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Evaluation of Pipe Weld NDE Indications

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ABSTRACT

This paper discusses the evaluation of non-destructive examination (NDE) indications in pipe welds. The evaluation procedure is described in a practical engineer’s view and examples are also given.

1 INTRODUCTION

The evaluation procedure starts with a classification of imperfections determined by NDE or in-service-inspection due to EN ISO 6520-1 [1] or national standards. An analysis of acceptability including a crack growth analysis follows to identify safety margins. The analysis method of acceptability depends on the classification of imperfections. The common practice evaluation methods for cracks are based on the R6-Routine which predicts precise results. But the experience shows, that assumptions are often necessary due to missing input data. This is outlined by some examples.

2 MODELLING A CRACK FROM NDE INDICATIONS

2.1 Non-destructive examination

Several test procedures for NDE with various sensitivities are available. Liquid penetration or magnetic particle examination procedures are applied at surface and near surface regions. Ultrasonic, radiographic and eddy-current examination procedures are suitable for both, volumetric and (near) surface examinations in pipe welds. The detection capability of these test procedures differs and shall be demonstrated prior to the initial application e.g. by using reference blocks.

The NDE indications are based on measured signals which indicate deviations from the ideal weld (further called ‘imperfections’). Therefore, a categorization of NDE indications helps interpreting and determining flaws, where ‘flaw’ is used in this paper for relevant imperfections. The correlation between NDE indications and flaws due to the German standard [2] are shown in Figure 1. The test procedures have a physically caused minimum detection level, where the indications differ clearly from the noise level. All indications exceeding the recording limit for examination during fabrication or in-service-inspection shall be registered. The recording level is defined with respect to the type and orientation of flaws for each test procedure. NDE indications exceeding the evaluation limit are called relevant indications which have to be evaluated as flaws. Therefore, a detailed examination should be done to determine orientation, size and type of flaw as far as possible.

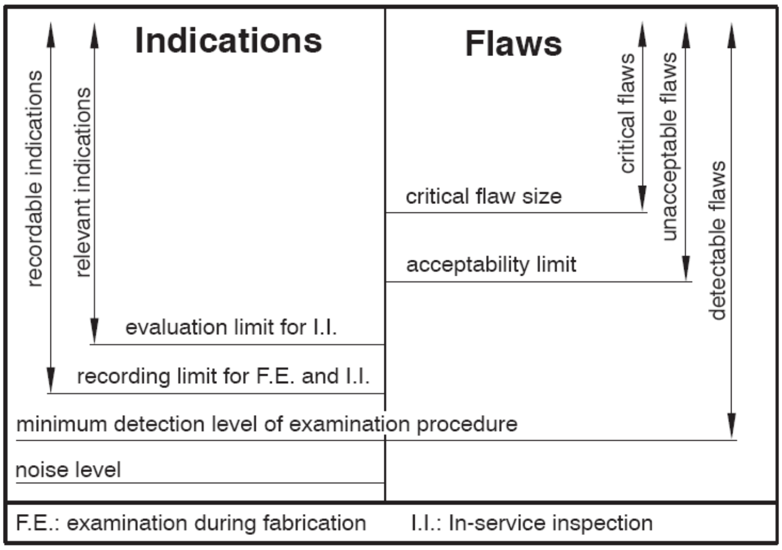
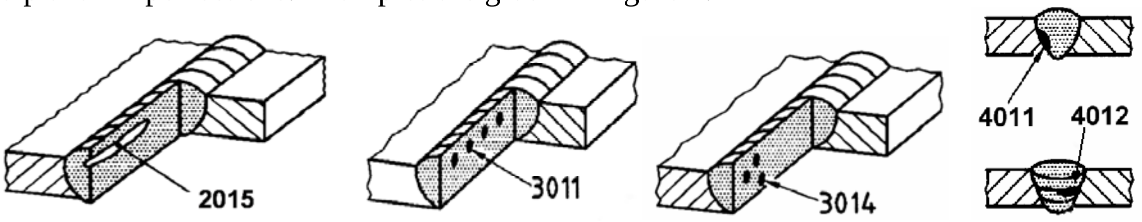


Figure 1**:** Indications and types of flaw [2]

To allow the evaluation of NDE indications exceeding the recording limit, the measured signals must be interpreted as flaws and should be classified. Depending on the classification the chosen evaluation method results in an acceptability limit for flaws, which is determined from the critical flaw size considering safety factors.

