Elastoplastic Finite Element Analysis of Cracked Nuclear Pressure Vessel under Proof Loading†

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Abstract

Three dimensional elastoplastic finite element analysis of a semi-elliptical surface crack in the axial direction at the inner surface of a nuclear pressure vessel is made to clarify the fundamental aspects of its elastoplastic behavior under proof loading. This analysis is originally concerned with SR cracking at the overlay part of the inner surface of a nuclear pressure vessel. By extending this investigation, it is hoped that the re-examination of the ASME Boiler and Pressure Vessel Code is possible.

1. Introduction

This paper describes the elasto-plastic finite element analysis of a semi-elliptical surface crack at the inner surface of a nuclear pressure vessel under proof loading. As is well known, *SR* cracking sometimes occurs at the stainless steel overlay part at the inner wall of a nuclear pressure vessel. Therefore, many efforts have been made to prevent such cracking from the standpoint of welding fabrication. But on the other hand it is required of the structural engineer that he performs a structural design which can guarantee safety even if such cracks are not detected by NDI. This paper analyzes the surface crack from the standpoint of a structural design. The most frequently cited code in practical structural designs of nuclear pressure vessels is ASME Boiler and Pressure Vessel Code. In its 1972 Appendix G the concept based on fracture mechanics was introduced into the design code, and in its Sect. XI, evaluation method of flaw indications based on fracture mechanics was codified. In Sect. XI, all flaw indications detected in pre-service inspection or in-service inspection, are reduced to equivalent semi-elliptical or semi-circular cracks to compare with allowable maximum crack size. And in Sect. III Appendix G, such maximum crack as its depth being 1/4 of the thickness, and length being 1.5 of the thickness for thicknesses between 4 inches and 12 inches, is assumed to judge the strength against brittle fracture by comparing with reference stress intensity factor value. In this paper, the elastoplastic analysis of a semi-elliptical surface crack in the axial direction is made under proof loading condition by referring to these Codes. Further, two methods, Yamada's method[1)] and Marcal's method[2)] which are both typical methods of elastoplastic finite element analysis, are used and compared.

2. Numerical Analysis

2.1 Input Data on Geometrical Configurations

A pressure vessel cylinder of a 1100 MWe nuclear pressure vessel is analyzed. The dimensions are inner radius R=3212 mm, and thickness t=156 mm. And a crack with length c=3a=93.6 mm and depth a=1/5t=31.2 mm is assumed by referring to the ASME Code. Further for the simplicity of calculations, the cylindrical geometry shown in **Fig. 1** is replaced by the rectangular prism with w=6c and l=280 mm shown in **Fig. 2.**

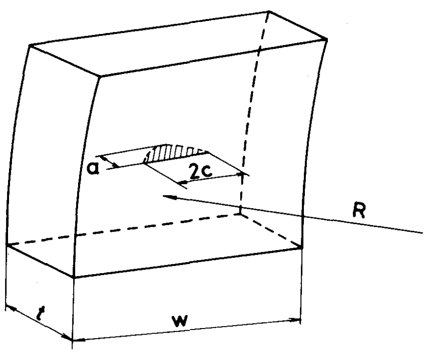

Fig. 1 Section of nuclear pressure vessel cylinder

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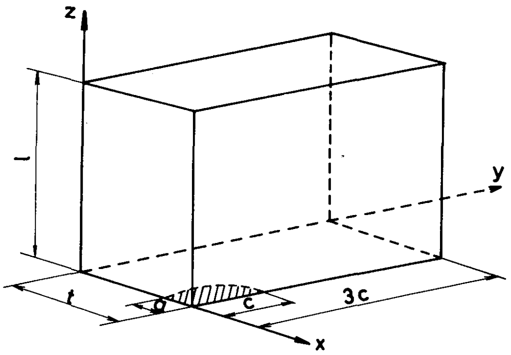

Fig. 2 Analyzed model

2.2 Input Data on Material Constants

The following material constants are assumed based on experiments; E=20300 kg/mm^2, ν=0.3, σ_y=33.0 kg/mm^2, H'=8.0 kg/mm^2.

2.3 Input Data on Proof Loading

The proof loading conditions are as follows; $\sigma_r=-1.1$ kg/mm^2 ($=\sigma_x$), $\sigma_l=10.8$ kg/mm^2 ($=\sigma_y$), $\sigma_t=23.4$ kg/mm^2 ($=\sigma_z$) at the inner surface (x=156) and $\sigma_r=0.0$ kg/mm^2 ($=\sigma_x$), $\sigma_l=10.8$ kg/mm^2 ($=\sigma_y$), $\sigma_t=22.3$ kg/mm^2 ($=\sigma_z$) at the outer surface (x=0) as shown in **Fig. 3**.

