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STRUCTURAL INTEGRITY ASSESSMENT OF A STEAM SUPERHEATER OUTLET HEADER

PROCENA INTEGRITETA IZLAZNOG KOLEKTORA KONVEKTIVNOG PREGREJAČA PARE

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Keywords
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- BS 7910 integrity assessment
- convective superheater steam collector
- welded joints

Ključne reči
- Dijagram analize loma (FAD)
- procena integriteta prema BS 7910
- kolektor konvektivnog pregrejača pare
- zavareni spojevi

Abstract

In this paper, the structural integrity assessment of the exit convective superheater steam collector at Unit 1 of the 'REK Bitola' thermal power plant is presented. The collector is newly fabricated as part of a reconstruction project intended to replace equipment that had exceeded forty years of service. Material verification is performed through mechanical, microstructural, destructive and non-destructive testing, while hydrostatic testing confirmed the pressure-tightness of the fabricated component. Integrity assessment is subsequently carried out using the Fracture Assessment Diagram (FAD) methodology in accordance with BS 7910 procedures. Influence of fully circumferential internal flaws and weld misalignment on structural integrity is analysed under operating loading conditions. Results demonstrate that the investigated collector possesses sufficient resistance to both fracture and plastic collapse, with acceptable flaw tolerance margins for the considered defect sizes. The study confirms that the fabricated collector satisfies the structural integrity requirements for safe and reliable operation.

Izvod

U ovom radu prikazana je procena integriteta izlaznog kolektora konvektivnog pregrejača pare na Bloku 1 Termoelektrane „REK Bitola“. Kolektor je napravljen u okviru rekonstrukcije postrojenja sa ciljem zamene opreme koja je bila u eksploataciji više od četrdeset godina. Verifikacija kvaliteta materijala izvršena je mehaničkim, mikrostrukturnim, ispitivanjima sa i bez razaranja, dok je hidroispitivanje potvrdilo zaptivenost i nosivost izrađene komponente. Procena integriteta potom je sprovedena primenom metodologije dijagrama procene loma (FAD) u skladu sa procedurama standarda BS 7910. Analiziran je uticaj potpuno obodnih unutrašnjih defekata i aksijalnog smaknuća zavarenog spoja na integritet konstrukcije u radnim uslovima opterećenja. Dobijeni rezultati pokazali su da kolektor ima dovoljnu otpornost kako na lom tako i na plastični kolaps, uz zadovoljavajuću toleranciju na razmatrane veličine defekata. Rezultati istraživanja potvrđuju da kolektor ispunjava zahteve integriteta konstrukcije i obezbeđuje bezbedan i pouzdan rad tokom eksploatacije.

INTRODUCTION

Components operating under elevated pressure and temperature conditions represent some of the most critical parts of thermal power plants. Their safe and reliable operation is essential for maintaining plant integrity and ensuring the designed service life. Therefore, special attention is devoted to manufacturing quality, inspection, and structural assessment of these components.

Welded joints are considered the most critical locations in pressure-retaining equipment due to the presence of geometric and metallurgical discontinuities that may influence local stress distribution and damage development. Consequently, the structural integrity of steam pipelines depends not only on operating conditions, such as pressure and temperature, but also on the quality level achieved during fabrication, /1-8/.

To ensure adequate structural performance, comprehensive material characterisation and non-destructive examination (NDE) are commonly performed after fabrication and installation. Mechanical testing and microstructural investigations provide essential information regarding material properties, while inspection techniques enable the detection and characterisation of weld imperfections.

Finite element analysis (FEA) is widely used to evaluate the influence of weld imperfections on the stress state of pressure components. Combined with fracture mechanics-based Engineering Critical Assessment (ECA) procedures, such as those defined in BS 7910, it allows the quantitative assessment of flaw acceptability and structural safety.

The objective of this paper is to investigate the influence of weld root misalignment on the structural integrity of a circumferential welded joint in a steam pipeline component.

FACILITY DESCRIPTION

The existing outlet header at Unit 1 is manufactured from 12H1MF steel (TU-14-3R-55-2001) during the construction of the thermal power plant in the late 1970s. Reconstruction of the header and connected piping system of the first-stage convective superheater was initiated due to a large number of tube failures, which resulted in unplanned outages and interruptions in electricity generation. Consequently, this section of the boiler piping system was assessed as unsafe and unreliable for further service, requiring its urgent replacement within the planned refurbishment project.