2.2 Classification of imperfections

The classification of imperfections determined by NDE is done due to international standard ISO 6520-1. This standard has been implemented as European standard EN ISO 6520-1 [1]. Regarding to evaluation methods the imperfections could be divided in volumetric and planar imperfections. Examples are given in Figure 2.



(a) elongated cavity (b) slag inclusion (linear & clustered) (c) lack of fusion

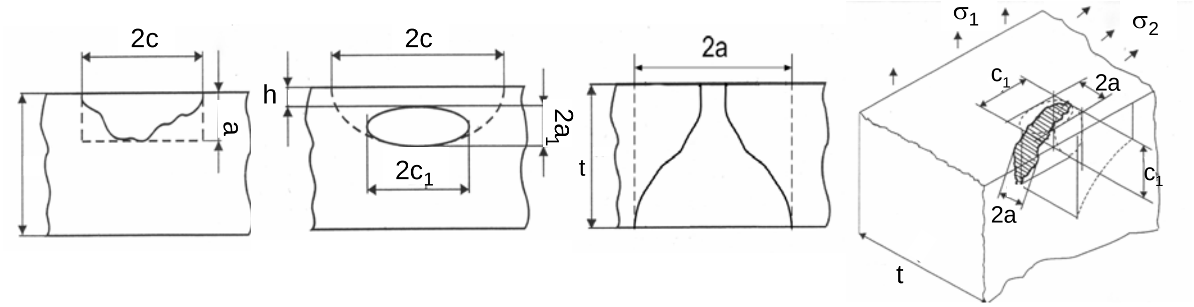
Figure 2**:** Examples of imperfections due to [1]

Volumetric imperfections, such as inclusions of slag, oxide or flux, pores, cavities etc., are free of sharp surfaces and could be treated as sectional weakening. Therefore a limit load analysis is sufficient for evaluation. Volumetric imperfections may be isolated (single) or multiple, e.g. arranged linear or clustered (Fig. 2(b)). Under the assumption of a single crack covering the multiple arranged imperfections, an evaluation with methods of fracture mechanics could be done. But these methods do not always give conservative results, especially for ductile materials (see Example 1), consequently the ligament should always be evaluated.

Planar imperfections are two-dimensional disconnections of material regions. The planar imperfections like undercuts, lack of penetration or cracks should be evaluated using methods of fracture mechanics. Imperfections are considered as cracks for the application of analytical evaluation methods.

2.3 Idealization of flaws

Analytical evaluations require an idealization of the imperfections to obtain a mathematical description of the flaw. The flaw is usually described as a half ellipse or a rectangular form in a plane. The mathematically described flaw (here called ‘crack’) has to cover the full size of imperfection indicated by NDE, see Figure 3.



(a) surface flaw (b) embedded flaw (c) throughwall flaw (d) complex flaw

Figure 3**:** Idealization of flaws

An embedded flaw (see Fig. 3(b)) close to the surface is idealized conservatively as a surface crack with a depth corresponding to the sum of embedded flaw depth ($2a_1$) and the distance to the nearest surface (h). An embedded flaw usually is harmless compared to a flaw at inner surfaces of pipes due to missing fluid contact, which possibly induce corrosion damage mechanisms. Throughwall flaws (Fig. 3(c)) are conservatively covered by a rectangular form. Crack growth mainly takes place in thickness direction of the pipe wall leading to a significant smaller flaw length at the surface of snap through compared to the flaw length at the surface of crack initiation (lower surface in Fig. 3(c)).

A flaw can be oriented in any part of volume in the pipe weld. Additionally, the flaw can kink off the flaw plane as illustrated in Fig. 3(d). The earlier discussed crack models do not match this complex crack forms. In accordance with analytical evaluation methods the complex crack is projected in the planes perpendicular to the principal stresses. Then the projected cracks are evaluated independently as single cracks.