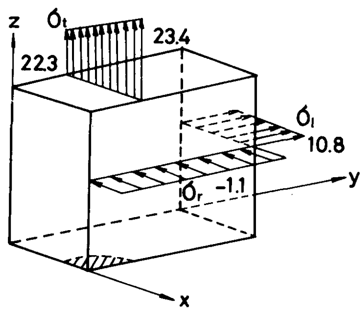

Fig. 3 Loading condition

2.4 Mesh Division

The following mesh division is employed; total number of units=14, total number of elements=635 (127×5), total number of nodes=498 (83×6), and the number of layers in z-direction=5 as shown in **Figs. 4** and **5**.

2.5 Elastoplastic Analysis

The finite element program used employs the unit divisioning method and Von Mises yield condition

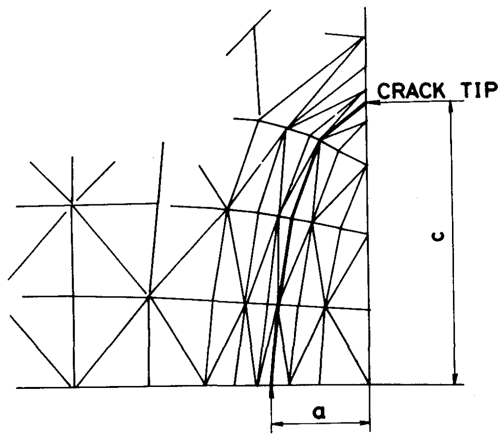

Fig. 4 Mesh division near crack

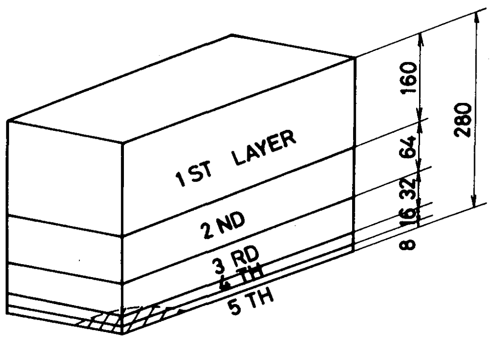

Fig. 5 Layer division

Table 1 Progressive yielding

INCRE	Newly Yield	Total Yield	⊿R	R	
0	1	1		0.7648	ELASTIC SOLUTION
1	0	1	0.05878	0.8236	
2	2	3	〃	0.8824	
3	0	3	〃	0.9412	
4	3	6	〃	1.0	LOAD GIVEN
5	2	8	〃	1.0588	
6	4	12	0.07648	1.1353	YIELDING SPREADS INTO 4TH LAYER
7	10	22	〃	1.2118	
8	11	33	〃	1.2882	
9	9	42	〃	1.3647	
10	10	52	〃	1.4412	YIELDING SPREADS
11	30	82	〃	1.5177	INTO 3RD LAYER
12	55	137	〃	1.5942	
13			〃	1.6171	NEARLY GENERAL YIELD

