New Approaches for Integrity Assessment

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In the lower shelf region, size effects are negligible, but at higher toughness values the brittle fracture toughness will be affected by a statistical size effect.

In the transition region cleavage fracture occurs after some ductile tearing. This region is specimen size dependent due to the statistical size effect.

The upper shelf is the temperature region where the fracture mechanism is fully ductile.

In all regions, the fracture toughness can be affected by specimen constraint.
“THE MASTER CURVE APPROACH”

TYPICAL RAW DATA

MASTER CURVE ANALYSIS

THEORETICAL SCATTER DESCRIPTION
STATISTICAL SIZE ADJUSTMENT
UNIFIED TEMPERATURE DEPENDENCE
Application of Master Curve and constraint correction for real cracks

Normally, the Master Curve parameters are determined using test specimens with "straight" crack fronts and comparatively uniform stress state along the crack front. This enables the use of a single $K_I$ value and single constraint value to describe the whole specimen.

For a real crack in a structure, this is usually not the case. Normally, both $K_I$ and constraint varies along the crack front and in the case of a thermal shock, even the temperature will vary along the crack front.

$$P_f = 1 - \exp \left\{ \int_0^s \left( \frac{K_{I\Phi} - K_{\min}}{K_{0\Phi} - K_{\min}} \right)^4 \cdot \frac{ds}{B_0} \right\}$$

$$P_f = 1 - \exp \left\{ \frac{B}{B_0} \cdot \left( \frac{K_I - K_{\min}}{K_0 - K_{\min}} \right)^4 \right\}$$

Standard MC
Application of Master Curve and constraint correction for real cracks

\[ K_{\text{IeffTref}} = \left\{ \int_{0}^{s} \left( \frac{K_{I\Phi} - K_{\min}}{K_{0\Phi} - K_{\min}} \right)^{4} \cdot \frac{ds}{B_{0}} \right\}^{1/4} \cdot (K_{0\text{Tref}} - K_{\min}) + K_{\min} \]

\( K_{I\Phi} \) is obtained from the stress analysis as a function of location \((\Phi)\). \( K_{0\text{Tref}} \) is the standard, high constraint, Master Curve \( K_{0} \) corresponding to a specific reference temperature along the crack front.

\( K_{0\text{Tref}} = 31 + 77 \cdot \exp[0.019 \cdot (T_{\text{ref}} - T_{0})] \)

A visualisation, that is in line with conventional practice, can be achieved by defining an effective stress intensity factor \( K_{\text{Ieff}} \) corresponding to a specific reference temperature. The reference temperature can e.g. be chosen as the minimum temperature along the crack front.

The procedure is to determine an effective driving force, which would give the same failure probability as a standard Master Curve presentation.
Postulated flaws

• Postulated flaws often contain unrealistically long crack fronts. Such flaws may be justified, purely from a driving force perspective (as originally has been the intention). From a statistical size adjustment point of view, the assumption is over-conservative.

• If such postulated flaws are analyzed using $K_{Ie}$, an upper limit size adjustment of 150 mm or $2 \cdot W$ is recommended.

• This value is in line with the original $K_{IC}$ data used to develop the ASME $K_{IC}$ reference curve and therefore justifiable in terms of the functional equivalence principle. The form of $K_{Ie}$ for an excessively large postulated flaw ($S > 150$ mm) becomes thus

$$K_{Ie,Tref} = \left\{ \int_0^s \left( \frac{K_{I(0)} - K_{min}}{K_{0(0)} - K_{min}} \right)^4 \cdot \frac{150 \text{ mm} \cdot ds}{B_0 \cdot S} \right\}^{1/4} \cdot \left( K_{0,Tref} - K_{min} \right) + K_{min}$$

• If NDE can guarantee a smaller value of $s$ than 150 mm, it can be reduced further.
$K_{0\Phi} = K_{0T,T-stress} = 31 + 77 \cdot \exp \left[ 0.019 \cdot \left( T - T_{0,T-stress=0} - \frac{T-stress}{12\text{MPa/°C}} \right) \right]$
CONCLUSIONS

• The MC enables a complete characterization of a materials brittle fracture toughness based on only a few small size specimens.

• The MC methodology has evolved, from only being a brittle fracture testing and analysis procedure, to a technological tool capable of addressing many more structural integrity issues like constraint and parameter transferability.

• The MC does not pretend to be the final truth. It is only an engineering tool that is constantly open for further improvements and changes.