3 EVALUATION METHODS

3.1 Introduction

Analytical evaluation methods based on the R6-Routine like the British standard BS 7910 [3], the Swedish SAQ-Handbook [4], or Appendix H of Section XI of ASME boiler and pressure vessel code [5] are common practice in nuclear industry. These evaluation methods are slightly different but with the same basic principles discussed next.

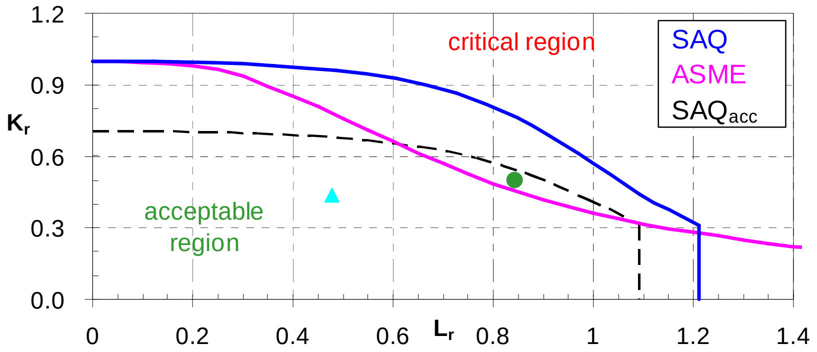


Figure 4**:** Failure assessment diagram containing two assessment points

An assessment point representing load, geometry, crack form and orientation is printed in a dimensionless Failure Assessment Diagram (FAD), which contains a failure line dividing the FAD in safe and (potentially) unsafe regions, in some codes also called 'critical regions'. The FAD could be interpreted as an interpolation between the failure states of brittle fracture represented by the ordinate (parameter K_r) and plastic collapse represented by the abscissa (parameter L_r or S_r) in the failure assessment diagram, see Fig. 4. The failure line is constructed by normalising the crack tip loading by the material's fracture resistance. The failure line - independent of geometry and load - used by conservative option 1 of the R6-routine and also by the mentioned evaluation methods is a material independent lower bound curve. In case of knowledge of the complete stress strain curve, which is rarely available, a material specific failure line is defined, known as the option 2 of R6-routine. This option 2 is not applicable within the App. H of ASME-code or the SAQ-Handbook. A crack growth analysis is included in all evaluation methods, but additionally a review should be done to prevent further imperfections caused by plant operation due to corrosion mechanism etc.

The orientation of a crack plays an important role to determine the stress distribution around the crack front. In the evaluation methods stresses perpendicular to the crack plane are considered. A separation of primary and secondary stresses is necessary for the application of all mentioned evaluation methods. Some of them use linearized stresses over flaw depth where other methods consider nonlinear stress distributions. Analytical methods are mainly applicable for circumferential and axial cracks in pipes and components. Manageable analytical solutions for complex geometries like nozzles or rotated cracks are not available but such geometries could be evaluated by a time-consuming finite-element analysis.

The important differences of the mentioned evaluation methods are discussed next.

3.2 Sec. XI of ASME-Code

The routine of Sec. XI of ASME-Code [5] is restricted to pipes under internal pressure having surface flaws in axial and circumferential directions, but rules are given for evaluation of flaws with other orientations. For circumferential flaws any combination of primary membrane and global bending stresses as well as expansion stresses could be considered in addition. Therefore the ASME-Code is applicable for straight pipes, but tees or bends are excluded because additional bending stresses over the wall thickness are not considered. The safety factors are directly put on the loads before calculating the assessment point and printing the failure assessment diagram.

3.3 SAQ-Handbook

The Swedish SAQ-Handbook [4] is developed for failure assessment of metallic structures containing defects and is verified extensively for steel alloys. Due to the input of a polynomial stress distribution, this method is applicable to a wide range of pipe components and pressure vessels. To obtain a compatibility with the ASME-procedure in nuclear applications the allowable design stress according to ASME-code was introduced to determine the failure curve in contrast to the average of tensile und ultimate strength used in the R6-Routine. Creating the advantage of using any reliable method including finite-element-analysis to calculate values of J-integral (representing the loading around crack front) the safety factors are set to unity to determine the critical conditions represented by the failure line in the FAD. An acceptable region (SAQ_{acc} in Fig. 4) is defined for the evaluation of nuclear components by reducing the failure line with fixed numerical values of safety factors. Within the acceptable region an assessment point implies a safe component. The approach was done to retain the safety margins expressed in ASME-Code, Sec. III and XI. This procedure avoids overconservatisms caused by plasticity effects resulting in large values of the J-integral in the App. H of ASME-Code, Sec. XI evaluation method. The different failure lines are compared in Fig. 4.

