
1D hybrid beam-shell tube model for progressive cracks in pipelines

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Abstract

The energy sector, from nuclear to oil and gas, manages large scale pipelines networks in both standard operation and accidental events. It is critical for them to know the reaction of the piping structure during nominal conditions, but also when unattended phenomenons occur. Those events can be rapid dynamic loading that cause damage and cracks in the pipe. The mechanical response of both intact and notched pipes under dynamic loading has been a subject of interest of recent published studies.

This type of unexpected event must be considered in the nuclear power plant (NPP) safety studies conducted at EDF R&D, including violent pipe deformation and fracture. The hypothetical events of pipe rupture in a NPP are the Loss Of Coolant Accident (LOCA) and High Energy Line Break (HELB), two scenario specific to the nuclear sector. The Loss Of Coolant Accident considers a crack in the primary loop causing a de-pressurization wave to propagate that may adversely affect the components of the primary loop and the vessel internals. The High Energy Line Break situation involves pipe that carry a high temperature and pressure fluid. In case of a break, such pipe will face violent deformation and whipping effects. Such phenomena are hard to model in 3D, as the structure are large and complex, and important local plastic deformation can occur. Therefore, this works aims to develop a high-fidelity 1D cracked pipe model to model the piping rupture scenario.

A uniaxial enriched beam model has been developed in previous studies to simulate straight pipe without any crack (intact). The model associates an Euler-Bernoulli beam kinematics that represents the pipe's global behavior, and a Kirchhoff–Love shell motion for the pipe's cross section deformation. The shell displacement fields of the model are expanded as a Fourier series on the pipe section angular variable

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θ , and the Fourier coefficients become the degrees of freedom of the shell kinematics for the 1D model. The stress is also integrated analytically across the section of the pipe and the thickness of the shell to compute generalized forces of the model. Formalized in a time-explicit framework, the model was implemented in the fast transient research and industrial code Europlexus. The details and analysis of the intact straight pipe model was presented in (1) and (2), where both static and dynamic behavior of the model were validated against a 3D finite element shell model.

The proposed work is focused on the extension of the enriched beam model to represent the evolution of a progressive crack in a pipeline. As a first step, the kinematics of the model is completed to depict a pipe with a straight lengthwise notch of a fixed length. To achieve this, a plausible kinematics is computed from an "open ring" analytical solution. Its addition to the Fourier expansion of the shell kinematics allows the representation of the opening of the pipe under various loads with three new degrees of freedom corresponding to the displacement jumps between the crack lips. This addition keeps the model uniaxial, as the displacement jumps only varies along the length of the cracked pipe. An a priori validation of the kinematics is conducted by comparison with full-scale numerical simulations. The full scale solution across a section is projected on the proposed kinematics function of θ , and the resulting function is compared to the full scale solution. The model is found to be in good adequacy with the full scale reference, especially for the loading of pipe under pressure. In addition, a sensibility analysis on the number of Fourier modes in the expansions is conducted.

After this verification, the new model of notched pipe is developed analytically in the same framework as the intact model. The contribution of the crack's degrees of freedom in the pipe motion and in the generalized forced is analyzed analytically. The new model is implemented in the same explicit dynamic code Europlexus, and comparison both static and dynamic are conducted with 3D numerical solutions for various type of boundary condition, such as internal pressure and bending. Even if the dynamic of the pipe is analyzed, the crack remains of a fixed length at this step of the development.

After this first step of extension of the model to notched pipe with a lengthwise crack on its surface, the problematic of pipe crack propagation is questioned. Indeed, a global linear fracture framework is chosen to study the crack propagation on the pipe. An analytical energy release rate of the crack can be computed from the degree of freedoms and a propagation criterion can be defined. Results are compared to references simulation and experiments of the litterature.

The resulting model is only meshed in 1D, and aims to model a complex behavior in an industrial tool for simulation of piping networks across a facility. Therefore, computation costs are greatly reduced. Toward future work, the 1D model also helps to add a fluid-structure interaction, as the fluid contribution can be computed analytically, and added as an exterior contribution in the equations of motions. Currently, the material is linear elastic, as the study focuses on the interest of the 1D model more than the material specificity. However, the model could be extended to more complex elasto-plastic behavior for better precision, and the computation of pipe whip phenomenon in case of a plastic hinge.