The reconstruction included the complete replacement of the outlet section of the first-stage convective superheater together with the associated piping system. The selected material for the new components was identical to that of the replaced equipment.

The need to replace the original material with an alternative grade was not considered, primarily because the existing material had demonstrated satisfactory performance under the specified operating conditions throughout nearly 50 years of service. Since the original equipment is made in Russia, it is decided to retain the material grade while redesigning and engineering the welding groove configurations in accordance with European codes and standards, specifically the EN 12952 series.

RECONSTRUCTION OF THE STEAM LINE

Extensive on-site activities during the reconstruction of the first-stage convective steam superheater were preceded by an even larger scope of workshop operations involving prefabrication of the outlet steam header and the associated superheater piping system. During fabrication of boiler piping components, a series of examinations and tests were performed to ensure the quality of final product, including:
- mechanical testing of the base material;
- chemical analysis of the base material;
- microstructural examination of the base material, including software-assisted evaluation of the bainitic phase fraction within the microstructure.

The chemical composition and mechanical properties of 12H1MF steel are presented in Tables 1 and 2, respectively. In addition, Table 2 includes the mechanical properties of the material determined both at room temperature.

Table 1. Chemical composition of steel 12H1MF (mass %).

Element	C	Mn	Si	S	P	Cr	Mo	Ni	V	Nb
%	0.15	0.53	0.19	0.009	0.010	1.03	0.25	0.40	0.153	0.04

Table 2. Mechanical properties of steel 12H1MF.

$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]	Z [%]	HB	KV [J]
≥ 404	545-551	≥ 27.8	≥ 77	162-163	78-95

The microstructure of 12H1MF steel is examined for all semi-finished products used in the fabrication of the outlet header of the first-stage convective steam superheater. In accordance with the requirements of the Russian technical specification TU-14-3R-55-2001, digital image analysis of metallographic micrographs is performed to determine the bainite content within the material microstructure. The bainite fraction represents a specific characteristic of this steel grade and serves as an important criterion for the assessment and classification of creep-resistant steels for elevated-temperature service.

Figure 1 presents the microstructure of a ∅32×6 mm 12H1MF steel tube at a magnification of ×200, with a measured bainite content of 26.5 % (Grade 2). These tubes are used for the fabrication of pipe bends and branch connections attached to the header body. Figure 2 shows the microstructure of a ∅133×25 mm 12H1MF steel tube at a magnification of ×200, with a bainite content of 20.3 % (Grade 3). This semi-finished product is utilised for the fabrication of the drain connection located between the two

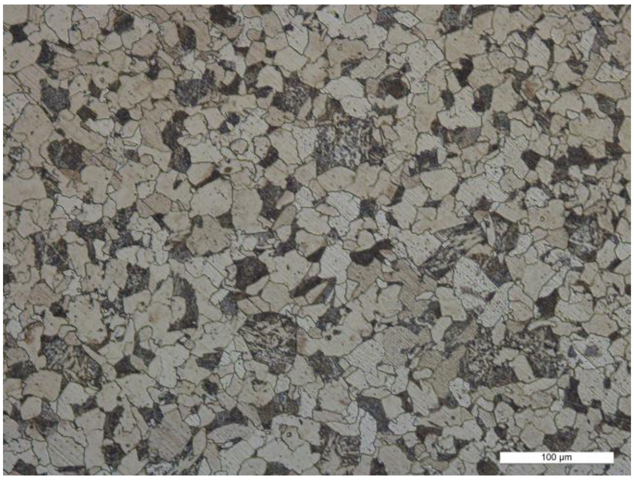

Figure 1. Microstructure of pipes Ø32x6 mm 12H1MF magnification 200x, proportion of bainite 26.5%.

