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APPLICATION OF THE PRINCIPLES OF FRACTURE MECHANICS TO ICE-PLUGGING

Ouajih Hamouda[1]

[1] Senior Technical Expert, Ontario Power Generation, ON, Canada (wajih.hamouda@opg.com)

ABSTRACT

Under some circumstances, particularly for excessively thinned piping in need of maintenance or replacement, it may not be possible, using conventional piping stress analysis methods, to demonstrate that the predicted stresses caused by a freeze-sealing operation do not exceed allowable limits. In such cases, the requirement to demonstrate structural integrity can be fulfilled by applying the principles of fracture mechanics. In this paper, the theoretical principles underlying such an approach are described, and further illustrated using two practical examples. These case studies demonstrate how, for situations necessitating the formation of an ice plug in a piping system in which a conventional stress analysis cannot satisfactorily demonstrate piping structural integrity, the principles of fracture mechanics can be deployed instead, thereby expanding the range in which this critical maintenance operation can be applied with confidence and assuring the continued safe operation of critical nuclear plant components.

INTRODUCTION

In an operating nuclear power plant, the need occasionally arises to employ ‘ice plugs’ for the isolation of a water-filled portion of a piping system. These are typically formed by blanketing the outside of a short section of pipe with liquid nitrogen at a temperature of around −195°C, thereby freezing the contained water within the pipe and effectively forming a seal. Among the pre-requisites to be satisfied prior to the installation of an ice plug is to demonstrate that the structural integrity of the piping system will not be compromised as a result. Conventionally, this is achieved by performing a flexibility analysis, which confirms that the piping can adequately withstand the resultant deformations without any undue consequences to its structural integrity.

Under some circumstances, particularly for excessively thinned piping in need of maintenance or replacement, it may not be possible, using conventional piping stress analysis methods, to demonstrate that the predicted stresses because of the freeze-sealing operation do not exceed allowable limits.

In such cases, the requirements of demonstrating structural integrity can be fulfilled by applying the principles of fracture mechanics. In this paper, the theoretical principles underlying such an approach are described, and further illustrated using two practical examples. The first example involves small-bore nuclear piping requiring isolation to facilitate the maintenance and refurbishment of critical fuel channel components. The second example involves large-bore piping experiencing excessive thinning over time, necessitating detailed inspections and/or replacements.

BACKGROUND

The use of liquid-nitrogen cooled heat exchangers to form internal ice plugs in pipes of various sizes is a routine maintenance task in nuclear generating stations today. Given the safety concerns in regard to maintenance personnel and the structural integrity of piping systems, a number of experimental laboratory studies were carried out in the 1980s by Ontario Hydro (see Flaman and Shah, 1985) to investigate material behavior at low temperatures, involving both ‘normal’ and ‘extreme case’ situations, which allowed safe and effective procedures to be established for applying ice plugs.

The procedure for creating ice plugs consists of blanketing a water-filled pipe at a location where it is desired to isolate a section of the pipe and filling the annular heat exchanger or ‘jacket’ with a refrigerant or cryogenic substance, such as liquid nitrogen, extracting heat from the pipe and its contents and gradually developing an ice plug. The liquid water to solid ice transition initiates at the pipe wall and grows slowly towards the center of the pipe. The fully formed plug or seal can then be relied upon to temporarily isolate a section of the piping system where no other means of isolation, such as valves, is readily available.

In addition to a significant frictional resistance developed between the ice and the internal irregular surface of contact at the pipe walls, an adhesive action involving molecular forces also exists between the two, creating a remarkably robust seal capable of withstanding internal pressures that can be even greater than those the piping system is originally designed to sustain in normal operation. According to the Electric Power Research Institute (2011), successful freeze seals have been attained with liquid nitrogen in nuclear power plant piping up to 762 mm in diameter, and up to 1219 mm diameter in other industries, with system pressures as high as 2.75 MPag and fluid temperatures as high as 54°C.

