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ESTIMATION OF PWR LOWER HEAD FAILURE TIMES USING THE METHOD ASTOR

P. Eisert, P. Gruner and W.M. Kuntze

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Köln, Germany

ABSTRACT

Failure times of a PWR lower head subjected to stationary pressure and temperature loads were calculated. The data were used to approximate times to failure if loads vary in time. Results are compared with those of more rigorous analyses.

1. INTRODUCTION AND OBJECTIVE

Analyses of the margin to failure of structures of the main cooling system of nuclear reactors subjected to severe accident loads are in most cases very tedious and time consuming. Hence, the performance of such an analysis within the framework of thermal hydraulic analysis codes is usually out of scope. For these cases more flexible methods are needed which can yield the required information quickly and with sufficient accuracy. In continuation of the work we began some time ago to estimate times to failure of primary circuit components /Suh 90/, first steps to develop a further suitable method were undertaken. The method will be described and its present status of applicability to the lower head (LH) of a reactor pressure vessel (RPV) of a pressurized water reactor will be documented by a few examples.

The initial step of the method to determine numerically failure times of a structural part under specified loads is conceptionally equivalent to a creep rupture test. As in a conventional uniaxial creep experiment, the LH is assumed to be quickly heated up to a certain stationary temperature at the inner surface of its wall and exposed to mechanical stresses which result from a given level of the vessel pressure. The failure time of the LH which is subjected to this specified step-function-like load combination is determined by a numerical analysis using some strain limit criterion. As parameters that characterize the time to failure, the LH - inner surface temperature and the internal pressure are used. Performing several numerical analyses of this kind to cover the ranges of temperatures and pressures to be expected in an accident yields a series of structural failure times which can be regarded as discrete pivots of a continuous failure time surface in the failure time-temperature-pressure space.

In the next step of the procedure the failure time surface is used in connection with some damage accumulation hypothesis to predict the time to failure of the structure when subjected to loads which are varying in time. In these cases the characterizing parameters, i.e. inner surface temperature and internal pressure, do change in the course of time. As of now, a linear damage hypothesis has been used, only. The failure times obtained according to this simplified approach which we termed ASTOR (Approximated Structural Time Of Rupture) are compared with the times to failure as obtained by more rigorous numerical evaluations for several predefined loading histories.

It must be pointed out that the failure time pivots and hence the failure time surface depend, aside from the characterizing parameters and the implied failure criterion, also on the initial state of temperature of the structure and on the heat transfer conditions to the environment, as well. Hence, there exist distinguished failure time surfaces for each of the mentioned conditions. The surfaces which belong to two different conditions have been analysed so far.

It is to be pointed out, too, that the method ASTOR can yield only estimates of the times to failure under transient loading conditions. The reason is, that transitional stress states within the wall and stress redistributions as they might occur due to possible unloading and reloading cannot be represented in the failure time surface which is constructed under the assumption of stationary loading conditions at the inner surface. Yet, the approximate method is expected to be a reasonable approach if the rate of change of the surface conditions is not too large.

In following chapters the finite element model of the LH which is used for heat propagation analyses and stress calculations as well as the material properties applied are briefly discussed. Then results of the calculated failure time surfaces are presented. In a final section failure times predicted by the method ASTOR are compared with finite element analysis results for a few transient loading conditions.

2. MODELLING OF THE RPV LOWER HEAD

Finite-element-analyses using ADINA were performed to determine failure times of a RPV-LH subjected to pressure and temperature loading beyond design limits.

An axisymmetric model representing a 0,25°-circular section of the RPV lower head wall was provided using 8-nodes 2D-solid elements. The wall-thickness of the RPV bottom was divided into 12 layers of elements. For an adequate consideration of steep temperature gradients near the inner surface of the RPV-LH the thickness of element layers was varied continuously over the wall-thickness with the thinnest element at the inner surface of the RPV.

The investigation proceeds from the assumption of an undisturbed spherical shell which is expanding in radial direction under constant pressure and temperature loading at the inner surface. As dynamic effects resulting from this loading are negligible a quasi-static analysis of the RPV behaviour was performed.

In version 6 of the ADINA-code multi-linear stress-strain curves with the possibility to define strain limits are provided for description of a nonlinear thermo-plastic material model. Temperature dependence of physical properties as well as temperature respectively stress dependence of creep are included. The calculations were performed using the Total-Lagrange-Method which can yield adequate results up to strain values of about 4%. For higher creep-strain the Updated-Lagrange-Method would have been better qualified. As of now, unresolved numerical problems forced however the application of the Total-Lagrange-Method also in the higher strain regime.

3. MATERIAL PROPERTIES

To give an adequate description of the behaviour of the RPV bottom loaded by different temperature distributions over the wall-thickness the following material properties with dependence on temperature must be known: thermal conductivity, thermal capacity, mass density, strength properties, thermal expansion, lateral contraction, and creeping behaviour.

The first 3 properties of this list were determined according to the material characteristics reported in the investigations of the German Risk Study NPP, Phase B.

