# GEOMETRIC INFLUENCES UPON STRESS INTENSITY DISTRIBUTIONS ALONG REACTOR VESSEL NOZZLE CRACKS

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## SUMMARY

This paper describes the results obtained by applying a computer assisted photoelastic technique developed by the senior author and his associates for estimating Mode I stress intensity factor (SIF) distributions for mathematically intractable three-dimensional problems to the reactor vessel nozzle corner crack problem. Two significantly different test programs were employed and results were compared with the literature.

Frozen stress photoelastic experiments were conducted on two classes of nozzle corner cracks:

(i) Researchers at the Delft University Laboratory for Nuclear Engineering have developed a nozzle-flat plate geometry which is loaded in remote uniaxial tension normal to the flaw. The transverse tension can then be included analytically. Their results indicate that such a model accurately predicts fatigue crack growth for the corresponding cracked nozzle in a pressure vessel for thin walled vessels. The test geometry identified as No. 4 in the Delft work was studied experimentally in the present work.

(ii) Researchers at Oak Ridge National Laboratory developed a technique for predicting SIF's in cracked nozzles in thick walled pressure vessels from residual static strength tests on fatigue cracked plastic models of nozzle-cylinder intersections. The test geometry identified as the "small thick walled vessel" in the Oak Ridge program was studied experimentally in the present work.

The crack geometry inserted into a finite element model of the Delft geometry No. 4 was obtained by monitoring the crack lengths in the plate and nozzle surfaces during fatigue tests on steel models and fitting a quarter elliptical shape to these semi-axes to form the crack front. In the photoelastic experiments, one crack was grown to match the No. 4 crack length in the plate surface, and, in a second identical model, the crack was grown to match the No. 4 crack length in the nozzle surface. These cracks were not only of different size (the latter being some 30% larger than the former) but the experimental cracks exhibited a flattening in the central part of the flaw border. This effect was also observed in the fatigue tested steel models at Delft University after the models were opened to show heat tinted zones. Nevertheless the SIF distribution predicted by the stiffness derivative FEM was similar to that found in the experiments, showing a minimum SIF near the midpoint of the flaw border and agreeing to within 5% in this region for approximately equal flaw depths. Near the plate and nozzle surfaces, the photoelastic results were about 15% below the FEM results.

The tests on the cracked nozzles in the thick walled pressure vessels also revealed a flattening of the flaw border similar to that observed in the plate models. However, SIF distributions were opposite those observed in the plate models. Nevertheless, normalized SIF values at the flaw border midpoints agreed well with the Oak Ridge results. It is conjectured that the vessel wall thickness and/or curvature may affect the SIF distribution along the flaw border.

## 1. Introduction

Stress intensity factor (SIF) determination for cracks emanating from the juncture of reactor vessels with inlet and exit nozzles has been a problem in the reactor vessel industry for many years due to the complex and widely varying geometries involved. To date, only approximate analytical solutions such as those of Hellen and Dowling [1], Reynen [2], Broekhoven and Spaas [3], and Schmitt [4] are available in the open literature but substantial additional efforts are also underway.

As a result of the degree of analytical intractability of the problem, and the need for experimental correlation of approximate analytical methods such as finite element methods (FEM), the authors have undertaken several experimental investigations for several different agencies. The experimental technique employed has been developed by the authors over a period of years [5] - [12] and consists of a marriage between the frozen stress photoelastic analysis of cracked bodies with a simplified digital computer analysis of the experimental data for extracting the SIF.

The aim of the present paper is to bring together results to date of the several studies in order to assess quantitatively the influence of the several parameters in the problem upon the SIF magnitudes and their distributions. In the sequel, a brief account of the analytical basis of the method is given together with a brief description of the experimental technique. However, the principal focus of this effort is upon integration of the results.

## 2. Analytical Considerations

One can express the maximum shearing stress in the nz plane along $\theta = \pi/2$ (Figure 1) near the crack tip in the form [9]:

$$\tau_{max} = \frac{A}{r^{1/2}} + B \qquad (1)$$

where $A = K_I/(8\pi)^{1/2}$, $K_I$ = SIF and B is the leading term of a Taylor Series expansion of the regular stress field near the crack tip. Data are taken along $\theta = \pi/2$ since fringes tend to spread in that direction (Figure 2). Then, from the Stress Optic Law

$$\tau_{max} = \frac{Nf}{2t'} \qquad (2)$$

where N is the stress fringe order, f is the material fringe value and t' is the slice thickness tangent to the crack front; one can determine experimentally the zone in which Equation (1) is valid. This can be done by rewriting Equation (1) in the normalized form:

