Development Methodology for Acceptance Criteria for Service-Induced Cracks in Reactor Pressure Vessels

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Abstract

To meet the rapid assessment requirements for cracks (service-induced cracks) identified during in-service inspection of Reactor Pressure Vessels (RPV), research on the methodology for establishing acceptance criteria for service-induced cracks and the development of such acceptance criteria for RPV are required. This paper analyzes the principles and methodology proposed by the Electric Power Research Institute (EPRI) for establishing acceptance criteria for service-induced cracks. By employing the postulated crack from the fracture prevention analysis during the RPV design stage as a reference crack and incorporating the safety criteria for establishing acceptance criteria for service-induced cracks, a mechanical analysis method for establishing acceptance criteria for service-induced cracks based on design postulated cracks and design safety factors is proposed. The acceptance criteria for service-induced cracks established for the RPV cylindrical shell using the method proposed in this paper are essentially consistent with those provided by ASME. The mechanical analysis method for establishing acceptance criteria for service-induced cracks proposed in this paper is also applicable to other nuclear pressure-retaining equipment.

Full Text

Study on the Establishment Method of Service-Induced Crack Acceptance Standards for Reactor Pressure Vessels

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Abstract

To meet the demand for rapid assessment of cracks detected during in-service inspection of reactor pressure vessels (RPVs)—referred to as service-induced cracks—it is necessary to develop a methodology for establishing acceptance standards and formulate corresponding RPV service-induced crack acceptance criteria. This paper analyzes the principles and methodology proposed by the Electric Power Research Institute (EPRI) for establishing service-induced crack acceptance standards. Using the postulated crack from fracture resistance analysis during the RPV design stage as a benchmark crack and incorporating the safety criteria for acceptance standard development, a mechanical analysis method for establishing service-induced crack acceptance standards is proposed based on design postulated cracks and design safety factors. The acceptance standard developed for an RPV shell using this method shows good agreement with the standard provided in the ASME Code. The proposed mechanical analysis method for establishing service-induced crack acceptance standards is also applicable to other nuclear power pressure equipment.

Keywords: Reactor pressure vessel; service-induced crack; acceptance standard; safety criterion

1. Introduction

The reactor pressure vessel (RPV) is a critical and non-replaceable component in nuclear power plants, and its safe and reliable operation constitutes the most important guarantee for nuclear power plant safety [1-2]. During manufacturing, installation, and commissioning of RPVs, microscopic cracks that are either negligible at the design stage or undetectable by inspection may exist within the equipment. Under the harsh operating conditions of nuclear power plants—including high temperature, high pressure, and corrosive environments—and due to gradual material degradation, these microscopic cracks may gradually propagate while new cracks may also initiate [3-4], posing potential risks to the safe operating condition and service life of RPV equipment. To ensure long-term safe, efficient, and reliable operation of nuclear power plants, both the French RSE-M [5] and American ASME [6] codes require regular non-destructive examinations of RPVs during service to analyze and evaluate the impact of detected crack defects on equipment safety and operational life. To satisfy engineering demands for rapid assessment of service-induced cracks, research on the methodology for establishing acceptance standards is required.

The RSE-M code Appendix 5.2 and ASME Section XI IWB-3500 provide acceptance standards for service-induced cracks to meet engineering needs for rapid evaluation. However, the crack acceptance criteria in RSE-M Appendix 5.2 lack engineering application experience both domestically and internationally, and no documentation on its development methodology has been reported. The service-induced crack acceptance standards in ASME Section XI were primarily developed based on EPRI research [7] and are applicable to nuclear power plants designed and constructed according to the ASME Code [8]. Chu Qibao et al. [9] studied the development principles of the "service-induced crack acceptance tables" in ASME Section XI, investigated the methodology for establishing allowable crack size acceptance standards for austenitic piping surface cracks, and presented calculation methods for allowable crack dimensions in austenitic piping during pre-service and in-service periods. Chen Mingya et al. [10] adopted plastic limit load as the critical state for austenitic pressure piping structures and proposed acceptance standards for service-induced cracks in austenitic stainless steel piping based on the principle of maintaining structural design plastic limit load, comparing the results with acceptable crack sizes in ASME and RSE-M codes. EPRI [7,11] conducted research on establishing service-induced crack acceptance standards, using a postulated crack with depth equal to one-quarter of the wall thickness (t/4) and length equal to 1.5 times the wall thickness (1.5t) from the fracture resistance analysis performed during the RPV design stage per ASME Section III Appendix G as the benchmark crack, and developed service-induced crack acceptance standards considering appropriate safety factors, which were subsequently incorporated into ASME Section XI.

