5th Int. Conference Structural Integrity of Welded Structures (ISCS2007), Timisora, Romania, 20-21 Nov 2007
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PVrisk: an approach integrating non-destructive testing and probabilistic fracture mechanics

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Abstract
The integration of non-destructive testing and probabilistic fracture mechanics offers the possibility to gain realistic fracture mechanical assessment results considering nearly all uncertainties of the input values. Therefore, a probabilistic analysis has to be performed using distributions instead of discrete values as input parameters. This concept was realized with the developed software PVrisk which allows deterministic, parametric and probabilistic analysis of cracks and flaws in pipelines, tubes and pressure vessels. The probabilistic approach is based on a Monte Carlo simulation. The features of the software are implemented in accordance to accepted standards and design rules. The capabilities of the PVrisk software are outlined. Several examples are shown and advances and limitations will be discussed.
The software was especially designed for taking non-destructive testing results into account. This possibility is strongly related to the probabilistic assessment. Therefore, the probability of detection of a non-destructive testing method has to be considered. Using non-destructive evaluation methods for inspection larger cracks can be detected in advance and the component will be repaired or replaced. This assumption forms the base of a probabilistic analysis under consideration of the probability of detection of the used non-destructive testing method. The result is a refined analysis. Furthermore, the efficiency of a non-destructive testing method can be evaluated.
The result of a probabilistic analysis is a probability of failure. There are several possibilities to visualize the results of such an analysis. Different concepts and possibilities are regarded and the salient features are discussed.
Keywords: Quantitative non-destructive testing, probabilistic fracture mechanics, Monte Carlo simulation, POD, Failure Assessment Diagram

1. Introduction

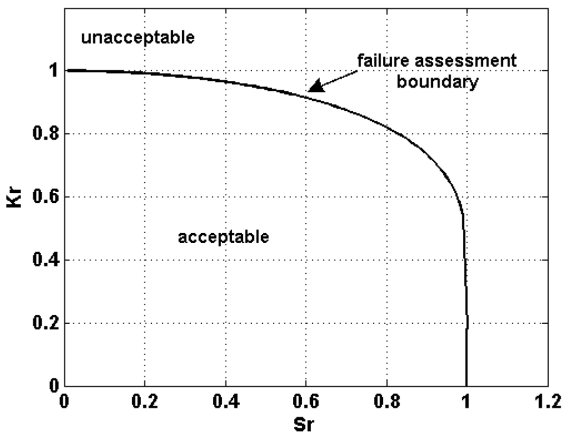
Each quantitative approach has to deal with uncertainties in order to achieve realistic predictions. The uncertainties are normally regarded as errors associated to a certain parameter. Concerning the failure analysis of a component such uncertainties have a severe influence on failure risk assessments. The Monte Carlo simulation offers the possibility to take uncertainties directly into consideration.

Failure risk assessment of components means analysing the state of the material which is given by the defect state, the microstructure state and the stress state. Characterizing the defect state is detection of defects, classification of crack-like and non-crack-like and sizing. Obviously, from the propagation potential point of view, cracks are the most critical flaws. NDT of microstructure and stress state characterization are not yet common in industry. However, first NDT equipment installations in steel industry exist [1].

For metals the Failure Assessment Diagram represents a tool which summarizes, in the deterministic case, the results in the form: failure or no failure [2, 3] (Fig. 1). The failure assessment as shown in Fig. 1 was developed for deterministic input values. It has become an accepted tool for failure analysis and is part of several standards and norms [4, 5, 6]. However, the FAD was originally designed for deterministic input information and, as already mentioned, realistic assumptions require the consideration of uncertainties. Therefore, the fracture mechanical approach was associated with Monte

Carlo simulation which takes the uncertainties from statistical distributions into account. The result of such an analysis is a quantitative assessment in terms of probability of failure.

The main field of application for the probabilistic approach is pressure vessel and piping assessment [7, 8, 9, 10, 11]. Some applications can also be found in the aerospace industry [12, 13].



$$K_r = \frac{K_1}{K_{1C}} \qquad (1)$$

$$S_r = \frac{\sigma_{ref}}{\sigma_f}, \quad \sigma_f = \frac{\sigma_y + \sigma_{UTS}}{2} \qquad (2)$$

Figure 1. Failure Assessment Diagram (strip yield model [14, 3]); failure occurs when the calculated assessment point (Sr, Kr) reaches the failure assessment boundary. If the assessment point lies within the acceptable area the component is considered as safe.

