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Proportionally and non-proportionally perturbed fatigue of stainless steel

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Abstract

Computational fluid dynamics and finite element based simulation of the cyclic thermal shock loading caused by turbulent mixing of water of different temperatures in the primary cooling system of a nuclear power plant, suggest a specific kind of non-proportional multi-axial fatigue loading exists on the inner surface cooling structures. Stress controlled experiments mimicking these loading conditions were designed and run on an axial-torsional fatigue testing system. The cyclic loading observed in the finite element simulations consists of the superposition of proportional loading and a second, non-proportionality inducing component, the latter with a substantially lower amplitude and running at a higher cycling frequency. The amplitude of the non-proportionality inducing loading component is of a magnitude so small that the fatigue loading criteria, typically used in engineering standards for nuclear power plant safety, do not recognize the difference with the reference loading without this component. However, first experimental results show that the endurance limit of stainless steel of grade 316L is reduced by this additional loading, which we name non-proportional fatigue noise. The fact that the endurance limit is unexpectedly lowered is a non-conservative safety issue that challenges the currently existing criteria used to estimate the fatigue damage for this type of loading.

Keywords: Non-proportional fatigue perturbation, Stainless steel

Glossary

A_{50} elongation measure using a 50 mm gauge length

E elastic modulus

N_f number of cycles to failure

R_m ultimate stensile strength

$R_\mathrm{p0.2}$ yield stress at 0.2% strain

$\boldsymbol{\sigma}$ stress tensor

κ ratio of the fully reversed uniaxial to the shear stress endurance limit σ_{-1}/τ_{-1}

DV superscript used to indicate a property related to the Dang Van criterion

LKG superscript used to indicate a property related to the Liu-Kang-Gao criterion

PCr superscript used to indicate a property related to the Papuga PCr criterion

Pap superscript used to indicate a property related to the Papadopoulos criterion

Sus superscript used to indicate a property related to the Susmel criterion

a subscript used to indicate the amplitude

max subscript used to indicate the maximum value during a loading cycle

m subscript used to indicate the mean value during a loading cycle

tr trace of a tensor (1/3$^\mathrm{rd}$ of third tensor invariant)

σ^H hydrostatic stress

$\sigma_\mathrm{a}^\mathrm{eq,DV}$ Dang Van equivalent stress amplitude

$\sigma_\mathrm{a}^\mathrm{eq,LKG}$ Liu-Kang-Gao equivalent stress amplitude

$\sigma_\mathrm{a}^\mathrm{eq,PCr}$ Papuga PCr equivalent stress amplitude

$\sigma_\mathrm{a}^\mathrm{eq,Pap}$ Papadopoulos equivalent stress amplitude

$\sigma_\mathrm{a}^\mathrm{eq,Sus}$ Susmel equivalent stress amplitude

$\sigma^\mathrm{eq,VM}$ von Mises equivalent stress

σ_a axial loading stress amplitude

σ_m mean axial loading stress

σ stress

τ_a torsional loading shear stress amplitude

τ shear stress

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