

Damage Evaluation Using Advanced Functionalities in Abaqus

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Abstract:

Linear-elastic fracture mechanics on the basis of advanced tools in FEM calculation (XFEM, contour integral) enable rapid and realistic evaluation of the fracture growth. This results in new possibilities, for example, for the derivation of testing intervals (damage tolerance analysis, contour integral) and for the carrying out of damage analyses.

Using an industrial example, procedures and results of the Abaqus-supported determination of stress intensity factors will be explained.

Considerations for the calculation of the fracture course with a dominant strain-induced load will be discussed.

Keywords:

Fatigue crack propagation, XFEM, stress intensity factor, cyclic strain induced loading

Introduction – findings, construction, process

The new tools in Abaqus/CAE (XFEM, J-Integral) were used to carry out crack propagation analyses in the context of an industrial order. In the process a procedure was selected that represents a combination of results from the newly implemented XFEM method and the already existing J-Integral calculation.

In so doing it proved advantageous that the damage event described in the following and the cracks detected in the process could be compared with the results of the calculation.

The skirt supports of several process containers ($D_i \times s = 5090 \times 80$ mm) were provided for protection from operational thermal loads with 82 expansion joints (290×10 mm) equally distributed over the circumference (Figure 1, left).

Indications of cracks were found at all expansion joints of the skirt supports in the context of inspections (Figure 1, right). The cracks started outside at the 12 o'clock position and, depending upon the period of usage of the containers, reached maximum crack lengths of approx. 12 mm (3 years) to 20 mm (9 years).

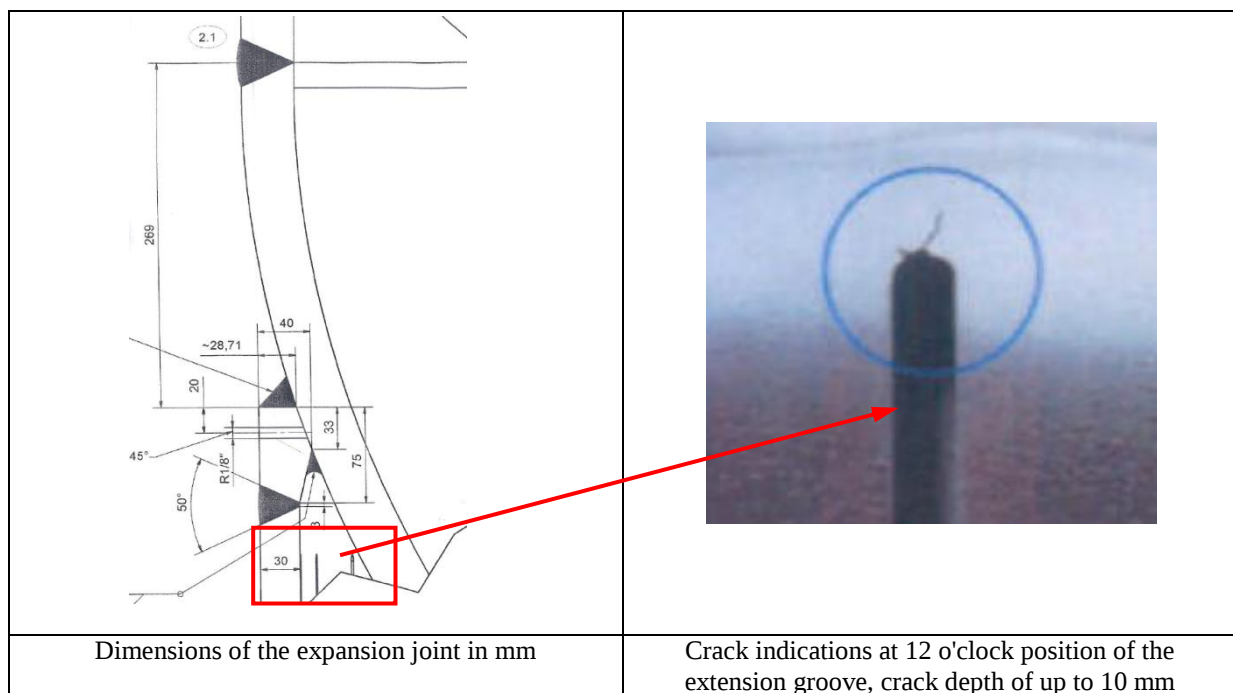


Figure 1. Versions of the skirt support upper part (crack in 12 o'clock position)

The containers manufactured from the creep-resistant material 16Mo3 /3/ (frame connector) are subject to frequent process-related temperature changes (app. 200 load variations per year).

Temperature load variation

- Start-up – Filling with liquid medium at 490°C
(temperature change from 275 to 410°C in 15 minutes,
 $v_T = 9$ K/min)
- Shut-down – Cooling off by feeding in cold water at 50°C
(temperature change from 300 to 50°C in 45 minutes,
 $v_T = 6$ K/min)

Other stresses are the result of own weight (115 t), full weight (approx. 450 t) and internal pressure (1.5 bar) and can be disregarded due to the minor contribution.