The probabilistic evaluations described in these examples are focused on the distributions of the material parameters. The scattering of fracture toughness, yield strength and tensile strength values are usually represented by one of the three distributions: Normal, Log-Normal or Weibull distribution. However, the geometric input parameters representing the type of crack or flaw considered in the analysis have also got a severe influence on the result of the analysis. If methods from the field of non-destructive testing are used for crack size determination the measurement error and the probability of detection (POD) of the used method itself have to be considered. Both aspects will be discussed.

2. Software Concept

2.1 Design and features of the software

Designing software for probabilistic analysis which is based on an originally deterministic approach leads to a modular software concept since deterministic, parametric and probabilistic studies should be possible. The deterministic and parametric analysis is the conservative version of the probabilistic analysis and therefore it is always recommended as a first benchmark.

The PVrisk software was developed for analyzing pressure vessels, especially pipelines. Cracks and flaws are identified in these specimens by standardized non-destructive testing methods during recurrent inspections.

Fig. 2 summarizes the concept of the PVrisk software. The software consists of 4 modules: Geometry, Material, FAD and POD Module. The user has to start in the Geometry Module and then proceed as indicated by the arrows in Fig. 2. When the FAD Module is reached the user can decide whether POD information should be considered or not. Several cracks or flaws can be analysed in succession. This is indicated by the long arrow from the FAD Module to the Geometry Module. When the first crack is analyzed the user moves on directly back to the Geometry Module and starts analyzing the next crack. The modular structure of the software enables a flexible handling of the different assessment procedures: deterministic/parametric and probabilistic analysis.

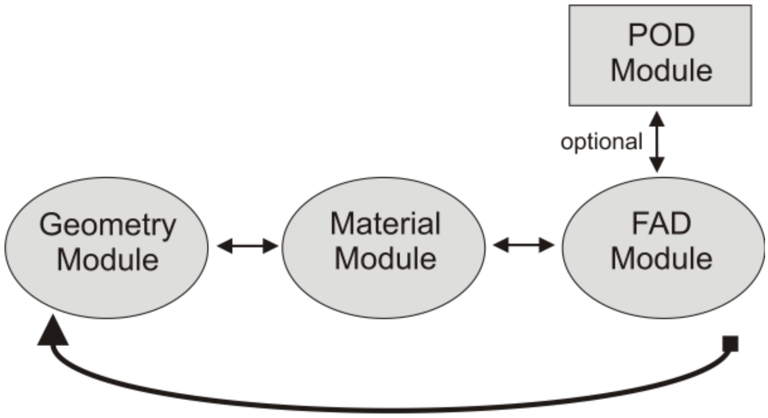


Figure 2. Concept of the developed probabilistic fracture mechanical assessment software PVrisk.

Within each module of the software several features are supplied. Tab. 1 to 3 summarize the capabilities of each module and references are also given on the sources of each procedure. The procedures are mainly taken from standards and rules.

Table 1. Feature list of the Geometry Module

	No. of crack/ flaw geometries	Solution types	Additional features	Welds	Distributions
Description	8 cases of cylindrical specimen	Analytical and numerical, numerical in tabular form (e. g. from FE analysis)	Bending can be considered, mostly in tabular form	Calculation of stress concentration factors (SCF), also for bending	Normal, Log-Normal and Weibull
Source		[15, 16, 6, 17]		[6, 18]	[19]

Table 2. Feature list of the Material Module

	Material parameters	Conversion routines	Distributions
Description	Ultimate strength (UTS), yield strength (YP), fracture toughness (Kc)	6 routines for Charpy to Kc conversion	Normal, Log-Normal and Weibull
Source	Measured data	[16, 20]	[19]

Table 3. Feature list of the FAD Module

	FAD types	Load	Secondary stresses	Analysis procedure	POD
Description	Strip yield, Level 1, Level 2, brittle material, ductile material	Pressure, tension, bending	Consideration of axial and circumferential welds, consideration of heat input for circumferential welds	Deterministic, parametric (crack depth, Kc, pressure load), probabilistic (Monte Carlo simulation)	Asymptotic exponential, asymptotic exponential lower threshold, log-logistic, asymptotic power-paw, interpolation of tabular values
Source	[15, 6]	[9, 6]	[6]	[6], own deve-lopment	[21, 22, 23]

2.2 Consideration of non-destructive testing results

2.2.1 Uncertainty

Each fracture mechanical analysis needs information about the geometry of the investigated crack. Then a fracture mechanical model can be allocated and the corresponding stress intensity factor can be calculated. If the geometry of the crack or flaw is determined using a non-destructive testing method, e. g. ultrasound or X-ray, the gained values for crack depth and crack length are affected by certain errors. A realistic analysis should consider these measurement errors. The allocation of the measured crack geometry to the crack model of the assessment procedure will produce an additional error (Fig. 3). Therefore, a realistic analysis has always to deal with an error due to uncertainty. In the assessment uncertainty is represented by distributions.