To be sure, metallic piping made of ductile materials such as carbon steel experiences a drastic reduction in fracture toughness during a freeze-sealing operation, to the extent that even minor flaws in the piping could potentially lead to a catastrophic pipe failure due to the combination of increased thermal and mechanical piping stresses, lower flexibility, and brittle behavior. The safety concerns are typically addressed via various administrative, procedural, and engineered barriers, including not creating ice plugs near regions of possible stress concentrations and piping discontinuities such as elbows and junctions or residual stresses such as welds, ensuring adequate piping flexibility in the ice plug affected regions by engineering analysis, verifying the absence of surface defects in the locations to be plugged using non-destructive surface inspection techniques, and considering the possibility of equipment and structural failures in the safeguarding of plant personnel and critical components.

By and large, a typical metallic piping material will not undergo significant changes in strength, toughness, or microstructure after being subjected to a liquid nitrogen freeze seal[1]. From an engineering standpoint, the main issues to be addressed in ensuring a successful freeze seal pertain to 1) a pipe rupture caused by pressure build-up in a region of trapped liquid water compressed by the expanding ice, 2) slippage of the ice plug and subsequent loss of isolation, and 3) a brittle fracture in piping subjected to near-liquid-nitrogen temperatures. The latter represents the focus of this paper. In the next section, other concerns are briefly discussed for completeness.

CONVENTIONAL ICE PLUGGING CONSIDERATIONS

The rupturing of a pipe during an ice-plugging operation is perhaps the most serious and undesirable outcome from the perspective of safety. Much of what is currently known about ice plugs and pipe behavior at low temperatures is a direct outcome of laboratory tests that were designed to investigate various aspects of the freeze sealing procedure. For instance, in one laboratory test performed at an extreme hydrostatic pressure in an attempt to dislodge an ice plug (Flaman and Shah, 1985), the enclosing carbon steel pipe burst first due to the over-pressurization before any slippage of the ice plug could be observed.

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[1] Rare exceptions to this are handled on a case by case basis. For instance, stainless steel may be sensitized if subjected to slow cooling through a range of high temperatures, rendering it susceptible to future limited martensitic transformation of the austenite phase at low cryogenic temperatures. This is precluded by steering clear of welds when selecting a suitable location for ice plugging.

Hydrostatic Pressure

Generally speaking, an ice-plugging operation can be safely performed provided that no increase in fluid pressure is permitted. If a contained volume of water is trapped by an expanding ice plug, excessive piping stresses may develop in the circumferential or hoop orientation. The pressurization is governed by the incompressibility of the liquid water, and the approximate rise in pressure is

$$\Delta p = -\frac{\Delta V}{V} B \tag{1}$$

where ΔV is the change in volume caused by the expansion of the ice plug, V is the volume of trapped water, and B is the water's bulk modulus of compression. In practice, this type of situation is avoided altogether either by venting or by another suitable means of pressure relief.

Piping Flexibility

Independently of the hoop stresses attributable to circumferential contraction of the pipe walls, a restrained straight pipe subjected to liquid nitrogen temperatures will tend to contract in the axial direction, establishing axial stresses whose magnitude depends on the flexibility of the piping under consideration,

$$\sigma = \frac{E\alpha l \Delta T}{L} \tag{2}$$

where E is the modulus of elasticity, α is the coefficient of thermal expansion, l is the length of the ice plug region, ΔT is the change in temperature, and L is the total length of straight pipe. For actual piping systems, structural integrity assurance is demonstrated by conventional piping stress analysis methods, with the customary positive coefficient of thermal expansion normally associated with elevated operating temperatures replaced by a negative coefficient of expansion (or a positive coefficient of contraction) as befitting the low temperatures experienced by the pipe wall material.

For horizontal piping specifically, where gravity plays a defining role in the formation of the ice plug, with the lower liquid region freezing before the upper region due to thermal convection effects. In such cases, a diametric thermal gradient is established across the pipe cross section, and the nonuniform thermal contraction leads to a 'bowing' effect that is not normally considered in piping analysis, as shown in Figure 1. In this event, the additional bending stress contribution is linearly superposed with the otherwise calculated tensile axial stresses and compared to the maximum allowable code limits.