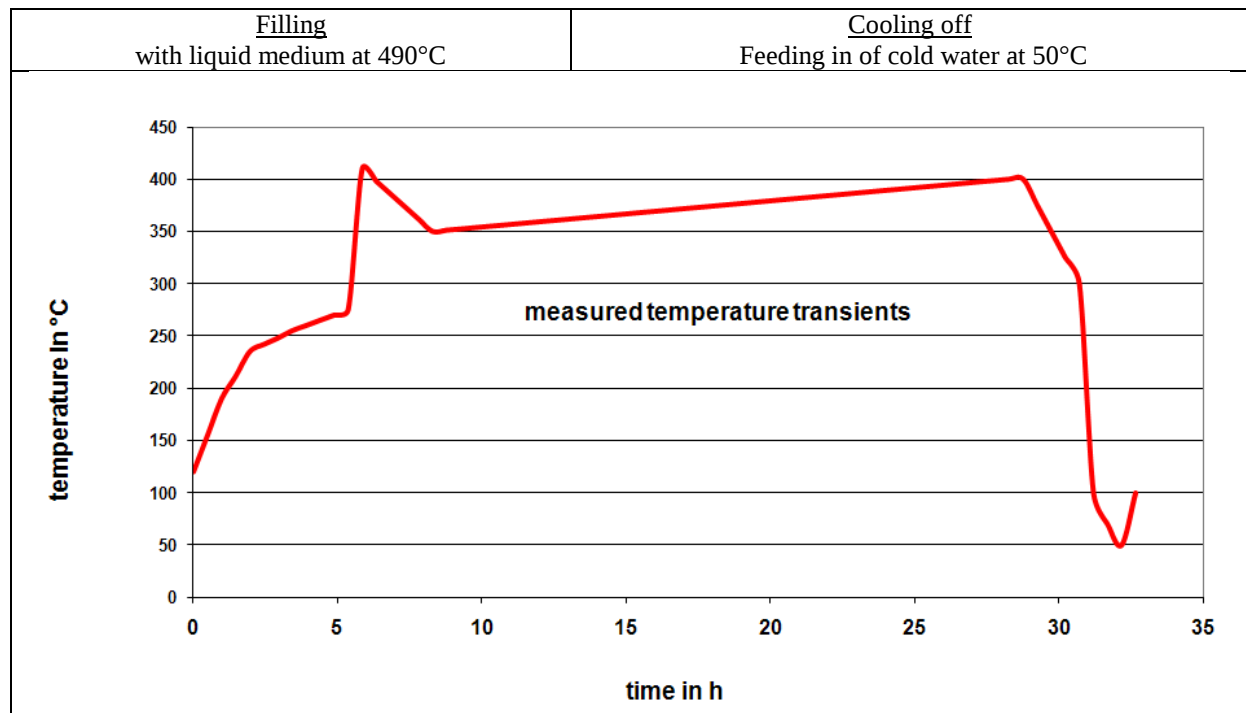


Figure 2. Measured temperature transients in the framework of an operating cycle

Linear –elastic stress and fatigue analysis

Modelling: Utilising the even load and the symmetrical design of the container, a solid model consisting of one 15° sector was modelled for the simulation. The area of the expansion joint at 12 o'clock was linked in accordance with the elementing requirements for carrying out notch stress analyses (quadratic element C3D20R – 20-node quadratic brick, reduced integration, 18 elements throughout the quadrant /6/).

The model refers to a polar coordinate system. Appropriate translation constraints were attached on the sides of the 15° sector. Because the frame is permanently mounted with threaded bolts, vertical and horizontal dislocations on the underside of the frame are prevented.

The temperature transients (Figure 2) and the temperature-dependent material properties /2/ necessary for the simulation were implemented in the FEM model. The calculation was carried out in the form of a sequentially coupled temperature field and stress analysis.

Results: At their ends, and especially at the 12 o'clock position, the expansion joints cause a stress maximum of 1,150 MPa due to the stress concentration there.

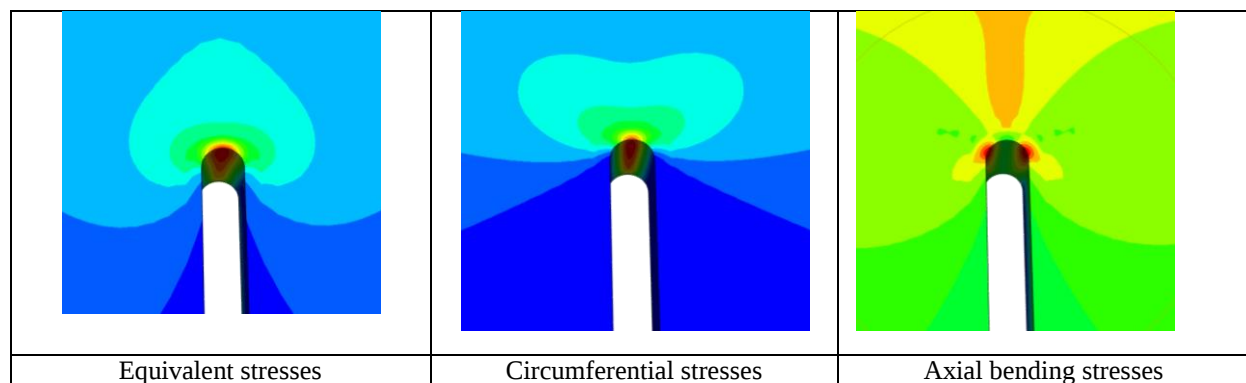


Figure 3. Stress distribution around the 12 o'clock position

These occur respectively at the beginning or at the end of the process at the point in time of maximum temperature change speeds. From the represented total stress progress it is possible to recognise that the heating up and cooling off processes create a tensile-compressive stress variation of approx. 2,300 MPa.