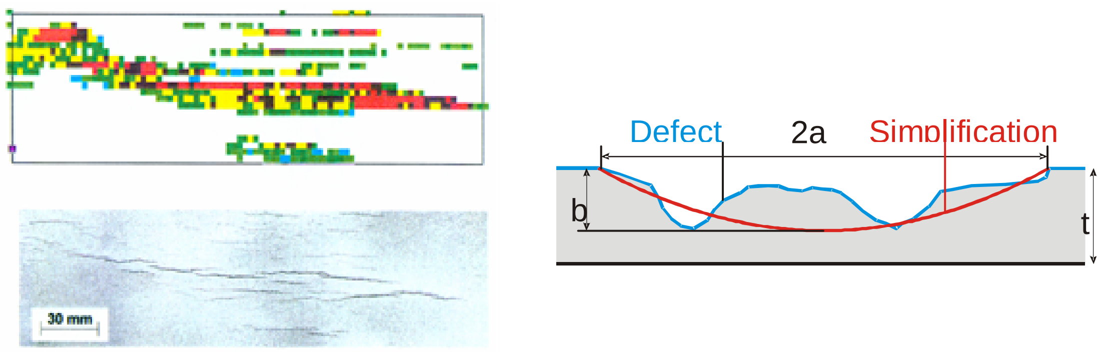


Figure 3. Left: crack detection result in a pipeline from an ultrasonic intelligent pig and corresponding crack pattern in the pipeline. Right: allocation principle of measured crack geometry to model geometry.

2.2.2 Variability

Concerning the material parameters which are primarily determined by destructive tests but which sometimes can also be determined by non-destructive methods the uncertainty due to the measurement procedure is again the cause of uncertainties in the result. Variability is an additional effect of chance since it resides in the nature of the involved physical laws which cause scattering of the results. Therefore, the material parameters are also not only represented by one deterministic value but by a distribution.

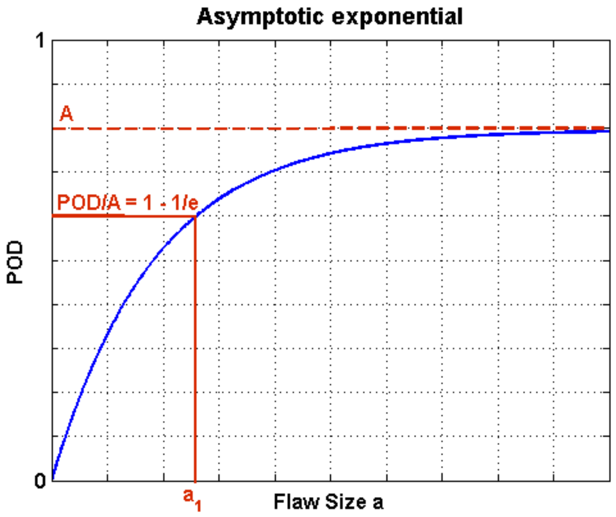
2.2.3 POD

A further often neglected factor of influence for performing a realistic fracture mechanical analysis which is based on NDT data is the probability of detection (POD). POD is an important part of the damage tolerance design principle. Extended investigations were carried out during the space shuttle program and during damage tolerance assessments in response to structural failures in jet aircrafts [24].

The POD is defined as the fraction of detected defects in the total number of all defects. It has to be determined individually for each NDT technique and technical application. So far, the irregularities of flaws are small in size, NDT techniques are very near the physical limit of detectability, i.e., the more the data to evaluate are in the range of electrical noise the less is the detectability [25].

In many cases the relationship between the gained hit/miss POD and the size of the crack is linearly related on a logarithmic scale. Therefore, the corresponding POD functions can be gained by a linear fit of the POD values corresponding to a certain crack size. The POD values have to be acquired during appropriate tests. Owing to the binomial statistics of hit/miss tests a large number of trials are required (minimum of 29 successful trials per crack length interval to obtain 90 % POD).