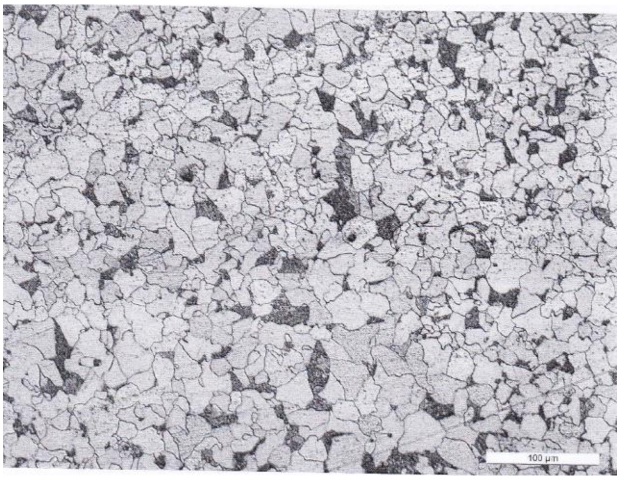

Figure 2. Microstructure of pipes Ø133x25 mm 12H1MF magnification 200x, proportion of bainite 20.3%.

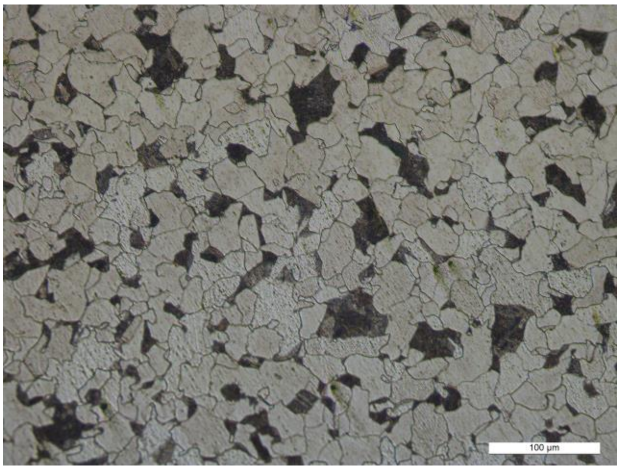

Figure 3. Microstructure of pipes Ø273x40 mm 12X1MF magnification 200x, proportion of bainite 17.4%.

end caps of the header. Figure 3 illustrates the microstructure of a ∅273×40 mm 12H1MF steel tube at magnification of ×200, with a bainite content of 17.6 % (Grade 4). This pipe section is employed for the fabrication of the main header body containing all branch and piping connections.

The obtained results confirm that the bainite content of all semi-finished products investigated satisfies requirements prescribed by the applicable specification, thereby verifying the suitability of the selected material for long-term operation under elevated pressure and temperature conditions.

Since the bainite content measured on all metallographic micrographs satisfies the acceptance criteria specified by the applicable material specification, the investigated material is assessed as being of acceptable quality. This finding, together with the results obtained from mechanical tests, provides additional confirmation of the suitability and quality of the base material for service under elevated temperature conditions.

Welding technology

Steam piping systems operating under elevated pressure and temperature conditions are subject to stringent quality requirements, particularly with respect to welded joints which are generally regarded as the most critical locations in pressure-retaining components. Due to the hazardous nature of the operating medium and severe service conditions involved, any fabrication-related imperfection may adversely affect the structural integrity and long-term reliability of the system. Therefore, special attention must be devoted to the selection, qualification, and implementation of appropriate welding procedures to ensure the required level of mechanical performance, structural integrity, and operational safety.

In addition to the selection of welding consumables, welding must include controlled preheating, post-weld heat treatment, and comprehensive quality assurance measures to minimise residual stresses and prevent the formation of detrimental microstructural constituents. Proper design of weld groove geometry is also a critical aspect, as it directly influences weld penetration, defect formation, accessibility during welding, and the overall quality of the completed joint.

Figure 4 presents the weld groove configuration adopted for the joint between the pipe and the header end cap manufactured from 12H1MF steel, together with the corresponding weld deposition sequence applied during fabrication. The selected groove geometry is designed to ensure complete fusion and adequate weld penetration while maintaining favourable conditions for stress redistribution and subsequent post-weld heat treatment. The welding sequence is established to achieve uniform heat input, reduce welding-induced distortion, and ensure compliance with the quality requirements specified for high-temperature steam piping systems.

For the welding of branch pipe connections to the header, the groove preparation and weld filling sequence differ from those presented previously due to the specific geometry of the branch connection. The groove configuration and weld filling sequence are shown in Fig. 5.