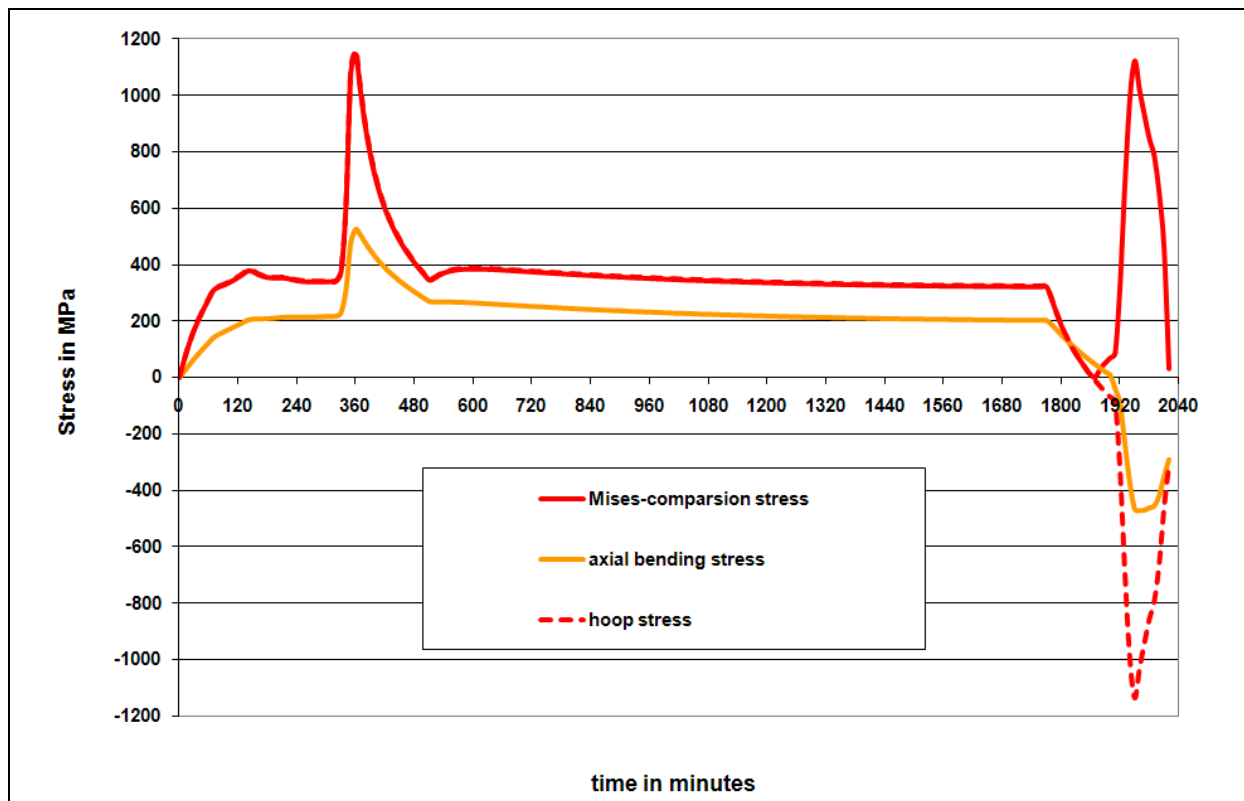


Figure 4. Course of the stress components during an operating cycle

This high stress variation is partially construction-related, but is also partially a consequence of the operation mode. The rapid temperature changes (filling with liquid hydrogen mixture at 490°C, cooling off by feeding in of cold water at 50°C) cause short-term dramatic temperature differences. The construction-related expansion constraint results in strong thermal stresses that in turn lead to the stress peaks at the beginning and end of the cycle as shown.

When using the fatigue curves for unnotched test rods of creep-resistant, ferrite and austenitic forged steels [4], a maximum permitted number of cycles of $n = 400$ can be derived.

Because the average annual number of cycles amounts to $n = 200$, one receives an operating period not subject to mandatory reporting of 2 years. When this value is subtracted from the operating time, the following input data for the crack growth results:

- Container 1, operating time of 3 years → crack growth of 10 mm in one year
- Container 2, operating time of 9 years → crack growth of 20 mm in seven years

In so doing, it was presumed for reasons of simplification that a crack capable of growth will form upon reaching the depletion level $D=1$.

