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Predicting the effect of large discontinuities on the fatigue strength of welds in turbine runners

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ABSTRACT

Hydraulic turbines, made of welded assemblies, inherently contain discontinuities. The fatigue strength of martensitic stainless steel 410NiMo, which has slag-type discontinuities, can be predicted using two numerical approaches. The first approach, used by Hydro-Québec, assumes the discontinuity behaves like a crack, predicted by Linear Elastic Fracture Mechanics (LEFM). LEFM's fatigue strength prediction is based on discontinuity size. The second approach, Linear Elastic Notch Mechanics (LENM), treats discontinuities as notches. This method can give more accurate predictions but requires detailed characterization of the local stress field.

This research aims to determine which approach better predicts the fatigue strength of welds with wormlike discontinuities, ranging from 0.18 mm to 2.94 mm in length. The process includes experimental and numerical steps. First, specimens are fabricated using robotic welding and flux addition to introduce surrogate discontinuities typical of the FCAW process. Next, the geometry of these discontinuities is characterized using high-resolution CT scanning (20 µm/voxel). Third, 3D models of welded zones with discontinuities are developed for finite element analysis (FEA) to analyze the stress field. The fourth step involves predicting fatigue strength using LEFM and LENM. The fifth step compares predictions with fatigue testing results. Post-mortem analysis of fracture surfaces using optical and electron microscopy provides insight into prediction discrepancies.

Simulation results showed complex stress distributions around discontinuities, with singularity exponents ranging from 0.27 to 0.45. A singularity exponent below 0.5 is characteristic of notch-like discontinuities, suggesting that LENM might provide more accurate predictions.

Fatigue tests on 14 specimens revealed fatigue strengths between 72 MPa and 171 MPa, compared to a reference value of 520 MPa for defect-free material. LENM overestimated fatigue strength by 34%, while LEFM provided more accurate predictions with an average deviation of 16%.

Fractographic analysis showed cracks initiated at micro-notches filled with flux, which were undetectable by CT scanning. This suggests that large, rounded discontinuities in welds may harbor microscopic cracks, even when FEA predicts a singularity exponent below 0.5. Foreign elements from flux residues were identified at initiation sites, potentially embrittling the material and affecting fatigue predictions.

This work introduces an innovative method for fabricating welded joints with controlled discontinuities and employs advanced characterization and simulations for fatigue strength prediction. The research confirms that LENM is not safe for predicting fatigue strength in FCAW-welded regions, supporting Hydro-Québec's approach.