3.4 British Standard BS 7910

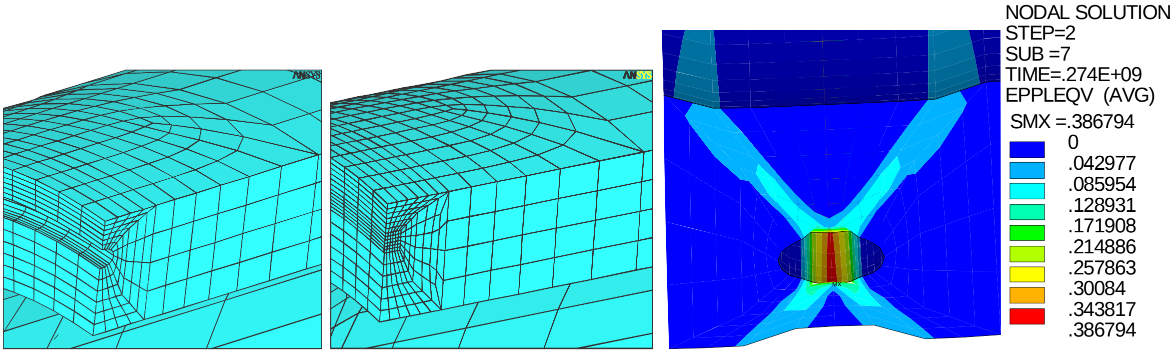
The more generalized British standard BS 7910 [3] outlines evaluation methods for all types of structures and components and provides three levels of fracture assessment but using similar methods depending on the available material data and required conservatism. Under assumption of elastic-ideal plastic material behaviour the simplified method of Level 1 is applicable when information on material, properties or applied stresses is limited. Level 1A uses a rectangular assessment line in a FAD containing in-built safety factors; Level 1B provides a manual estimation which does not involve a FAD. Level 2 is defined as ‘normal assessment’ [3]. For Level 2A a generalized material independent FAD, comparable to the SAQ-Handbook [4], is used. In Level 2B a material specific FAD is suggested requiring detailed information about stress-strain data. Therefore Level 2B is not suitable for flaws positioned in heat affected zones (HAZ) of pipe welds. Evaluation methods for ductile material that exhibit stable tearing are provided with level 3. No inherent safety factors are included in Level 2 and 3 methods. But partial safety factors may be applied to several input data for different target probabilities of failure.

4 EXAMPLES

4.1 Example 1: Slag inclusions in pipe weld

The NDE of an austenitic pipe weld with outer diameter of 220 mm and wall thickness of 19.5 mm indicated linear slag inclusions around the whole circumference with a maximum depth of 3.3 mm and an axial dimension of 6 mm. Therefore an embedded flaw surrounding the whole circumference was assumed to perform a limit load analyses. A volumetric flaw but also a planar flaw was assumed considering linear elastic ideal plastic material behaviour.

The nearly similar results for normal operating conditions demonstrate a safety margin of 1.78. A slightly higher collapse moment was found for the planar flaw model due to the smaller sectional weakening in the two dimensional flaw model (Fig. 5(b)). The volumetric flaw model (Fig. 5(a)) shows a strain distribution recognized from planar flaw models, the zones with maximum strain are extended to a 45 degrees angular starting at the crack tip as shown in Fig 5(c). This equals to the position of the highest flaw depth in the volumetric flaw model and underlines the similarity of the models for limit load analysis.



