ASSESSMENT OF STRUCTURAL INTEGRITY OF MONJU STEEL LINER AGAINST SODIUM LEAKAGE AND COMBUSTION

- Modeling of Thinning Process of Liner due to Corrosion in Structural Analysis -

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ABSTRACT

The lining structure of LMFBR (Liquid Metal cooled Fast Breeder Reactor) has an important role to prohibit leaking sodium from touching a concrete floor in a sodium leakage incident. JNC (Japan Nuclear Cycle Development Institute) experienced a sodium leakage incident in 1995 in the secondary heat transport system room of the prototype LMFBR MONJU. In this incident, a part of the liner was covered with a certain amount of high temperature leaked sodium and its compounds. Visible but small distortion and thinning of the liner were detected, which were due to heating by sodium fire and chemical corrosion, respectively. To simulate the MONJU incident, JNC conducted a series of sodium leakage tests, in one of which severer corrosion (molten salt type corrosion) than that in the MONJU incident was observed. In order to secure the conservativeness in the integrity assessment of the liner, consideration of a severest corrosion process was demanded. This means that the loss of parts of the structure with time should be considered in the structural analyses. In this study a modeling of thinning process of the liner was developed in order to realize reasonable analysis from the point of view of actual phenomena. The concept of the method is to release the stress of the lost region by using artificial creep and reducing Young's modulus. The necessity of this kind of model and the validity was verified through an application analysis of the liner in the secondary heat

transport system room of MONJU.

INTRODUCTION

The lining structure of LMFBR (Liquid Metal cooled Fast Breeder Reactor) has an important role to prohibit leaking sodium from touching a concrete floor in a sodium leakage incident. Therefore, the integrity of the liner against this incident should be confirmed. JNC (Japan Nuclear Cycle Development Institute) experienced a sodium leakage incident in 1995 in the secondary heat transport system room of the prototype LMFBR MONJU[1]. In this incident, a part of the liner was covered with a certain amount of high temperature leaked sodium and its compounds. Visible but small distortion and thinning of the liner were detected, which were due to heating by sodium fire and chemical corrosion, respectively. To simulate the MONJU incident, JNC conducted a series of sodium leakage tests, in one of which severer corrosion (molten salt type corrosion) than that in the MONJU incident was observed[2]. Thinning of the liner at this incident was much smaller than that in the sodium leakage test where molten salt type corrosion occurred. However, consideration of a severest corrosion process in the integrity assessment of the liner was demanded to secure the conservativeness. This means that the loss of parts of the structure with time should be considered in the structural analyses.

Temperature analysis and strain analysis are needed for evaluation of structural integrity of the liner after determination of thermal loading conditions due to leaking sodium, and it is examined if the obtained maximum strain exceeds a certain strain limit or not. The thinning rate due to corrosion was modeled based on the upper bound of 95% reliability band of molten salt type corrosion test data for conservatism and was given as the function of temperature. The thinning process is considered only in the strain analyses, since the thickness of the liner is relatively thin. From the observation, in the early stage the thinning of the liner due to corrosion progresses gradually compared with the rise of temperature of the liner even if the thinning rate in case of molten salt type corrosion is assumed.

In this study a modeling of thinning process of the liner was developed in order to realize reasonable analysis from the point of view of actual phenomena. The concept of the method is to release the stress of the lost region by using artificial creep and reducing Young's modulus. The necessity of this kind of model and the validity was verified through an application analysis of the liner in the secondary heat transport system room of MONJU computed by 'FINAS'[3] (the name of general purpose finite element analysis program) equipped with this thinning model as users' subroutines.

MODELING OF THINNING PROCESS

CONCEPT OF METHOD

It is not easy to treat the processes of losing a part of whole structure and forming new surface in the structural analysis which is based on the continuum mechanics. In such a case, the object region of analysis changes with time. However, the equivalent equilibrium with this kind of phenomena can be attained in the structural analysis by releasing the stress of lost region of the structure artificially, while maintaining the initial object region of analysis. This approach has the similarity with the methods of structure optimization.

Fig. 1 illustrates the concept of this method. When the lost region in the figure vanishes during the time interval , the stress —' corresponding to the lost region is released with the whole region. This means that the stress at t_0 and the stress increment during are forced to be zero as expressed by following two equations.

—'$_0$ 0 @(—$_0$ ¤ 0) C— ' 0 @(E ¤ 0)

If iteration is adopted for every time increment to obtain the convergence, calculation can be done without the second condition in the above equations, since unbalanced force is corrected. However, the second condition should be added from the point of computation efficiency. When this method is applied to the finite element method, every integration point should be judged whether it belongs to the lost region or not at the time. In this study, in order to utilize the existing finite element analysis code without reconstruction if possible, we used artificial creep and reduction of Young's modulus as illustrated in Fig. 2(a) and (b). The lower part of Fig.2(a) shows the magnified figure of thinning part of the liner. V-shaped region is vanishing from n-th to (n+1) th step and gray points denote the integration points in this region. The upper region of V-shaped region has already vanished by n-th step and white points denote the integration points in this region. The lower region of V-shaped region is the existing region at (n+1) th step and black points denote the integration points in this region. Fig. 2(b) shows the behaviors of stress and Young's modulus from n-th to (n+1)th step at these three kinds of integration points.