$$\frac{\tau_{max}(8\pi r)^{1/2}}{q(\pi a)^{1/2}} = \frac{K_I}{q(\pi a)^{1/2}} + \frac{B\ (8\pi r)^{1/2}}{q(\pi a)^{1/2}} \qquad (3)$$

$$\text{or} \quad \frac{K_{AP}}{q(\pi a)^{1/2}} = \frac{K_I}{q(\pi a)^{1/2}} + \frac{B(8)^{1/2}}{q}\left(\frac{r}{a}\right)^{1/2} \qquad (4)$$

where $K_{AP} = \tau_{max}\ (8\pi r)^{1/2}$ is defined as "apparent" SIF and q = p, the internal pressure or $q = \bar{\sigma}$ the remote uniform stress normal to the flaw surface. Equation (4) when plotted as $K_{AP}/q(\pi a)^{1/2}$ vs $(r/a)^{1/2}$ yields a straight line which when extrapolated to the origin will yield $K_I/q(\pi a)^{1/2}$, the normalized SIF.

The above approach for Mode I loading has been extended to cover the mixed mode [6], [11] situation also.

In general, when Mode I loads are applied to the crack tip, blunting at the crack tip occurs which produces a nonlinear zone that extends roughly out to a distance $r/a \approx 0.04$ from the crack tip along $\theta = \pi/2$. Moreover, the linear zone described by Equation (4) tends to extend substantially from the crack tip in problems with slowly varying effects along the flaw border (as in the two-dimensional case). Conversely, a constriction at the singular zone occurs in problems with strong three-dimensional effects. However, if a linear zone is present in the raw data plot of normalized apparent SIF versus $(r/a)^{1/2}$, then the presence of the desired data zone is assured.

## 3. Experiments

Two basic classes of experiments were conducted: i) Uniaxial tensile tests of plates, each containing a cracked nozzle of the geometry of Figure 3a and ii) internal pressure loadings on thick-walled cylindrical pressure vessels each containing a cracked nozzle of the geometry of Figure 3b. In order to complement this work, a third series of tests were conducted on thin-walled cylindrical pressure vessels each containing two diametrically opposite cracked nozzles of the geometry of Figure 3c.

The test procedure was as follows:

a) Starter cracks were introduced into the "inner" surface of the juncture of the plate vessel wall with the nozzle at point P (Figure 1) and the photoelastic models were placed in a test rig in a stress freezing electric oven and heated to a critical temperature.

b) Plates were then loaded with dead weights producing uniform remote uniaxial tension and the vessels were pressurized while being supported in soft, surface matching, part-spherical bases. These loads were increased until the flaws were grown to desired dimensions after which the models were cooled under reduced load to room temperature, freezing in both fringe and deformation fields.

c) Slices were then removed mutually orthogonal to the flaw border and the flaw surface at intervals along the flaw border. These slices were coated with a matching index fluid and analyzed via the Tardy Method in a crossed circular polariscope at about 10X utilizing a white light field and reading tint of passage.

d) Optical data were introduced into a least squares computer program which extracted estimates of the SIF.

## 4. Data and Results

Figure 4 shows a set of raw data from one of the plate tests illustrating how one extrapolates across the nonlinear zone at the crack tip in order to obtain a valid $K_I$ estimate. This graph may be regarded as typical. A spectrum of flaw sizes were studied for each nozzle geometry and it was found that the flaw generally begins with nearly a quarter elliptical flaw border. However, as shown by Figure 5(a) for the thick walled vessels, the flaw shape flattens significantly as flaw depth increases, and the deepest flaw even exhibits a "dimple" in the central region. In studies at Delft University of Technology by Broekhoven [13], heat tinting of tension fatigue tests on steel plates containing cracked nozzles also revealed this flattening. In fact, fatigue crack geometries from the Delft steel plate tests coincided exactly with those obtained in the stress freezing tests. However, in obtaining the crack shapes for the FEM, the Delft investigators measured the crack lengths at cycle intervals along the nozzle and the plate and fitted a quarter ellipse to semiaxes so obtained. While this procedure did not allow for the "flattening" described above, it was found that at points where the flaw depth in the FEM was close to that in the photoelastic experiment, very good agreement between SIF values provided by the stiffness derivative FEM and the frozen stress technique was obtained [14].

Derby [15] grew nozzle corner cracks in thick walled pressure vessels using cyclic pressure followed by residual static strength tests. The authors conducted frozen stress tests on the same geometries as Derby and obtained SIF values [16] which correlated well with those of Derby, except for shallow flaws where the authors' results were some 15% lower than Derby's values. However, Derby's SIF values for the shallow flaws exhibited scatter of about ±7%. The details of the above comparisons are found in references [14] and [16] as noted.