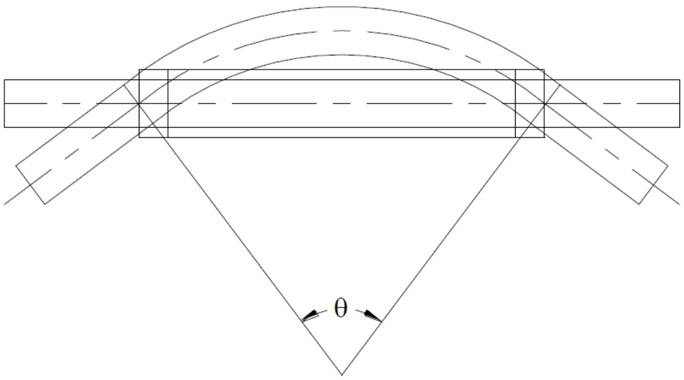

Figure 1. Bowing effect due to diametric thermal gradient (exaggerated for clarity).

Non-Destructive Examination

The use of conventional piping stress analysis approaches is predicated on the absence of cracks in the piping material that might invalidate some of the underlying analytical assumptions. To this end, piping is inspected before and after an ice plug is created to detect any potential flaws. A variety of non-destructive examination techniques are available including visual inspections, magnetic particles, dye penetrants, volumetric ultrasonic or radiographic inspections, and acoustic emissions monitoring.

Operational Controls

Having established a safe configuration for a specific ice plug by engineering analysis, the results can be translated into a set of operational controls to support maintenance and operations personnel in the field. This will typically include limitations on permissible actions, such as ensuring adequate provision for pressure relief in regions susceptible to pressure build-up, limiting acceptable plug locations to long ‘flexible’ sections of pipe free of degradation, establishing a minimum required distance away from pipe discontinuities and weld locations, and maintaining adequate flow of coolant throughout the freeze sealing operation.

When returning a frozen section of pipe to normal service, it is equally important to maintain a monitored and controlled rate of heating throughout the thawing operation. In particular, the scenario of a dislodged sliding ice plug accelerated by an upstream to downstream pressure differential may cause considerable damage and is to be avoided. This is suitably achieved by backfilling the downstream section, either using a downstream source of water, or melting a portion of the ice plug to create a bypass flow that equalizes the pressure on either side while the ice plug remains attached to the pipe wall.

FLAW TOLERANCE

The majority of piping materials used in nuclear power plant piping systems are designed for elevated temperatures. As such, the effects of the low temperatures encountered during freeze sealing on the material properties need to be carefully considered. This paper deals primarily with ferritic steel materials.

Material Properties

The yield and tensile strengths and the modulus of elasticity of carbon steel materials increase as the temperature drops below room temperature. Around the range from −10°C to 50°C, a typical carbon steel material undergoes a ductile to brittle transition. At temperatures above this point, the material fails by ductile tearing, where fracture propagation is accompanied by significant inelastic deformation. Below this point however, a fracture propagates in a brittle fashion with little plastic deformation and much less crack driving force required.

Fracture Toughness

A stressed material’s tolerance to internal defects is measured by the material’s fracture toughness, which predicts the magnitude of the stress at which a particular flaw results in unstable crack propagation, or equivalently, the flaw size at which a particular stress level results in unstable fracture. To establish structural integrity for a piping system with an ice plug in place, a flaw tolerance analysis can be performed to the requirements of an accepted jurisdictional code (e.g. ASME, 2011). Note that, given the brittle behavior of carbon steels at liquid nitrogen temperatures, it is imperative to isolate the piping from any potential source of dynamic loading throughout the ice-plugging procedure, and great care is taken in practice to prevent the ice plug location from being subjected to any vibration or impact loads.

