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Limit load interaction of cracked branch junctions under combined pressure and bending

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ABSTRACT

This paper describes the effect of cracks on the plastic limit loads of branch junctions under combined pressure and bending, based on three-dimensional finite element limit analyses. For combined pressure and bending to the run pipe, the circular interaction rule can be used to estimate plastic limit loads. For combined pressure and bending to the branch pipe, either a circular or parabolic interaction rule can be used depending on the branch type. For through-wall cracked branches, the interaction curves move toward the linear interaction rule with increasing crack length. For surface cracks, the interaction diagrams change smoothly between the limiting cases of the un-cracked and through-wall cracked branch.

1. Introduction

Information on limit loads of cracked branch junctions is important in structural integrity assessment of piping components. Despite its significance, however, existing works in literature are limited. Yahiaoui et al. [1] presented experimental test data of un-cracked and cracked equal-diameter forged branches under internal pressure, out-of-plane bending and their combinations. Lynch et al. [2] presented FE limit loads of welded equal-diameter branches under combined pressure and out-of-plane bending. Xuan and co-workers [3,4] also reported experimental test data of un-cracked and cracked equal-diameter forged branches under internal pressure, and semi-analytical solutions of equal-diameter cracked branches under internal pressure. Above works are confined to equal-diameter branches. Recently the authors [5] presented systematic results of plastic limit loads of the cracked large bore branch junction. Various loading conditions were considered; internal pressure and (in-plane and out-of-plane plane) bending either to the run pipe or to the branch pipe. Both through-wall and part-through surface cracks were considered either in the flank or in the crotch. They showed that the effect of the crack on normalised limit loads (with respect to limit loads of un-cracked branches) could be quantified using simple functions (such as linear or quadratic). It should be noted that, via systematic three-dimensional (3-D) finite element (FE) limit analysis, the authors [6–8] recently reported closed-form limit load solutions of uncracked branch junctions, covering all possible ranges of branch geometries. Various loading conditions were also considered: internal pressure [6]; in-plane bending to the branch and to the run pipe [6]; out-of-plane bending to the branch and to the run pipe [8]; and combined pressure and bending [7,8].

In practice, piping systems are always subject to combined pressure and system loading, and thus studies need to be carried out for combined loading. Although Moffat and co-workers [1,2] reported experimental and numerical data of cracked equal-diameter branches under combined internal pressure and out-of-plane bending (to the branch pipe), their results may

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Nomenclature

a	crack depth
M	bending moment
$M_L(P = 0)$	limit moment of un-cracked/cracked branch junction under pure bending
P	internal pressure
$P_L(M = 0)$	limit pressure of un-cracked/cracked branch junction under internal pressure
R, r	mean radius of the run (main) pipe and the branch for branch junctions
T, t	thickness of the run (main) pipe and the branch for branch junctions
σ_0	limiting strength of an elastic-perfectly plastic material
α, θ	half crack angle for the flank crack and crotch crack, respectively

not sufficient to draw general conclusions on plastic limit loads of cracked branch junctions under combined loading. In this respect, systematic FE analysis for cracked branch junctions under combined loading may be needed.

This paper presents plastic limit loads for branch junctions with part-through surface and through-wall cracks under combined pressure and bending. Two types of branch junctions, a large bore and a medium bore branch junction, are considered. Limit loads are obtained from 3-D FE limit analyses assuming an elastic-perfectly plastic material. Section 2 describes the FE limit analyses employed in the present work. Section 3 briefly reviews plastic limit loads for un-cracked and cracked branch junctions under single loading. The results for combined pressure and bending to the branch pipe are presented in Section 4, and those for combined pressure and bending to the run pipe in Section 5. The present work is concluded in Section 6.

2. Finite element limit analysis

2.1. Geometry and loading

To investigate the effect of cracks on plastic limit loads for branch junctions, a large bore and a medium bore welded branch component [9,10] were chosen. The mean radius of the run pipe is denoted by R, and that of the branch pipe by r. The thicknesses of the run and branch pipes are denoted as T and t, respectively. The branch vessels considered are depicted in Fig. 1, including details of the welded intersection region. The relevant dimensions are also summarised in Table 1.

Either a through-wall or a part-through surface crack is postulated in the branch intersection. The crack is assumed to be located either in the crotch or in the flank location, as shown in Fig. 2a. Furthermore it is positioned either in the upper weld toe or in the lower weld toe, as shown in Fig. 2b. The profile of the crack is defined by the surface projected normally onto the inner surface of the run pipe (Fig. 3) and its length is characterised by the half angle, θ, for the crotch crack and by α for the flank crack. The values of the relative crack length, θ/π or α/π, were varied from $\theta/\pi(\alpha/\pi) = 0$ to $\theta/\pi(\alpha/\pi) = 0.5$. The part-through surface crack is assumed to be constant-depth a, having a straight crack front; the relative crack depth, a/t, was varied from 0 to 1.0.

The branch is assumed to be subject to combined pressure and bending. The bending can be either in-plane or out-of-plane and applied either to the branch pipe or to the run pipe.

2.2. FE limit analysis

Three-dimensional elastic-perfectly plastic FE limit analyses were performed to determine the plastic limit loads of the cracked branch junctions using ABAQUS [11]. The materials was assumed to be homogeneous and elastic-perfectly plastic, and non-hardening J_2 flow theory was used. For efficient computation, symmetry conditions were fully utilised and thus a half model was used. The plane of symmetry depends on the crack position and the loading mode. Twenty-node iso-parametric quadratic brick elements with reduced integration (ABAQUS type C3D20R) were used. Fig. 4 depicts typical FE meshes used in the present work. The crack-tip is designed with collapsed elements, and a ring of wedge-shaped elements was used in the crack-tip region. For through-wall cracks, the numbers of elements and nodes in typical FE meshes ranged from 3094 elements/16,857 nodes to 6682 elements/33,532 nodes. For part-through surface cracks, they ranged from 5192 elements/26,610 nodes to 13,771 elements/63,628 nodes. Finite element analysis was performed using the geometrically linear (small strain) option.

Combined pressure and bending were applied in a non-proportional manner; that is, internal pressure was applied in the first step and then bending in the second step. The internal pressure was applied as a distributed load to the inner surface of the FE model, together with axial tensions equivalent to the internal pressure applied at the ends of the branch and main pipes to simulate closed end conditions. In the case of in-plane or out-of-plane bending to the branch pipe, the nodes at the end of the branch pipe were constrained using the MPC (multi-point constraint) option within ABAQUS, and sufficiently large rotation was directly applied. For the kinematic boundary condition, the two ends of the main pipe were clamped for