Fig. 4 shows the asymptotic exponential POD function. A special form of the asymptotic exponential POD function is the Marshall POD function which resulted from the round-robin test program using ultrasonic inspection on heavy components of carbon steel (PISC-program). For the Marshall POD A=0.995 and a_1=8.85mm has to be chosen. Further examples of POD functions can be found in [26]. A detailed description of the theory how to get a POD function can be found in [21].



$$POD = A\left(1 - e^{\frac{-a}{a_1}}\right) \qquad (3)$$

Figure 4. Asymptotic exponential POD function and corresponding formula.

Only within a probabilistic analysis the POD of the used non-destructive testing method can be applied. However, this is performed in a direct way since it is assumed that a crack or flaw of a certain depth and/or length is detected with a high probability and the corresponding component is therefore already repaired or replaced.

3. Probabilistic assessment

3.1 Example and corresponding input values

Uncertainty, variability of the input parameters and the POD information can only be considered in a probabilistic analysis. A deterministic as well as a parametric analysis leads to a fail/safe decision e.g. in form of a safety index (deterministic) or in form of a critical crack depth, pressure or fracture toughness (parametric). A probabilistic analysis leads to a probability of failure since distributions and a probability of detection are considered as input values.

The following example will show a probabilistic assessment example, discuss all required assumptions and the influence of a POD from a non-destructive testing method on the resulting probability of failure. The calculations are based on the presumption that a crack-like defect pre-exists in a pressure vessel and is modelled by a long external axial surface crack. The geometry of the vessel (Fig. 5) is taken from the CEGB pressure vessel test 1 program [27]. The vessel tested in this program was made of A533B steel. The internal pressure was selected to be 15 MPa which corresponds to a typical value in, e. g., nuclear power plants. The material characteristics of A533B steel for the calculation are taken from [28]. Tab. 4 summarizes the geometry and material parameters.

The probabilistic analysis of this example was performed assuming a normal distribution of the material and the geometry values. In contrast to the original CEGB pressure vessel test 1 a long axial outer surface crack was assumed (Fig. 1) with a mean crack depth of 42 mm and a standard deviation of 2 mm. The material values given in Tab. 4 are taken as mean values. The standard deviation of tensile strength and yield strength was calculated from measurement values taken from [27]. It is 2% (tensile strength) and 2.5% (yield strength). Concerning fracture toughness a standard deviation of 3% was assumed.

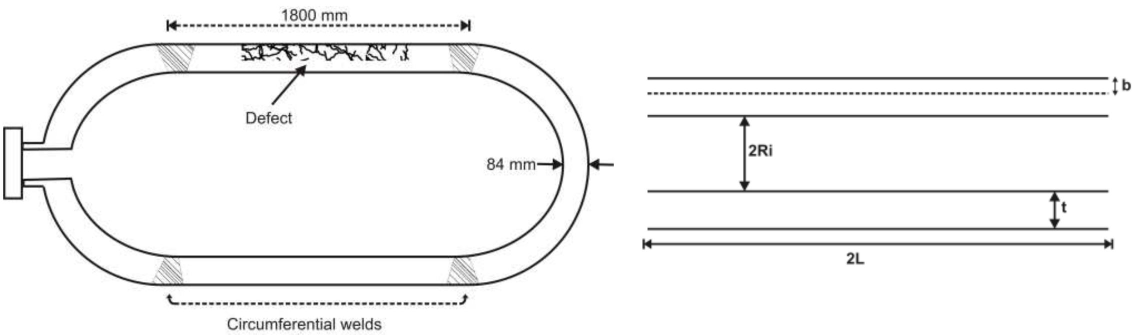


Figure 5. Left: Modified CEGB Test 1 pressure vessel with assumed defect. Right: fracture mechanic crack model used to describe the assumed long external axial surface crack.

Table 4. Input parameters for probabilistic calculation

Outer radius	Wall thickness	Tensile strength	Yield strength	Fracture toughness	Pressure	FAD type
1099 *mm*	84 *mm*	870 *MPa*	641 *MPa*	194 $MPa\sqrt{m}$	15 *MPa*	Level 2, Lr

3.2 Assessment procedure

The core of the probabilistic analysis is a Monte Carlo simulation. Therefore, a large number of iterations ($\geq 10^6$) is required. Each iteration leads to one assessment point in the FAD. The result is a cluster of points relative to the assessment boundary. A detailed description of such results and the corresponding interpretation can be found in [29].