This paper draws upon the development philosophy and safety criteria presented in EPRI research to propose a mechanical analysis method for establishing service-induced crack acceptance standards based on postulated cracks from design-stage fracture resistance analysis and design safety factors. Using this method, acceptance standards for service-induced cracks in RPV shell components were developed and compared with those in ASME and RSE-M codes.

2. Discussion of EPRI's Method for Establishing Service-Induced Crack Acceptance Standards

In Reference [7], EPRI employs mechanical analysis as the core approach to determine acceptable crack sizes for service-induced cracks, while simultaneously comparing the equivalent crack sizes derived from acceptable indications in manufacturing-stage non-destructive examinations with those determined through mechanical analysis, selecting reasonably conservative crack size values as the acceptance standards. EPRI established the primary safety criteria and methodology for developing service-induced crack acceptance standards for nuclear power plant equipment [7], which were applied in the formulation of acceptance standards in ASME Section XI [6].

When developing acceptance standards for RPV service-induced cracks, EPRI used the postulated crack from the fast fracture analysis conducted during the

RPV design stage per ASME Section III Appendix G—characterized by a depth of t/4 and length of 1.5t (denoted as aIII)—as the benchmark crack. Considering safety margins on design stress intensity, they established the acceptable crack size aXI in Section XI acceptance standards. This approach mechanically ensures that the accepted crack aXI, after applying safety factors, possesses equivalent crack driving force to the design-stage postulated crack aIII, representing the key safety criterion in EPRI's methodology for establishing service-induced crack acceptance standards.

The fast fracture analysis method in ASME Section III Appendix G remains unchanged to date; therefore, EPRI's methodology for establishing RPV service-induced crack acceptance standards remains applicable to nuclear power plants designed according to the ASME Code. However, for RPV equipment designed per RCC-M [12] 2007 edition and later versions, the postulated crack size in the design stage was revised from t/4 to 20 mm (approximately t/10), which differs significantly from the benchmark crack size used in EPRI's acceptance standard development. Consequently, the mechanical analysis method employed in EPRI's acceptance standard development is no longer applicable, although the underlying safety criteria and philosophy remain valuable for reference.

3. Method for Establishing Service-Induced Crack Acceptance Standards Based on Design Crack and Design Safety Factor

Based on fracture mechanics theory and the safety criteria for establishing service-induced crack acceptance standards presented in EPRI Report [7], this section proposes a mechanical analysis method for developing service-induced crack acceptance standards using the postulated crack ad considered in the equipment's design-stage fracture resistance analysis as the benchmark crack and the design safety margin Fm considered in the fracture resistance evaluation criteria for various loading conditions as the safety factor fs. Using the design safety margin Fm as the safety factor aligns with EPRI's safety criterion that "the structural integrity safety margin for components containing cracks should not be lower than the safety margin requirements related to material toughness behavior used in the equipment design under normal plant operating conditions" [7].

According to fracture mechanics theory [13], the general method for calculating the stress intensity factor (SIF) at a crack tip is given by Equation (1):

$$K_I = Y\sigma\sqrt{\pi a} \tag{1}$$

where Y is the crack shape factor, which depends on crack depth, crack shape, and structural geometry and can be obtained from SIF calculation handbooks or methods provided in codes; σ is the stress distribution at the crack location; and a is the crack size.

The method for establishing service-induced crack acceptance standards is as follows:

(1) Based on Equation (1), the postulated crack ad in the equipment design stage is expressed by Equation (2):

$$a_d = \left(\frac{K_{Id}}{Y_d \sigma}\right)^2 \frac{1}{\pi} \tag{2}$$

where KId is the SIF for crack ad and Yd is the shape factor for crack ad.