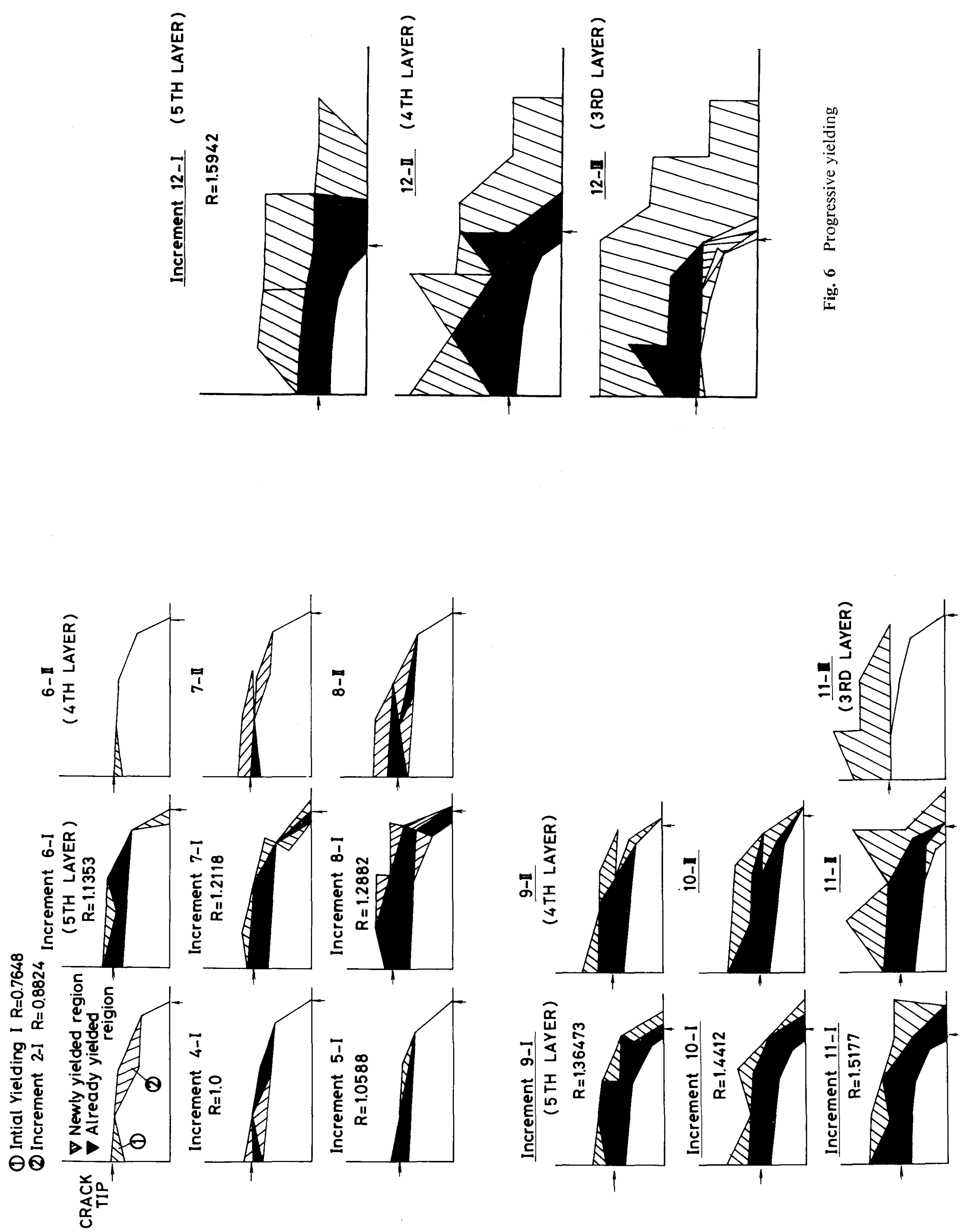

Fig. 6 Progressive yielding

is adopted. Two methods of elastoplastic analysis are used and compared; Yamada's method and Marcal's method.

3. Numerical Results

Table 1 shows how yielding occurs at each incremental stage. The column "newly yielded" means the number of elements newly yielded at that stage and the column "total yielded" means the total number of elements yielded up to that stage. ΔR denotes the load increment factor. In Marcal's method, the increment of load ΔL is given by $\Delta L = \Delta R \times$(the load given in section 2.3). R denotes the load ratio= the load at that stage/the load given in section 2.3. Although Table 1 shows the result obtained by using Marcal's method, almost identical result is obtained by using Yamada's method, except the column "ΔR" which is automatically determined in Yamada's method. **Fig. 6** shows how plastic zones spread. And **Figs. 7** and **8** show the stress distribution of σ_z along x axis and on the crack border respectively. **Fig. 9** shows the stress—strain (σ_z—ε_z) relation of the 615th element. **Table 2** shows the comparison of CPU time between Marcal's method and Yamada's method. Although Marcal's method seems to take more time than Yamada's in Table 2, this is due to the fact that Computer Center, University of Tokyo adopts the multi-programming system so that CPU time differs by whether files are used or not or by what kind of files are used or by what kind of jobs are run simultaneously, therefore it may be concluded

