Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

On a new method of residual stress field measurements

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SUMMARY : The structures of nuclear power stations are submitted to a lot of loadings which are combined with residual stresses due to manufacturing operations (quenching and tempering, cutting, welding, ...), leading eventually to damages on a component. This explains the numerous methods existing to measure residual stresses and the variety of technical fields involved (X rays and neutrons interferomety, hole drilling, ultrasonic waves...).

This paper presents the fundamentals of an original destructive method based on the measurement of crack opening displacement of a small crack like defect created in a structure. It details the theory and 2D finite element simulations performed on a plate geometry in view of determining the coefficients of a third degree polynomial stress field. Then, the analysis of the perspectives and the experimental applications are shown and discussed.

PROGRAMME

NOTATIONS

a	:	defect length
W	:	structure width
E	:	Young's modulus
ν	:	Poisson's coefficient
A_0, A_1, A_2, A_3	:	stress polynome coefficients
V_1, V_2, V_3, V_4	:	weight functions of the opening displacement
δ	:	opening displacement

1 INTRODUCTION

A lot of residual stress measurement methods (ref. [1] to [5])·are at the mechanical engineer's disposal for the analysis of structures. Among those based on material removing including strain variations (such cutting or drilling hole), it is not clear if these methods are valid in some cases such high surface stress gradients, encountered in welded structures for instance. That's why the theory of an alternative method, intended to work in these cases, has been developed at CEA Cadarache. The principle consists in the cutting of a crack like defect in the tested structure, the normal stress profile being determined by means of Crack Opening Displacement measurements.

The purpose of this paper is the presentation of the theoretical background, followed by the results of finite element calculations that are necessary to apply the method in the case of a two-dimensional plate. Then, the possible extensions as well as the uncertainties are discussed.

2 THEORETICAL BACKGROUND

We have applied the principle of superposition in elasticity domain, very often used in fracture mechanic studies such in reference [6]. More details are given in figure 1. In a few words, the stress intensity factor can be written, in the polynomial stress field $\sigma = A_0 + A_1 x + A_2 x^2 + A_3 x^3$ through the thickness of a two-dimensional piece :

$$K_I = \sqrt{\pi a}\left[A_0 F_1 + A_1 a F_2 + A_2 a^2 F_3 + A_3 a^3 F_4\right]$$

where a is the crack length and F_1, F_2, F_3, F_4 are geometrical dependent functions, which must be determined.

In order to remain consistent with the litterature [7] and with the precedent formulation, we assumed the opening displacement, as defined on figure 1, was :

$$\delta = \frac{4a}{E'}\left[A_0 V_1\left(\frac{a}{w}\right) + A_1 a V_2\left(\frac{a}{w}\right) + A_2 a^2 V_3\left(\frac{a}{w}\right) + A_3 a^3 V_4\left(\frac{a}{w}\right)\right]$$

where E' is equal to E (Young's modulus) in plane stress conditions and to $E/(1-\nu^2)$ in plane strain hypothesis, V_1, V_2, V_3, V_4 are unknown weight functions.

Each weight function should be calculated separately by application of stress fields A_0, $A_1 x$, $A_2 x^2$, $A_3 x^3$ on the lips of the defect. For instance, V_1 is determined by :

$$V_1\left(\frac{a}{w}\right) = \frac{E' \delta (a)}{4 a A_0}$$

Some 2D finite element simulations have been carried out to obtain the functions V_1, V_2, V_3, V_4 in case of a long plate submitted to a polynomial stress profile. All the following calculations have been performed with the code CASTEM 2000 developed at CEA and described in reference [8].

3 DETERMINATION OF WEIGHT FUNCTIONS

The choosen mesh represents a plate of 50 mm width and 400 mm total length (see figure 2), and permits the study of defect length between 2 and 36 mm (corresponding respectively to ratios $\frac{a}{w} = 0.04$ to 0.72). The mesh was made of about 570 elements (depending of the defect length and the polynome order), triangles with 6 nodes and rectangles with 8 nodes. All the calculations have been performed in plane strain conditions.

The normal stresses were applied on the defect lips and the transverse displacements of the uncracked symmetry axis were blocked.

We show on figure 3 an example of deformed plate shape obtained with the third degree stress term applied on the lips of a 12 mm depth defect, and on figure 4 is presented the corresponding normal stress in the defect section. The calculated V_1 function is given on figure 5, while the remaining weight functions, smaller, are plotted on figure 6.