(2) Maintaining the same crack driving force KId as in the design-stage fracture resistance analysis and applying a safety factor fs to the crack driving force, the allowable crack aa in the in-service acceptance standard is given by Equation (3):

$$a_a = \left(\frac{K_{Id}}{fs \cdot Y_a \sigma}\right)^2 \frac{1}{\pi} \tag{3}$$

Conservatively assuming that in-service operating loads are identical to design loads, combining Equations (2) and (3) yields the allowable crack aa in the service-induced acceptance standard as Equation (4):

$$a_a = \left(\frac{Y_d}{fs \cdot Y_a}\right)^2 a_d \tag{4}$$

Based on Equation (4), using the postulated crack sizes ad for different loading conditions in the design stage and the safety margins Fm for different conditions in the code, and by consulting shape factors Y for various crack geometries, the service-induced crack acceptance standards can be obtained.

4. Case Study

Using an RPV designed per the 2007 edition of RCC-M as the object, this case study examines surface cracks in the RPV shell using the method proposed in Section 3. The RPV shell has a wall thickness t = 200 mm and inner radius Ri = 1995 mm [14].

4.1 Stress Intensity Factor Calculation According to RCC-M, the influence function method is used to calculate crack SIF. First, the stress distribution at the crack location is fitted using a polynomial as shown in Equation (5), and then the crack SIF is calculated using Equation (6):

$$\sigma(x) = \sum_{i=0}^{4} \sigma_i \left(\frac{x}{L}\right)^i \tag{5}$$

$$K_I = \sqrt{\pi a} \sum_{i=0}^{4} \sigma_i i_i \tag{6}$$

where x represents the distance from the point to the vessel wall (0 ≤ x ≤ L); L represents the distance for stress polynomial fitting (0 ≤ L ≤ t), with t being the structural wall thickness; i0, i1, i2, i3, and i4 are influence functions; and a is the crack depth.

Assuming the stress on the crack plane is membrane stress and conservatively equals the maximum stress at the structural cross-section where the crack resides, the crack SIF simplifies to Equation (7):

$$K_I = \sigma \sqrt{\pi a} \cdot i_0 \tag{7}$$

Transforming Equation (7) yields the crack size expression in Equation (8):

$$a = \left(\frac{K_I}{\sigma i_0} \right)^2 \frac{1}{\pi} \tag{8}$$

According to fracture mechanics theory, the influence coefficient i0 in Equation (8) is actually equivalent to the shape factor Y in Equation (4).

4.2 Benchmark Crack Size and Safety Margin Using the postulated crack from the fracture resistance analysis performed per RCC-M Appendix ZG during the RPV design stage as the benchmark crack ad, the benchmark crack has a depth ad = 20 mm and aspect ratio a/2c = 1/6. The design safety margins Fm in the fracture resistance evaluation criteria for various loading conditions are shown in Table 1 . Conservatively, the maximum design safety margin under normal operating conditions (Level A criterion) is taken as the safety factor fs, i.e., fs = 2.

Table 1. The Safety Margin Fm for the Criteria of Fast Fracture Resistance Analysis in RCC-M

Level A Criterion	Level C Criterion and Test Conditions	Level D Criterion
	Safety margin for preventing brittle fracture and plastic collapse	Safety margin for preventing crack initiation

4.3 Results of Service-Induced Crack Acceptance Standard Development Based on Equation (8) and the relationship between allowable crack aa and benchmark crack ad from Equation (4), the allowable crack size aa in the service-induced crack acceptance standard can be obtained as Equation (9):

$$a_a = \left(\frac{i_{0d}}{fs \cdot i_{0a}} \right)^2 a_d \tag{9}$$

where i0d is the influence coefficient for the benchmark crack and i0a is the influence coefficient for the acceptable crack. In this analysis, the ratio of wall thickness to radius is approximately t/Ri = 1/10. Influence coefficients for cracks of various depths and aspect ratios can be obtained from the influence coefficient tables provided in RSE-M Appendix 5.4 [5]. For a shell surface crack, interpolation yields i0d = 0.9827, and the resulting service-induced acceptance standard is presented in Table 2 .