All welded joints involved in the reconstruction, as well as those located in the immediate vicinity of the reconstructed joint, are subjected to non-destructive examination (NDE). The inspection results confirm compliance with specified quality requirements, and all examined welds satisfy the applicable acceptance criteria.

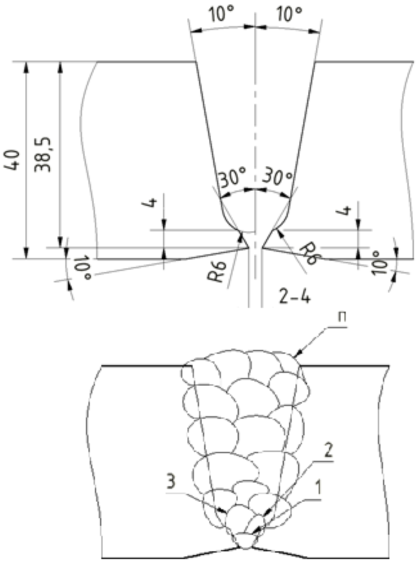

Figure 4. Layout of the groove and filling plan of the welded pipe and manifold joints: material 12H1MF.

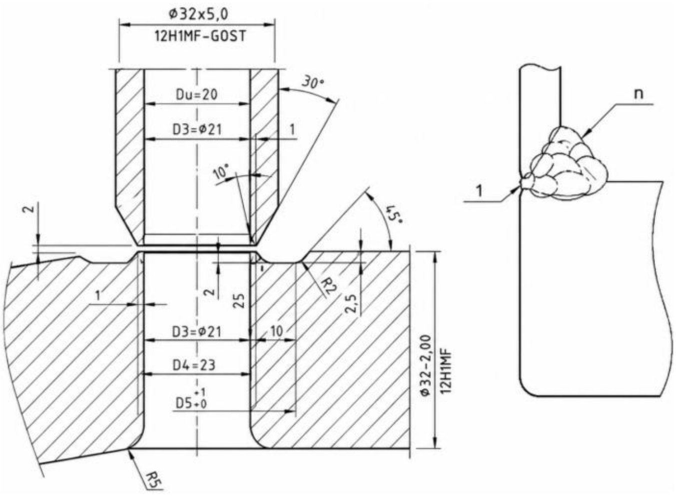

Figure 5. Groove layout and filling plan of stitch connections in the collector, the welded connection of pipe bends and collector pipe: material 12H1MF.

The required weld quality can be achieved through appropriate preheating to a temperature of ≥ 200 °C. Following welding, all welded joints are subjected to post-weld heat treatment (PWHT) at 700 °C for a period of 90 to 120 min., depending on the thickness of the base material. This heat treatment is performed to relieve residual stresses generated during phase transformations of the steel and to obtain a tempered bainitic microstructure.

Welded joints are fabricated using the following welding processes: GTAW for branch connections, and a combination of GTAW and SMAW for pipe-to-pipe and pipe-to-header end cap joints. For GTAW welding, a filler metal designated DMV 83-IG (WMoVSi, SRPS EN ISO 21952-A) is employed, while SMAW welding is performed using FOX DMV 83-Kb electrodes (E MoV B 42 H5, SRPS EN ISO

3580-A), manufactured by Böhler, /9/. The weld root and face are protected using 100 % argon shielding gas.

Prior to welding, the FOX DMV 83-Kb electrodes are dried at 300 °C for 2.5 hours in accordance with the manufacturer's recommendations to ensure low hydrogen conditions and minimise the risk of hydrogen-assisted cracking.

POST-WELD TESTS

To verify the fabrication technology of the outlet header of the first-stage convective steam superheater, a series of non-destructive examinations (NDE), /10/, are performed following the completion of welding activities. Subsequently, a hydrostatic pressure test is conducted using cold water. In addition, a numerical model is developed to simulate loading conditions corresponding to the operating regime of the component.

The following NDE techniques are applied: visual testing (VT); magnetic particle testing (MT); ultrasonic testing of welded joints (UT); hardness testing (HT).

Results of these examinations are used to confirm the quality of the fabricated welded joints and to provide necessary input data for the structural integrity assessment of the reconstructed steam piping component.

