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Plastic limit loads for pipe bends with circumferential through-wall crack under torsion moment

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ABSTRACT

In this work, finite element (FE) method is used to determine plastic limit load solutions for pipe bends with circumferential through-wall crack under torsion moment. Both extrados and intrados crack are considered regarding of crack location. Based on FE results estimated solutions are proposed for application, and are also compared with corresponding solutions in previous literatures showing that existing solutions are unfit for prediction of torsion load. The weakening factor W decreases with crack length increasing, and the decreasing rate exhibits three typical stages which performs a similar trend to that with bending moment. Finally a detailed analysis for the mechanical behavior of pipe bends has been conducted which provides some evidence to explain the weaken effect caused by the presence of crack. In torsion mode results show that the non-uniform distributed shear stress is performing symmetric to the profile plane and may have a crucial influence on the weakening factor, while in bending mode the distribution in axial stress and circumferential stress is symmetric to the profile plane and has a decisive influence. Therefore crack is pulled open by in-plane bending load while torn open by torsion load. Some evidence also can be obtained from the Mises stress distribution, where similar variation rule will provide another argument to support such description.

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1. Introduction

For the design and assessment of engineering structure with respect to failure, estimation of maximum load-carrying capacities is required, and thus information on plastic limit loads is important [1]. One of the important problems which appear in the structure is the presence of defects. These flaws present due to the technological process of manufacturing or the service which can cause a failure of the whole system. Prediction of defects assessment has become a crucial matter in the structure design [2]. To assess the significance of crack defects, plastic limit load analyses for cracked components are often performed. Results of plastic limit loads can be used directly to estimate maximum load-carrying capacities of cracked components, when the material of interest is sufficiently ductile [3]. Furthermore, in the reference stress approach [4], it can be used to estimate non-linear fracture mechanics parameters such as J and $C*$ integrals [5,6].

Pipe bends (or elbows) are commonly used components in a piping system, which are widely used in petroleum, chemical and nuclear power industries [7]. Knowledge on maximum load-carrying capacities of pipe bends is important in design and assessment of piping systems in power plants. For straight pipes without any defect, exact limit load solutions are available for different complex loadings [8]. Even for cracked pipes, analytical, experimental and finite element (FE) solutions have been well documented [8,9,10]. For pipe bends without defects or with crack defects, some limit load solutions are available in the literature [11–16]. Compared to those of straight pipes, plastic limit analysis of pipe bends are complicated not only due to more geometric variables involved, such as the bend radius and angle, but also due to the large geometry change effect [17]. Pipe bends are more flexible than straight pipes with similar dimensional parameters [18] due to the complex deformation they exhibited under bending loads. Pipe bends tend to show different mechanical properties as the interaction of geometrical nonlinearity and material nonlinearity when they are under these combined loads. Due to the self-weight, valve weight, fluid weight in addition to heat expansion in the pipe system bending and torsion moment cannot be overlooked. The bending stress caused by bending moment and torsion is possibly greater than membrane stress only by pressure. In the bending mode, flatting will occur, as the stress increases, buckling will even eventually produce due to maximum compression stress from bending deformation and ovalization of circular cross-section of pipe bend, and collapse prior to the structure fracture [19]. Meanwhile for pipe bends torsion may exist with the

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out-of-plane bending. So research on pipe bends under torsion moment is vital to maintain the structure integrity of piping system.

Integrity assessment of piping components is very essential for safe and reliable operation. In piping system with crack-like defects three typical plastic failure modes could occur resulting from the material's properties, which could be called brittle fracture, elastic–plastic fracture and plastic limit failure, respectively [20,21]. Corresponding failure assessment methods have been proposed in accordance with these failure modes. The brittle fracture assessment method is determined by stress intensity factor K or the J-integral approach and is seldom adopted in piping system. The ductile assessment method is determined by failure assessment diagram based approach. The plastic limit load method is determined by plastic deformation. According to the paper of Guo [22], pipes normally with thinner thickness can display plastic limit load behavior distinguished from plastic fracture. Compared with fracture analysis, plastic limit load analysis can be economically acquired and provide great convenience to engineers. In addition, failure of piping components with highly ductile materials and often used in elevated temperature pressure circuits is frequently dominated by plastic collapse [13]. It is especially important for nuclear power plants because of the application of leak-before-break (LBB) concept which involves detailed integrity assessment of primary heat transport piping systems taking into account the postulated cracks [23,24]. According to LBB concept, in certain case, it may be possible that a flaw can grow through the wall of a component without causing a catastrophic failure [25]. One important application of LBB is the plastic limit load analysis for pipes with postulated circumferential through-wall cracks [26]. As is also demonstrated by Guo [22], circumferential crack is dominated among other oriented crack modes which could possibly cause failure during operation process. Although extensive work has been done for developing plastic limit load analysis methods for circumferential through-wall cracked pipes, they are mainly for bending moment.