CASE STUDIES

In the following, the theoretical principles underlying the fracture mechanics approach for ice plugging applications are described and illustrated using two practical examples. The first example involves small-bore nuclear feeder piping requiring isolation in order to facilitate the maintenance and refurbishment of critical fuel channel components. The prevailing failure mechanism of concern is brittle fracture in this case, adequately modelled using Linear-Elastic Fracture Mechanics (LEFM) theory. The second example involves large-bore piping experiencing excessive thinning over time, necessitating detailed inspections and/or replacements. Here, Elastic-Plastic Fracture Mechanics (EPFM) theory is additionally required to evaluate piping that is remote from the ice plug region.

Linear-Elastic Fracture Mechanics

In the first case study, the structural integrity concerns are associated with increased pipe stresses due to forced displacements, as well as the possibility of brittle failure under stress due to the significant drop in the fracture toughness of the pipe wall material in the regions directly exposed to liquid nitrogen. The fracture mechanics analysis of such configurations proceeds with the objective of demonstrating that any pre-existing cracks or flaws in the regions of interest would remain stable under all postulated loading conditions, as established using a fracture tolerance analysis. The failure mode here is assumed to be brittle and is modelled by LEFM theory using the plane-stress form of the Irwin plastic-zone correction.

If a freeze-sealed pipe is disconnected for maintenance, then the concomitant activities may result in increased stresses due to the physical manipulations and forced displacements, as well as a possibility of brittle failure under stress due to the significant drop in fracture toughness of the ice plug affected zones. A typical configuration is illustrated in Figure 2. Successful execution requires demonstrating that any proposed displacements are acceptable, using a piping stress analysis, and that the maximum allowable flaw sizes based on postulated crack geometries are not exceeded in the ice plug affected regions, using a fracture tolerance analysis. The ice plug affected zone is where the fracture toughness of the pipe is significantly impacted by the temperature drop due to the application of the liquid nitrogen blanket. Applying the ice plug sufficiently far away from welds, bends, and heat affected zones ensures that the ice plug affected region has negligible residual stresses.

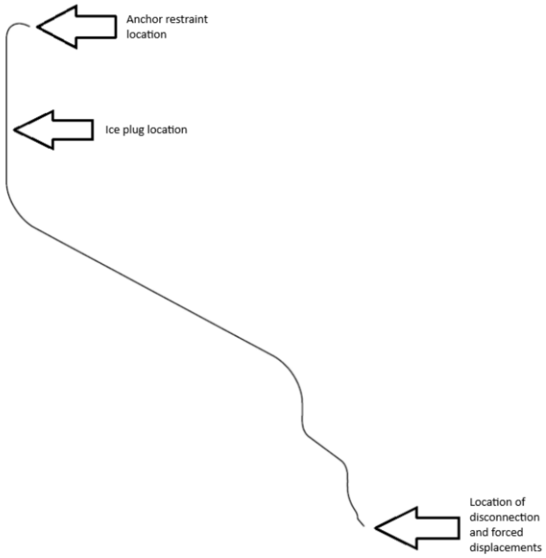

Figure 2. Illustration of typical ice-plugged pipe configuration.

The stress-intensity factor (SIF) at the tip of a crack of length $2a$ in an infinitely wide plate with the stress σ oriented perpendicular to the crack is

$$K = \sigma\sqrt{\pi c} \tag{3}$$

The value of K for which a crack propagates unstably is K_{IC}, the plane-strain fracture toughness of the material, independent of the geometry of a structure. By defining the margin on the SIF as the ratio of the material's fracture toughness to the SIF corresponding to the applied crack driving force, where the calculation of the applied SIF includes all mechanical and thermal loads, this margin on the SIF then represents crack stability under a brittle cleavage failure mode for postulated circumferential and axial cracks, with a margin equal to or greater than 1.0 indicating that the crack is stable and no catastrophic cleavage failure will occur. Using a factor of safety of two, a margin of 2.0 on the SIF can be adopted in any specific calculation. (This is consistent with the Structural Factors specified in ASME 2011, Section XI, Appendix C, Subsection C-2620, and Appendix H, Subsection H-4200.)