The analysis function based on this method has been installed in the finite element nonlinear structural analysis system 'FINAS' [3].

APPLICATION TO SHELL ELEMENT

For functional check of shell element a simple problem was solved.

-finite element: QFLA4S ~ 5 (in x-direction)
(4-node quadrilateral shell element)

-material properties: E=10000 kgf/mm^2
¸ =0.3

-dimensions: see Fig. 3
L=50 mm, H=10 mm, t=10 mm
L_1=10mm (thinning region)
final loss of thickness: 4.4 mm

-boundary conditions:
x=0; $u_x=u_z=$ ˇ $_y=0$
x=50; u_x (common), u_z (common), ˇ $_y$(common), ˇ $_z=$ ˇ $_x=0$
y=0; $u_y=$ ˇ $_z=$ ˇ $_x=0$
y=10; u_y (common), ˇ $_z=$ ˇ $_x=0$

-loading condition;
1 step; displacement u_x=0.05 mm at x=50
2-11 step ; thinning process of 1st layer
12-26 step; thinning process of 2nd layer
27-46 step; thinning process of 3rd layer
46-71 step; thinning process of 4th layer

Fig. 4 and Fig. 5 show the analysis results. Fig. 4 shows the change of x-direction stress distribution along the thickness. It is confirmed that the stresses in lost region of each step are zero and stress distribution changes to satisfy the equilibrium condition.

Fig. 5 shows the change of x-direction stresses of 9 integration points distributed along the thickness. It is observed that the stress in the thinning layer relaxes to zero, the stresses in the lost region keep zero and the stresses in the existing region change to compensate the stress balance during each thinning stage of four. In addition resulted reaction forces coincided well with the theoretical prediction.

APPLICATION TO MONJU LINER

STRUCTURE OF THE LINER

The liner built in the secondary circuit piping system room of MONJU mainly consists of liner panel, frame and rib as shown in Fig. 6. The liner panel catches sodium and its compounds and prevents them from touching concrete floor. The frame supports the liner panel and the rib stiffens the liner panel.

OUTLINE OF ANALYSES

The area of 4500mm ~ 9000mm of the liner is considered and high temperature area due to leaking sodium is assumed by the elliptical area located on the center of the liner as shown in Fig. 7. Thinning area is also drawn in the figure by a circle whose radius is 1435mm. The region of analysis is a quarter of the whole region (0 X 2250, 0 Y 4500) considering symmetry as shown in Fig. 7 by hatching. The shape of the lost region, that is to say, cross section of the thinning area, is triangle as shown in the lower part of Fig. 2(a). The final depth and width of the triangular lost region are 3mm and 45mm respectively. The maximum temperature of the liner reaches 880 deg. of Centigrade at the top. The material of the liner is a carbon steel, SM400. Plasticity, creep and temperature dependency of the properties are considered in the analyses. The time histories of the temperature of high temperature area and the depth of lost region are given by Fig. 8. Before stress and strain analysis, temperature analysis is conducted in order to obtain temperature distribution of the liner and its history. Stress and strain analysis is conducted by using the result of temperature analysis as input data. Fig. 9 shows the finite element mesh model by the shell elements with deformed shape obtained by stress and strain analysis. Maximum strain appeared at the location pointed by the arrow in the figure.

RESULTS

Fig. 10 shows the out-of-plane (Z-direction) displacement distribution at around 500 sec. It is found that the high temperature region rises due to thermal expansion. Fig. 11 shows the inelastic strain distribution at top surface at around 500 sec with the detailed figure of the local area pointed by arrow in Fig. 9. It is found that the large strains are limited to very small area and most are below 2% in other area. The coordinates of the location are x=0 and y=1435.5mm of the liner panel which is close to the end of the rib.

Fig. 12, Fig. 13 and Fig. 14 compare the differences of inelastic strain behaviors at top and bottom surfaces of three kinds of analysis cases each other. The strain behaviors in Fig. 12 were obtained by the analysis without considering thinning. Those in Fig. 13 were obtained by the analysis using the ultimate thinned shape without consideration of the thinning process. And those in Fig. 14 were obtained by the analysis considering thinning process by present method. Comparing Fig. 12 with Fig. 14, the behaviors are similar in the early short period (0-500sec) because lost region is small (see Fig. 8), but the difference becomes significant especially at top surface after the period. On the other hand, the strain rise in the beginning period in Fig. 13 is very large compared with those of other two cases. The reason is inferred that the behavior at thinned area is strongly dominated by the circumferential movement due to thermal expansion, since the rigidity of this area is very small from the beginning in this case compared with other two cases.

DISCUSSION

The present method for modeling thinning process in the structural analysis is easy to equip in existing general purpose structural analysis programs, since ordinary creep function can be utilized in this method.

Through the application analysis, the validity of the present method was verified. For such structural analyses as those in which vanishing of material fairly proceeds simultaneously due to corrosion, melt, etc., the process of vanishing of material should be considered in the analyses, otherwise, it is possible to not only lose accuracy but also fail in catching the phenomenon.

