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Predicting the limit pressure capacity of pipe elbows containing single defects

Mohsen Khalaj Khalajestani[a,*], Mohammad Reza Bahaari[a,1], Alireza Salehi[b,2], Siamak Shahbazi[c,3]

[a] School of Civil Engineering, College of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran
[b] Kharazmi University, Tehran, Iran
[c] Department of Civil Engineering, Shahid Chamran University, Ahvaz, Iran

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ABSTRACT

Numerous studies have investigated the weakening effect of corrosion or erosion induced defects on the limit pressure capacity of straight pipes, but few have focused on elbows. In this paper the roles of material and geometric parameters of an elbow with a single defect were studied and formulized by means of a vast nonlinear parametric finite element analysis followed by artificial neural network. Results showed that length, depth and circumferential position of the corroded area have the most effects on the limit pressure capacity. In addition to the primary approach of this paper, an analytical approach was also used by combining some ideas from previous relevant studies to reach to a simple and easy-to-use formula. The predictions of the two methods were compared with each other. This paper presents the first part of two-part study investigating elbows with single defects (part 1) and interacting defects (part 2).

1. Introduction

The implementation of subsea large-diameter, high-pressure and high-temperature pipelines for delivering gas and oil are increasing with the growing rate of the exploration and utilization of the offshore oil and gas resources. Initial defects in pipelines are either inherent in the material, introduced during welding, or caused by internal or external corrosive environment [1]. The main protection against corrosion is the pipeline coating, however, as offshore pipelines ages, the coating system may degrade leading to corrosion [2,3]. Corrosion can originate either from corrosive internal gas ingredients containing CO_2 dissolved in water forming carbon acids (internal corrosion) or from the aggressive nature of seawater which is a kind of strong electrolyte by having more than 3% of dissolved salts (external corrosion). Sulfur dioxide and carbon dioxide in the marine environment also result in corrosion [4].

Corrosion defects reduce the bursting capacity of these structures, increasing the possibility of leakage and subsequent pollution of the surrounding sea area. Hence, structural integrity and safety of these structures are very important both from an economical side and environmental aspect and possible threats and should be warily evaluated [5]. Periodical non-destructive inspections provide information about the corrosion damage of the pipeline system. After inspection the pipeline should be analyzed to determine its remaining pressure capacity. By comparing the remaining capacity and operational desired capacity, decisions about future inspection and maintenance are made [6].

Because of the bend radius, the behavior of elbows is different from straight pipes and naturally the stress distribution due to internal pressure in an elbow is different from a straight pipe of the same material and geometry. In a thin, straight and intact pipe the stress distribution is uniform both in longitudinal and circumferential directions, but in an intact elbow as the bend radius decreases the circumferential stress at the intrados increases and at the extrados decreases. This makes elbow as the weakest part of a piping system [7].

Many studies have been devoted to corroded straight pipelines under common loads such as internal pressure and/or bending moment [8–12]. More importantly, two well-known codes, namely ASME-B31G [13–16] and DNV RP-F101 [17–19] have proposed some solutions for assessing corroded straight pipelines, however for elbows there are fewer studies and no worldwide accepted methodology available. Oh et al. [20] quantified the effect of local

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* Corresponding author. Tel.: +98 9358751895.
E-mail addresses: khalaj_mohsen@yahoo.com, mohsen.khalaj@alumni.ut.ac.ir (M. Khalaj Khalajestani), mbahari@ut.ac.ir, bahaari@ioec.com (M.R. Bahaari), salehi.alireza.1987@gmail.com (A. Salehi), shahbazi_siamak87@yahoo.com (S. Shahbazi).
[1] Tel.: +98 21 6649 8981; fax: +98 21 8893 7882.
[2] Tel.: +98 9363108257.
[3] Tel.: +98 9387228605.

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wall thinning on plastic behavior of elbows under pure in-plane bending, by use of three-dimensional finite element analyses (FEA). However, this and some other similar studies neglected internal pressure and only considered elbows under bending moment [21–23]. For intact elbows under pure internal pressure, Goodall [24] proposed a lower bound to the limit pressure; Li et al. [7] used this solution for modifying the old version of ASME-B31G (1991) formula [14] to present a new analytical solution. However it is known that ASME-B31G (1991) formula is much more conservative than recent versions of DNV formula [19,25], hence the method proposed by Li which is based on old solutions, seems to be conservative for today's applications. Wang et al. [26] studied many elbows with single defects using FEA and determined the influence of the defect dimensions on the limit pressure load. Duan and Shen [27] investigated the same problem, but more experiments were conducted and only extrados corrosions were considered.

The main aim of this study is to provide a general and accurate solution for determining the remaining pressure capacity of elbows with single defects, considering a wide range of geometric dimensions. For this purpose, parametric FEA in combination with ANN, as a powerful method [28–31] was implemented. An analytical approach by modifying DNV 2015 formula was also developed and discussed.