In the present discussion, we will focus upon a flaw geometry which penetrates approximately half way through the juncture ($a/T \simeq 0.5$; Figure 1) in order to correlate results from the plate-nozzle tension tests, the thick walled pressure vessel-nozzle tests and complementary tests on thin walled pressure vessel-nozzle tests, all containing cracks. Figure 5(b) shows the three nozzle configurations scaled to a common value of T. Since nozzle detail differed only away from the crack starting point (P in Figure 1), it was conjectured that SIF variations due to variation in the outer nozzle wall away from P might not be large. Figure 6(a) shows a comparison between the normalized SIF distributions along the flaw border for thin and thick walled vessels. Although the shapes of the curves are somewhat similar, their ordinates differ by an order of magnitude. The authors believe that the bulk of this difference is due to the membrane or $t/R$ effect. Moreover, it seems apparent that the contribution of the pressurized nozzle is small for the thin walled vessel (i.e. it is essentially a thick walled vessel), but probably not for the thick walled vessel. Figure 6(b) compares test results for the plate-nozzle test with the thin walled vessel results. The normalizing factor $\overline{\sigma}$ for the thin walled vessel was computed from $pR/t$. Using the stiffness derivative FEM, Broekhoven [13] predicts that the plate-nozzle curve would be further elevated by about 5 to 10% due to the presence of an axial stress $\overline{\sigma}/2$. On the basis of these results, one may conjecture that the thin walled pressure vessel geometries produce an order of magnitude greater SIF level in the nozzle juncture cracks than thick vessels. The distribution of the SIF along the flaw border does not seem to be strongly influenced by the transition from thin to thick walled vessel. One may conjecture further that since both analytical and experimental results for the plate-nozzles show a SIF distribution (Figure 6b) which is concave downward in the middle (as contrasted to the opposite effect in the pressure vessels) then perhaps the crack face pressure together with constraint variation due to vessel curvature effects and nozzle pressure may account for the difference in distributions observed in Figure 6(b).

## 5. Summary

A frozen stress photoelastic technique for estimating stress intensity factors in cracked nozzle-vessel junctures was briefly described. Results from its application to plate-nozzle and thick and thin walled pressure vessels also containing cracked nozzles were cited. On the basis of limited experimental evidence, it is conjectured that for moderately deep flaws ($a/T \simeq 0.5$ Figure 1)

i) Nozzle-vessel juncture crack shapes exhibit a flattened region near the center of the flaw which destroys ellipticity of the flaw shape. This may be conjectured to be due to the influence of the stress gradient at the reentrant corner of the uncracked flaw as modified by the flaw. However, SIF's computed from quarter elliptic FEM's agreed well with experiments at points of equal flaw depths.

ii) The most important effect on the magnitude of the SIF's is the wall thickness of the pressure vessel. Thin vessels will generate order of magnitude higher SIF's than thick vessels.

iii) The SIF distribution does not appear to be significantly affected by the vessel wall thickness. However, variations in the distribution were observed between junctures with and without crack face pressures. It may be conjectured that crack face pressure together with constraint variation due to vessel curvature and nozzle pressure may alter the SIF distribution.

There are many potential sources of error in the experiments described above. However, in the experience of the authors, they expect scatter to be no greater than ±6% with techniques employed here. They note, however, that the present study encompassed only a very limited range of vessel and crack geometries and do not recommend extrapolation of results. Studies on thin walled pressure vessels with cracked nozzles are continuing.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Hellen, T. K. and Dowling, A. H., "Three Dimensional Crack analysis Applied to an LWR Nozzle-cylinder Intersection", International Journal of Pressure Vessels and Piping, Vol. 3, pp. 57-74, 1975.

2. Reynen, J., "On the Use of Finite Elements in the Fracture Analysis of Pressure Vessel Components", ASME Paper No. 75-PVP-20, June 1975.

3. Broekhoven, M. G. J. and Spaas, H. A. C. M., "Application of the Finite Element Technique to a Complex 3-D Elastic Problem (Nozzle Junction with Cracks)", Rep. MMPP101 Laboratory for Nuclear Engineering Delft University of Technology, August 1974.

4. Schmitt, W., Bartholome, G., Gröstad, A., and Miksch, M., "Calculation of Stress Intensity Factors for Cracks in Nozzles", International Journal of Fracture, Vol. 12, No. 3, June 1976, pp. 381-390.

5. Smith, D. G. and Smith, C. W., "A Photoelastic Investigation of Closure and Other Effects Upon Local Bending Stresses in Cracked Plates", International Journal of Fracture Mechanics, Vol. 6, No. 3, pp. 305-318, September 1970.