The technical stress-strain diagrams of the RPV-steel 22 NiMoCr 37 provided by MPA-Stuttgart /MPA 91/ represent the basis for the investigations of the RPV lower head. The stress-strain characteristics were determined by uniaxial hot tension tests for specified temperature levels from 24° to 1000°C. Taking into account the multiaxial stress conditions in the RPV lower head the measured uniaxial rupture strains were reduced by the triaxiality factor /JU 84/.For spherical symmetry the global reduction factor is 2. The influence of local variations of stresses on the triaxiality factor as caused in particular by thermal effects was not considered in this investigation. The stress-strain diagrams of the RPV-steel which are modified by this factor are shown in fig. 1. They exhibit a rapid decrease in strengthening behaviour of the material with increasing temperatures. For calculations up to temperatures of 1600°C appropriate stress-strain curves were extrapolated from the measured data.

The formulas provided in ADINA for the description of creep behaviour were adapted to approximate measured creep curves.

4. HEAT TRANSFER CALCULATIONS

Prior to the structural analyses time dependent temperature profiles across the wall-thickness of the RPV-LH were calculated which result from the temperature loading of the inner surface of the LH. (In this calculation thermal isolation of the outer surface of LH was assumed.) Calculations of heat propagation through the wall of the RPV-LH were performed for a set of step-function-like inner surface temperatures with different levels each of which remained constant following the jump of temperature. The results of these calculations were taken as temperature loading for the following structural analyses with ADINA. To each level of internal surface temperature of the LH wall there belongs a certain thermal stressing and straining which varies in time according to the variation of the corresponding temperature profile.

5. DETERMINATION OF FAILURE TIMES

The structural behaviour of the section model of the RPV-LH loaded by a constant internal pressure and by a step-function-like inner surface temperature leads on account of the temperature field propagating in the wall to complex conditions of varying plastic states.

The strain behaviour of the last element at the outer surface of the section model was taken as basis for decision of failure of the RPV-LH because local effects at inner regions of the wall are minimized here. Two types of failure modes are distinguished:

- Structural failure may occur if the ability of mechanical resistance to the internal pressure is lost. This type of failure occurs in particular when high pressure coincides with high temperatures. The calculation is stopped automatically by the program when temperature dependent limiting strain values as indicated in fig. 1 are reached.
- Another failure mode is produced by creep behaviour resulting in longer times to failure especially in connection with lower internal pressure values. As failure criterion a creep strain value of 20% was taken with consideration of the triaxiality factor 2. A strategy to cope automatically with creep strain limits is not yet available within the program.

Failure times were determined for 2 initial reference temperatures representing RPV failure scenarios influenced by low system pressure (T_{ref} = 178°C) and by high system pressure (T_{ref} = 320°C), respectively.

From the structural analyses of the RPV section model resulted numerous failure time values (pivots of the failure time surface) in the range of about 300 to 1200 seconds which are shown in fig. 2 for the initial temperature T_{ref} = 320°C. Each pivot represents the time to failure of the lower head if a certain pressure level and a certain inner surface temperature are held fixed in time. As can be seen from the figure the number of calculated pivots is sufficient to spread the respective failure time surface with an adequate degree of accuracy.

6. PREDICTION OF THE TIME TO FAILURE ACCORDING TO THE METHOD ASTOR AND COMPARISON WITH RESULTS OF FINITE ELEMENT ANALYSES

The failure time surfaces of the previous section were obtained for quasi-stationary inner surface loads. In order to apply these data also for cases of time varying loads, a damage parameter was introduced. It is assumed that the rate of damage increase at time t, resulting from a certain pressure level of p(t) and a temperature T(t) at the inner surface of the lower head, can be approximated by the reciprocal of the failure time $\tau[p(t),T(t)]$, as determined for quasi-stationary surface loads. Integration of the damage rates along a loading path in the p(t)-T(t)- plane up to a certain time t yields an approximation to the actual damage state D(t). The trace of such a path on the failure time surface is schematically presented in Fig.3. According to this linear damage accumulation hypothesis, failure of the structure will occur if the damage parameter becomes equal to one. The time corresponding to this latter condition is assumed to be a sufficient approximation to the time to failure of the structure when subjected to time varying loads.

As of now, the method has been used to estimate failure times for a few different p(t)-T(t) loading paths. The comparison with corresponding failure times which were obtained by finite element analyses indicate that the errors range within a few minutes,only. For example, in the case of transient pressure loading between 2 and 16 MPa and transient temperature loading between 178 and 1537°C a failure time of 2275 seconds was obtained by ASTOR, the finite element analysis yielded 2380 seconds, i.e. a difference in the region of 1-2 minutes.

7. CONCLUSIONS

With the approximative method ASTOR failure times of the lower head of a PWR were estimated for pressure-temperature loads of various temporal behaviour. Comparisons with results of more rigorous finite element analyses indicate the method's potential for a time saving, yet sufficiently accurate procedure. However, further verifications are still needed in order to quantify error bands for the method. In future investigations, the precision of the failure time surface will be improved by taking into account implementation of stress state dependent triaxiality, application of Updated-Lagrange-Method and cut-off procedure of local bearing capacity if creep limits are exceeded.

