I-47 PROPAGATING BUCKLE ANALYSIS OF DEEP-WATER PIPELINES

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1. INTRODUCTION: Pipeline stability is of great concern during the pipelaying operation, since the pipe is exposed to external pressure, bending and tension. These combined loads can lead to local damage. If the external pressure in the neighborhood of the damage is high enough, further collapse occurs and a buckle is initiated and propagates along the pipe at a high speed and damages a substantial length of expensive pipeline [1]. This phenomenon has become known as the propagating buckle. The lowest pressure required for buckle propagation is called the propagation pressure and is much lower than the collapse pressure for which pipelines are normally designed. Once initiated, the collapse front of the propagating buckle will move along the pipe until it enters a region of pressure lower than the propagation pressure, or until it encounters a stiffener, usually referred to as a buckle arrestor. The present study analyzes quasistatic buckle propagation in deep-water pipelines accounting for large deformation and elastoplastic material behavior of the pipe in three dimensions using a finite element technique. Below, the technique is briefly described and computational results are presented and compared with experimental data.

2. TECHNIQUE: The nonlinear finite element technique developed in the course of the present study uses a Lagrangian, convected-coordinate formulation of the field equations. For a continuum occupying the region V_o in the reference configuration with boundary B in the current configuration, the principle of virtual work can be written as follows:

$$\int_{V_o} \delta U_{k,j}(\mathbf{G}^k \cdot \mathbf{g}_i)\tau^{ij}\, dV_o = \int_{B} \delta u_i T^i\, dB \tag{1}$$

in which δu_i is covariant components of the virtual displacement on the current base vectors ; $\delta U_{k,j}$ are the covariant components of the gradient of $\delta\mathbf{u}$ on the reference base vectors; $\mathbf{G}^i, i = 1,2,3$, are the contravariant base vectors in the reference configuration and $\mathbf{g}_i, i = 1,2,3$, are the covariant base vectors in the current configuration; τ^{ij} and T^i are the contravariant components of the Kirchhoff stress and the boundary traction on the current base vectors. The finite element technique in this work is based on the nine-node isoparametric shell finite element (degenerate bricks) originally developed by Ahmad et al. [3] for linear analysis. This element was adapted to nonlinear analysis using the convected-coordinate formulation. The elastoplastic constitutive equations relating the Jaumann rate of Kirchhoff stress to the rate of deformation are based on J_2-plasticity with isotropic hardening. For the purpose of tracing equilibrium paths of the pipe under uniform change of pressure during buckle propagation, the shell finite element is equipped with an additional node. The so-called pressure node [2] has a single degree of freedom, namely, the uniform change of pressure on the element, denoted by Δp. The discretized version of the variational equation (1) along with the pressure node can be written as follows:

$$\begin{bmatrix} \mathbf{K}_e & \int_{B^e} \mathbf{N}^T\mathbf{n}\, dB^e \\ \int_{B^e} \mathbf{n}^T\mathbf{N}\, dB^e & 0 \end{bmatrix} \begin{bmatrix} \mathbf{\Delta U} \\ \Delta p \end{bmatrix} = \begin{bmatrix} \mathbf{P} \\ \Delta\hat{V} \end{bmatrix} \tag{2}$$

where $\mathbf{K}_e$, $\mathbf{\Delta U}$, $\mathbf{P}$, $\mathbf{N}$ and $\mathbf{n}$ denote the element stiffness matrix, the vector of incremental nodal displacements and rotations, the load vector, the matrix of nodal interpolation functions and the outward unit vector normal to the boundary B^e. Along unstable equilibrium paths, the required change of pressure Δp is solved by specifying the change of the volume-like variable $\Delta\hat{V}$. The unstable equilibrium path of a pipe is traced successfully around its limit points using a pressure node connected to all elements. The evaluation of stiffness matrix and load vectors of the element is performed using reduced Gauss-Legendre quadrature, i.e., a 2×2 array of integration points over any lamina. The reduced integration alleviates the locking of the element that is known to occur with full integration, but generally results in the appearance of spurious zero-energy modes of