6. Smith, D. G. and Smith, C. W., "Photoelastic Determination of Mixed Mode Stress Intensity Factors", Engineering Fracture Mechanics, Vol. 4, No. 3, pp. 357-366, 1972.

7. Smith, C. W., McGowan, J. J. and Jolles, M., "Effects of Artificial Cracks and Poisson's Ratio Upon Photoelastic Stress Intensity Determination", Experimental Mechanics, Vol. 16, No. 5, pp. 188-193, May 1976.

8. McGowan, J. J. and Smith, C. W., "Stress Intensity Factors for Deep Cracks Emanating from the Corner Formed by a Hole Intersecting a Plate Surface", Mechanics of Crack Growth, ASTM STP 590, American Society for Testing and Materials, pp. 460-476, 1976.

9. Jolles, M., McGowan, J. J. and Smith, C. W., "Use of a Hybrid Computer Assisted Photoelastic Technique for Stress Intensity Determination in Three-Dimensional Problems", Computational Fracture Mechanics, ASME-AMD-SP Proceedings of Second National Congress on Pressure Vessels and Piping, E. F. Rybicki and S. E. Benzley, eds., pp. 63-82, 1975.

10. Smith, C. W., Jolles, M., and Peters, W. H., "Stress Intensity Determination in Three-Dimensional Problems by the Photoelastic Method", Proceedings of the Second International Conference on Mechanical Behavior of Materials, pp. 235-239, 1976.

11. Smith, C. W., Jolles, M., and Peters, W. H., "Stress Intensities for Cracks Emanating from Pin Loaded Holes", for Proceedings of 10th National Symposium on Fracture Mechanics, 1976.

12. Smith, C. W., Jolles, M., and Peters, W. H., "Stress Intensities in Flawed Pressure Vessels", for Third International Conference on Pressure Vessel Technology, 1977.

13. Broekhoven, M. J. G., "Computation of Stress Intensity Factors for Nozzle Corner Cracks by Various Finite Element Procedures", Rep. Mmpp 119 Paper G 416 Third SMIRT Conference, London 1975, Delft University of Technology Laboratory for Thermal Power and Nuclear Engineering, May 1975.

14. Smith, C. W., Jolles, M. and Peters, W. H., "An Experimental Study of the Plate-Nozzle Tensile Test for Cracked Reactor Vessel Nozzles", V.P.I.-E-76-26, 23 pp., Nov. 1976, see also Proceedings of Fifteenth Midwestern Conference on Applied Mechanics, March 1977.

15. Derby, R. W., "Shape Factors for Nozzle Corner Cracks", Experimental Mechanics, Vol. 12, No. 12, pp. 580-584, Dec. 1972.

16. Smith, C. W., Jolles, M. and Peters, W. H., "Stress Intensities for Nozzle Cracks in Reactor Vessels", V.P.I.-E-76-25, 21 pp., Nov. 1976.

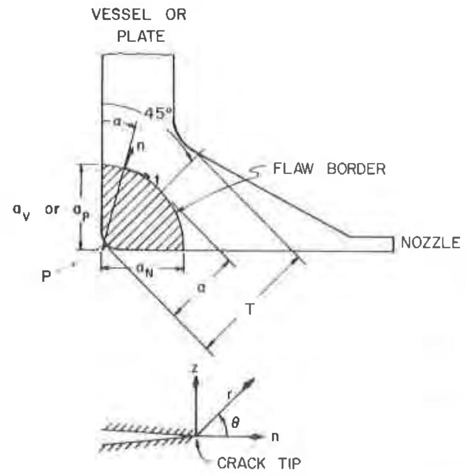


Figure 1 - Problem Geometry and Notation.

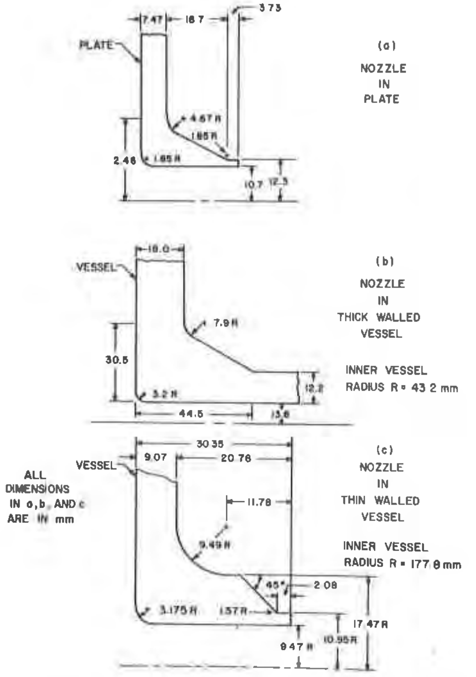


Figure 3 - Nozzle Geometries Studied.

