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Fitness-for-service assessment of spherical pressure vessels with hot spots

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Abstract

Spherical shapes are used in industry as hemispherical vessel heads or high-pressure storage vessels due to the inherent strength associated with the shape. Structural integrity of such components needs to be evaluated periodically to prevent failure of the vessels under operating conditions. The paper develops a method for Level 2 (as defined by API 579 [(2000). Fitness-for-service, API 579. Washington, DC: American Petroleum Institute]) fitness-for-service estimation of spherical shapes subject to local hot spots where the temperatures are elevated due to local damage. The decay length for spherical shells is determined, and the size of hot spot to be identified as *local* is proposed. A lower bound "remaining strength factor" (RSF) for spherical pressure vessels containing hot spots is formulated by the application of Mura's variational formulation and the m_α-multiplier method. The effectiveness of the proposed Level 2 method is evaluated and demonstrated through an example.

Keywords: Fitness-for-service; Hot spots; Decay length; Spherical shell; Remaining strength factor; Mura's formulation; Structural integrity

1. Introduction

Structural integrity is of considerable importance in order to avoid failures of mechanical components and structures in a number of industrial sectors. The ability to demonstrate the structural integrity of an in-service component that sustained some damage or contains a flaw is termed as integrity assessment or fitness-for-service (FFS) and is extensively dealt with by assessment procedures such as R6 [1]. The FFS evaluations are conducted periodically to determine whether a component with existing damage is suitable for continued service until the end of some desired period of operation such as the next shutdown, a specific future date or the end of its useful life. The assessments include determination of current serviceability to ensure safe operation in the present condition, and remaining service life of the equipment.

For pressurized equipment in operating plants, API 579 [2] prescribes three levels of structural integrity evaluations. Levels 1–3 are progressively more sophisticated. Each assessment level provides a balance between the degree of conservatism, the amount of required input, the skill of the practitioner, and the complexity of the analysis. Level 1 assessments are the most conservative screening criteria that generally include the use of charts and tables, which can be implemented by plant technicians with a minimum quantity of inspection and component information. Level 2 assessments involve detailed calculations intended for use by plant engineering personnel with the help of a recommended procedure. Level 3 assessments require a full rational analysis by specialists where advanced computational techniques such as nonlinear finite element analysis are engaged.

The procedures in API 579 are developed to overcome the shortcomings of the former inspection codes for pressure vessels and piping which are mainly based on empirical data and past experience [3]. In developing them, extensive validation based on both numerical analysis and physical testing has been applied to various damage modes such as metal loss and crack-like flaws. In that regard, further enhancements to Level 2 procedures in damaged

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areas such as hot spots are of significant interest. The current paper focuses on estimating fitness for service of pressurized components of spherical shape subject to damage in the form of localized hot spots with elevated temperatures.

Localized ''hot spots'' are typical of damage that occurs in ageing pressure vessels, piping or storage tanks. They are caused by damage due to loss of refractory lining on the inside wall of pressure components or due to maldistribution of flow containing catalyst and reactive fluids. They are detected through thermography or temperature sensitive paints. An FFS assessment is required to determine the acceptance of continued service of a component containing hot spots. The parameter generally used in such assessments is the remaining strength factor (RSF). The RSF is defined as the ratio of the collapse pressure of the damaged component to the collapse pressure of the undamaged component.

For loads in excess of the limit load it is not possible to have a statically admissible stress field that falls inside the yield surface. In addition, the stress fields for limit loads calculated by using kinematically admissible velocity fields should be on the yield surface. Mura et al. [4,5], eliminated such strict requirements by introducing the concept of integral mean of yield criterion to the variational formulation.

Among several limit load multipliers arising from Mura's extended variational formulation, the m_α-multiplier proposed by Seshadri and Mangalaramanan [6] has proven to offer significantly improved lower-bound estimates. The m_α multiplier is determined on the basis of a linear elastic finite element analysis in conjunction with the nesting surface theorem and the idea of leap-frogging to the limit state. Seshadri [7] evaluated the RSF for thin-walled cylindrical pressure components containing hot spots based on the m^{o}, m_{L} and m_α multipliers. The concept of the localized effect of discontinuities on the cylindrical shell is discussed in detail, and the concept of reference volume is introduced as the kinematically active portion that participates in plastic action.

Indermohan and Seshadri [8] proposed a Level 2 FFS methodology for evaluating locally thinned areas and local hot spots in cylindrical shells. For the problem considered by them, the recommended RSF calculated using m_α-multiplier provides a close lower bound approximation compared with nonlinear finite element analysis model. The ideas proposed lead to a simple and yet practical Level 2 assessment of RSF. These ideas include the use of decay lengths and other intuitive concepts meshed with variational principles.

As mentioned above, the present work focuses on developing a Level 2 structural integrity assessment method for spherical pressure vessels containing local hot spots. It is based on extended variational formulations in plasticity similar to those presented by Seshadri [7]. The concept of decay length is applied to the calculation of reference volume and RSF. The size of hot spot area that can be labelled as local hot spot is identified.

2. Decay lengths in spherical shells

The estimation of decay length is of substantial importance in design and integrity assessment because it identifies the reference volume and is necessary to identify the interaction of multiple local loads. Reference volume defines the containment of effects of local stresses and strains acting on the structure. Decay or characteristic length can be estimated by evaluating the effect of a local force on the spherical shape. Decay length is defined as the distance from the applied force to the point where the effect of the force is almost completely dissipated or at least becomes negligible. A larger decay length generally indicates better energy dissipation of the structure and leads to higher loading capacity whereas a smaller decay length suggests severe local effects due to the applied forces. It must be noted that the decay lengths studied in the current paper are based on elastic analysis. The elastic decay lengths are likely to be smaller than those calculated from plastic analysis. This leads to an overestimation of the damage severity and thus results in conservative RSFs. It must also be noted that the entire Level 2 procedure developed here and the variational formulation associated with it are based on using elastic analysis to simulate the limit behaviour. Hence, the use of elastic analysis for estimating decay lengths (although slightly conservative in the present case) is justified. A more detailed discussion on this is given in [14].

2.1. Spherical shell loaded by concentrated normal force

Lukasiewicz [9], among others, has discussed the problem of spherical shells extensively. The shell differential equations in terms of the radial displacement w and stress function Φ, take the form:

$$\left(\nabla^2+\frac{2}{R^2}\right)\left[D\left(\nabla^2+\frac{1+v}{R^2}\right)w-\frac{1}{R}\left(1-\frac{h^2}{5(1-v)}\nabla^2\right)\Phi\right] = \left[1-\frac{(2-v)h^2}{10(1-v)}\nabla^2\right]P_z, \tag{1a}$$

$$\left(\nabla^2+\frac{2}{R^2}\right)\left[\frac{1}{Eh}\left(\nabla^2+\frac{1-v}{R^2}\right)\Phi+\frac{w}{R}\right]=-\frac{v}{2E}\nabla^2 P_z, \tag{1b}$$

where R is the mean radius, h is the shell thickness, v is Poisson's ratio, P_z is the component of body forces normal to the shell surface, and E is the modulus of elasticity of the material. The flexural rigidity of the shell is expressed as $D = Eh^3/12(1-v^2)$, and $\nabla^2 = (1/l^2)(\partial^2/\partial x^2+\partial^2/\partial y^2)$ is the Laplacian operator in terms of $x=\bar{x}/l$ and $y=\bar{y}/l$, where, l is a certain characteristic length.

Consider a spherical shell loaded by a concentrated normal force P in the outwards direction at $x=0$ and $y=0$ as shown in Fig. 1. The force can be represented by