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STRESS ANALYSIS INCORPORATING FRACTURE MECHANICS AND MATERIALS ASPECTS FOR COMPONENTS UNDER COMPLEX LOADING

P.H. HIRT, N. JAUSSI and M. PRODAN

MOTOR-COLUMBUS Consulting Engineers Inc., Baden, Switzerland

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The title deals with a complex subject. Stress analysis with consideration of fracture mechanics and material properties is subject to research and development worldwide. A final answer is not possible. This is only an attempt to discuss the problem.

In the following, three examples are discussed. Due to the size of the problems, extensive use of references (with more detailed information) is made. The examples are: a pressure vessel nozzle, a disc with crack, and a thick walled vessel.

1. Introduction

The integrity of components such as pressure vessels and pipe work, are for chemical and nuclear power plants of upmost importance. For proof of the integrity such methods as stress analysis, fracture mechanics and probabilistic analysis are employed. The use of computers cannot be avoided. A variety of programs should be available, so that costs can be optimized.

The following three examples show the application of the methods stress analysis, fracture mechanics and probabilistic analysis as they are used by engineers [1–3] or in Research Institutes [4–6].

2. Example "pressure vessel nozzle"

A nozzle in the transition zone "shell/head" of a custom made heat exchanger was analyzed [2]. Due to geometry a three dimensional modelling was required. Fig. 1 shows the geometry of the model used for analysis. The model has 5500 three-dimensional, 8 nodal point elements or 7600 nodal points.

Eleven temperature transients of the cooling media sodium were conservatively reduced to five transients. The internal pressure of the secondary loop, connecting pipe loads and restraining forces had to be considered. The temperature fields were analyzed with the program system ANSYS, whereas for the stress analysis the program system NASTRAN was used. Fig. 2 and fig. 3 show the temperature and the stress distribution in a section of the body at a certain time of a transient.

The nonlinear characteristic of the heat transfer mechanism was considered in the thermal analysis.

The material used was steel X6 CrNi 1811 (1.4948).

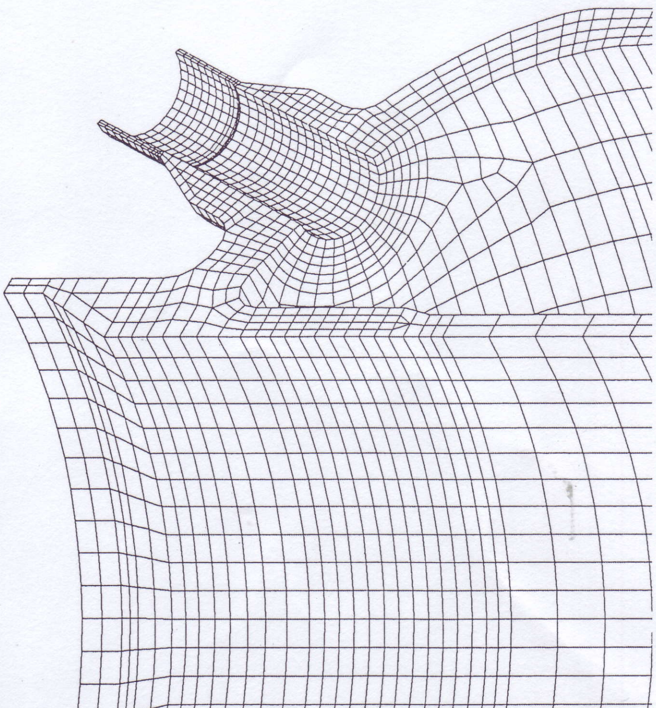

Fig. 1. Finite element mesh of the vessel nozzle.