2. Finite element analyses

2.1. Schematic of the models

Corrosion in pipelines causes section losses over either large areas (general corrosion) or local areas (local corrosion) [32]. General corrosion is usually modeled as an overall thickness reduction of the pipe/elbow. This paper addresses local corrosion only. The geometry of local corrosions is usually irregular in depth and in surface, but for engineering purposes, it is very common to idealize these irregular defects with equivalent rectangular shapes [7,33]. More details about this idealization is provided in DNV (2015) [19].

The schematic shape of a 90° elbow with an external defect at the extrados, connected to two straight pipes at both ends is shown in Fig. 1. Important geometric parameters are bend radius (R), cross-sectional radius (r), wall thickness (t), remaining wall thickness at corroded area (t_c; $t_c = t - d$), length and width of the corroded area (L and W). The circumferential position of a defect (the extrados, crown or intrados) can have a huge effect on the remaining pressure capacity which is investigated in this paper. The longitudinal position of the defect along the elbow has minor effect [26]; therefore, in favor of a plane of symmetry (plane A, in Fig. 1), the defect was located in the middle of the elbow length.

According to the DNV (2015) [18] there is no difference between the effect of internal or external corrosions in straight pipes (inner or outer surface); however this is not the case for elbows, so the outcomes of this paper, in which only external defects were considered, should be used with caution for internally corroded elbows.

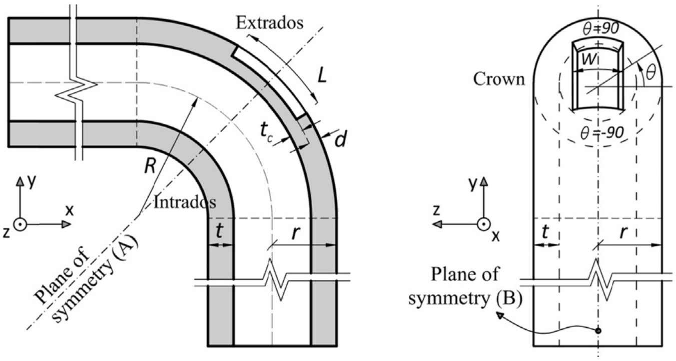

Fig. 1. The geometry of an elbow containing defect in two different views.

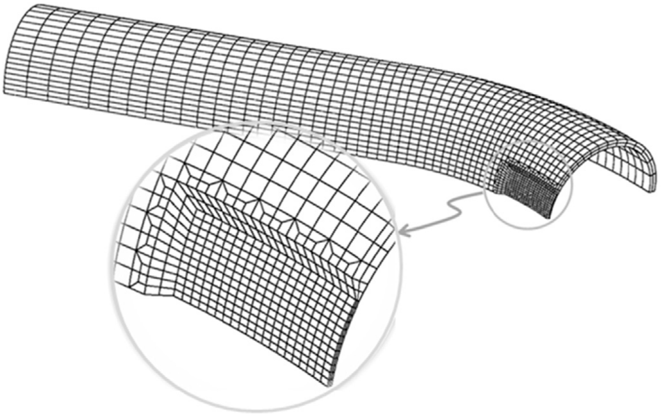

Fig. 2. A typical finite element mesh.

As can be seen in Fig. 1 when the defect is located at the intrados or extrados, there are two planes of symmetry (A and B), but when the defect is located at the crown, there will be only one plane of symmetry (A). Each plane of symmetry can reduce computational effort to half.

The model should include the two connected straight pipes, because the plastic yielding zone extends to the attached pipes, as well as the elbow, making the resulting limit pressure higher than that for an elbow without connected straight pipes [34]. By a trial-and-error process, it was found that a length of the six times the mean cross sectional radius (r), is enough for modeling the connected straight parts.

ABAQUS (version 6.10) [35] was used to perform three-dimensional elastic-plastic FEA. In nearly all analyses bulging deformation occurred around the defect. For this reason the non-linear geometry option in ABAQUS (NLGEOM) was invoked to simulate large inelastic deformation during the analyses. 20 nodes reduced integration quadratic elements were used. As shown in Fig. 2, mesh refinement at the region of the defect was included to improve the accuracy of stress and strain calculation at these regions. In this figure, a region of mesh transition (from four elements reduces to two elements) can be seen which was applied for more efficiency. This typical mesh distribution was found to be adequate based on convergence studies.

2.2. Loading and boundary conditions

Uniform pressure loading was applied on the inner surface of the entire elbow and the straight pipes. Elastic-plastic FEA was performed for the developed models. In these analyses, the value of the pressure loading was increased incrementally and the failure was assumed to occur once the von Mises equivalent stress reached the ultimate strength at some point in the FE model.

Due to geometric and loading symmetry, mentioned earlier, when the defect is located at the crown, one-half of the structure was modeled, but when the defect is located at the intrados or extrados, only one-quarter of the full structure was modeled. Appropriate boundary conditions on the symmetry planes and other boundaries were applied which are shown in Fig. 3. For each boundary condition, element nodes are constrained in the displayed directions. Note that this figure is related to the cases of extrados (or intrados) defects.