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Worn pipes collapse strength: Experimental and numerical study

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ABSTRACT

After drilling an oil or gas well the open well-bore is usually cased with steel pipes, which must be properly designed to support all predicted loads (pressures) along its service life. Such casing can be subject to material loss after deployed. One of the reasons for material loss comes from that the well-bore is drilled deeper with rotating drill pipes after casing installation. The interaction between the rotating drill-pipes and casing inner wall leads to the casing wear, which can significantly reduce the wall thickness at particular regions. Casing designers usually assume evenly distributed inner casing wear. Under this assumption the remaining wall is constant and the predictive burst and collapse strength equations presented by standards are applied, but resulting in much lower strength values than the real case.

Few authors studied the pipe remaining strength under more realistic wear assumptions. Kuryama et al. presented an analytical formulation based on pipes with circular cross-section and an equivalent wall thickness eccentricity to simulate material loss over an angular section. Sakakibara et al. presented a model for collapse strength prediction of worn pipes with initial geometric imperfection (cross-section ovalization) and constant pipe wall loss within a given angular section. None of them combined real initial (ovalization and eccentricity) and produced (casing wear) geometric imperfections. This paper presents the full scale experimental set up and results for thin and thick walled intact and worn pipes under applied external hydrostatic pressure. The test procedure included pipes' geometry mapping and wear production to match real conditions. The specimens were collapsed and numerical analysis based on finite element analysis and an analytical model were carried out to simulate physical conditions. The numerical results were then extended to a broad range of pipes with different geometries and steel grades representative of drilling well applications. As expected, one developed model developed predicts really well thin walled pipes, but not for thicker ones.

1. Introduction

After drilling an oil or gas well the open well-bore is usually cased with steel pipes, which can have from hundreds to thousands meters of length. The pipes are installed together through threaded connections and are subject to a harsh downhole environment. A proper casing design has to address possible chemical reactions or mechanical interactions leading to pipe wall material loss (as corrosion and erosion), and the remaining pipe wall thickness must support all predicted loads (pressures) along the well life. If the material is properly designed, corrosion rate can be neglected.

Usually the well-bore is drilled deeper with rotating drill pipes inside steel casing after it is installed. The interaction between the rotating drill-pipes and casing inner wall can lead to the so-called casing wear, which can significantly reduce the wall thickness at particular regions. Assessing properly the strength of the worn pipe can be the key to achieve a feasible technical and economical well design. Casing designers usually assume evenly distributed inner casing wear. Under this assumption the remaining wall thickness is constant and equal to minimum remaining wall. Predictive burst and collapse strength equations presented by API 5C3 (API BULL, 1994) or ISO TR 10400 (ISO TR, 2007) are applied. Assuming the remaining wall thickness as the lowermost possible results in the lowermost strength values.

Few authors studied the pipe remaining strength under more realistic wear assumptions. Some authors developed analytical models to account the wear at inner wall to evaluate the burst strength (Wu and Zhang, 2005; Shen and Beck, 2012), or to evaluate the stress concentration of plain dents due to mechanical damages in steel pipes subjected to internal pressure (Pinheiro, 2006). Regarding to the remaining collapse strength for worn

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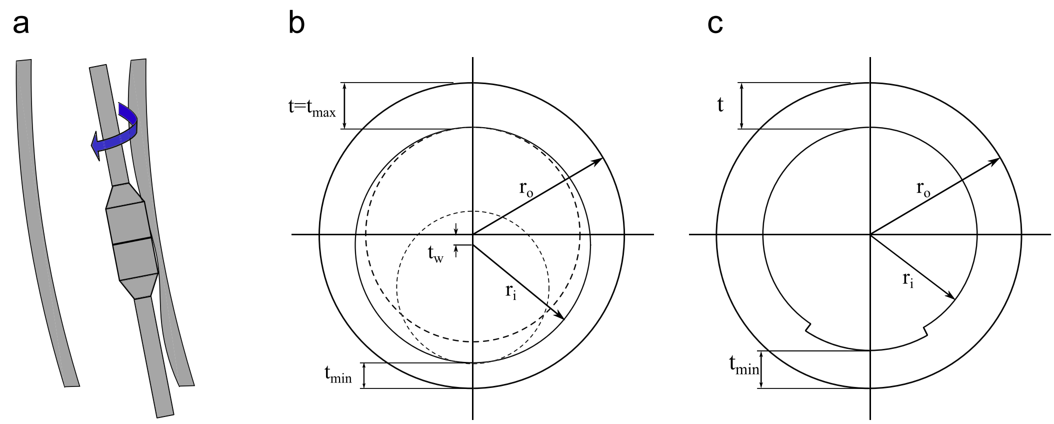