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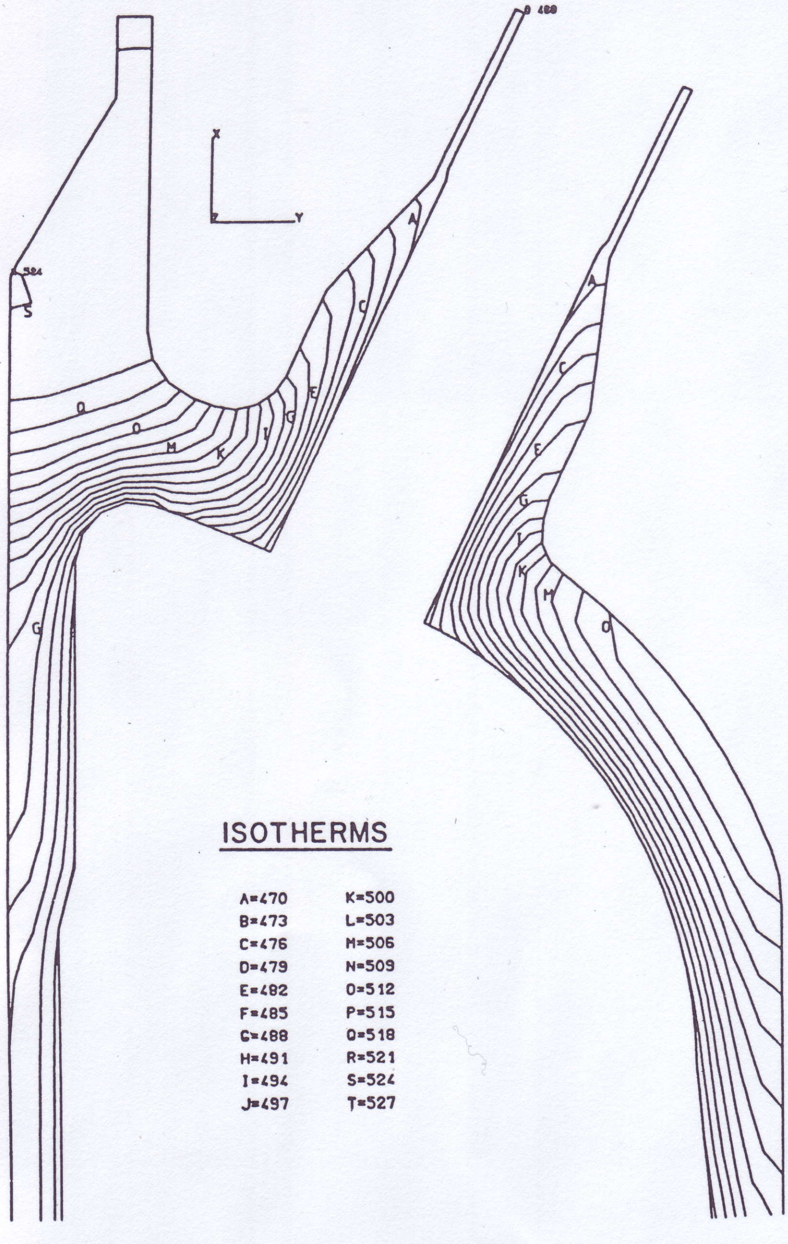

Fig. 2. Isotherms.

2.1. Stress limitations

Following the stress analysis load combinations (stress superpositions at the stress component level) were made and compared with the allowable stress limits of the ASME Code or the relevant code cases. The comparison of the allowable stresses was made with the help of the post processor CASAFE. Such a post processor is normally not available with general purpose FE-programs. The FE-analysis produces on each element node six stresses, three normal stresses and three shear stresses. For the code calculation these stresses had to be added, averaged or linearized per stress component and then the principal stresses calculated. The stress intensities P_m, $P_m + P_b$ are differences between the three principal stresses.

The stress intensities were only calculated on previously selected locations (sections through the wall). CASAFE compares the following stresses with the allowables:

– primary stresses (P_m, $P_m + P_b$),
– creep (for wall temperature > 427°C for austenite, an option in the program),
– stress range (primary and secondary stresses without