Two orientations, circumferential and axial, are used to calculate the crack driving forces. The two orientations represent the two most severe crack failure conditions, and the results are therefore bounding and applicable to cracks of all orientations (actual flaws must be projected to the circumferential and axial planes, See ASME 2011, IWA-3340 or Subsection C-2400). The circumferential and axial cracks are modelled as partly through-wall cracks with a semi-elliptical geometry on both the inside and outside surfaces of the pipe walls. The circumferential crack propagation is driven by the axial stress and the axial crack propagation is driven by the hoop stress. Both the axial and hoop stresses are calculated based on thin-walled cylinder theory. The axial stress is comprised of the maximum internal pressure (direct pressure on the crack surface for inside surface cracks), maximum axial force (due to deadweight, force displacement, thermal, and end-cap axial force from internal pressure), and maximum bending moment (due to deadweight, forced displacement, and thermal loading), whereas the hoop stress is calculated based only on the maximum internal pressure.

The forces and moments obtained from the mechanical and thermal loading conditions are combined by calculating the root of the sum of squares. This treatment of forces and moments used in the fracture tolerance analysis is conservative since it represents the absolute maximum possible loading. Furthermore, the forces and moments are assumed to act in the most severe crack opening direction (Mode I crack failure). This represents the worst-case failure scenario and is therefore conservative. The thermal stress due to the application of the liquid nitrogen blanket and the subsequent formation of the ice plug itself is largely dependent on the pipe boundary constraints and can be accurately estimated using a detailed finite element thermal stress analysis. This additional thermal stress contribution is assumed to be homogeneous, tensile, and constant throughout the wall thickness in both the axial and hoop directions. For the piping stress analysis, the material properties are typically available, whereas the fracture toughness properties may need to be ascertained from test results performed at comparable temperatures.

The analysis then proceeds in two steps. In the first step, the piping stress analysis is performed to find the maximum allowable displacements at specified locations and to provide loads for the fracture tolerance analysis. In the second step, the fracture tolerance analysis is performed to establish maximum allowable crack sizes in the ice plug affected region of the piping. The piping stress analysis is based on the Principle of Superposition, which requires all load cases to be linearly elastic, exhibit small deformations, and have the same boundary conditions. The maximum axial stresses caused by the deadweight, imposed movements, and thermal loads are algebraically summed. The objective of the piping stress analysis is therefore to ensure that the pipe stresses remain below the yield strength.

The fracture tolerance analysis is performed to ensure that no brittle cleavage failure will occur in the ice plug affected regions. The maximum forces and moments are obtained from the stress analysis. The maximum allowable surface crack sizes in the postulated axial and circumferential orientations are subsequently obtained using the LEFM method. In general, the SIF is found to be most significantly influenced by the crack depth. To simplify the analysis, a fixed crack length can be chosen for the circumferential cracks, with an equivalent length determined for the axial cracks enabling a direct comparison between the two geometries for establishing a bounding flaw size. In the fracture tolerance analysis, a crack length of $L_c = 2\theta$ is employed for circumferential cracks and equivalent crack lengths $L_a = \theta(D_O - t)$ are used for axial cracks, where D_O is the pipe outside diameter and t is the pipe wall thickness.

The stress intensity factor for Mode I loading is

$$K_I = Y\sigma\sqrt{\pi a} \tag{4}$$

where Y is the dimensionless shape factor, or geometry correction factor, accounting for the particular crack geometry. Under LEFM assumptions, a small plastic zone forms ahead of the crack tip due to local stresses surpassing the yield strength. The plane-stress form of the Irwin plastic-zone correction accounts for the limited plastic deformation at the crack tip through a simplified approximation for the radius of the plastic zone under plane-stress conditions,

$$r_p = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_Y}\right)^2 \tag{5}$$

where σ_Y is the yield strength of the material, and the effective crack length is adjusted by adding the plastic zone size, $a_{eff} = a + r_p$.

