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Characterization of plastic collapse load determination in circumferentially through-wall cracked elbows

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Abstract

The solutions of cracked elbow are shown to be excessively conservative and on occasion, non-applicable to the cases for which they are intended. The objective of the work described in this paper is to use the 3D non-linear finite element method (FEM) backed up with experimental results to determine the collapse limit load. Non-linear finite element analyses were performed considering both material and geometrical non-linearity using the advanced fracture analysis code WARP3D. Various alternative methods are used to determine plastic collapse loads based on the FEM calculated load–displacement curves. The predicted collapse loads are compared to collapse loads determined by available solutions and finally these are compared to experimental results. The work can be considered as the source of the benchmark data that helped to shape the engineering treatment of piping elbows in design codes.

1. Introduction

The possibility of fracture in pressure vessels and piping components of nuclear power plants has always been considered as a main problem and has indeed been one of the driving forces behind the development of fracture mechanics. This necessitates detailed flaw evaluation of different piping components such as straight pipes, elbow and branch tees. Elbows are considered as the most flexible members in piping systems, and severe stress concentration may results from thermal expansion, dead weight and seismic load. Thus, prediction of elbow behaviour is very important in understanding the response of a piping system. While a large amount of papers (Brust et al., 1995; Rahman, 1997; Chattopadhyay et al., 2000a; Xinqi et al., 2001; Takahashi, 2002) is found reporting of crack in straight pipes, only a few articles (Shalaby and Younan, 1998; Chattopadhyay et al., 1995; Moulin et al., 1997; Yahiaoui et al., 2002; Chattopadhyay et al., 2000b; Chattopadhyay, 2002) deal with cracked pipe elbows. It is important to know its limit load for the safe operation of the plant. Elbow collapse loads can be determined experimentally or by simplified analytical techniques. These methods generally neglect the effect of material strain hardening, stress distribution and in-elastic ovalization of the elbow cross-section. The limit load solution of elbow tries to account for the strain hardening through the use of flow stress; it does not consider the strain-hardening exponent in the formula. The ovalization of the elbow cross-section plays an important role in its collapse. Under faulted condition the ovalization of the cross-section must be limited to ensure functional capability. The limited existing knowledge on cracked elbows has been catalogued in a review presented in Yahiaoui paper (Yahiaoui et al., 2002). The circumferential through-wall crack is at the intrados (under in-plane opening bending mode) or at the extrados (under in-plane closing bending mode) is considered as the most critical defects in elbows. It is recommended (Yahiaoui et al., 2002) that this type of defects need to be focused on in any future investigation.

Due to ductility and enhanced material toughness of this pressure bearing structures elastic–plastic fracture mechanics analyses in connection with leak-before-break problem are of primary interest. The objective of the research described in this paper is to use the 3D non-linear finite element method (FEM) backed up with experimental results to determine the limit load. The limit load is required to check whether plastic collapse precedes the onset of unstable ductile tearing or not. Geometric non-linearity is very important to accurately capture the elbow deformation under closing/opening bending loading

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Nomenclature

c	half crack length = $\theta.r_m$
D_m	mean diameter of the pipe
E	Young's modulus
h	pipe factor ($= tR_b/r_m^2$)
M	limit moment for cracked elbow
M_h	limit moment for healthy elbow
M_{hp}	limit moment for healthy pipe
n	Ramberg–Osgood exponential constant
r_m	mean radius of the pipe
R_b	mean pipe bend radius
t	thickness of the pipe

Greek letters

α	Ramberg–Osgood multiplicative constant
σ_f	flow stress = 0.5 ($\sigma_y + \sigma_u$)
σ_u	ultimate stress
σ_y	yield stress
θ	semi-circumferential crack angle
ν	Poisson's ratio

(Chattopadhyay et al., 2000b). Non-linear finite element analyses were performed considering both material and geometrical non-linearities. The paper investigates analysis of four elbows using advanced fracture analysis code WARP3D (Gullerud et al., 2002). The solutions of cracked elbow are shown to be excessively conservative and on occasion, non-applicable to the cases for which they are intended. The results are dependent on two interacting effects: the strength of uncracked elbow and with the presence of the crack. It should be noted that most of the analytical treatments do not distinguish between the opening and closing mode of bending as well as position of crack (intrados and extrados). This contribution summarizes the comparison of 3D non-linear FEM and available solution results with recent experimental results of cracked elbows with straight pipes. With reference to one healthy elbow and three circumferential through-wall cracked (TWC) elbows having crack at intrados (under opening bending mode) and extrados (under closing bending mode), the accuracy of these solutions, for determining the limit collapse load in elbows, is judged. In the following, the results of elastic–plastic finite element calculation will be presented, whereby the 90° elbows with straight pipe is loaded by in-plane bending load (Fig. 1). Elbow with straight pipe is hinged at one end, at the other end, subjected to loads corresponding to in-plane opening or closing bending moment. A circumferential through-wall crack is located at intrados and extrados positions of the elbow in three separate models. Load–deflection curves were obtained and from these curves, collapse limit loads were determined. The collapse load by FEM results is calculated for each elbow considered in the analysis using three alternative method and the results are compared with experimental maximum load and collapse loads calculated by existing solutions. The work can be considered as the source of the benchmark data that helped to shape the engineering treatment of piping elbows in design codes.

2. Existing solution of collapse limit load

2.1. Healthy elbow

Limit load solutions in healthy elbow under in-plane bending was first reported by Spence and Findlay (1973). They utilized previously existing analyses in conjunction with the limit theorems of perfectly plasticity. These expressions for in-plane limit

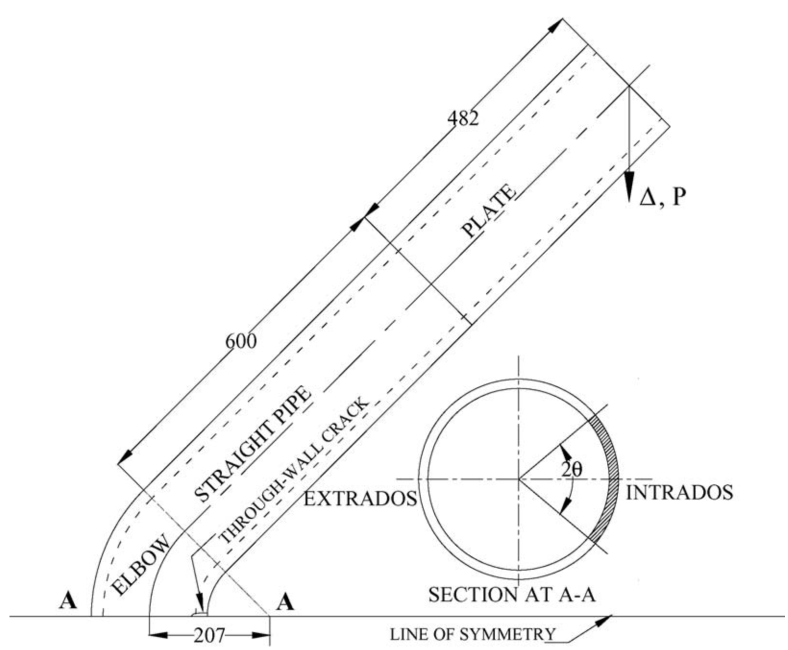

Fig. 1. Circumferential through-wall cracked elbow subjected to bending load (All dimensions are in mm).