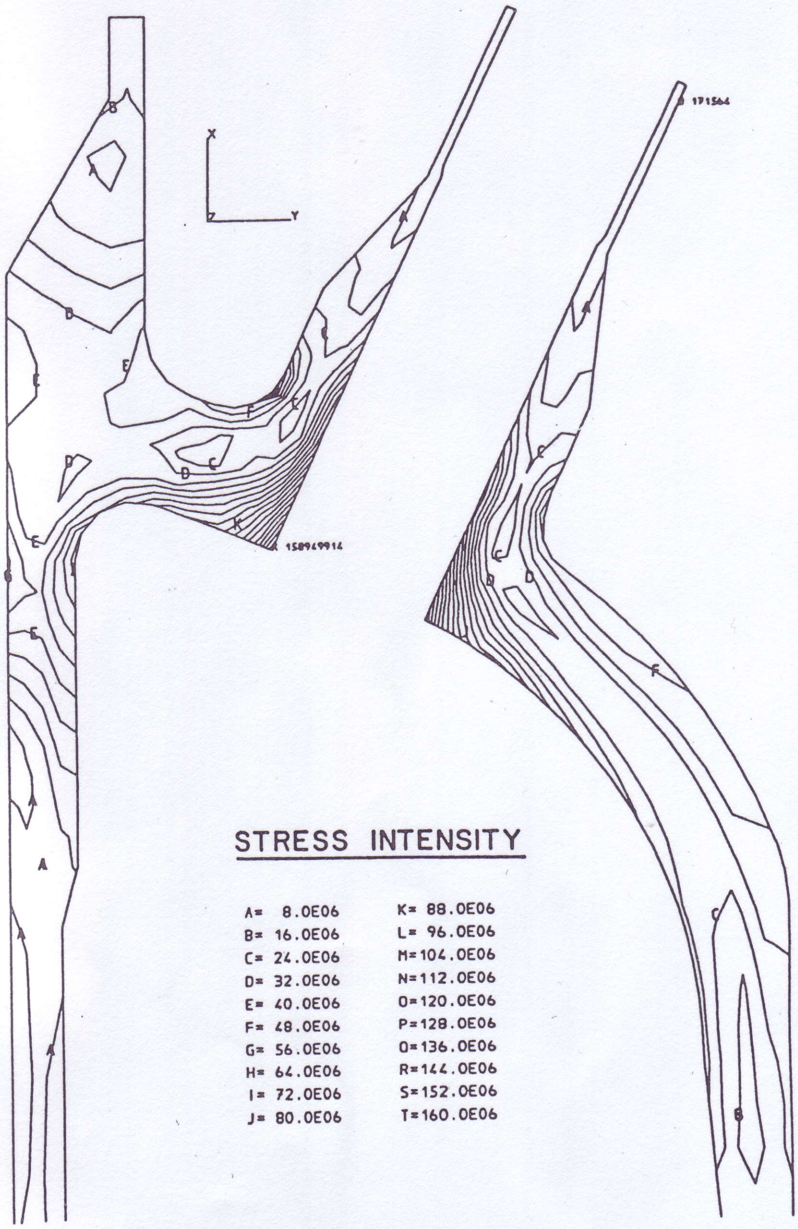

Fig. 3. Iso-stress intensities.

peak) and determination whether the K_e-factor is relevant,
- cumulative usage factor.

The stress limitations were not exceeded as table 1 shows. The symbols S_{zul1} and S_{zul2} are stress allowables, t_ν and $t_{\nu m}$ are operating hours or allowable operating hours for the actual stresses and are used for the creep evaluation.

Stress range$/3S_m$ is calculated for the determination whether the K_e-factor is to be determined ($K_e > 1$). It is used in the evaluation for the cumulative usage factor U.

2.2. Data processing

To allow for the data transfer from ANSYS to NASTRAN and to the post processor, the analysis was made with identical eight node three-dimensional elements.

The amount of data and data handling was large. Several hundred time steps and integration steps for the determination of the transient temperature distribution at 7600 nodes were necessary. For the determination of the stresses, again the 7600 nodes model was used, and on each node six stresses were determined. With 27

Table 1

P_m/S_{zul1}	$\frac{(P_m+P_b)}{S_{zul2}}$	$t_\nu/t_{\nu m}$	$\frac{\text{Stress range}^{a}}{3S_m}$	U
0.36	0.24	0.01	1.748	0.1616

[a] K_e-factor = 3.33.

basic loads and the 30–40 load combinations, millions of data have to be processed. The data were managed with CASAFE.

Since the stress intensities were determined only in 150 predetermined sections of the FE-model, the data to be managed was substantially reduced. The 150 sections were fully evaluated in accordance with the design specification (ASME code, subsection NB and code cases). Load combinations are made by the program CASAFE. Therefore, loads were combined only on the 150 preselected sections.

The above discussed and in [2] extensively covered analysis of a 3-D-model pressure vessel nozzle was, together with another problem on the same vessel and in close location (lifting lug), within one half year completed with the costs in the range of SFr. 100000.-. We believe that the costs are typical for the size of the problem. In ref. [5,6] a problem of comparable size is discussed.