The results of the fracture tolerance analysis can be expressed in terms of the maximum allowable crack sizes, based on curves of the critical crack depth versus the SIF margin. Figure 3 below shows an example where the maximum allowable crack size in the ice plug affected region of the pipe is 1.1 mm, with the circumferential crack orientation bounding. Having satisfied all pre-requisites, the planned maintenance activities can then proceed with assurance that brittle failure due to unstable crack propagation will not occur, provided that any flaws in the ice plug affected regions are below the maximum allowable flaw sizes.

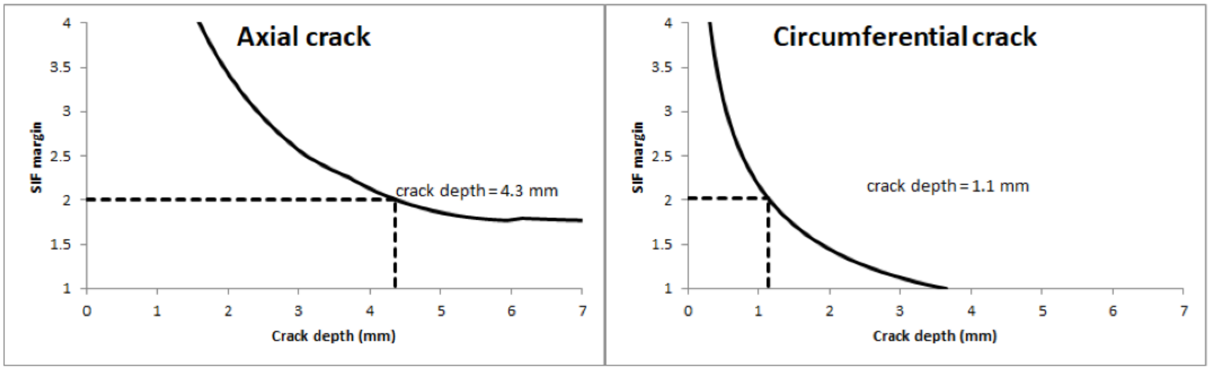

Figure 3. Results of LEFM flaw tolerance and crack stability analysis.

Elastic-Plastic Fracture Mechanics

The second case study deals with a maintenance scenario requiring the ice-plugging piping in which significant wall thinning has been observed. Continued fitness-for-service is established by demonstrating that applying the ice plugs will not result in sudden uncontrollable pipe failures in the regions exhibiting local wall thinning, and for piping remote from the thermally affected zones, that ductile failure will not occur. LEFM is used to assess thinned or cracked piping within the ice plug affected zones, where the yield stress is markedly higher and the fracture toughness is significantly lower, with an assumed brittle cleavage failure mode, while EPFM theory is additionally used to assess the thinned or 'cracked' piping beyond the ice plug affected zones, where plastic or ductile tearing is the assumed failure mode.

Similar to the previous case study, successful execution of the maintenance activities requires demonstrating that the piping stresses are below allowable limits, and that the existing 'crack' depths, which represent wall thinning, are smaller than the maximum allowable crack depths established by a fracture tolerance analysis for postulated crack geometries. A piping model is developed using average pipe wall thicknesses measured during field inspections. These thickness measurements are typically variable along the lengths and circumferences of inspected pipes, and as a simplification, the relevant piping sections are modelled with a uniform thickness corresponding to the average circumferential thickness measured at the axial location exhibiting the lowest measured local thickness. This simplification gives realistic piping loads and cylinder geometries for flaw evaluation. The specific locations of minimum local thickness are then evaluated separately using a fracture tolerance analysis.

Two separate analyses are required, one representing normal operating conditions and another representing the ice-plugging conditions. To be conservative, whichever analysis gives the maximum mechanical and thermal loading is used as input to the fracture mechanics analysis. Once again, the forces and moments are assumed to act in the most severe crack opening direction (Mode I crack failure), which conservatively represents the worst-case failure scenario.

