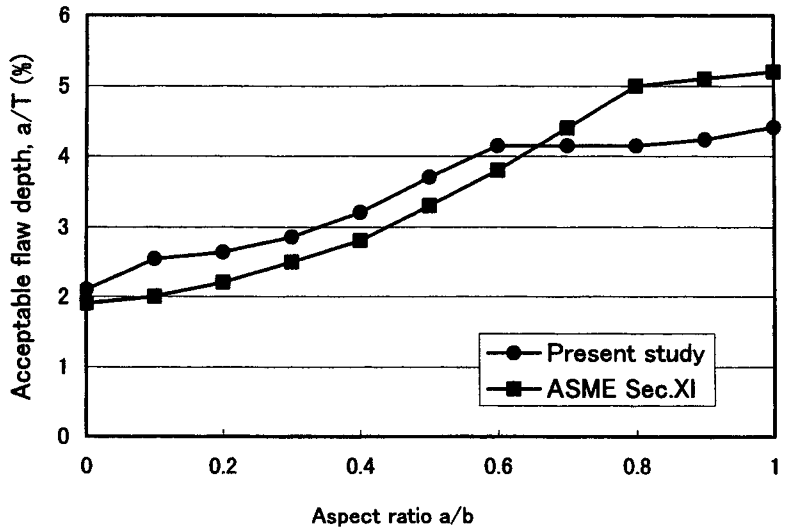


Fig.9 Comparison of acceptable flaw depths in Sec,XI and by the present study

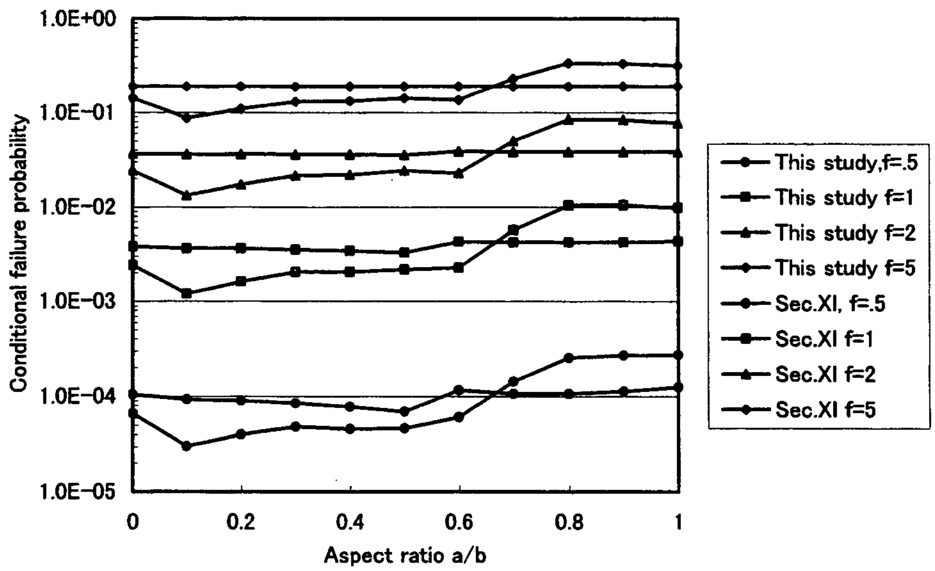


Fig.10 Comparison of failure probability vs. aspect ratio curves between ASME Sec.XI and present study