3. Example "disc with surface crack"

A fracture mechanic analysis had to be performed on the disc with surface crack as a model for an engineering component. With the help of this example the value of fracture mechanics for stress analysis and safety analysis shall be demonstrated [4]. Fracture mechanics extends stress analysis such that cracked parts can be evaluated. Cracks represent singularities in stress and strain fields. The theory of fracture mechanics accepts parameters such as stress intensity factor K or the so-called J-integral to characterize the load condition in the vicinity of a crack. They are used to prove the safety margin to fracture with fracture mechanics analysis. Computer programs are already available to calculate K and J for a large number of crack types and load combinations.

How it is done is suggested by fig. 4. For this configuration the stress intensity factor K can be numerically determined as follows:

$$K=\frac{\sigma\sqrt{\pi a}}{\Phi}F\left(\frac{a}{c},\ \phi,\ \frac{a}{t}\right),\qquad h/W\geqslant 1;\ c/W\leqslant 0.25; \tag{1}$$

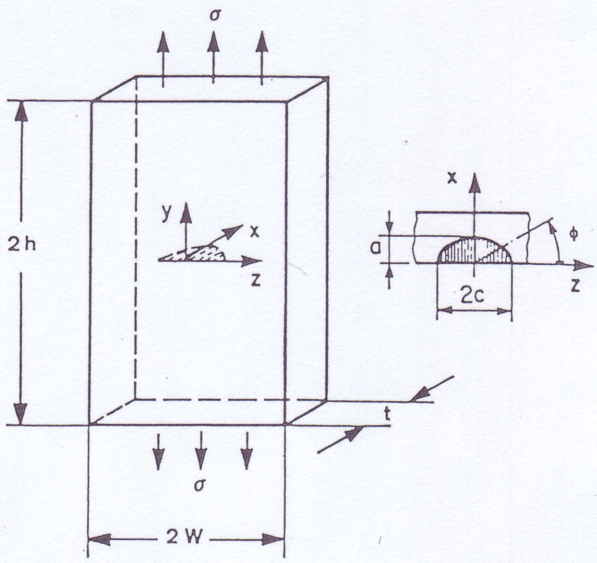

Fig. 4. Semi-elliptical surface crack in a tensile disc.

$$\Phi=\int_0^{\pi/2}\left(\sin^2\phi+\left(\frac{a}{c}\right)^2\cos^2\phi\right)^{1/2}\,\mathrm{d}\phi. \tag{2}$$

The symbols of eqs. (1) and (2) are explained by fig 4. Values of the correction function $F(a/c,\ \phi,\ a/t)$ are tabulated in table 2, based on 3-D linear elastic FE calculations by Raju and Newman. With an easy programable 2-D Lagrange interpolation (program INTERP) the correction function $F(a/c,\ \phi,\ a/t)$ can be calculated for values inbetween the values tabulated in table 2.

The practical importance of half elliptic surface cracks is based on its application when safety margins to brittle fracture, or stable crack growth due to fatigue, have to be evaluated. It is understood that a disc is a plate-like body, which is loaded perpendicular to its thickness. Similar results are also available for bent specimens (plates) with surface cracks and other typical cracks of plant components.

The results can be applied for the following problems: Determination of critical crack sizes, calculation of critical loads, determination of required toughness, prediction of undercritical crack growth and arrangements of tests.

The material used for the tests in ref. [4] is ferritic perlitic fine grain steel BH 43 W (St.E 43).

4. Example "thick walled container"

A probabilistic failure analysis had to be performed for a container carrying highly toxious contents [3]. In

Table 2
Values of the function $F(a/c, \phi, a/t)$ based on 3-D linear elastic FE calculations by Raju and Newman