Hydrostatic pressure test

The hydrostatic pressure test of the outlet header is performed in accordance with the requirements of SRPS EN 12952-5 at a test pressure of 251.5 bar. The test medium is clean water, free from substances that could cause corrosion of the pipe material, with a temperature maintained between +10 °C and +50 °C. The total test duration is 90 min, including 30-min. holding period at the prescribed test pressure.

The pressure-time diagram obtained during hydrostatic testing of the reconstructed first-stage convective steam superheater is presented in Fig. 6.

The hydrostatic pressure test is conducted in accordance with the requirements of the Serbian Regulation on Pressure Equipment (Official Gazette of the Republic of Serbia, No. 114/21) and the relevant provisions of the European standard EN 12952-3, /11, 12/, with the objective of verifying the pressure-tightness and structural integrity of the reconstructed component prior to commissioning.

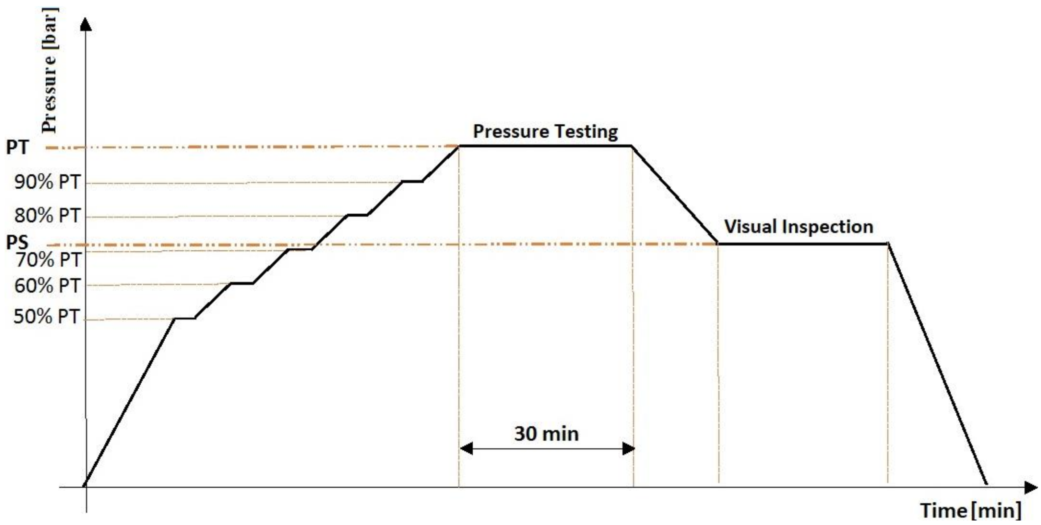

Figure 6. Pressure-Time Diagram of the Cold Hydrostatic Pressure Test.

Following the completion of the tests on the first-stage convective steam superheater, no signs of failure are observed during examination. No permanent deformation, leakage, local constriction, sweating, or other indications of loss of pressure boundary integrity are detected in either welded joints or base metal. Furthermore, no pressure drop is recorded on the calibrated pressure gauge during the test period.

Based on the obtained results, the reconstructed component successfully satisfied the acceptance criteria for the hydrostatic pressure test, confirming its pressure tightness and structural integrity under prescribed testing conditions.

Finite element analysis

To further substantiate the previously described activities and obtained results, a numerical simulation is performed in order to verify the adequacy of conventional engineering design methods commonly applied to pressure equipment. As an additional confirmation of the structural integrity of the header, a finite element model is developed, and a numerical analysis of the stress state is carried out under the design internal pressure of $p = 13.73$ MPa.

Finite element mesh and stress distribution in the outlet header of the first-stage convective steam superheater are shown in Fig. 7.

Following the numerical stress analysis, no regions with unacceptable stress levels are identified within either the welded joints or the base material. Furthermore, no indication of plastic deformation, associated with exceeding the material yield strength, are observed. The maximal equivalent stress, evaluated according to the von Mises criterion, is approximately 180 MPa. This value remains below the yield strength of 12H1MF steel at operating temperature, indicating that the component operates within the elastic range under prescribed loading conditions. The obtained stress distribution reveals no critical stress concentrations that could adversely affect the structural integrity of the outlet header. Therefore, the numerical simulation confirms the adequacy of the adopted design and provides additional verification of the safe operation of the reconstructed convective steam superheater header under service conditions, /7/.