4 DISCUSSION

At this point, it should be emphasized that :

- the $V_1\left(\frac{a}{w}\right)$ function has been compared with the results of reference [7] leading to a very good agreement in all the domain $0.04 \le \frac{a}{w} \le 0.76$,
- the $V_2\left(\frac{a}{w}\right)$ weight function has been verified on the particular case of a plate in bending from reference [7]. The comparison has been found independent of the width W of the plate, and the agreement was fine in all the domain $0.04 \le \frac{a}{w} \le 0.72$.

Additionally, the important question of the inverse problem solution should be pointed out.

It consists of the determination of the initial stress in the plate depth from opening displacement values.

Let us imagine an experimental step by step machining of a defect in a piece, in view of residual stress estimation :

- it is an evidence that the first step of defect machining (depth a_1), which corresponds to the first measurement of opening displacement ($\delta(a_1)$), will give an estimation of the A_0 stress constant term :

$$A_0 = \frac{E'\,\delta(a_1)}{4\,a_1\,V_1\left(\frac{a_1}{w}\right)},$$

- then, the next increment of defect machining (depth a_2) gives an other value of the opening ($\delta(a_2)$) and leads to the solving of a system of 2 equations with 2 unknowns (A_0 and A_1) :

$$\delta(a_1) = \frac{4a_1}{E'}\left[A_0\,V_1\left(\frac{a_1}{w}\right) + A_1\,a_1\,V_2\left(\frac{a_1}{w}\right)\right]$$

$$\delta(a_2) = \frac{4a_2}{E'}\left[A_0\,V_1\left(\frac{a_2}{w}\right) + A_1\,a_2\,V_2\left(\frac{a_2}{w}\right)\right]$$

This can be reproduced at each following step with the terms of higher orders.

To conclude this presentation, an other important point is the translation of the theoretical results to an efficient experimental method.

- First, the machining of the defect will be very thin to respect the objectives of the study (measurement of high surface and depth stress gradients). The more accurate cutting technique seems to be the electroerosion method, which is able to create defect as thin as 0.2 mm width with depth greater than 6 mm.
- In addition, the measurement of displacements will be carried out by recording of a grid placed at the surface of the plate with a CCD camera. The grid could be virtually as small as we want, allowing measurements of very small displacements, and this, very close to the defect lips.
  An experiment is programmed in 1995 to prove the feasability of the method.

5 CONCLUSION

The principles of an original method of residual stress measurement have been presented in this paper. The method is based on the machining of a crack like defect and on the measurement of the opening displacement, and is intended to give a better estimation of surface and depth stress gradients than the existent methods.

The results of finite element calculations performed with the CEA code, CASTEM 2000, have been presented, and it leads to a formula giving opening displacement from the in depth stress :

$$\delta(a) = \frac{4a}{E'}\left[A_0\,V_1\left(\frac{a}{w}\right) + A_1\,a\,V_2\left(\frac{a}{w}\right) + A_2\,a^2\,V_3\left(\frac{a}{w}\right) + A_3\,a^3\,V_4\left(\frac{a}{w}\right)\right]$$

The way to solve the inverse problem, i.e. to determine the initial stress profile from different opening displacement values,. has also been established, as well as the techniques assumed to be valids for the translation of this theoretical study to an experimental method.

Acknowledgement : This work was sponsored by EDF that we thank for its financial and technical support.

REFERENCES

[1] J. LU, A. NIKU-LARI, J.F. FLAVENOT,
"Recents developpements de la mesure des contraintes résiduelles par perçage incrémental", matériaux et techniques, Déc. 1985, p. 709-718.

[2] W. CHENG, I. FINNIE, M. GREMAUD, M.B. PRIME,
"Measurement of Near Surface Residual Stresses Using Electric Discharge Wire Machining"
Journal of Engineering Materials and Technology" Vol. 116, n° 1, pp 1-7.

[3] C. BOUHELIER, J. LU,
"Mesure des contraintes résiduelles dans les soudures. Les méthodes disponibles, exemples d'applications"
Conférence "Les contraintes résiduelles dans les constructions soudées", Senlis (FRANCE), 3 Déc. 1987, CETIM.