a/c	a/t	ϕ [°]								
		0.00	11.25	22.50	33.75	45.00	56.25	67.50	78.75	90.00
0.20	0.20	0.617	0.650	0.754	0.882	0.990	1.072	1.128	1.161	1.173
0.40	0.20	0.767	0.781	0.842	0.923	0.998	1.058	1.103	1.129	1.138
0.60	0.20	0.916	0.919	0.942	0.982	1.024	1.059	1.087	1.104	1.110
1.00	0.20	1.174	1.145	1.105	1.082	1.067	1.058	1.053	1.050	1.049
2.00	0.20	0.821	0.749	0.740	0.692	0.646	0.599	0.552	0.512	0.495
0.20	0.40	0.724	0.775	0.883	1.009	1.122	1.222	1.297	1.344	1.359
0.40	0.40	0.896	0.902	0.946	1.010	1.075	1.136	1.184	1.214	1.225
0.60	0.40	1.015	1.004	1.009	1.033	1.062	1.093	1.121	1.139	1.145
1.00	0.40	1.229	1.206	1.157	1.126	1.104	1.088	1.075	1.066	1.062
2.00	0.40	0.848	0.818	0.759	0.708	0.659	0.609	0.560	0.519	0.501
0.20	0.60	0.899	0.953	1.080	1.237	1.384	1.501	1.581	1.627	1.642
0.40	0.60	1.080	1.075	1.113	1.179	1.247	1.302	1.341	1.363	1.370
0.60	0.60	1.172	1.149	1.142	1.160	1.182	1.202	1.218	1.227	1.230
1.00	0.60	1.355	1.321	1.256	1.214	1.181	1.153	1.129	1.113	1.107
2.00	0.60	0.866	0.833	0.771	0.716	0.664	0.610	0.560	0.519	0.501
0.20	0.80	1.190	1.217	1.345	1.504	1.657	1.759	1.824	1.846	1.651
0.40	0.80	1.318	1.285	1.297	1.327	1.374	1.408	1.437	1.446	1.447
0.60	0.80	1.353	1.304	1.265	1.240	1.243	1.245	1.260	1.264	1.264
1.00	0.80	1.464	1.410	1.314	1.234	1.193	1.150	1.134	1.118	1.112
2.00	0.80	0.876	0.839	0.775	0.717	0.661	0.607	0.554	0.513	0.496

fig. 5 the geometry and the most important dimensions are shown, fig. 6 shows the nomenclature and the assumptions made for the probabilistic analysis. The material assumed was cast steel GS 50.

4.1. Probability of failure by buckling

The deterministic calculations are the basis of the following probabilistic analysis. The allowable maximum pressure $p_{\text{buckl},z}$ was determined to be 400 bar. The actual external pressure p is 300 bar. The trivial criteria of non failure $p \leqslant p_{\text{buckl},z}$ is satisfied.

For the probabilistic analysis the symbols of fig. 6

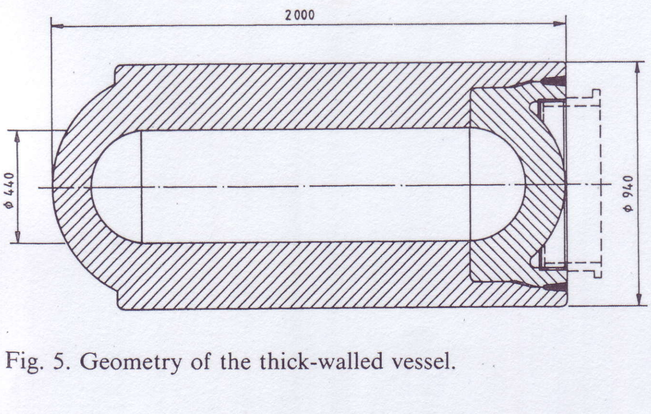

Fig. 5. Geometry of the thick-walled vessel.

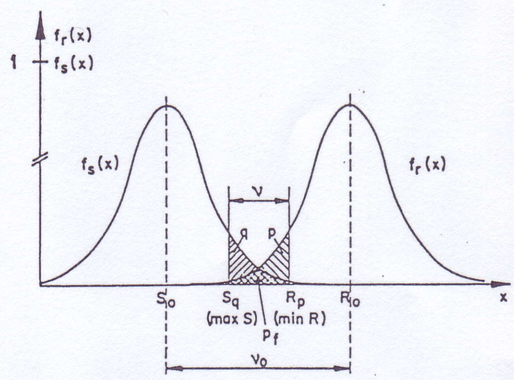

Fig. 6. Probability density functions of the load and the structural resistance with related notations.

S_0 = mean value of the load, e.g. external pressure,
R_0 = mean value of the resistance, e.g. buckling load,
S_q = "maximum" load acc. to the deterministic approach,
R_p = "minimum" resistance acc. to the deterministic approach,
p, q = fractions (see shaded areas),
$\nu_0 = R_0/S_0$ = safety factor acc. to the mean values,
$\nu = R_p/S_q$ = safety factor acc. to min R/max S,
p_f = failure probability,
$f_s(x)$ = probability density function of the load,
$f_r(x)$ = probability density function of the resistance.

were used and the following assumptions were made:

$R_0 = 2000$ bar $(5 \times (p_{\text{buckl},z} = 400 \text{ bar}))$,

$S_0 = 220$ bar $(< p = 300$ bar$)$,

$\sigma_R = 220$ bar standard deviations of R and S

$\sigma_S = 50$ bar (or $p_{\text{buckl},z}$ and p).