(a) volumetric flaw model (b) planar flaw model (c) plastic strain for volumetric flaw model

Figure 5: Example 1

Applying the evaluation method of App. H of Sec. XI of ASME-Code [5], a safety margin of 1.65 was calculated for normal operating conditions. This result depends strongly on the chosen fracture toughness parameter. For ductile materials or regions far away from weld and HAZ higher values of fracture toughness are usable resulting in higher safety margins may be exceeding the safety margins estimated in limit load analysis. The FAD also takes into account failure due to plastic collapse but shows higher allowable loads. This is originated by the different material models. The limit load analysis considers linear elastic ideal plastic material behaviour contrary to evaluation methods based on the FAD containing a more detailed description of the plastic range. Consequently, for ductile materials the minimal ligament should be evaluated performing a limit analyses to maintain high safety margins. For brittle materials, an evaluation with methods of fracture mechanics leads to conservative results and should also be done additionally to exclude brittle failure.

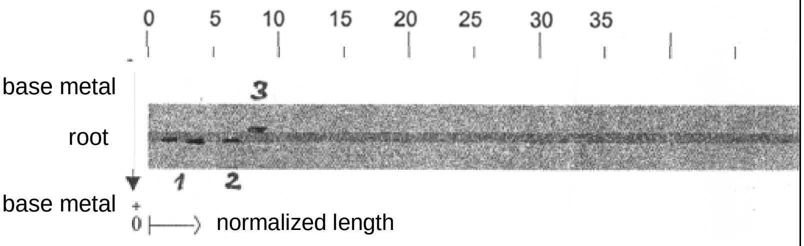
4.2 Example 2: Lack of side wall fusion

During ultrasonic examination three indications exceeding the evaluation limit were found in a pipe weld with outer diameter 114.3 mm. Therefore a radiographic examination had follow in order to determine type and size of flaws. An extract of the NDE protocol is shown in Fig 6. In accordance with EN ISO 6520-1 [1] the indications are classified as lack of side wall fusion with a maximum length of 15 mm. The flaw depth was not given but assumed to be 50 % of wall thickness. Applying App. H of Sec. XI of ASME-code [5] the flaws were evaluated as single cracks because the distance between the single cracks is larger than the maximum crack length. Due to an unknown stress distribution at the pipe weld, the stresses were estimated from the highest stress ratio of the pipe system. This maximum stress ratio was found in a document regarding the pipe system analysis.

Information on NDE indications:

Indications: 4011, 5013, 5041, 3041
Relevant indications: 4011

projection of weld



Relevant indication:	1	2	3
Position:	2 - 4	6	8
Type:	4011	4011	4011
Length [mm]:	15	5	5

Figure 6**:** Extract of NDE protocol for Example 2

The evaluation results in an acceptable single flaw size with a length of 17 mm and a depth of 75 % of wall thickness. The ASME-Code restricts flaw depth to a maximum of 75 % of wall thickness. Assuming an aggregation of all three single flaws induced by crack growth, a covering flaw with a depth of 52 % of wall thickness is acceptable. Significant transients were not specified therefore a crack growth analysis had not to be performed. Assumptions of missing input data done by an experienced engineer although allow evaluations of NDE indications.

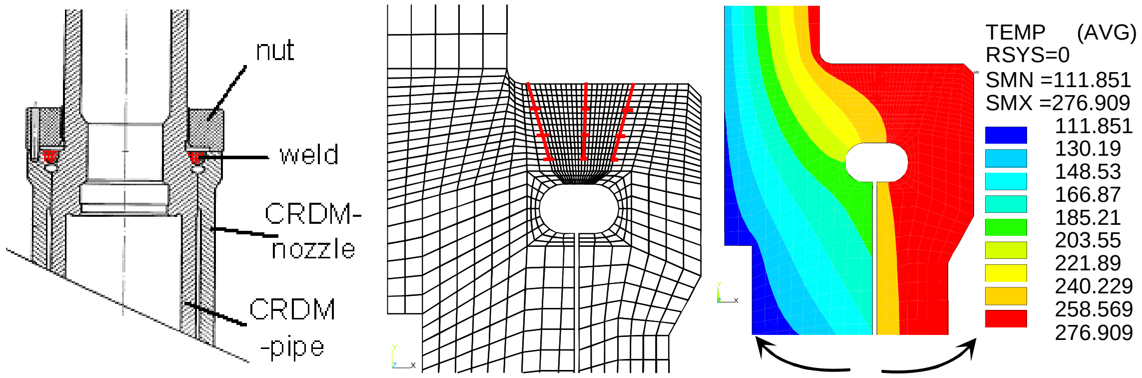
4.3 Example 3: Lack of root fusion in a reducer