Even a simple comparison of the data shows that the crack growth slows with increasing operating time.

Fracture mechanics evaluation

XFEM method: The XFEM method in Abaqus /1/ enables the examination of crack paths without the need for an adaptive network adjustment.

The MAXPS criterion was used for the component examined here. In so doing, Maxps describes the development of the cracks and the subsequent crack growth using an initiation stress (e.g. yield strength). In /1/ a "domain" was defined in which the crack expanded. An initiation stress was also prescribed and an evolution law defined for the crack growth. The energy released at the crack opening (energy release rate) was estimated on the basis of the fracture toughness of comparable materials.

The XFEM method makes it possible to study the crack path. For one thing, as in the present case, a comparison with the cracks found in the inspection can be carried out. In the event of agreement, this is a clear indication that the simulation correctly illustrates the stresses that resulted in the damage. The method can thus assist in verifying the cause of damage.

On the other hand, contour integrals can be calculated in a subsequent step. In doing so, the position of the crack level in the component and the exact course of the crack front can be designed very realistically according to the specifications of the XFEM results.

In the present case, dominant circumferential stresses (Mode I) result in a crack initiation at the end of the expansion joint. Due to the uneven stress distribution in the frame connector above the expansion joint, the crack clearly grows more rapidly on the outside of the frame connector than on the inside (see Figure 5).

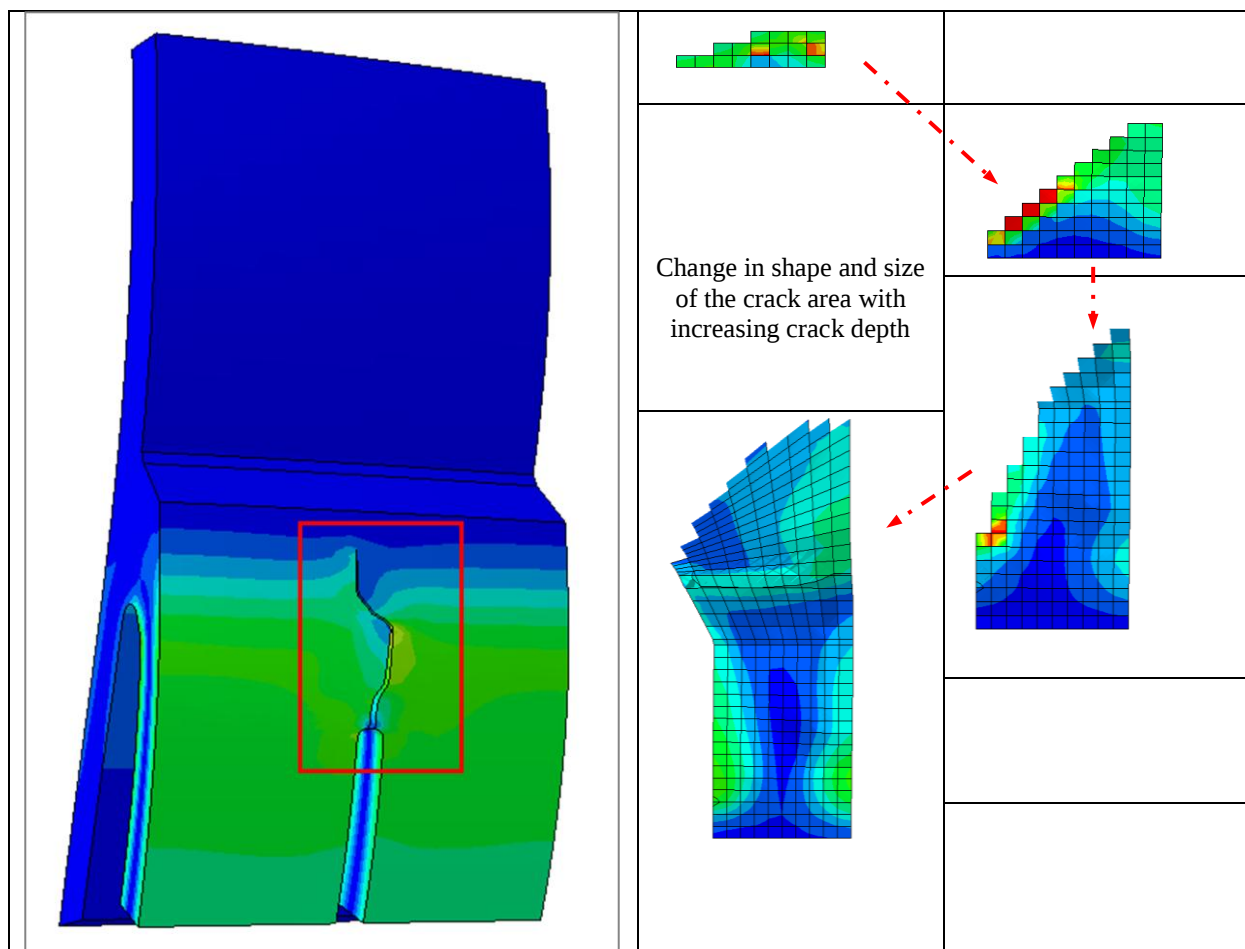


Figure 5. Crack growth depending upon the crack depth

Contour integral calculation: In order to calculate the stress intensity values, a series of contour integral calculations for various crack depths and shapes was carried out in Abaqus /1/. With the existing tools in /1/ it is possible to construct a crack model. The variation of the crack depth can be carried out in /1/ with only a few adjustments (Figure 6).

