Uncertainty quantification of the reference temperature T_0 of Reactor Pressure Vessel steel with experimental and numerical computation of fracture toughness tests

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Nuclear plant life extension requires accurate evaluation of the embrittlement of reactor pressure vessel (RPV) steels caused by neutron irradiation. This irradiation induces a shift towards higher temperatures of the ductile-to-brittle transition range. To predict this shift, pre-cracked Compact Tension (CT) specimens - made of representative RPV steel - are used in irradiation surveillance programs to perform fracture toughness tests. These data allow the application of the Master Curve methodology from ASTM E1921 standard [1], which describes the evolution and scatter of fracture toughness depending on the material temperature. The Master Curve enables the determination of the reference temperature, T_0, representing the ductile-to-brittle transition temperature.

However, results from toughness test programs reveal many uncertainties in the evaluation of T_0. Firstly these uncertainties are related to the material variabilities, such as the inherent scatter of fracture toughness and its dependency on temperature, which generate different T_0 values from one test program to another. Because of the limited amount of material available, especially in the irradiated state, the number of tests is restricted, which amplifies deviations in T_0 values. To perform further tests with remnant material, we use mini-CT specimens. Nevertheless, geometric variabilities such as the size of the CT specimen, machining defects and the length and shape of the pre-crack affect the results of T_0.

In order to enhance the robustness of fracture toughness evaluation, we propose to quantify the influence of the uncertainties of T_0 mentioned above by identifying their effects. To do so, we use experimental data and we develop numerical models to perform statistical analyses and sensitivity analyses using machine learning methods. Firstly, a finite element code (FEC) simulates tensile tests on CT specimens at a given temperature. The results are post-processed in a stochastic brittle fracture model (Beremin), providing the probability of failure of the specimen, P_f, according to the measured stress intensity factor K_J. By interpolating these data, our stochastic model allows us to emulate any number of fracture toughness tests, plot the Master Curve and evaluate T_0. Based on this global model, we carry out statistical analyses that enable us to quantify the effects on T_0 of the number of tests, the test temperature, and the specimen size. Then, we apply sensitivity analyses such as Sobol's method to identify the geometric and material parameters that have the most influence on T_0. In particularly, we use crack front values from the EuroDataSet database [2] to develop a Karhunen–Loève model that generates stochastic crack fronts in our FEC. Thus, we quantify the effect of crack front on T_0, and we illustrate the most influential modes of curvatures. These results complete the conclusions from a similar study by Lindqvist et al [3], with this time large data sets and varying crack front curvatures.

These results contribute to developing more cost-effective and optimized test methods to estimate T_0 of RPV steels. However, as our FEC is costly to evaluate, we are developing a surrogate model to substitute it for ongoing and further work.

References

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