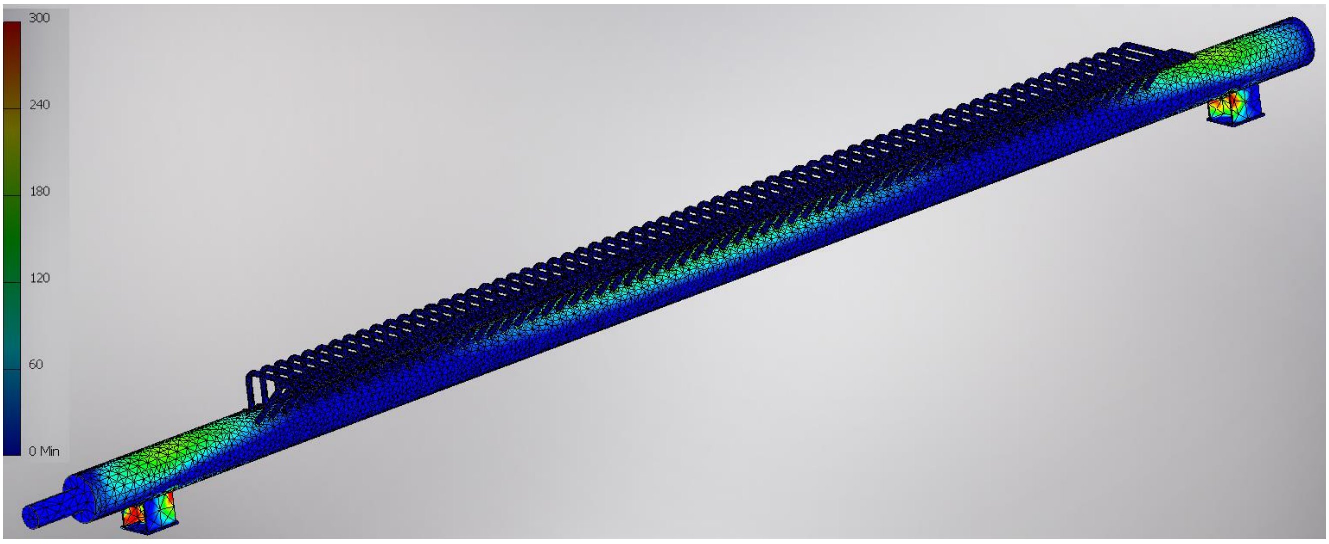

Figure 7. Finite element model (FEM): stress distribution in the superheater.

STRUCTURAL INTEGRITY ASSESSMENT

Among the imperfections that may occur during fabrication and assembly of steam piping systems, weld root misalignment is one of the most common geometric discontinuities. This type of imperfection may alter the local stress distribution, increase stress concentration effects and consequently affect the resistance of welded joints to crack initiation and propagation. Although weld root misalignment is typically controlled through fabrication tolerances and quality assurance procedures, its influence on structural integrity must be quantified, particularly for components operating under elevated pressure and temperature conditions. Therefore, the Engineering Critical Assessment (ECA) /13, 14/, based on fracture mechanics principles is performed to evaluate the influence of weld root misalignment on flaw acceptability and structural integrity of the reconstructed steam pipeline system.

The assessment is conducted for a circumferential welded joint with circumferential internal flaw located at the weld root, Fig. 8. Initial defect size is assumed to be $a = 0.3$ mm.

Two axial weld root misalignments, namely 1.5 mm and 2.0 mm, are investigated to evaluate their effect on flaw tolerance and structural integrity margins. Selected values are used to represent realistic fabrication deviations that may occur during manufacture and assembly of steam piping systems. Relevant material properties at working temperature are: yield stress 225 MPa; tensile strength 450 MPa, Young modulus E = 183 MPa, fracture toughness $K_{Ic} = 124$ MPa$\sqrt{\text{m}}$. Loading is set as membrane stress 27.1 MPa. Results obtained by using Crackwise 5.0 /15/, are presented in Figs. 9 and 10 for weld root misalignment of 1.5 mm and 2 mm, indicating critical defect sizes 3.48 and 3.74 mm, in respect.