The calculated stress intensity values can subsequently be derived from the result files /1/ and evaluated. The maximum of the circumferential stresses responsible for opening up the crack and thus the stress intensity factor occurs respectively at the end of the steep section of the temperature transients (after 6h) (Figures 2 and 4).

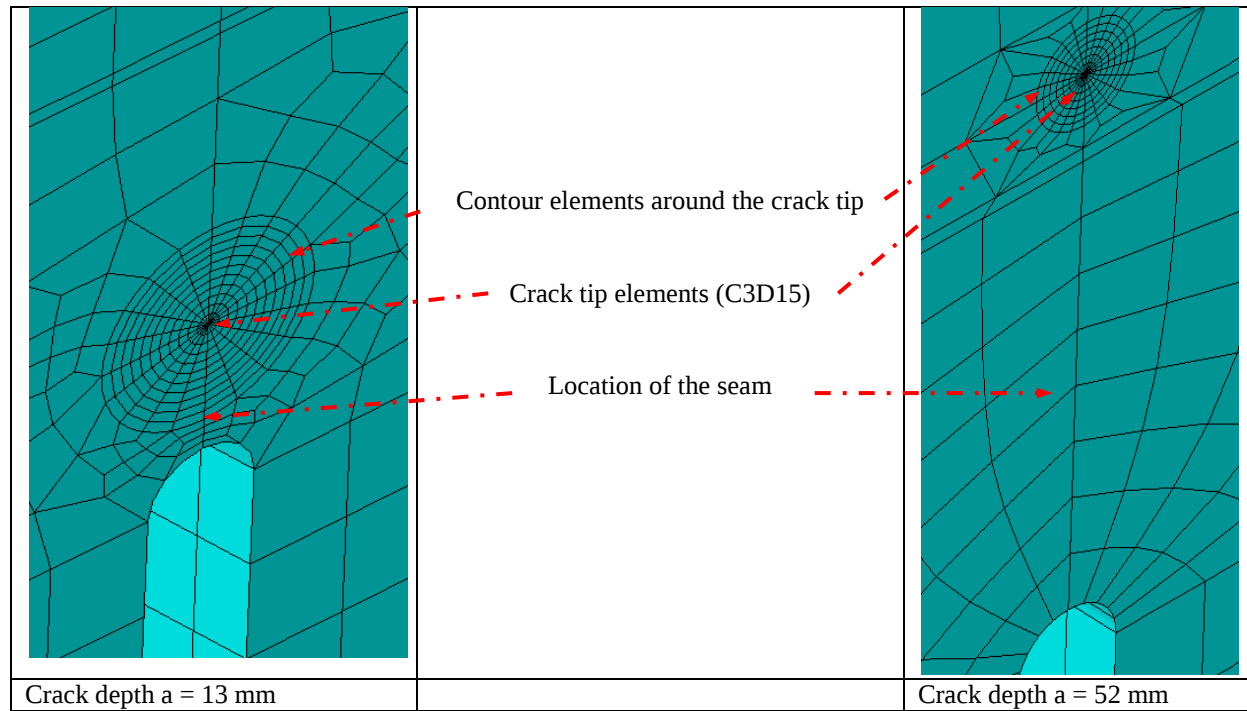


Figure 6. Contour integral modelling in Abaqus

In the context of the evaluation, the stress intensity factors along the crack front were written out for several cracks with increasing crack depth. For the subsequent examination of the crack growth, the stress intensity factors on the outside and a stress intensity factor determined using the wall strength were used as a basis (Figure 7).