Fig. 1. Sketches of wear mechanism and casing cross-sectional worn geometry: (a) rotating drill-string connection (tool joint) causing a wear groove located only at one side of inner wall; (b) pipe circular cross-section with outer radius r_o and inner radius r_i. The circle representing the inner wall presents an offset t_w, which is chosen to match an equivalent geometry of the worn area (modified from Kuriyama et al., 1992). Dashed line represents the real casing wear and (c) constant wear geometry of thickness t_{min} for a given circular sector (modified from Sakakibara et al., 2008).

pipes, Kuriyama et al. (1992) presented an analytical formulation based on pipes with perfectly circular cross-section and an equivalent wall thickness eccentricity to simulate material loss over an angular section (Fig. 1(b)). Sakakibara et al. (2008) presented a model for collapse strength prediction of worn pipes with initial geometric imperfection (cross-section ovalization) and constant pipe wall loss within a given angular (1-(c)). Though the latter presents good match with experimental results, the produced wear does not match the geometry usually produced by rotary pipes inside casings.

To accurately predict collapse strength of worn pipes, the initial (cross section ovalization and wall thickness eccentricity) and resulting (casing wear) geometrical imperfections must be included in any analysis. This paper presents the full scale experimental set up and results for thin and thick walled, intact and worn pipes, under applied external hydrostatic pressure. The test procedure included pipe geometry mapping, before and after producing wear, to account both initial and produced (wear) geometrical imperfections. Casing wear was produced to match real conditions. The specimens were collapsed and numerical analysis based on finite element analysis and model developed by Sakakibara et al. (2008) were carried out to simulate physical conditions. The numerical results were then extended to a broad range of pipes with different geometries and steel grades representative of drilling well applications.

2. Material and methods

2.1. Full scale samples preparation

The full scale physical tests were addressed to collapse specimens prepared from two-representative pipe configurations: (i) representing thick pipes (with $d_o/t = 13.5$, herein called type 1), and (ii) representing thin pipes (with $d_o/t = 20.3$, type 2). Both configurations are usual for oil and gas industry (Table 1). Intact and worn samples were prepared making possible to compare the effect of material loss and collapse mechanism (elastic versus "plastic" collapse). With full-scale geometry it was possible to build a representative damage at the inner pipe wall.

Table 1
Nominal geometry of chosen pipes to evaluate hydrostatic collapse loads (measures in parentheses are in inches).

Pipe type/specimen series	d_o-mm (in.)	t-mm (in.)	d_o/t
1-80	273 (103/4)	20.24 (0.797)	13.5
2-90	245 (95/8)	11.99 (0.472)	20.3

Table 2
Typical material properties for both pipes (which are different steel grades). The values inside parentheses are in psi.

Specimen series	E - MPa (psi)	σ_o - MPa (psi)	ν
80	3×10^7 (207,532)	1070 (155,215)	0.29
90	3×10^7 (207,532)	1002 (145,455)	0.29

The samples prepared from pipe type 1 were called series 80, and from pipe type 2 series 90 respectively. Samples were prepared long enough to avoid end effects during collapse tests.[1]

Samples geometry (d_o, t) were gathered before and after machining (to produce worn pipes). The geometrical data were gathered from measurements over 12 equally spaced cross sections spanned by 200 mm, called sections A till L, depicted at Fig. 2. Typical values are presented in Tables 3 and 4 before machining, and Table 5 for intact (non-machined) samples. These data are representative of the collapsed cross sections during tests. The initial ovalization was evaluated by Eq. (1) below, where $D = \max_{d_o \in \mathcal{S}}\left(d_o\right)$ and $d = \min_{d_o \in \mathcal{S}}\left(d_o\right)$ represent the maximum and minimum measured outside diameter at a given cross-section $\mathcal{S}$ $\{\mathcal{S}:=A, B\ldots, L\}$:

$$\triangle = \frac{D - d}{D + d} \times 100\% \tag{1}$$

It is important to remember that geometry mapping was done before and after machined (see Fig. 3). Herein the pipes' types 1 and 2 were sampled and labeled according machined (label 83 and 93 respectively) or non-machined (84 and 94 respectively). The machined samples from pipe type 1 (namely 83-1, 83-2, and 83-3) were prepared in order to present maximum wall thickness reduction of 20%. The machined samples from pipe type 2 (namely

[1] The samples dimensions criteria to collapse tests were followed as recommended by ISO 10400 (ISO TR, 2007). According to these recommendations, the samples prepared for tests shall have a minimum length in relation to the outer diameter of the sample. For pipes with outer diameter lower or equal than 95/8 in., the sample shall have a length of at least 8 times its diameter. For pipes with outside diameter of 103/4 in. or larger, the ratio is at least 7 times the outer diameter. These limits are established for the purpose of eliminating the influence of the ends in the collapse strength. Small samples present higher stiffness and therefore are not representative of collapse strength values. From Fig. 2 it is possible to see that the length is at least 10 times the outside diameter.