The failure quotient p_f is calculated with the additional assumption of standard distribution and tabulated values from reference books.

$$p_f = \Phi\left(-\frac{R_0 - S_0}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right) = \Phi(-7.9) = 0.15 \times 10^{-14}. \quad (3)$$

Eq. (3) is based on the general eqs. (4) and (5) where p_f is expressed by the integral

$$p_f = F_v(1) = P(R \leqslant S) = \int_0^\infty F_r(x) f_s(x)\, dx, \quad (4)$$

$$F_r(x) = P(0 < R \leqslant x) = \int_0^x f_r(\xi)\, d\xi. \quad (5)$$

The probability of failure $F_1(t)$ in the time interval $(0, t)$ is:

$$F_1(t) = 1 - \left[\int_0^\infty \sum_{r=0}^{\infty} p_r(t) \{F_s(x)\}^r f_r(x)\, dx\right]. \quad (6)$$

With the help of the reduced equations derived from eq. (6) $F_1(t)$ is calculated. The method is extensively explained in [3].

$$F_1(t) \simeq 1 - (1 - p_f)^t, \quad (7)$$

$$F_1(t = 1000 \text{ y}) \simeq 1.5 \times 10^{-12},$$

$$F_1(t) \simeq 1 - \exp(-p_f t), \quad (8)$$

$$F_1(t = 1000 \text{ y}) \simeq 1.5 \times 10^{-12}.$$

The quoted results are explained and commented in ref. [3]. Due to the extent of reasoning necessary only the remark to [3] shall be made that a probabilistic reliability analysis is difficult for two reasons:

- there is a variety of technical equipment to consider,
- each component is exposed to a variety of influences and mechanism which can lead to failure.

Failure data and statistics from the conventional pressure vessel industry were used for comparison with these theoretical results of the probabilistic analysis.

5. Discussion

Aspects of stress analysis, fracture mechanics and probabilistic failure of components have been discussed. An attempt shall be made to connect these three analytical methods.

Even though only partial aspects have been considered, a general solution for the analysis of complex components seems possible.

It is obvious that these are not only partial problems but overall and interdisciplinary tasks.

A common problem is that a component is fully analyzed under the assumption of no flaws, but in the course of inspection, and after manufacturing, flaws are detected.

For the example of the pressure vessel nozzle, assuming a semi-elliptic crack, the large amount of time and money spent for the stress analysis is now useless.

Possible solution: The stress analysis is not without value, but it is not the only evaluation basis. It must be combined with fracture mechanics. But the so-called influence (correction) functions, which are necessary for calculating the fracture mechanics parameter such as K and J, are more complex than in the case of the relative simple configuration of the disc. Also, the material aspects must be expanded to include K and J.

The following methods are possible:

(1) Hand calculations with diagrams and tables from fracture mechanics handbooks, codes and regulations or other references.

(2) New calculations of the relevant fracture mechanics parameter such as J and K with expensive computer programs, a de facto new analysis of the already analyzed components.

The application of the results is to some extent doubtful. In practice it is generally felt that repair is better than the existence of some small flaws.

Another connection would be between the fracture mechanics example (disc) and the probabilistic analysis (thick walled vessel). The question in this case would be: how to proceed in the case of a flaw in the thick walled vessel? The solution in this case is the so-called probabilistic fracture mechanics, developed from reliability analysis and deterministic fracture mechanics.

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FESTIGKEITSANALYSEN UNTER BERUECKSICHTIGUNG VON BRUCHMECHANIK UND WERKSTOFFASPEKTEN FUER ANLAGENBAUTEILE BEI KOMPLEXER BELASTUNG

Stress Analysis Incorporating Fracture Mechanics and Materials Aspects for Components Under Complex Loading

P. H. Hirt, N. Jaussi, M. Prodan

MOTOR-COLUMBUS Ingenieurunternehmung AG
Baden/Schweiz

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Festigkeitsanalysen unter Berücksichtigung von Bruchmechanik und Werkstoffaspekten für Anlagenbauteile bei komplexer Belastung

P. H. Hirt, N. Jaussi, M. Prodan

MOTOR-COLUMBUS Ingenieurunternehmung AG
Baden/Schweiz

ZUSAMMENFASSUNG

Der Titel spricht eine verwickelte Thematik an. Das Thema "Festigkeitsanalyse unter Berücksichtigung von Bruchmechanik und Werkstoffaspekten" ist weltweit Gegenstand von Forschungs- und Entwicklungsarbeiten. Es kann dementsprechend in diesem Referat nicht abschliessend behandelt werden. Es soll vielmehr versucht werden, einen Beitrag zur Diskussion obiger Problematik zu leisten.