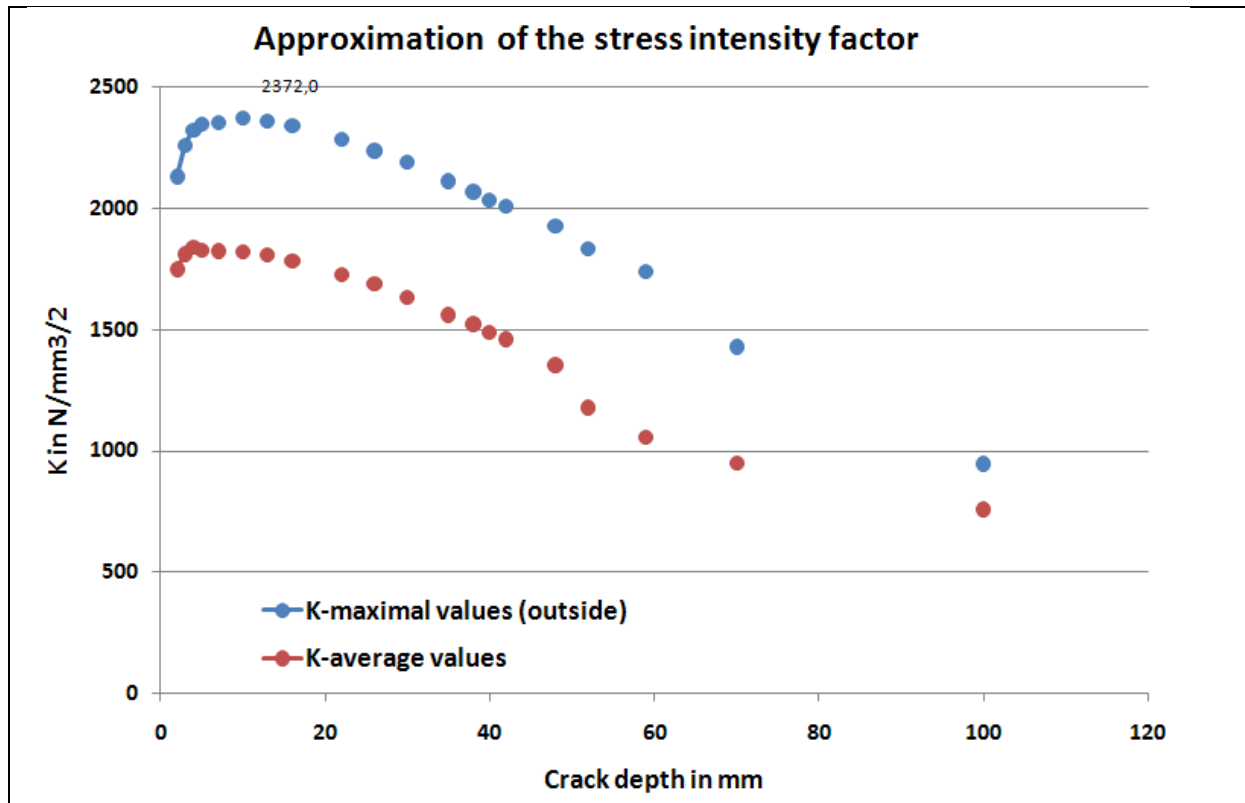


Figure 7. Course of the stress intensity factor as a function of crack depth

The course shows that the stress intensity factors lessen with increasing crack depth. The cause for this is the temperature distribution between the "cold" frame connector and the "hot" wall of the container. As a consequence, a change from tensile stress to compressive stress takes place between the frame connector and the container.

For the following analytical calculation of the crack growth, the course of the stress intensity factors is approximated by the linear functions shown in Figure 8.

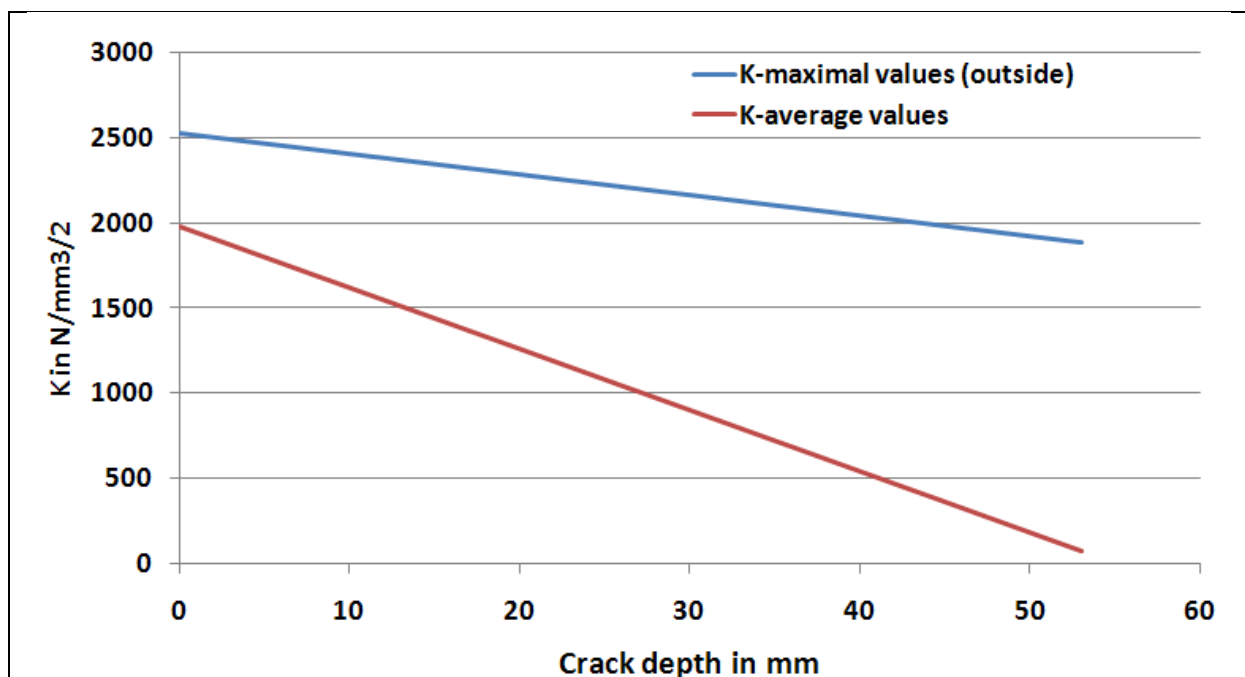


Figure 8. approximated linear functions of the stress intensity factors as a function of crack depth

The steeper course for the medium stress intensity factors results from the uneven growth of the crack throughout the wall thickness (Figure 5). For this reason these values must refer to the smaller crack depths in the middle of the wall.