CONCLUSION

The method for modeling thinning process of structures based on artificial creep and reduction of Young's modulus was developed in order to realize reasonable analyses from the point of view of actual phenomena. The necessity of this kind of model and the validity of the present method were verified through the application analysis of the liner in the secondary heat transport system room of MONJU.

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[3] FINAS (Finite Element Nonlinear Structural Analysis System) V. 13.0 Users' Manual, 1995, Japan Nuclear Cycle Development Institute (PNC TN9520 95-014) (in Japanese; Currently English version is available for V. 12.0. (PNC TN9520 95-013)).

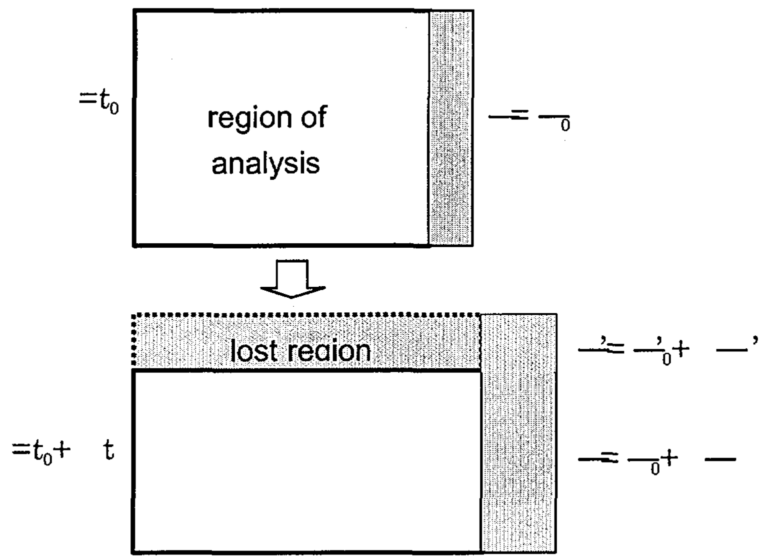

Fig. 1 Concept of the method

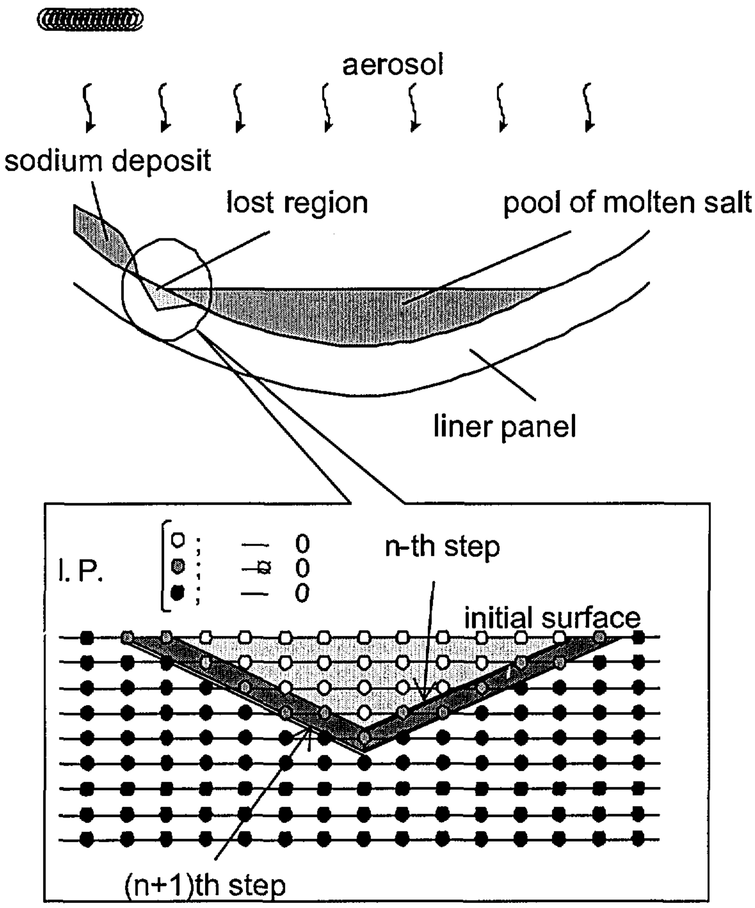

Fig. 2(a) Expression of thinning process of liner

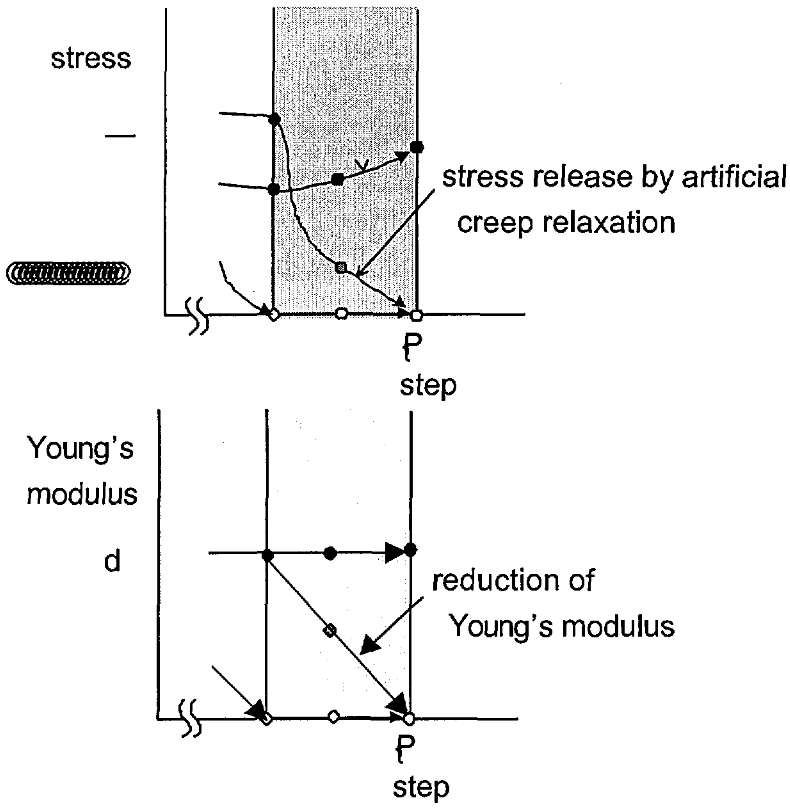

Fig. 2(b) Expression of thinning process of liner