Some analytical methods according to various plastic failure criterions have been adopted in previous studies, among which net-section-collapse (NSC) analysis [27] is a simple and straightforward method for predicting failure load of a cracked pipe containing circumferential cracks. NSC is widely used in some codes and standards [20] and has already become the main method for the safety assessment of circumferential crack pipes under tension and bending moment. However these analytical methods have some drawbacks. Due to the complicated structures and loading conditions it is unclear to determine the stress states near the crack front for cracked pipe bends under torsion moment.

In recent years numerical method was widely applied in the design of engineering structures with respect to failure [28–31]. With the rapid development of commercial software, finite element simulation to investigate the elastic–plastic behaviors is widely used by many researchers. On the basis of it, large quantities of estimated limit load expressions for assessment have been proposed directly, which have modified and improved some shortcomings in design codes. Based on this procedure Kim and Oh [1,32] proposed estimated equations for limit and collapse loads of pipe bends under combined pressure and in-plane bending. Lee et al. [33] suggested simple regression equations between the yield strength-to-elastic modulus ratio and plastic

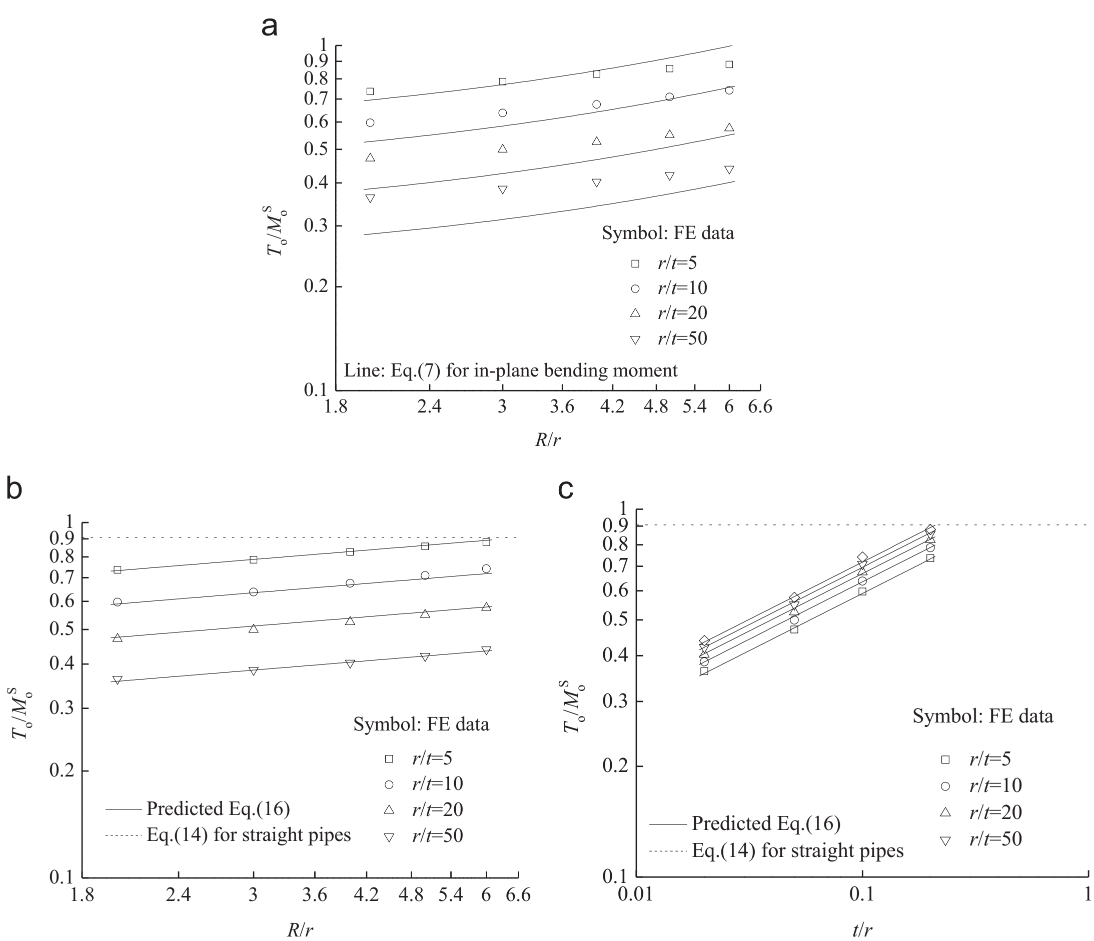

Fig. 1. Comparisons of FE results for plastic limit torsion moment with some proposed Eqs. (7), (14) and (16).

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