Crack progress calculation: The calculation of the crack progress was carried out on the basis of the classic Paris' law, using the stress ratio of R. Due to the active cooling at the end of the operating cycle (Figure 2) and the related crack closure caused by compressive stress (see Figure 4), the stress ratio of R=-1 and thus (1-R)=2 was set.

The coefficients C, m of the Paris' law were derived from the FKM guideline /4/ for a comparable material referring to the room temperature. Material constants were not contained in /4/ for the operating temperature of 310 - 350°C prevailing in the upper segment of the frame connector (Figure 9).

material	T [°C]	R _{p0,2} [MPa]	R _K	C	m	ΔK _{th} [Mpa√m]
23CrNiMo747	room temperature	652	-1	4,88·10 ⁻¹²	3	11,1 – 12,5

Figure 9. Constants of the Paris' law depending upon the temperature /4/

The procedure for deriving the relationship for the crack growth with the provided or derived quantities is demonstrated in the following as a flow chart:

$$\frac{da}{dN} = C \cdot \Delta K^m \quad \text{Paris' law with } C = 4.88 \cdot 10^{-12}, m = 3 \quad (1)$$

(entries in mm/LW)

$$\Delta K = b_0 - b_1 \cdot a \quad (2)$$

(from contour integral calculation)

$$a = f(N) \quad \text{Crack growth relationship} \quad (3)$$

The integration of the Paris' law (see Equation 1) with the initial conditions: a = 1 mm at N = 0 was carried out respectively for the K(a) functions represented in Figure 8. The results are compared for both functions in Figure 10.

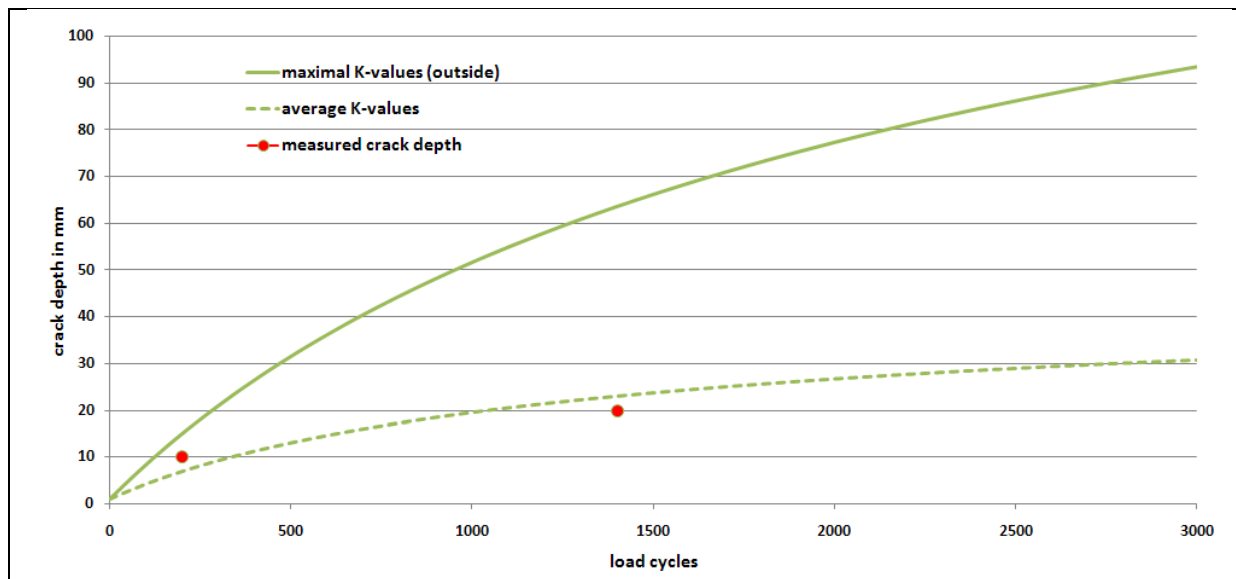


Figure 10. Crack growth in the frame connector depending upon the number of cycles

It can be seen that the K values determined from the function through the wall thickness agree relatively well with the detected crack lengths. In comparison to the calculation with the measurement, it becomes apparent here that clear differences occur at higher numbers of cycles, which means that the subsequent crack growth is overestimated.

Comments, discussion

Expansion of the Paris' law for strain-induced loads: Generally, the temperature transients in thick-walled components cause a compressive-tensile stress course over the thickness of the wall. This stress distribution is typical for strain-induced stressed components and differentiates itself fundamentally from components that are subjected exclusively to pure primary stress. This stress distribution can result in a reduction of the impetus for the crack growth with increasing length. The crack grows from the inside, which is subjected to high tensile stress, into the pressure area, which dampens the crack growth or arrests it entirely.

