Enabling the decarbonisation of Australia's energy networks

Future Fuels CRC RP3.2-06: Two Page Summary of Research

Development of a New Fracture Propagation Model Based on Advanced Damage Models Accounting for the Effects of Stress-State on Failure

Research background

Between 2016 and 2019, the Energy Pipelines CRC and DNV conducted two full-scale fracture propagation tests under the CO_2Safe-Arrest joint industrial project for CO_2 transportation pipelines.

Despite its effectiveness, full-scale fracture propagation testing is cost-prohibitive and impractical for widespread use on pipeline projects. However, it is sometimes the only means to demonstrate the performance of designs outside the envelop of applicability of the Battelle-Two Curve Method, as can be case with dense-phase CO_2 designs, high grades pipelines, etc.

The current project delved into the potential of a relatively new fracture model, pioneered by Wierzbicki's research group at MIT and based on the failure strain locus. This fracture model, renowned for its versatility across stress states, originated in automotive research. In the past decade it has progressively gained traction among pipeline researchers. It can theoretically be applied to all fracture-related issues on pipelines: initiation, propagation, arrest and fatigue. In some instance it has been applied to study the temperature driven brittle to ductile fracture transition mode of failure.

Project outcomes

Within the current project, five failure locus-based fracture models, namely the Xue-Wierzbicki model, the Bai-Wierzbicki model, the modified Mohr-Coulomb model, the Hosford-Coulomb model, and the DF2016 model, underwent comparison. To calibrate these fracture models, three types of lab-scale tests were conducted: flat bar tensile tests, pure shear tests, and punch tests.

The calibration method employed plays a pivotal role in the development of the fracture model. The predominant approach utilised is the hybrid experimental-numerical method. However, this method, reliant on finite element analysis (FEA) simulations, presents two notable drawbacks: the complexity of calibration due to a large number of parameters and issues related to mesh dependency.

The current project has devised an alternative calibration approach that eliminates the necessity for FEA simulations, relying exclusively on digital image correlation (DIC) measurements. The calibration method developed also takes into consideration the stress state history. Comparative analysis using this calibration method indicates that the Bai-Wierzbicki model outperformed the others.

In the current project, a simplified model for the full-scale burst test has been developed. The simulation predicts that the material is subjected to bi-axial tensile stress states, followed by a plane strain condition. Utilising the stress history obtained from the full-scale test simulation, the application of the Bai-Wierzbicki fracture model predicts the failure strain. While not all results align with experimental data, some predictions do, demonstrating the promising potential of failure locus-based fracture models calibrated by the DIC-based method developed in this project.

Applications and implications

The failure locus-based models represent a paradigm shift in understanding and modelling failure. It has the potential to transform future fracture mechanics assessments. However, widespread adoption may take time, as its application in the pipeline industry remains primarily within the realm of research for now.

The advantages and disadvantages of the failure locus-based models could be summarised as follows:

Advantages:

- Offers significant benefits over traditional fracture mechanics by focusing on material properties, eliminating challenges associated with geometry dependence, such as thickness effects, plane strain/plane stress transitions, and restraint issues.
- Enhances understanding of post-necking material behaviour (strain beyond ultimate tensile strength).
- Inherently compatible with FEA, with some implementations in commercial packages already available.

Disadvantages:

- Calibration is complex and challenging.
- Limited availability of key material properties for model calibration.
- Cannot be calibrated using standard mill certificate information.
- Requires additional data from existing tests (DWTT, Charpy, tensile) for calibration. While specialised tests have been used to develop the theory, these three standard tests are sufficient for practical application.

For most pipeline design and assessment scenarios, the level of accuracy offered by this model is not essential, as significant safety margins are already built into current designs. However, there are specific applications where the industry might find its use beneficial:

- **CO_2 Transport in Dense Phase:** The existing models are limited in their accuracy and applicability, especially across varying wall thicknesses, diameters, and other parameters.
- **Hydrogen Transport:** While currently more relevant for research purposes, the model could enable parametric studies of hydrogen's effects, particularly in relation to the triaxiality of the stress state. It could also be integrated with detailed hydrogen diffusion models.
- **Girth Weld Matching:** Useful for applications such as Engineering Critical Assessments (ECA) and girth weld designs, offering the ability to incorporate factors like residual stresses.

Additionally, the failure locus model could play a key role in material design, shifting from merely measuring material properties to specifying materials with the desired properties.

European researchers are advanced in this methodology and its application to pipelines. The University of Regensburg is establishing "virtual labs" that utilize numerical simulations, with the failure locus-based model playing a significant role. Their models have been used in several industry projects and supported by full-scale burst tests.

At this stage, failure locus models are only available through collaboration with experts. If the industry is interested, it is recommended to engage with universities actively working on these models.

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