[4] M. GREMAUD, W. CHENG, I. FINNIE, M.B. PRIME,
"The Compliance Method for Measurement of Near Surface Residual Stresses - Analytical Background"
Journal of Engineering Materials and Technology, Vol. 116, Oct. 1994, pp. 550-555.

[5] K. MASUBUCHI,
"Analysis of Welded Structures"
1980, Pergamon Press.

[6] C.B. BUCHALET, W.H. BAMFORD,
"Mechanics of Crack Growth"
ASTM STP 590, pp 385.

[7] Y. MURAKAMI,
Stress Intensity Factors Handbook
Volume 1, Pergamon Press.

[8] A. HOFFMANN, A. COMBESCURE,
"CASTEM (CEA/SEMT) : a system of finite element computer programs"
Paper 40 presented at Conference on "structural analysis, design and construction in nuclear power plant" Porto Alegre, Brazil, 1978.

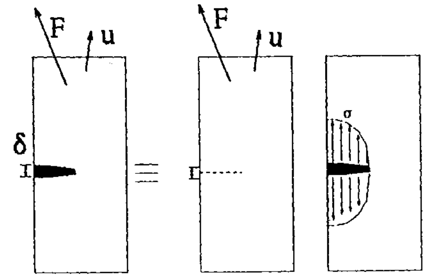

Figure 1 : principle of superposition, usually applied in fracture mechanics.

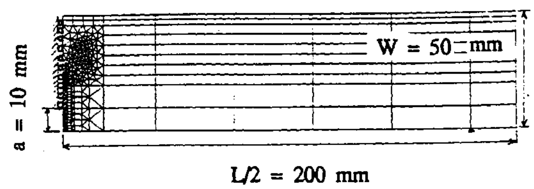

Figure 2 : example of mesh used for determination of weight functions.

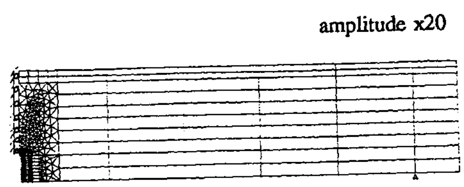

Figure 3 : deformed plate after application of a polynomial stress $\sigma = x^3$ on the defect lips (12 mm depth).

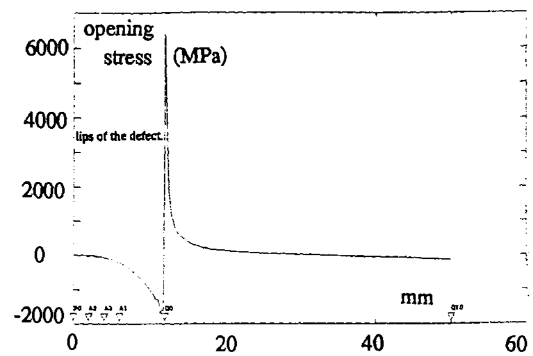

Figure 4 : stress profile in the plate section, in the case of application of a polynomial stress $\sigma = x^3$ on the defect lips (12 mm depth).

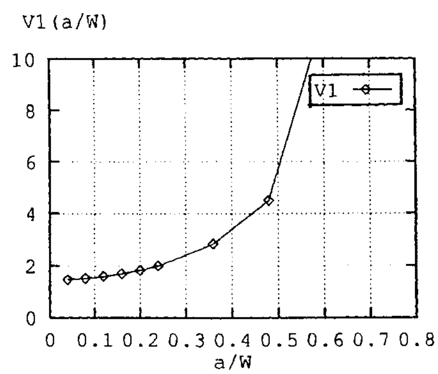

Figure 5 : weight function $V_1(a/W)$ for a plate of width W containing a defect of depth a.

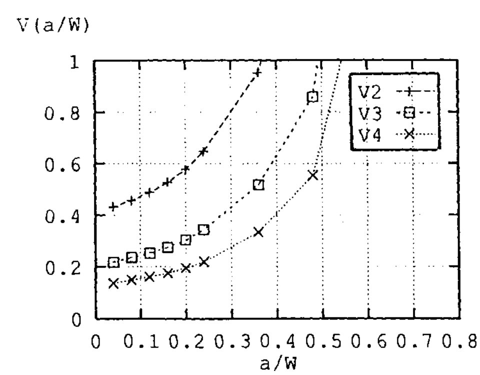

Figure 6 : weight functions V_2, V_3, V_4 for a plate of width W containing a defect of depth a.