Table 2. The Service-Induced Crack Acceptance Standard for the Out-Surface Crack of RPV Shell

Crack Aspect Ratio a/2c	Influence Coefficient i0a	Allowable Crack Depth aa (mm)	Allowable Dimensionless Crack Depth a/t
0.167*	0.9827	3.76	1.88%
0.15	0.9750	4.00	2.00%
0.125	0.9650	4.36	2.18%
0.10	0.9520	4.86	2.43%
0.083	0.9450	5.06	2.53%
0.071	0.9350	5.46	2.73%
0.0625	0.9200	6.18	3.09%
0.05	0.9050	6.86	3.43%
0.04	0.8850	7.68	3.84%
0.033	0.8700	8.64	4.32%
0.025	0.8500	9.78	4.89%
0.02	0.8300	11.20	5.60%

*Result corresponding to crack aspect ratio a/2c = 1/6.

A comparison between the service-induced crack acceptance standard developed in this paper and those provided in ASME and RSE-M codes is presented in Table 3 and graphically illustrated in Figure 1 [Figure 1: see original paper].

Table 3. The Comparison of the Service-Induced Crack Acceptance Standard Between This Paper and Nuclear Codes

Crack Aspect Ratio a/2c*	Allowable Crack Depth aa (mm) from This Study	Allowable Crack Depth (mm) per ASME Code	Allowable Crack Depth (mm) per RSE-M Code
0.167	3.76	3.8	5.0
0.125	4.36	4.5	6.0
0.10	4.86	5.0	6.5
0.083	5.06	5.3	7.0
0.0625	6.18	6.4	8.0
0.05	6.86	7.1	8.5
0.04	7.68	8.0	9.0
0.033	8.64	8.9	9.5
0.025	9.78	10.0	10.0
0.02	11.20	11.3	10.5

*RSE-M code only provides acceptance standard results for the crack aspect ratios shown in the table.

Figure 1. The Comparison of the Acceptance Standard Between This Paper and Nuclear Codes

The comparative analysis demonstrates that the acceptance standard developed using the proposed method shows essentially consistent results with the ASME code acceptance standard, validating the rationality of the analysis method. The minor differences from the ASME standard primarily arise from the use of shape coefficients from RSE-M code for SIF calculation, which differ from those in ASME code. Additionally, the ASME acceptance standard simultaneously considers equivalent crack sizes derived from acceptable indications in non-destructive examinations. Furthermore, the analysis reveals that the acceptance standard provided in RSE-M code is more lenient than that in ASME code.

This case study focused on the RPV shell component; however, the mechanical analysis method for establishing service-induced crack acceptance standards proposed in this paper can also be applied to develop acceptance standards for service-induced defects in other nuclear pressure-bearing equipment.

5. Conclusions

To ensure long-term safe and efficient operation of nuclear power plants, it is necessary to establish RPV service-induced crack acceptance standards to meet engineering demands for rapid assessment. This paper proposes a mechanical analysis method for developing equipment service-induced crack acceptance standards and applies it to establish acceptance standards for RPV shell service-induced cracks, with results compared against existing nuclear code acceptance standards.

1) Due to the difference between postulated crack sizes in equipment design fracture analysis and the benchmark crack size used by EPRI for establishing service-induced crack acceptance standards, the acceptance tables provided by EPRI are not applicable to RPV equipment designed per RCC-M 2007 edition and later versions.
2) Drawing upon EPRI's development philosophy and safety criteria for service-induced crack acceptance standards, a mechanical analysis method for establishing service-induced crack acceptance standards is proposed based on postulated cracks from design-stage fracture resistance analysis and design safety factors.
3) Applying the proposed method to develop RPV shell service-induced crack acceptance standards and comparing the results with ASME and RSE-M codes shows that the acceptance standard developed by this method is essentially consistent with that in the ASME code, thereby validating the rationality of the proposed method.

It should be noted that the method presented in this paper addresses the issue of establishing service-induced crack acceptance standards from a mechanical analysis perspective. Integration with engineering practice should also incorporate appropriate modifications based on non-destructive examination requirements, which will be the subject of continued research.

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Note: Figure translations are in progress. See original paper for figures.