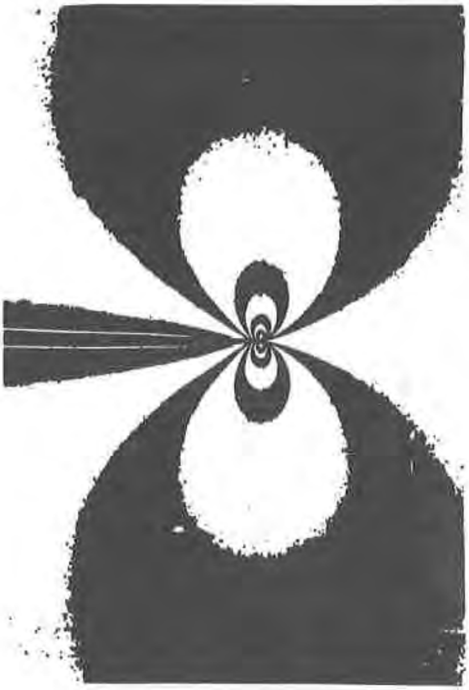


Figure 2 - Spreading of Fringes in nz Plane Normal to Crack Tip.

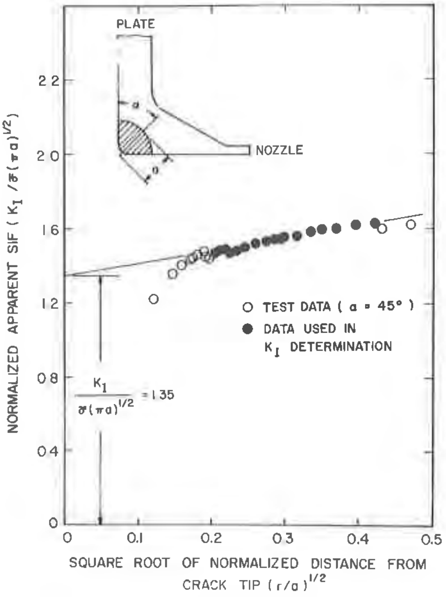
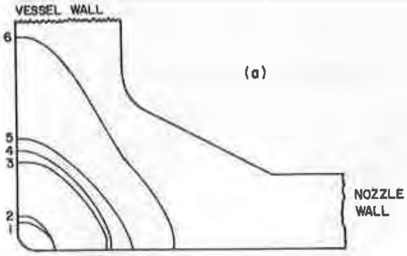


Figure 4 - Typical Set of Raw Data Showing SIF Estimate.



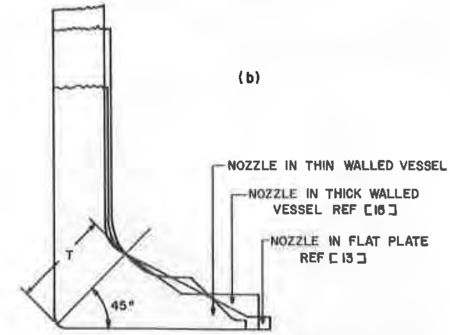


Figure 5(a) - Flaw Geometries for Thick Walled Vessel.

Figure 5(b) - Nozzle-Wall Junctures Scaled to a Common Thickness T.

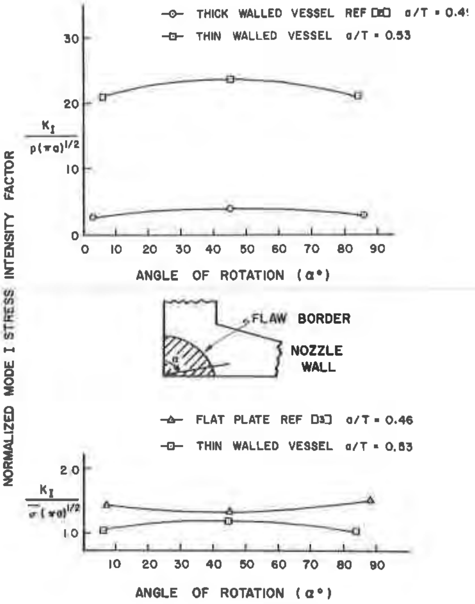


Figure 6(a) - Thick Versus Thin Walled Pressure Vessel Results.

Figure 6(b) - Thin Walled Pressure Vessel Versus Plate Results.