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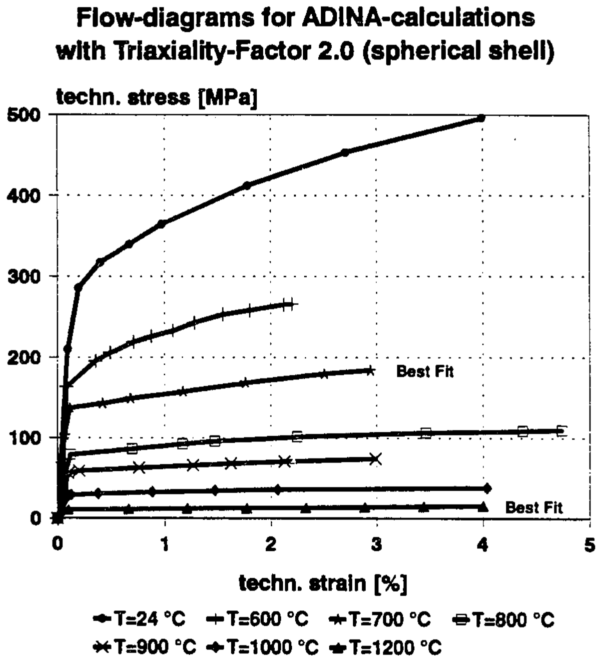
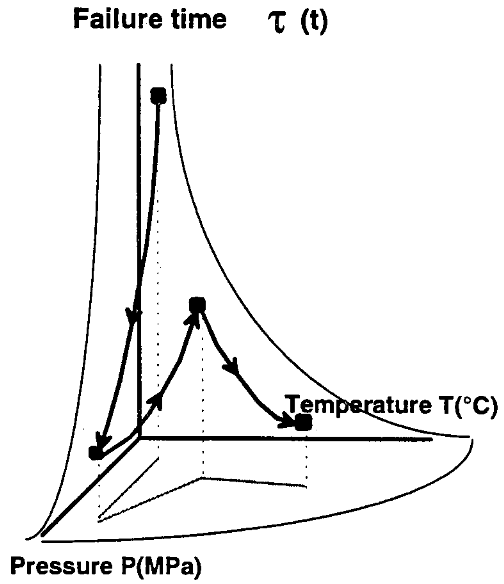
Material: 22 NiMoCr 37



Reference: MPA-flow-diagrams

fig. 1



Approximated Structural Time Of Rupture (ASTOR)

fig. 3

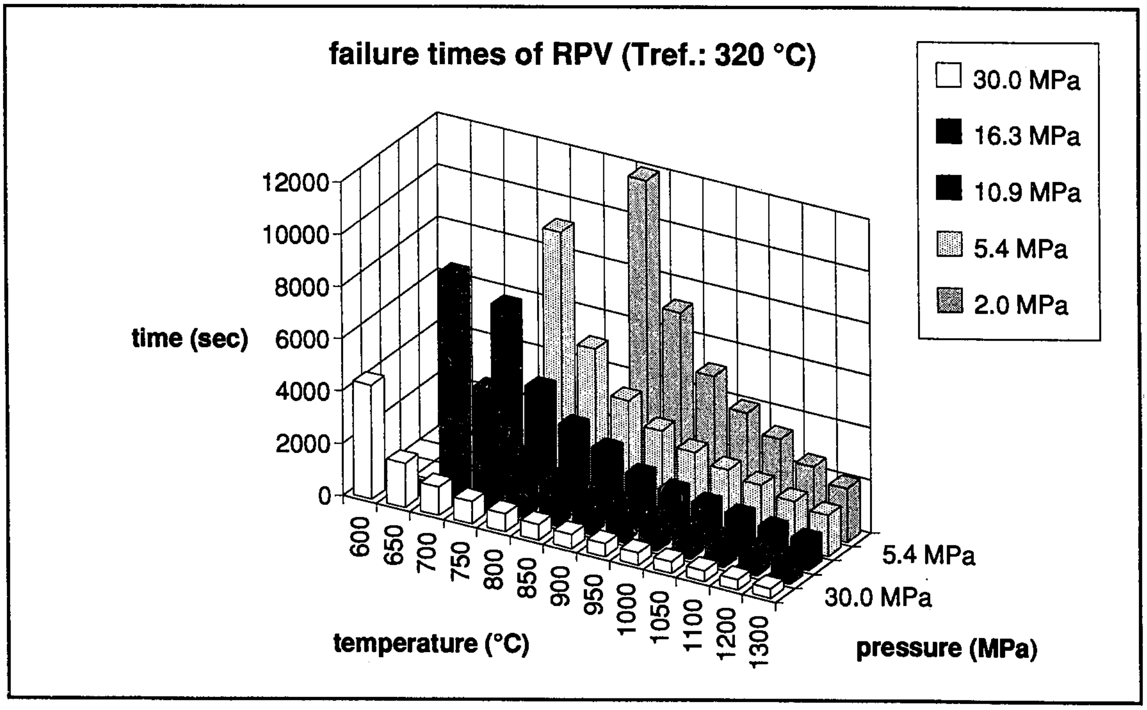


fig. 2