The two potential piping failure mechanisms considered in the analysis are brittle failure in the ice plug affected zones for thinned piping, and ductile failure at piping locations with wall thinning, outside the ice plug affected zones. Fitness for service of any remaining piping sections outside the ice plug affected zones and without significant wall thinning is established by conventional piping stress analysis. For the flaw tolerance analysis, locations of significant local wall thinning are conservatively idealised as sharp-edged cracks on the inside wall surface of a uniform pipe of wall thickness equal to the average measured wall thickness around the pipe circumference, with the analysed cracks sizes based on actual measured thickness profiles. Figure 4 shows an example piping system subjected to detailed wall thickness inspections at various specified locations.

Unlike LEFM, the EPFM approach explicitly accounts for large-scale plastic deformation near crack tips by characterizing crack-tip fields using the J-integral parameter, which measures the energy release rate in nonlinear elastic-plastic materials,

$$J = \int_{\Gamma} \left(U dx_2 - T_i \frac{\partial u_i}{\partial x_1} ds \right) \tag{6}$$

where U is the strain energy density, T_i and u_i are the traction and displacement components, respectively, and Γ is a contour path enclosing the crack tip. To assess the ductile fracture resistance of materials such as carbon steel, the J-integral is plotted against the crack extension ΔT, generating a J–Resistance curve, which quantifies stable crack growth. A standard textbook of fracture mechanics (for example Anderson, 2017) can be consulted for more details on the EPFM approach.

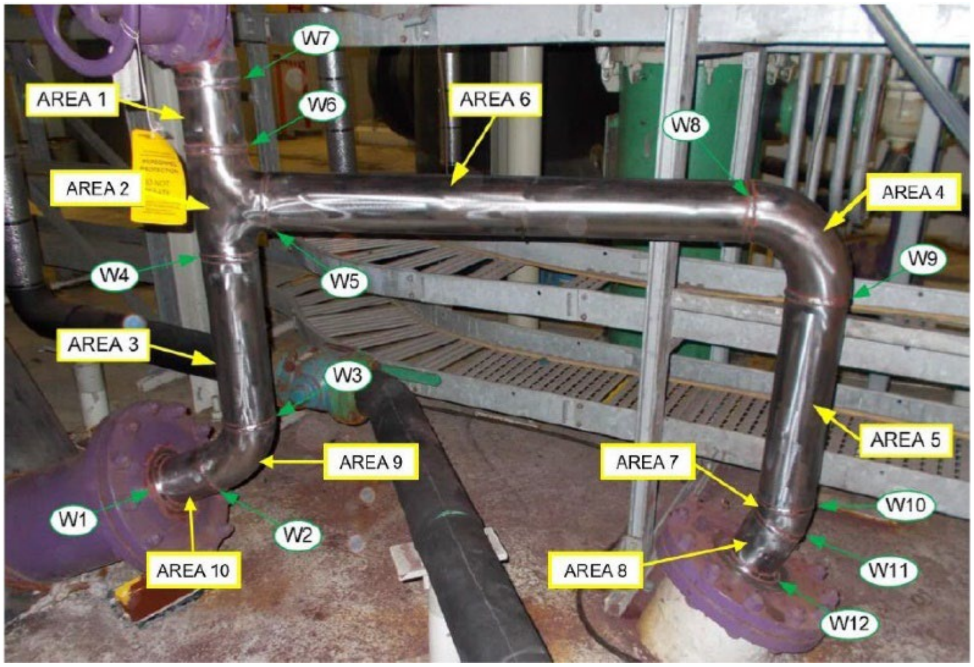

Figure 4. Areas of wall thickness inspections on a sample piping system.

The stress–strain behavior is modeled using the Ramberg–Osgood correlation, which captures the nonlinear elastic-plastic response via the relationship

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \left(\frac{\sigma}{\sigma_0}\right)^n \tag{7}$$

where ε is the total strain, $\varepsilon_0 = \sigma_0/E$, σ_0 is a reference stress, the yield stress, E is the linear modulus of elasticity, and α and n are the Ramberg–Osgood coefficient and exponent, respectively, governing the nonlinear plastic deformation. The yield stress σ_Y serves as the threshold for significant plastic deformation. The flow stress, which is the average of the yield and ultimate tensile strengths, $\sigma_F = (\sigma_Y + \sigma_T)/2$, provides a representative stress value during the plastic deformation.