In this connection it must be considered whether the Paris' law is suitable as a pure growth law for the description of components subjected primarily to secondary stresses. A possible ad-hoc approach would be to expand the Paris' law (Equation 1) with an additional damping term $(G-a)/G$.

$$\frac{da}{dN} = \frac{C \cdot \Delta K^m}{1-R} \cdot \frac{G-a}{G} \quad \text{For } G > a \quad (4)$$

For $a \rightarrow G$ in equation 4, the crack growth would slow down increasingly and cease entirely upon reaching the threshold value. The growth limits designated in Equation 4 with G could be determined because the crack depth belonging to the threshold value from the calculated stress intensity function could be used. This can be achieved, for example, by continuing the progress of the stress intensity factor shown in Figure 8 to the crack depth connected with the K_{Th} threshold value. This would subsequently result in a damping factor $G \approx 50$ to 60 mm.

In order to examine the influence of the suggested expansion on crack growth, equation 4 was integrated using the results from Figure 8 ($\Delta K = 1977.7 - 36 \cdot a$) and the material exponents $m=3$.

$$\int \frac{da}{(b_0 - b_1 \cdot a)^m \left(\frac{G-a}{G} \right)} = \int C dN \quad (5)$$

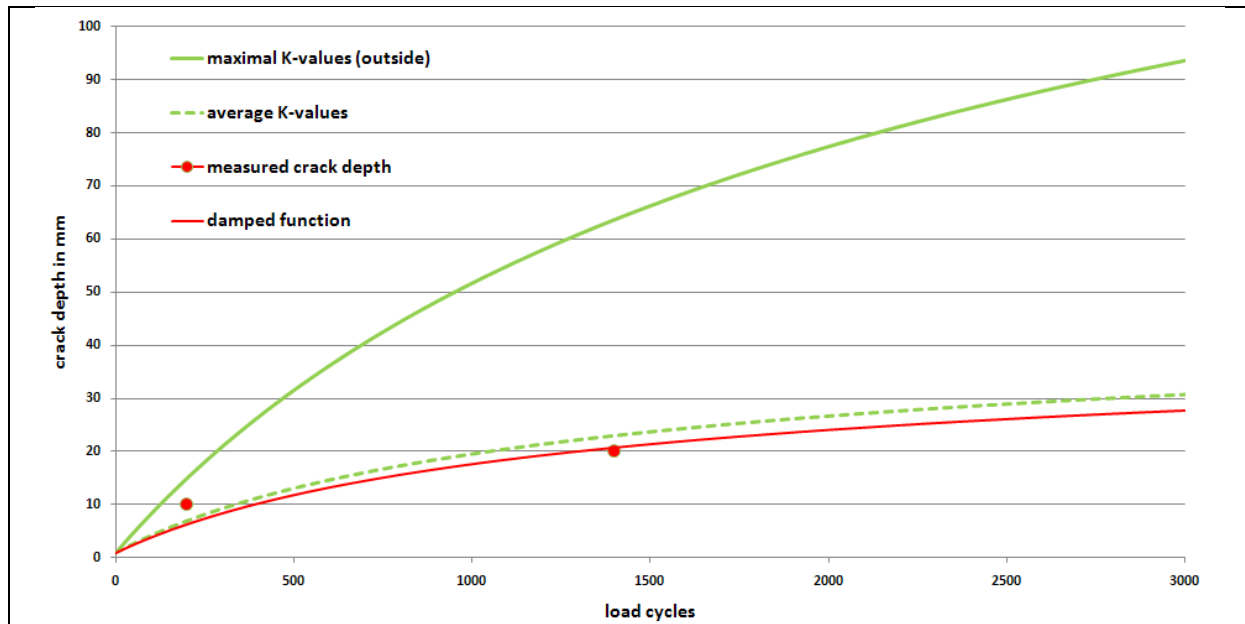


Figure 11. Crack growth in the frame connector depending upon the number of cycles for the expanded crack propagation equation

The analytical integration results in very complicated expressions that no longer allow for a simple resolution according to the crack depth $a(N)$.

The comparison of the solutions from equation 5 for the threshold value $G = 60$ mm carried out in Figure 11 shows that a considerably improved description of the crack path is possible with the expansion.

Summary

The procedure for the crack propagation analysis was demonstrated on an industry example using the new tools in Abaqus. A high level of agreement between the detected crack lengths and the calculation was achieved in the process.

Taking the practical application case as a starting point, an ad hoc suggestion was derived for the expansion of the Paris' law to stress-induced strains.

It was possible to show that the new tools in Abaqus (XFEM method) and their implementation in Abaqus/CAE (XFEM, J-Integral) enable a very realistic and economical analysis of the crack propagation. This makes wide usage of these methods possible for industrial use. The definition of inspection intervals and the calculation of the useful life reserves prior to breakage can in future take place promptly and efficiently.

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