In a circumferential weld of a reducer at the intersection of cylinder and conus with outer diameter of 1300 mm, a lack of root fusion with a length of 130 mm was indicated. The evaluation method provided in SAQ-Handbook [4] was chosen. The stress distribution was calculated by finite element analysis using a crack free model. Fracture mechanical properties were not available for the material of the reducer but they could be estimated from impact strength. The allowable flaw depth was calculated to be just 20 % of the wall thickness. To estimate the safety margins against global failure of the weld, a determination of critical throughwall crack size was added. The critical throughwall crack length of 1000 mm (one third of circumference) implies a high safety margin and underlines the acceptability of the flaw. This example and also Example 2 implies that detailed evaluation methods are often not applicable due to missing input data. Considering the assumptions of input data, a more conservative evaluation method should be applied to retain higher safety margins.

4.4 Example 4: Nozzle of control rod drive mechanism (CRDM)

In German boiling water reactors (BWR) the pipes of control rod drive mechanism (CRDM) are inserted through nozzles in the bottom of the reactor pressure vessel (RPV), see Fig 7(a). The fusion weld between the CRDM-pipe and the CRDM-nozzle has a height of 20 mm and an inner diameter of 133 mm. To prevent a shoot-out of the CRDM-pipe in case of a failure of the fusion weld a nut is installed. During fast shut down (SCRAM), the CRDM-pipes are charged with nitrogen under high pressure to inject the control rod into the core. This causes a fast thermal transient cooling down the CRDM-pipe from 286 °C to 60°C resulting in a non negligible bending moment. The temperature distribution at the time of the maximum bending stress is plotted in Fig 9(c). Due to an axial Force of 22.3 kN induced by the structural weight and an additional axial force of 73 kN during SCRAM, high shear stresses are generated. The load and geometry implies that manageable analytical evaluation methods are not applicable.

The NDE indicated volumetric flaws with a maximum height of 11.5 mm and a maximum tangential length of 14 mm corresponding to 12 degrees of circumference. Due to the high safety importance, several analyses were done. Limit load analyses assuming circumferential cracks (in a 2D model, this means a surrounding crack) with variable depths and positions in the weld as shown in Fig 9(b) were performed as well as throughwall cracks. Additionally, stress intensity factors (SIF) were calculated for identical positions chosen in the limit load analysis. In absence of an analytical evaluation method the calculated SIF were compared to fracture toughness. To exclude a significant increase of flaw size a crack growth analysis was done additionally.



(a) geometry (b) evaluated flaw positions (c) temperature distribution

Figure 7: CRDM-nozzle of Example 4

The limit load analysis show acceptable crack depths of 15 mm corresponding to 75 % of weld thickness for all analysed crack positions. A throughwall crack with a circumference of 220 degrees is acceptable. These results imply a relative low loading level which is also confirmed by the calculated values of stress intensity factors. The calculated SIF's with a maximum value of 275 N/mm$^{3/2}$ for a surrounding crack (260 degrees) with a depth of 75 % of wall thickness show a high safety margin of nearly 15 compared to the fracture toughness with a value of 4000 N/mm$^{3/2}$. The crack growth up to the end of plant life is smaller than 0.1 mm and negligible. Finally, the indicated flaw is acceptable; a replacement of the weld is not required.

5 CONCLUSION

NDE indications are measured signals which indicate deviations from the ideal weld. To get a mathematically described flaw for application of an analytical evaluation method an interpretation and idealization of the NDE indications has to be done. This step includes approximations and further assumptions of load, flaw orientation etc. are necessary. The most common evaluation methods based on the validated R6-Routine give precise results when detailed input data is available. In contrast to this, the experience shows that assumptions are often necessary due to missing input data. Therefore detailed analysis methods like options 2 or 3 of R6 routine or BS7910 are rarely applicable and more conservative methods have to be chosen. Analytical solutions are not always available due to complex geometry or load but such cases could be evaluated by a time consuming finite element analysis.

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