The probability of failure (POF) is defined as the number of points which crossed the boundary line relative to the total number of iterations. This leads to a certain probability of failure for each probabilistic analysis. However, with the consideration of POD the probabilistic analysis is refined since it can be assumed that certain cracks are detected and the component is repaired or removed. Concerning the example described in section 3.1 POF of a mean crack depth of 42 mm is 0.69 without considering the POD and 0.0089 when the Marshall POD function as described in section 2.2.3 is used. This is a difference of two scales.

Visualizing the assessment points in form of a scatter-plot is one possibility. However, then the additional information of the point density is ignored. Therefore, a further possibility is to use the probability density. Fig. 6 shows two colour coded plots of the probability density of the probabilistic assessment example discussed in this section, one without considering the POD information (Fig. 6, left) and the other using the POD information (Fig. 6, right) . The probability density shows the extension of the cluster of assessment points and furthermore reveals the point density (colour coding). The refinement in case of POD consideration is visible since the extension of the colour coded area shrinks. The probability density decreases due to the reduced number of assessment points in case of POD consideration. However, the colour coding is normalized to the local density maximum and therefore the colour coding of the two plots in Fig. 6 is not quantitatively comparable.

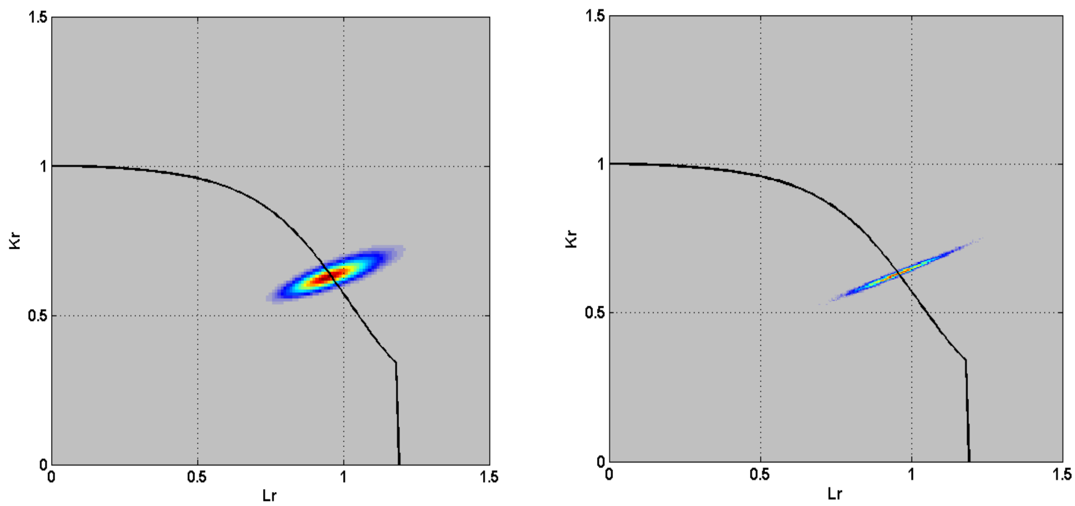


Figure 6. Representation of probability density of probabilistic assessment without considering the POD (left) and with considering the POD information (right). Note that the colour scale is not comparable since the largest value is automatically set to red and the lowest automatically to grey. Therefore, only a qualitative comparison of the visualization of the results is possible.

4. Conclusions

The FAD is an accepted tool for assessing the failure risk owing to cracks and flaws in metallic components. Furthermore, it can be coupled with probabilistic assessments in order to take into account data scattering and measurement errors.

The PVrisk software was developed for the assessment of cracks and flaws in cylindrical pressure vessels like pipelines. The modular concept of the software allows flexibility during assessments. Furthermore, the features are based on accepted standards and rules like BS 7910:2005, API 579 and the R6 procedure. Test calculations showed that applied concepts, not necessarily chosen from one of the standards or rules, lead to reliable results. Furthermore, the software allows parametric and comparative studies between various potential models.

If the cracks or flaws which should be assessed are detected by NDT methods the probabilistic analysis of PVrisk contains also the possibility to consider the corresponding POD. Using this information additionally the probabilistic assessment can be refined since it is assumed that cracks or flaws of a certain depth or length are detected in advance and the component is repaired or replaced. The numerical example reveals that the POF can be reduced by two scales when the POD information related to the current NDT practice is considered.

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