Der Vortrag befasst sich mit drei Beispielen zu dem im Titel genannten Problemkomplex. Dazu werden eigene und Gemeinschaftsarbeiten benutzt. Wegen der Fülle der behandelten Fragen wird eine kondensierte Darstellung mit Hinweisen auf Referenzen geboten. Die Beispiele sind ein Behälterstutzen, eine sogenannte bauteilähnliche Scheibe, und ein dickwandiger Behälter.

1. EINFUEHRUNG

Von besonderer Bedeutung für die Sicherheit von Nuklear- und Chemieanlagen ist die Integrität ihrer Komponenten, d. h. Behälter, Rohrleitungen und anderer Anlagenelemente. Beim mechanischen Nachweis dieser Integrität bzw. der Festigkeit werden u. a. die Methoden der Spannungsanalyse, der probabilistischen Zuverlässigkeitsanalyse und der Bruchmechanik benutzt. Der Einsatz von Computerprogrammen ist dabei unumgänglich. Je nach Art und Grösse des Problems sollten aus Kostengründen die angewendeten Programme (FEM/Schalen) optimal ausgewählt werden. Dem Ingenieur muss also heute eine Palette von Programmen für eine angepasste, optimale Lösung der Aufgaben zur Verfügung stehen.

Im folgenden wird anhand dreier Beispiele gezeigt, wie Spannungsabsicherungen, probabilistische Analysen und Bruchmechanik auf druckführende Komponenten von Ingenieuren angewendet werden, sei es in einer Ingenieurunternehmung [1 - 3], sei es in Versuchs- und Forschungsanstalten [4, 5].

2. BEISPIEL BEHAELTERSTUTZEN

Es stellte sich die Aufgabe, eine Spannungsanalyse durchzuführen. Gegenstand war eine Nuklearkomponente, ein Stutzen und der Uebergang zum Aussenmantel und Zentralrohr eines speziellen Wärmetauschers [2]. Der Stutzen schliesst sich schräg der Behälterwand an (nicht rotationssymmetrisch), wodurch eine dreidimensionale Modellierung notwendig war. Fig. 1 zeigt die Geometrie des Rechenmodells. Mit diesem Finite-Elemente-(FE-)Modell, bestehend aus 5500 dreidimensionalen 8-Knoten-Elementen oder aus rund 7600 Knoten, wurde eine Festigkeitsanalyse erstellt. Hierbei wurde von einem reduzierten Belastungspaket ausgegangen. 11 instationäre Transienten der Temperaturen des Kühlmittels Natrium wurden durch 5 spannungsmässig abdeckende Transienten eingegrenzt. Innendruck infolge des Sekundärkreislaufes, Rohrkräfte und Verspannkräfte aus dem Gesamtwärmetauscher waren zu erfassen. Die Berechnungen der Stahlstrukturteile wurden mit den Programmsystemen ANSYS (Temperaturfelder) und NASTRAN (Spannungs- und Verschiebungsfelder) ausgeführt. Für einen einzeln herausgegriffenen Zeitpunkt einer Temperaturtransiente zeigen Fig. 2 und 3 in einem Längsschnitt die Isothermen und Isospannungen (zweifache Tresca-Spannungen). Aus den sog. Grundlastfällen wurden Lastkombinationen erstellt. Bei der Temperaturberechnung waren die nichtlinearen Abhängigkeiten der Wärmeübertragungsmechanismen an der Strukturoberfläche und in der Struktur zu berücksichtigen. Der Werkstoff war der Stahl X6 CrNi 1811 (1.4948).

2.1 Spannungsabsicherung

Im Anschluss an die Spannungsanalyse musste der Nachweis erbracht werden, dass die errechneten Spannungen innerhalb der von ASME-Code und anderen Regelwerken vorgeschriebenen Grenzen liegen. Diese Absicherung der Spannungen wurde mit einem dreidimensionalen Absicherungsprogramm CASAFE gemäss ASME-