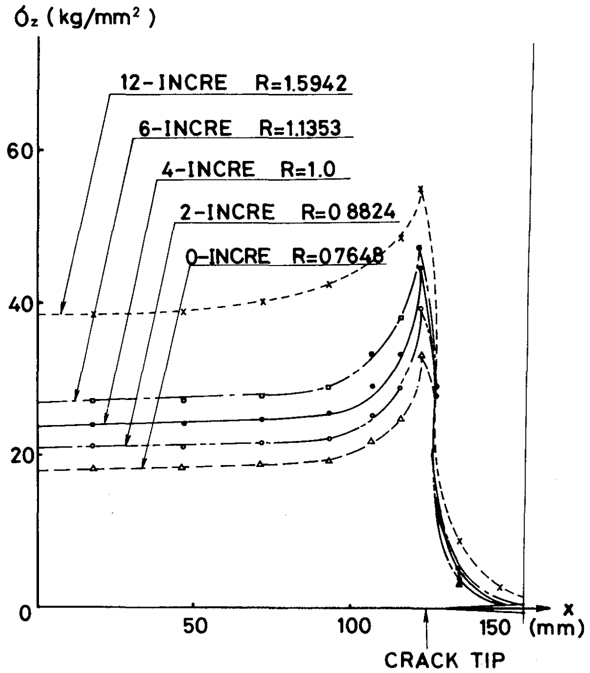

Fig. 7 Stress distribution of σ_z on x axis

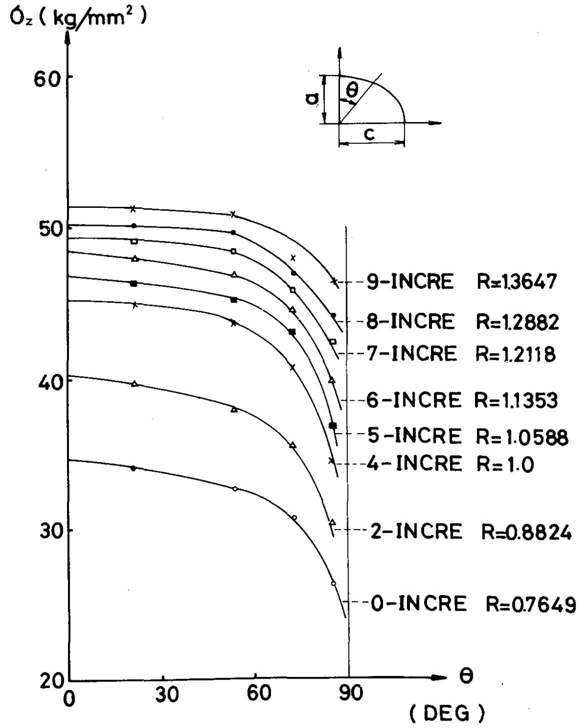

Fig. 8 Stress distribution of σ_z on crack border

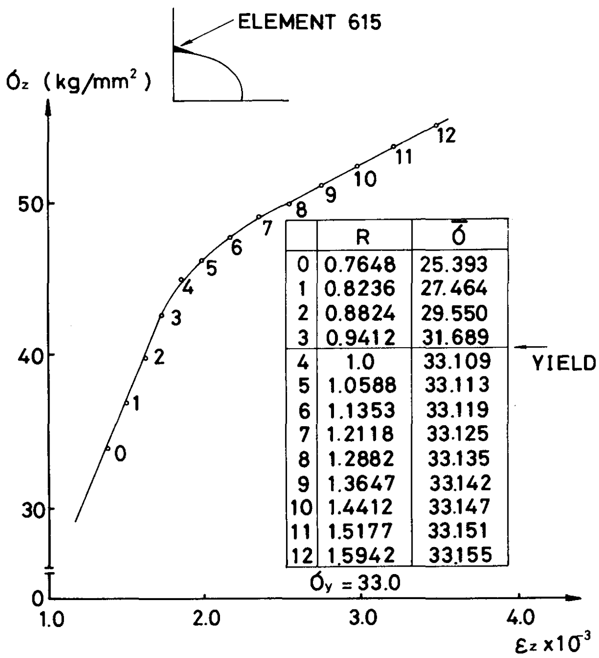

Fig. 9 Stress-strain ($\sigma_z - \varepsilon_z$) relation of 615th element

Table 2 Comparison of CPU time between Marcal's and Yamada's method

Increment	Marcal's method	Yamada's method
Incre 1	350 sec	353 sec
Incre 2	378	352
Incre 3	388	374
Incre 4	401	371
Incre 5	414	400

that at least for this job, there is no appreciable difference of CPU time between these two methods.

4. Summary

Elastoplastic finite element analysis of a semi-elliptical surface crack in the axial direction at the inner surface of a nuclear pressure vessel is made to clarify the fundamental aspects of its elastoplastic behavior. By extending this investigation, it is hoped that the re-examination of the ASME Code is possible.

References

1) Y. Yamada, N. Yoshimura and T. Sakurai, "Plastic stress-strain matrix and its application for the solution of elastic-plastic problems by the finite element method", Int. J. Mech. Sci., Vol. 10 (1968), p. 343
2) P.V. Marcal and I.P. King, "Elastic-plastic analysis of two-dimensional stress systems by the finite element method", Int. J. Mech. Sci., Vol. 9 (1967), p. 143