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Two-parameter fracture assessment of surface cracked cylindrical shells during collapse

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Abstract

The present study addresses the use of CTOD and T-stress in fracture assessments of surface cracked shell structures. A new software is developed for this purpose, denoted $\text{LINK}_{\text{pipe}}$. It is based on a combination of a quadrilateral assumed natural deviatoric strain thin shell finite element and an improved linespring finite element. Plasticity is accounted for using stress resultants. A power law hardening model is used for shell and linespring materials. A co-rotational formulation is employed to represent nonlinear geometry effects. With this, one can carry out nonlinear fracture mechanics assessments in structures that show instabilities due buckling (local/global), ovalisation and large rigid body motion. Many constraint-measuring parameters have been proposed, with the Q-parameter or the T-stress being the most popular ones. Solid finite element meshing for complex structures such as pipes containing semi-elliptical surface cracks in order to compute Q is at present not a feasible approach. However, shell structures are most conveniently meshed with shell finite elements, and the linespring finite element is a natural way of accounting for surface cracks. The T-stress is readily obtained from the linespring membrane force and bending moment along the surface crack. In this study we present a new approach to analyse cracked shell structures subjected to large geometric changes. By numerical examples it is shown how geometric instabilities and fracture compete as governing failure mode.

Keywords: Plasticity; Large rotations; Co-rotated formulation; Assumed strain thin shell finite element; Linespring finite element; Nonlinear fracture mechanics; Ductile crack growth

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1. Introduction

Surface cracked shell structures occur in many industrial applications, e.g. pressure vessels, pipelines, tubular joints etc. In the present study offshore pipelines for oil and gas transportation have a special focus. Such tubular structures are subjected to many challenging load cases. A very convenient method for pipe laying is reeling. Then the pipeline is continuously un-winded from a spool. During this sequence significant inelastic straining due to high bending evolves. As pipe segments are joined by girth welds, some defects have to be expected and assessed with respect to fracture. Furthermore, free spans for seabed pipelines pose challenging fatigue life calculations due to vortex induced vibrations. External and/or internal pressure also needs to be accounted for. An important point in fracture assessment of pipelines is that the stresses in the shell are mainly of membrane type (tension or compression), even for a pipe subjected to global bending moments. This lowers the constraint in the plastic zone at the crack tip in comparison to the constraint in shells with high local bending moments. It is well known that reduced constraint of the plastic zone in front of the crack tip provides higher fracture toughness than in a high constraint situation. And in many structural applications the low constraint condition is the actual one. Using a fracture toughness based on high constraint test specimens then results in overly conservative capacity of the structure. Put in other words, the low measured toughness in combination with traditional capacity checks may lead to an assessment that does not allow for any cracks or defects at all in a component subjected to high loading. This is unacceptable for welded structures, where some defects have to be expected. A methodology to account for reduced constraint is proposed by Chiesa et al. [1], where a single edge notched tensile specimen is employed as fracture test specimen instead of the usual (high constraint) three point bend specimen.

Traditionally, three-dimensional solid finite elements are employed in discretising the shell structure in order to account for the crack. This puts high demands on both pre- and post-processing in addition to long cpu times. An alternative is to use shell finite elements. Then the challenge is to account for the crack. This may be done using linespring finite elements at the crack location. A factor of 10 in reduced cpu is typical. But the main benefit of using shell/linespring elements is the reduced time spent in pre- and post-processing.

Using linesprings, the crack is modelled as nonlinear springs between the shell elements, with a varying compliance as a function of crack depth and plastic deformations. A complicating factor in the shell fracture assessment is the fact that large global motion and local instabilities due to local buckling may occur. So it is an interplay between nonlinear geometry effects and the crack driving forces, Skallerud [2]. This is accounted for in the present simulations, providing answer to whether geometrical or fracture mechanical instabilities governs the shell capacity.

The present study addresses the use of CTOD, *T*-stress, and ductile tearing curves in fracture assessments of surface cracked shell structures using tailored software denoted $\mathrm{LINK}_{\mathrm{pipe}}$ [3]. It is based on a co-rotated kinematical formulation using quadrilateral thin shell and linespring finite elements. The shell element is a non-conforming high performance finite element based on assumed natural deviatoric strains, denoted ANDES. It was originally developed by Felippa and Militello [4], and further extended for use in large rotation inelastic analyses by Skallerud and Haugen [5]. The linespring formulation was derived for elastic materials by Rice and Levy [6]. Elasto-plasticity was incorporated by Parks and White [7]. Closed form yield surfaces also valid for the short crack regime were developed by Chiesa et al. [8] and are employed herein. Some additional yield surface refinements are included in the current version of the software. A detailed presentation of numerical aspects and implementation is given by Skallerud et al. [9]. Validation of the software, comparing with detailed 3D solid finite element analyses using ABAQUS, is provided in [9–11].

The first part of the paper addresses some of the theory behind the shell and linespring formulations, and two-parameter fracture mechanics. Then numerical test cases are presented. Here both elastic and