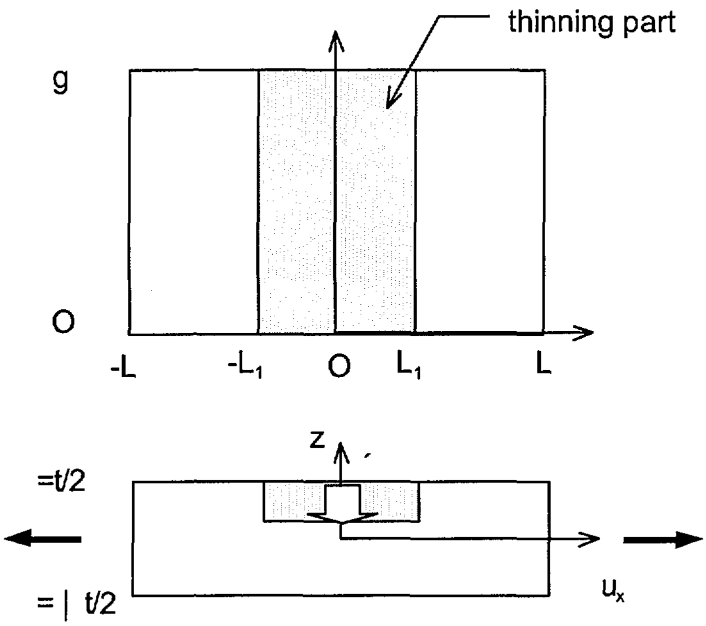

Fig. 3 shape and dimensions of plate

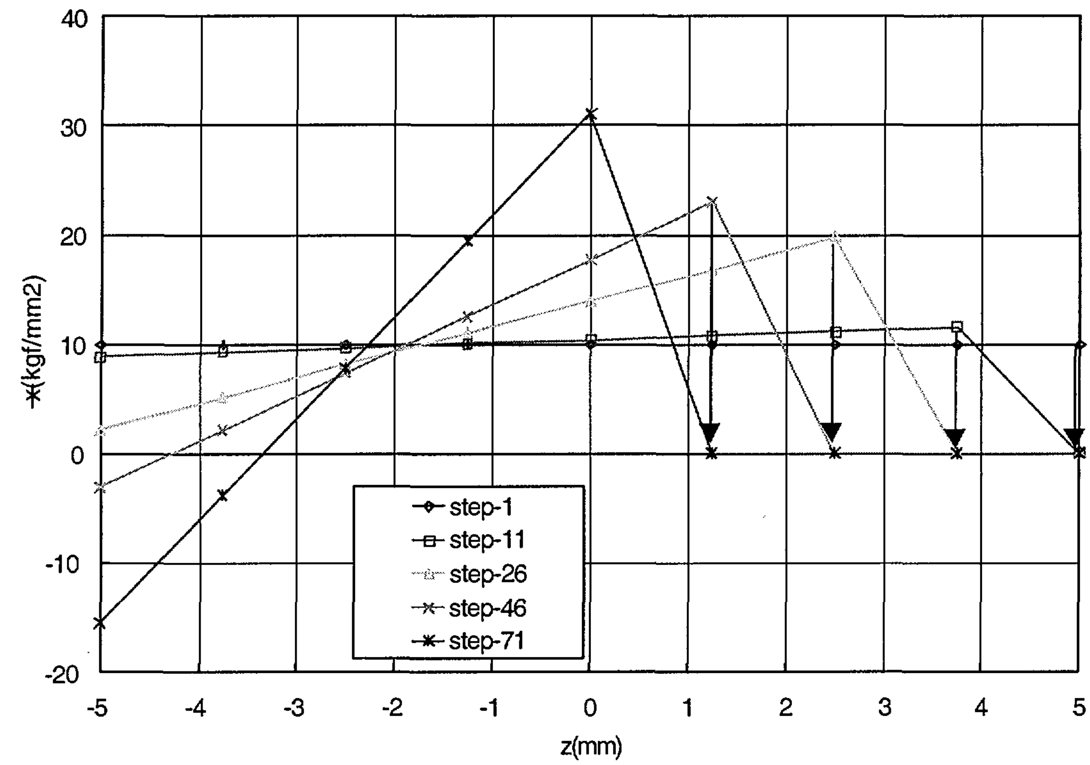

Fig. 4 Change of stress distribution along thickness

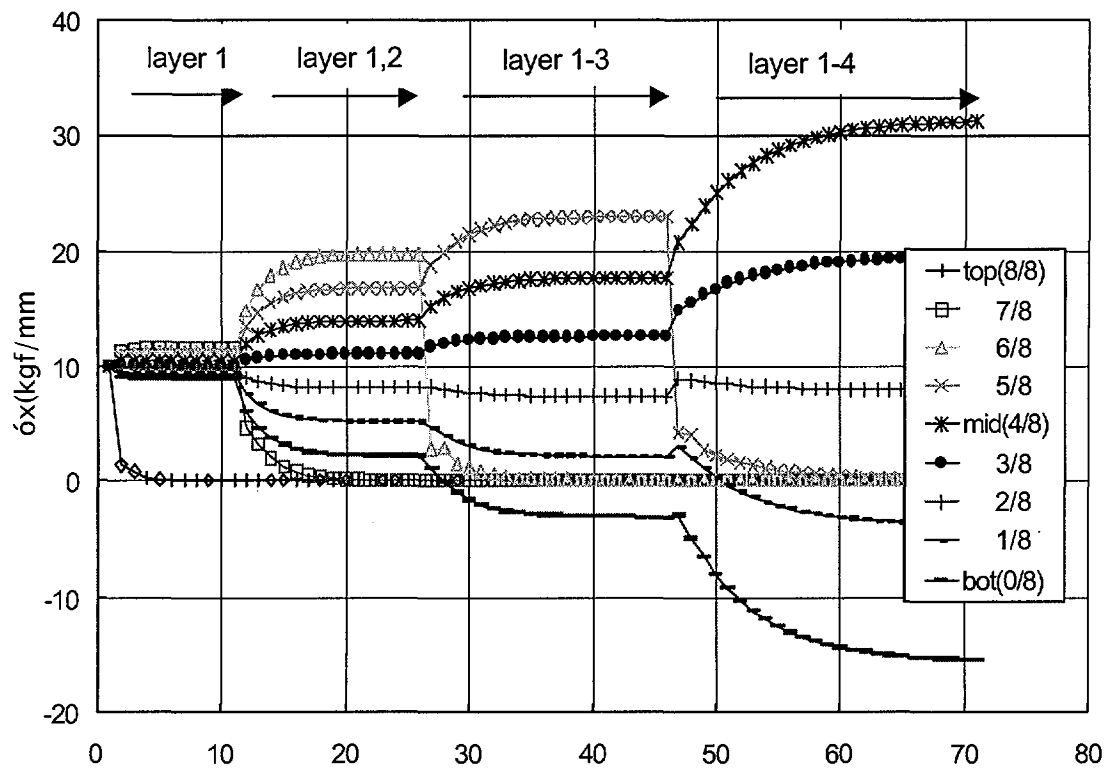

Fig. 5 Change of stresses due to thinning

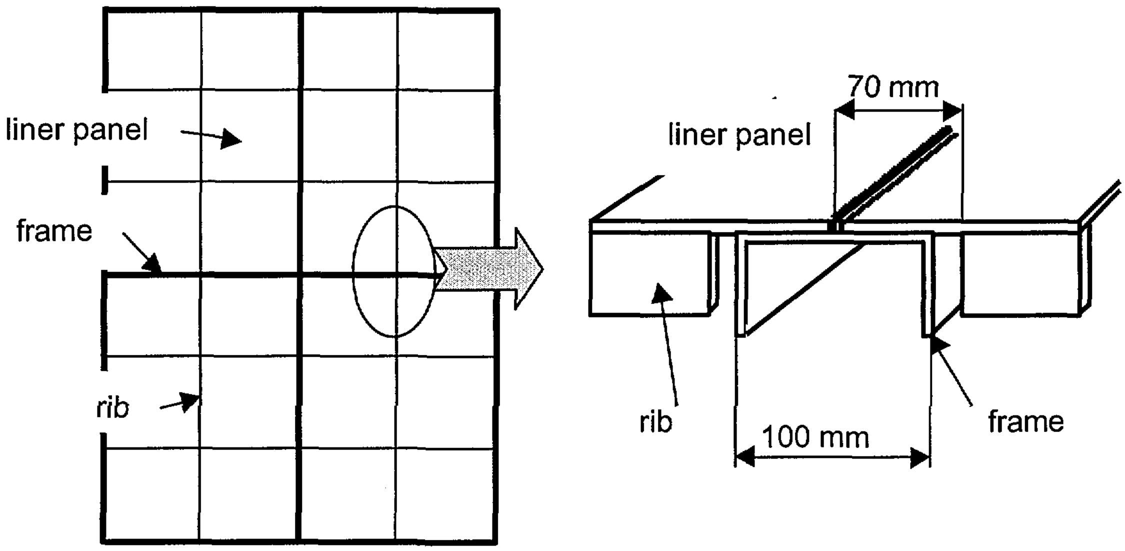

Fig. 6 Structure of liner