Similar to LEFM, the EPFM analysis requires a set of material properties and parameters obtained from a suitable laboratory test program carried out at temperatures of −195°C. The analysis considers all mechanical (deadweight and internal pressure) and thermal (wall temperature) loading conditions. Given that the ice-plugging process is a temporary one-time event, with no additional wall thinning expected during the process, the analysis can be based on measured wall thicknesses disregarding any fatigue or crack growth effects.

The idealised crack model consists of a uniform pipe with a surface crack on the inside wall. Both circumferential and axial cracks are considered. Circumferential cracks are modelled as semi-elliptical cracks on the inner surface. The crack depth is the difference between the uniform pipe wall thickness and the minimum measured pipe wall thickness, $a = t_{ave} - t_{min}$. A circumferential half-crack angle is calculated for the corresponding crack depth, making the cross-sectional area of the ‘cracked’ pipe the same as the cross-sectional area of the thinned pipe based on the measurements, $\theta = \Delta A/\big((2R_i + a)a\big)$, where ΔA is the difference between the cross-sectional area of the crack model and that of the measured pipe. Axial cracks are modelled as rectangular cracks on the inner surface of the pipe wall, with a depth and length equivalent to the circumferential crack. The idealised surface crack profile is shown in Figure 5.

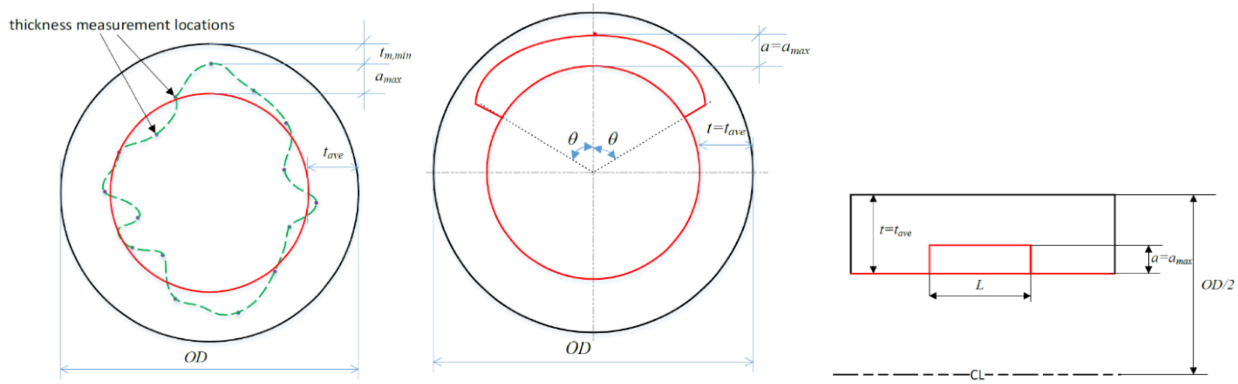

Figure 5. Idealised surface crack profile.

To be consistent with the approach outlined in Article C-2620 of Section XI of the ASME BPVC (2011), the pressure is multiplied by a ‘structural factor’ of 2.4 in the analysis of axial cracks, a structural factor of 2.7 is applied to mechanical tensile forces and a structural factor of 2.3 is applied to mechanical bending moments, whereas no structural factor is applied to thermal loads. The fitness for service analysis then proceeds in two steps, where the piping analysis is performed first to evaluate piping stresses and provide loads for the subsequent fracture tolerance analysis, performed to determine crack stability for the calculated crack sizes. Fitness for service is established if the inspected crack depths, representing the local wall thinning, are smaller than the maximum allowable crack depths.

CONCLUSION

For situations necessitating the formation of an ice plug in a piping system in which a conventional stress analysis cannot satisfactorily demonstrate piping structural integrity, the principles of fracture mechanics can be deployed instead, thereby expanding the range in which this critical maintenance operation can be applied with confidence and assuring the continued safe operation of critical nuclear plant components.

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