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Effect of creep on the failure probability of bolted flange joints

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ABSTRACT

The case of a bolted flange joint that is part of a model steam generator (SG) for sodium-cooled fast reactor (SFR) is studied to establish the statistical nature of the time to failure due to relaxation of gasket stress. Continued relaxation over a period of time lowers the gasket stresses to a critical sealing limit, causing failure due to leakage, one of the key modes of failure of bolted joints. An analytical model based on deformation compatibility is used to predict gasket load relaxation with time, which includes flexibility and creep behavior of joint members. A corresponding structural analysis was carried out to validate the analytical model. A probabilistic approach is taken to quantify the effect of uncertainties associated with the design variables on the failure of joint using the analytical model. In order to obtain probability of joint failure, Monte-Carlo sampling method was used for statistical trials. Further, sensitivity analysis was carried out to identify the critical design parameters.

1. Introduction

Bolted flange joints are widely used in nuclear, petro-chemical and thermal power industries for connections or end closures of their pressurized piping systems and pressure vessels. Bolted flange joint located at steam header is a critical part of sodium heated SG for SFR. It is a source of potential failure due to leakage, however, the comparative ease of disassembly and re-assembly of flange joint makes it suitable for inspection and maintenance. Leakage from SG flange of SFR is a serious concern for safety and operation of nuclear plant. Prevention of fluid leakage during operation, the prime design requirement of bolted flange joint, is ensured by the compressive stresses in the gasket induced by tightening of the bolts. The gasket stress distribution during service is strongly dependent on pre-tightening of bolts, operating conditions, materials used for the components and the geometry of the joint. After pre-tightening, pressurization causes an additional tensile load on bolts resulting in elongation of bolts, and therefore, relaxation of stresses in the gasket. One of the key modes of failure of bolted joints is the leakage due to relaxation of stresses in the gasket, when continued relaxation of gasket stresses reaches the critical sealing limit [1,2].

For high temperature applications, the dependence of elastic properties on temperature, thermal expansion as well as the time dependent creep behavior of components play a crucial role in relaxation of gasket stresses with time as reviewed by Sears and King [3]. Thus, it is important to study the factors that influence the integrity of bolted joints at high temperature and pressure and identify the critical variables that affect the reliability of the joints during its operational life.

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International design codes such as DIN, ASME, BS provide the procedures for design of flanged joints. Allowable stress in these codes is based on creep or stress-to-rupture properties of material to avoid catastrophic failure and thus do not predict the effect of relaxation characteristics of bolted flange joints on the mode of failure due to leakage [4].

The earliest studies that address loss of tightness in bolted joints due to creep developed simplified analytical models based on plate theory and experiments [5–9], which formed the basis of widely used Taylor-Forge method for design of flanges. However, these initial analytical models ignored the stiffness of the cylindrical shell, flange as well as the gasket. Kraus and Rosenkrans extended the work of initial studies by including the strain hardening creep behavior and showed that the time to failure of joint is shorter under assumption of steady state creep and therefore the assumption of steady-state is a conservative estimate of the performance of the joint [10].

Subsequently, a number of analytical and experimental studies have been conducted to address the load relaxation in bolted joints by Nagy [11], Kauer and Strohmeier [12], Nassar and Alkelani [13], Krishna et al. [14], Nechache and Bouzid [15] and Grigore and Creitaru [16]. Though these studies include the flexibility of joint members and the effect of creep on compressive stress in gasket of bolted flange joints, the influence of variation in temperature in the joint assembly has not been accounted for in the structural analysis. Also it was assumed that the design variables are deterministic in nature, however, in reality, design variables are stochastic in nature due to various uncertainties associated with applied load, material behavior, geometric dimensions of the components etc. A better approach for safe operation of any structure is to incorporate the effects of the variations in the key parameters on its failure [17]. In the context of the flange joint, this requires taking a probabilistic approach to estimate the effect of the uncertainties in the applied load, material behavior and geometric dimensions of the flange members on the probability of failure of joint during its operational life.

It is well established that the behavior of bolted joints under operating conditions is primarily influenced by the elastic interaction of the joint members. The complexities associated in prediction of the behavior of joint in service are due to its statically indeterminate nature and dependence on a large number of design variables. For higher temperature application, behavior of joint is significantly more complex due to creep in joint members. The existing literature has not taken a probabilistic approach that accounts for the variability of design parameters in evaluation of the probability of failure of the joint during its operational life. In the present study significant temperature variations from inner wall of flange assembly to outer end where bolts are located is incorporated in the estimation of effect of creep on gasket stresses relaxation and further taken a probabilistic approach to identify the critical variables that affect the reliability of the joints during its operational life.

2. Development of a deformation compatibility model

As the bolted joint is a pre-stressed statically indeterminate structure, to determine the stresses in the joint members, an analytical model ensuring deformation compatibility for the interaction between joint members has been developed. Analytical model has been developed to have a better understanding of the contribution of individual joint member deformation on gasket load during operation due to interaction between joint members. The joint members are assumed to behave like elastic spring following the methodology given by Spence and Tooth [18] and Bouzid and Chaaban [19]. Schematic diagram of the analytical model is shown in Fig. 1.

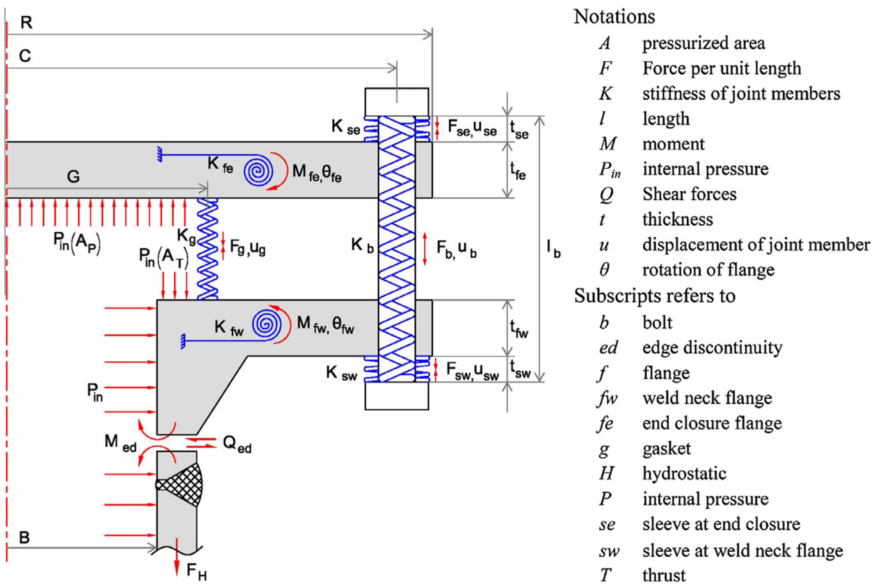

Fig. 1. Schematic diagram of the deformation compatibility model of joint.