COUPLING OF A GRADIENT-ENHANCED GTN MODEL TO THE BEREMIN MODEL FOR THE SIMULATION OF DUCTILE-TO-BRITTLE TRANSITION

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Abstract

Ductile-To-Brittle transition modeling for ferritic steels used in the nuclear industry has been studied for years. This paper proposes a two-step coupled modeling representing ductile crack growth thanks to a gradient-enhanced GTN model and applying a modified Beremin model to evaluate the probability of failure of CT specimens at -50°C.

1. Introduction

The safety of the primary vessel of a nuclear pressurized water reactor (NPWR) is primordial to allow the operation of the power plants or the extension of their life span. Ferritic steel fracture behavior depends on temperature, and it is possible to determine a transition temperature below which fracture becomes brittle (Ductile to Brittle Transition (DBT)). The general method to assess the safety of the pressure vessel is based on the lack of fracture under normal and accidental conditions. The approach is deterministic: the structure loading is compared to the resistance to fracture characterized by the material's toughness. This global approach does not consider the failure micro-mechanisms, particularly the influence of preceding ductile crack growth on brittle fracture assessment. The local approach for brittle fracture developed in Beremin model allows accounting for fracture micro-mechanisms and can be applied even if cleavage is preceded by ductile tearing. Therefore, in the DBT, it becomes necessary to simulate ductile crack extension before evaluating the risk of brittle failure. A correct evaluation of stresses during ductile crack extension is primordial as they are the input data for cleavage models. For that purpose, it is important to use a regularized damage model to simulate ductile cracking so that spatially converged objective results are obtained. This work aims at modeling ductile crack growth using a gradient-enhanced Gurson-Tvergaard-Needleman model and then applying the Beremin approach to evaluate the resulting Weibull stress and the corresponding probability of failure. The work is carried out on a ferritic steel (18MND5) using an existing test database. Mechanical tests include cracked specimens (CT and SENT) and smooth (ST) or notched axisymmetric (NT) bars. Test temperatures are: -150°C, -100°C, -50°C, and -20°C.

2. Method and results

The study is split into several steps:
Step 1: We assume that there is no ductile tearing before cleavage at low temperatures. The Beremin approach with two parameters (σ_u, m) is used to calculate the probability of failure after evaluation of the Weibull stress (σ_w):

$$P_f = 1 - \exp\left(-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right) \text{ with } \sigma_w = \left(\int_\Omega \left(\max_{\tau<t}\left(\sigma_{I|_{\dot{\varepsilon}_p>0}}\right)\right)^m \frac{d\Omega_0}{V_0}\right)^{\frac{1}{m}}$$

where σ_I is the principal stress, $\dot{\varepsilon}_p$ the cumulated plastic strain rate and Ω the volume of the structure. Application of this model enables to calibrate the Beremin parameters at -100°C . It has been shown that the identified model can deal with different geometries: for example at this temperature the identification of the model was conducted on CT50 and CT25 specimens and then applied on all specimens. As presented in figure 2, the probability of fracture is in good agreement with the experimental ones for all type of specimens. The transfer of the model to higher temperatures requires a new calibration of the model parameters and particularly of σ_u value.

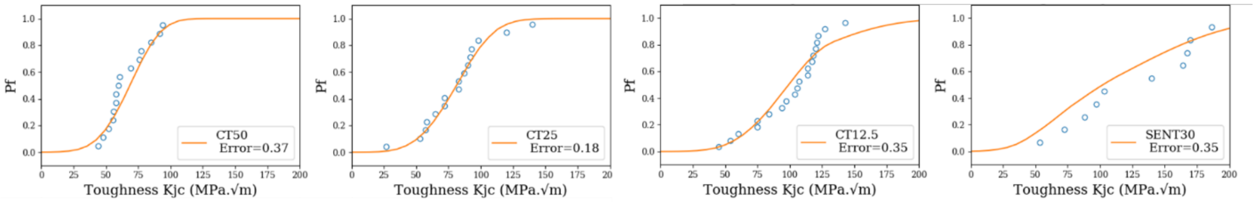

Fig.1 – Beremin model predicted probability of fracture, P_f^{th}, compared to experimental probability, P_f^{exp}, for $(m, \sigma_u) = (8.8, 6258MPa)$ identified on CT25 and CT50 at $-100°C$. Error $= \left\| P_f^{exp} - P_f^{th} \right\|_2$.

Step 2: The ductile crack growth is modeled by means of a gradient-enhanced energy GTN model. The model takes into account the interaction of neighboring material points through a plasticity gradient term in the Helmholtz free energy, hence controlling the localization band width. A mixed finite element formulation is used in this work to deal with volumetric locking and improve the evaluation of stresses. The ductile behavior is first identified at -20°C on NT and CT specimens. At this temperature, no cleavage is experimentally observed. The application on a CT specimen at -50°C presented in figure 2 confirms the transferability of the model at lower temperatures.

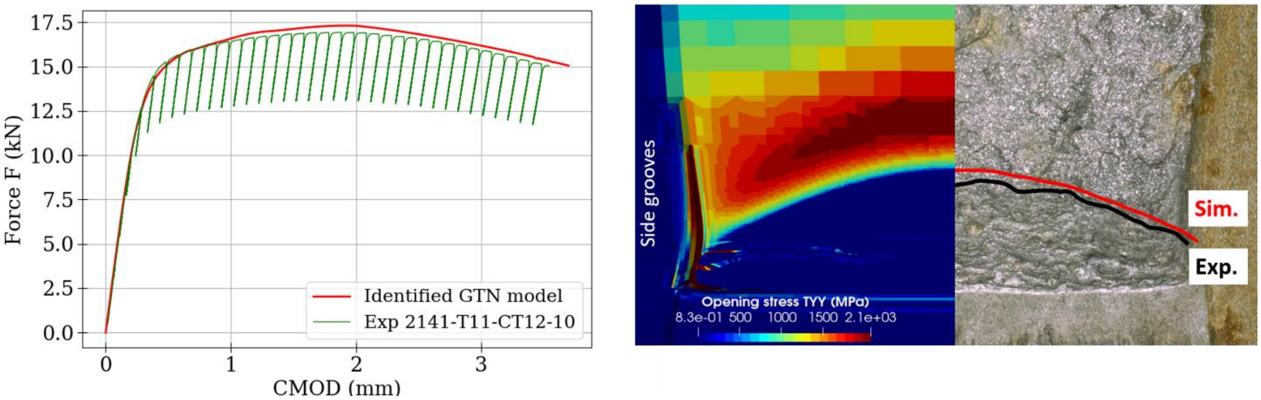

Fig.2 – CT12.5 non-local GTN simulation at -50°C. Force-opening curve and final profile of the crack.

Step 3: The last step consists in applying the proposed GTN model at -50°C and then in computing the Weibull stress to assess the probability of failure. The first results show that Beremin's formulation needs to be modified to account for the nucleation of voids in ductile failure. The stress fields resulting from GTN calculations also require a special treatment to avoid any divergence of the Weibull stress calculations.

3. Conclusions

This work aims at modeling the top of the DBT through a coupling between a regularized GTN model and the Beremin model. Both models have been calibrated separately at temperatures where there is no coupling. It has been shown that Beremin model could be applied to different geometries. The identified GTN model could be transferred to lower temperatures. Work in-progress emphasizes the necessity of a special treatment of the stress field resulting from the GTN model to compute the Weibull stress and the use of a modified Beremin model accounting for the void volume fraction.