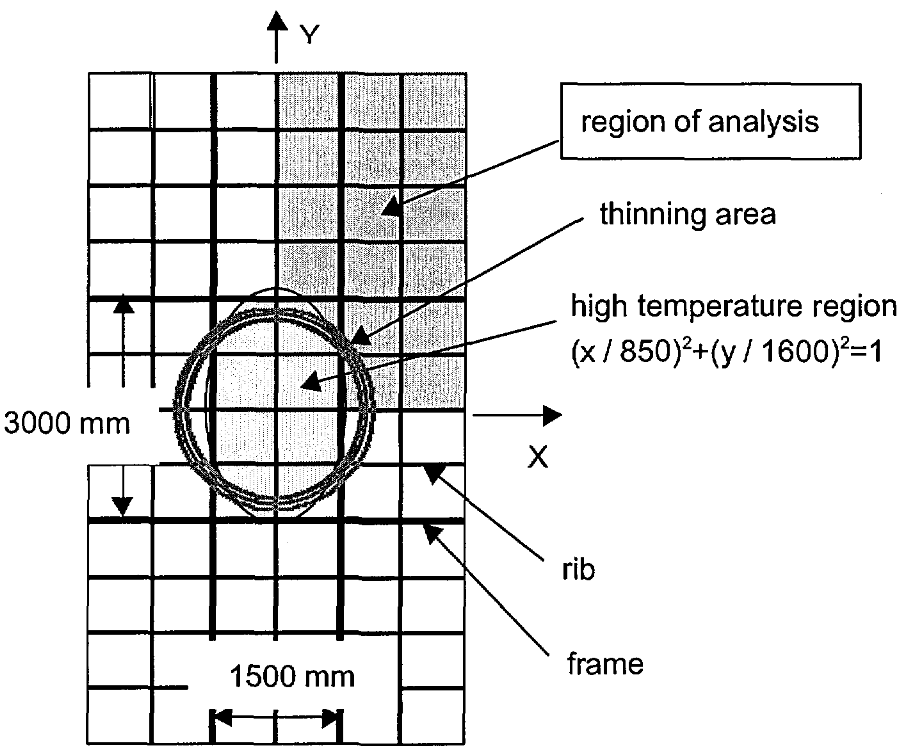

Fig. 7 Region of analysis

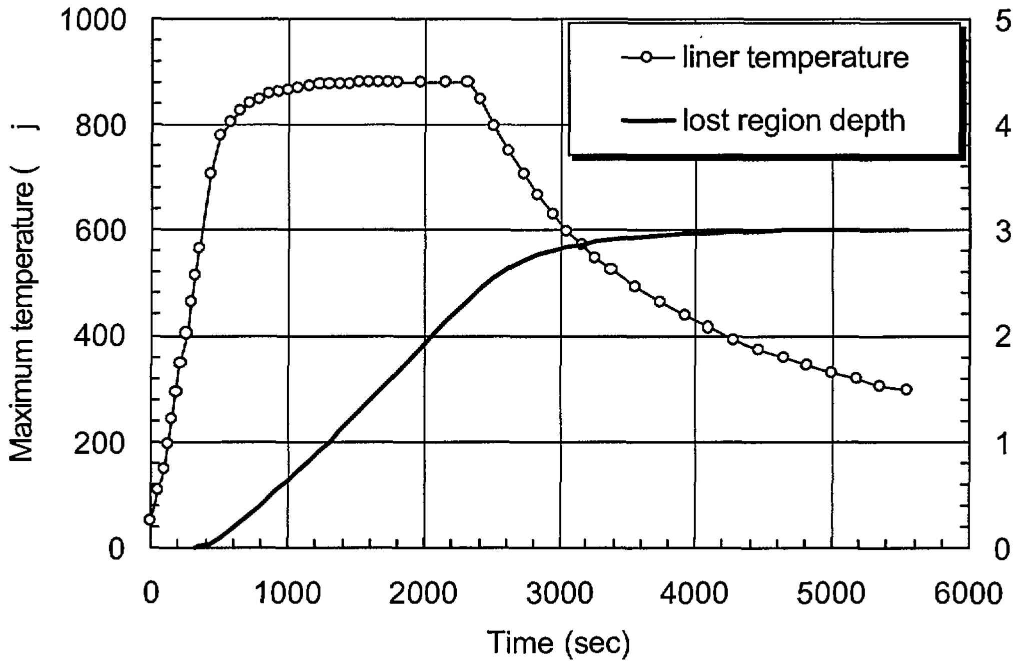

Fig. 8 History of temperature and thinning

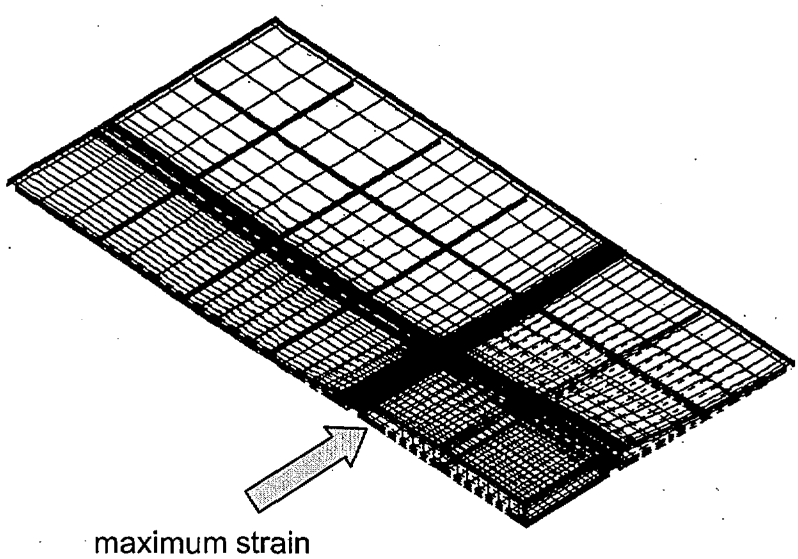

Fig. 9 Finite element mesh model

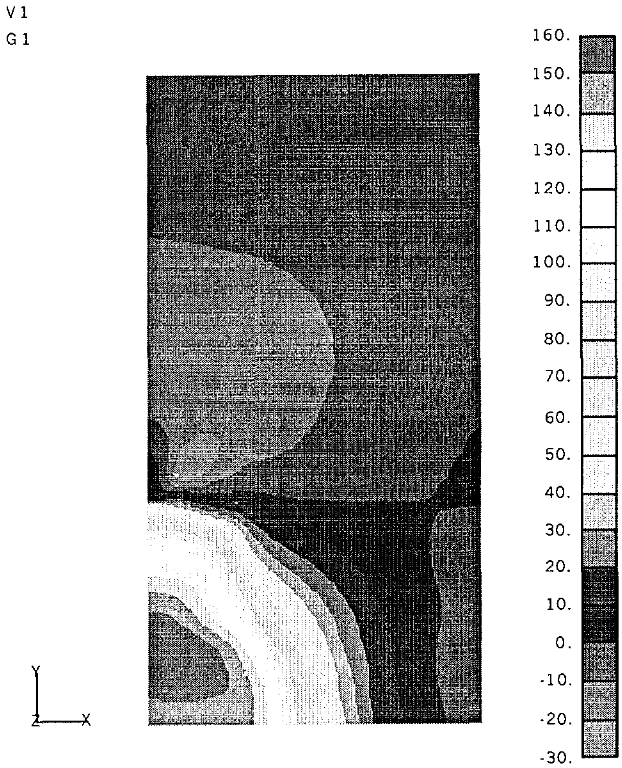

Fig. 10 Z-direction displacement distribution (mm)