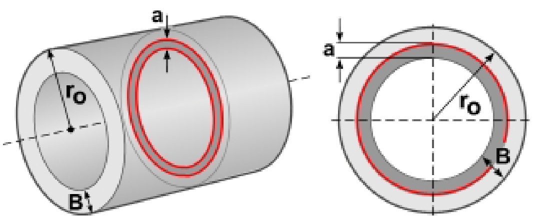

Figure 8. Geometry of a defect.

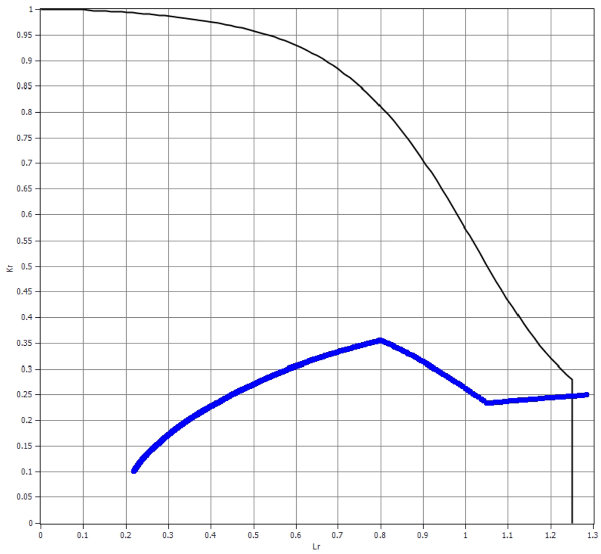

Figure 9. FAD for a weld root misalignment of 1.5 mm.

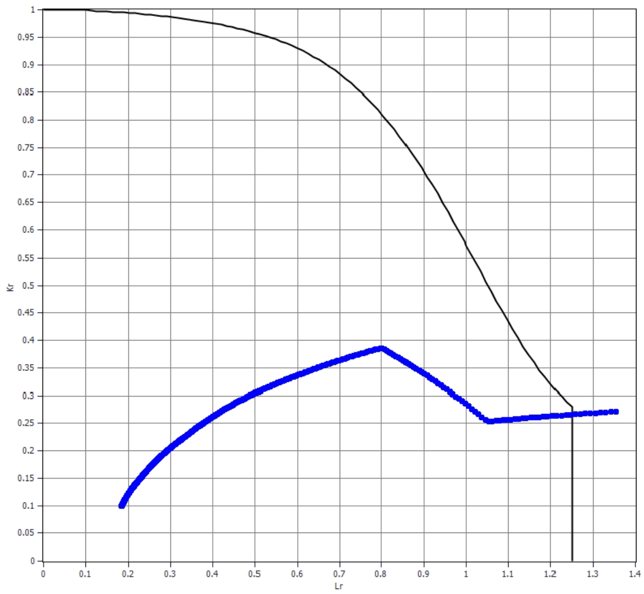

Figure 10. FAD for a weld root misalignment of 2.0 mm.

Fracture mechanics assessment complements the results obtained through metallographic investigations, mechanical tests, non-destructive examination, hydrostatic pressure tests and finite element analysis. The combined results confirm that the reconstructed outlet header and associated steam piping system satisfy structural integrity requirements for long-term operation under prescribed service conditions. Furthermore, the achieved weld quality and fabrication procedures provide an adequate reserve of structural reliability with respect to potential fabrication-related imperfections.

CONCLUSIONS

The obtained results demonstrate that the investigated welded joints possess adequate resistance to both fracture and plastic collapse under prescribed operating conditions. For all analysed cases, the assessment points remain within the acceptable region of the FAD curve.

Particular attention is devoted to the influence of weld root misalignment on flaw acceptability. The investigated misalignment levels of 1.5 mm and 2.0 mm both satisfy the acceptance criteria and exhibit significant tolerance to fully circumferential internal flaws. The corresponding critical flaw heights are approximately 3.48 mm and 3.74 mm, in respect, demonstrating considerable safety margins relative to the assumed initial flaw size.

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