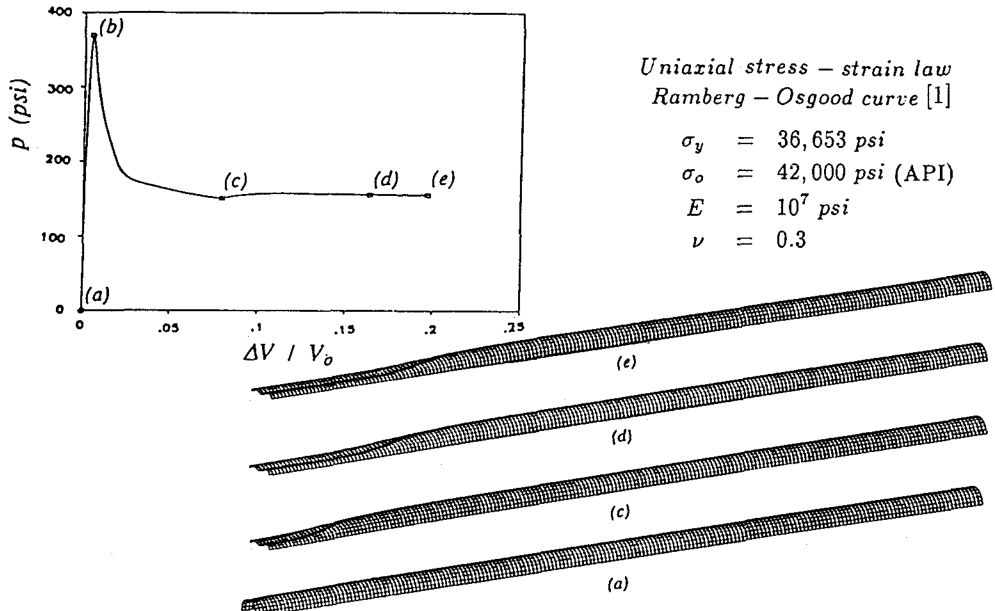

Figure 1: Deformed pipe configurations during buckle initiation and propagation

deformation. However, if these modes are restrained by the boundary conditions, as is the case in the problems of interest in this work, the underintegrated elements perform very well. Through the thickness of the element, 5-point Gauss-Legendre quadrature performed satisfactorily for the pipe analyzed in this work. To account for contact between regions of the interior wall of the pipe during buckle propagation, contact elements are implemented on the basis of the penalty formulation.

3. RESULTS: Results are presented for an aluminum-alloy (Al–6061–T6) pipe with outside diameter $D = 1.250$ *in*, thickness $t = 0.035$ *in* ($D/t = 35.7$) and initial imperfection $0.008D$[1]. The material properties are given in Fig. 1. A quasistatic buckle propagating was initiated on the $24D$ pipe with a local damage (see Fig. 1 (a)) by applying decrements of the enclosed volume. Fig. 1 presents deformed pipe configurations in the course of buckle initiation and propagation, along with a graph of the applied pressure, p, versus the reduction of volume enclosed by the pipe, ΔV, normalized by the initial volume, V_o, enclosed by the pipe. It can be seen in Fig. 1 that upon formation of the buckle, the pressure attains a steady value, about 156.1 *psi*, which is the analytical estimate of the propagation pressure and is in very good agreement with the value, 155.8 *psi*, obtained from the experiment [4]. The technique was more extended to dynamic propagating buckles for the propagation speed and dynamic behavior of the buckle propagation in a pipeline [1].

4. CONCLUSIONS: A finite element technique has been developed and implemented for the analysis of propagating buckles, making use of nine-node isoparametric shell elements and considering the nonlinearities due to large deformation, i.e., large rotation and strain, elastoplastic material behavior and contact. The analysis of quasistatic buckle initiation and propagation in a pipe was conducted. The propagation pressure was obtained and found to compare favorably with the experimental data.

5. REFERENCES:

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