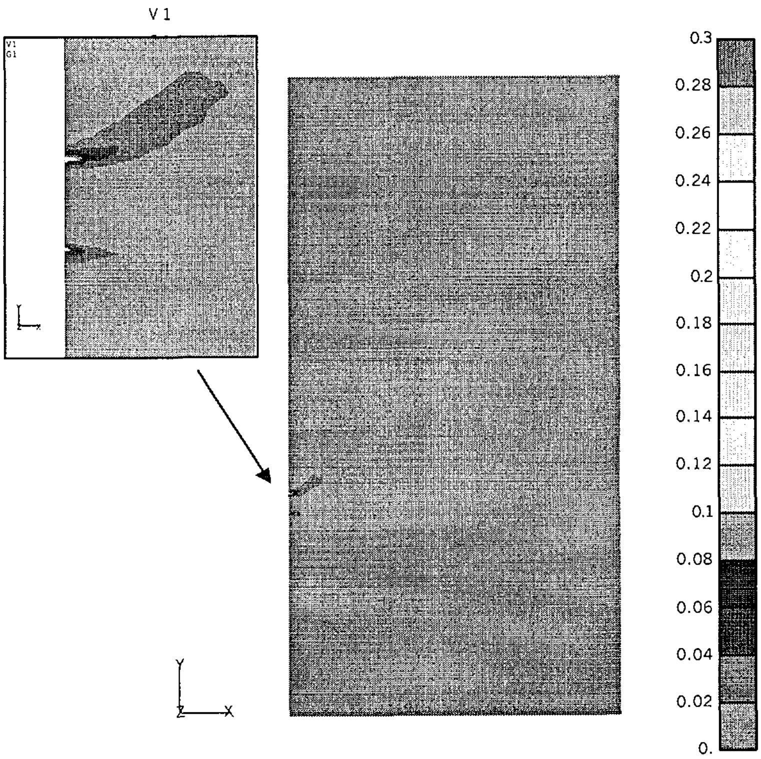

Fig. 11 Inelastic strain distribution at top surface

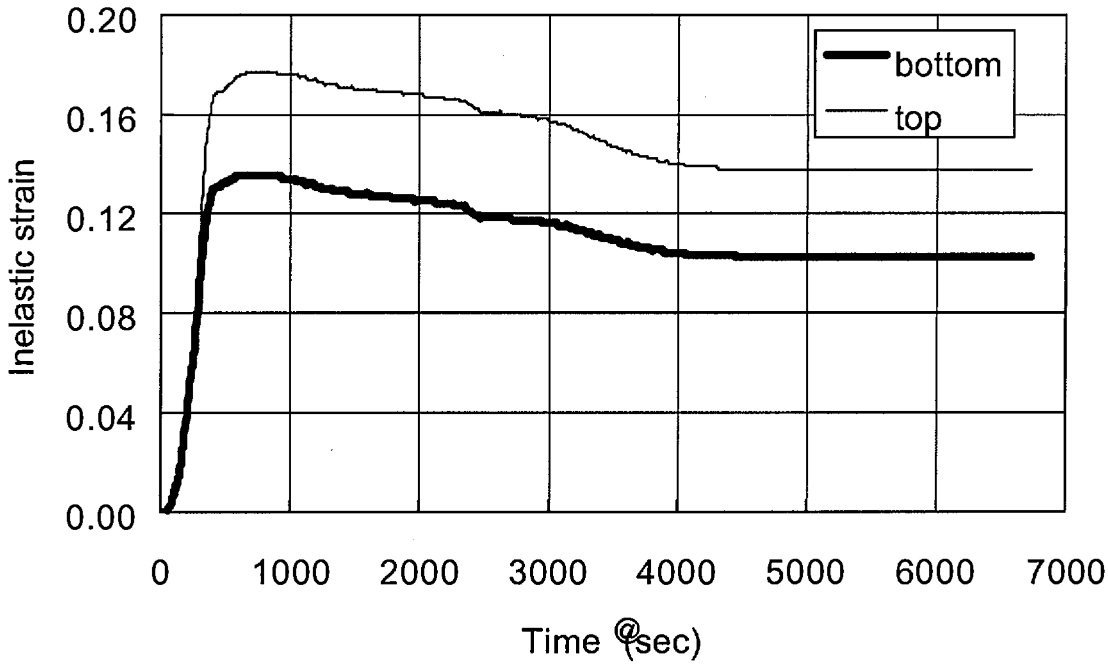

Fig. 12 Inelastic strain behavior without thinning

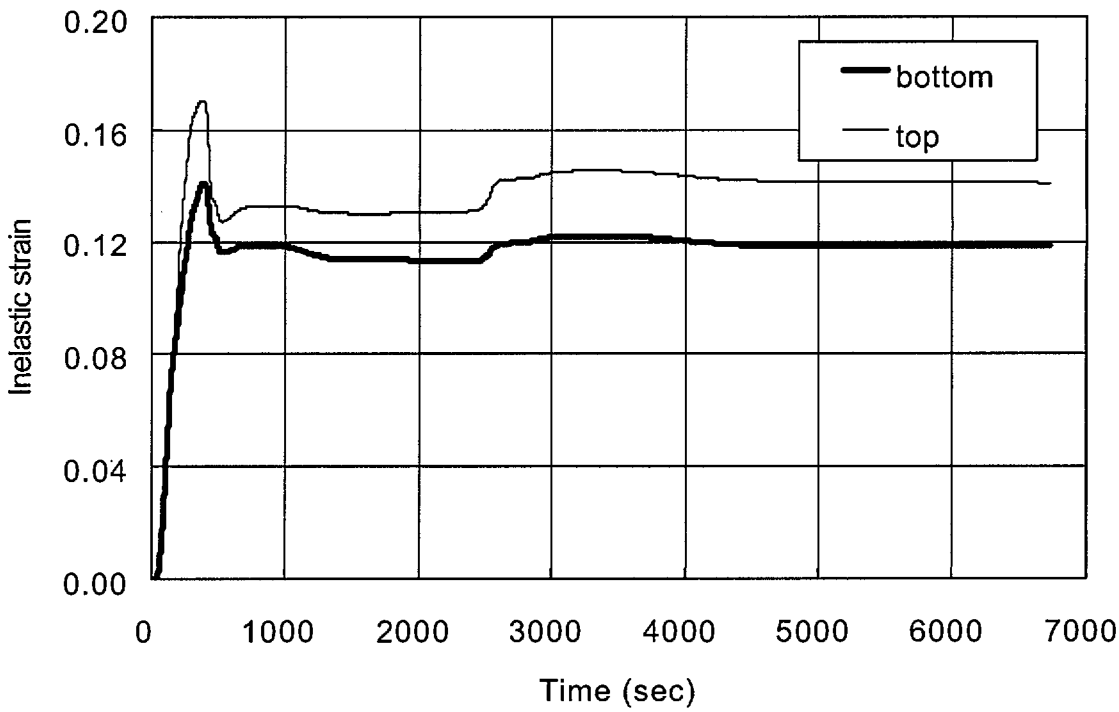

Fig. 13 Inelastic strain behavior with ultimate thinned geometry