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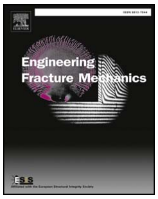

A cohesive element with degradation controlled shape of the traction separation curve for simulating stress corrosion and irradiation cracking

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ABSTRACT

A cohesive element with extended environmental degradation capability was developed and implemented into an Abaqus user element. The element uses a virgin and a fully degraded Traction Separation Law (TLS) as input. The use of the potential based PPR model enables flexibility in the softening shapes for both TSL. When the element is degraded, the TSL gradually goes from the shape of the virgin material to the fully degraded TSL shape. This transition was made with a new parameter χ that can govern a more ductile or brittle crack growth behaviour at degradation. The effect on the plastic zone due to changing the softening shape is shown, where the convex shaped softening TSL gives higher plastic dissipation and larger plastic zones than the concave and more brittle TSL. The new degradation method was evaluated against a Hydrogen Embrittlement (HE) experiment showing improved agreement with the experiment compared to the literature. The effect of different susceptibility zones at the crack tip was also investigated, showing that a uniform degradation throughout the susceptible zone is more influenced by the χ parameter than a triangular susceptible zone.

1. Introduction

In many engineering fields it is increasingly important to understand the susceptibility to fracture in materials with ageing processes. In nuclear power plants, Intergranular Stress Corrosion Cracking (IGSCC), Irradiation Assisted Stress Corrosion Cracking (IASCC) and Hydrogen Embrittlement (HE) play important roles in plants service time [1]. In IGSCC an oxide is formed at the crack tip and may extend along the grain boundaries which degrade the mechanical properties. The process is known as film-rupture [2]. Other kind of degradations are when the process solely depends on film rupture [3] or when the film rupture frequency, i.e. crack growth, depends on strain [4,5]. Later similar models with the same concept were typically denoted “slip oxidation mechanism” [6], “film rupture slip dissolution” [7] and “slip dissolution-repassivation” [8]. A common denominator of the existing film-rupture models is a limited definition of the underlying strains. IGSCC in nuclear power plants is not only limited to oxide growth mechanisms, it can also be a result of HE [9]. In a similar ageing process, IASCC, the material is embrittled by irradiation changing the mechanical properties, especially at the grain boundaries [10]. This process is a more uniform degradation process through the grain boundary than IGSCC or HE which are more concentrated to the tip of the crack where the adsorption takes place.

The intergranular degradation process was here only considered at the grain boundaries making it convenient to use cohesive elements at the grain boundaries. The cohesive framework was introduced by Barenblatt [11] and Dugdale [12] and later brought

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Nomenclature

a_0	initial crack length
$\boldsymbol{b}$	body force vector
$b_0,b_1,\ldots$	coefficients of polynomial
B	thickness of specimen
C	normalized hydrogen concentration
D_{eff}	effective diffusion
E	Young's modulus
E_m^i	Fourier coefficients
H	hardening modulus
J	J-value
L	length of specimen
L_1	length of diffusion process zone
s	crack path coordinate
$\boldsymbol{S}$	second Piola-Kirchhoff stress
t,t_1	time
T_n,T_1	normal and tangential traction
$T_{*,n}$	lowest maximum normal traction
T_n^{ini},T_1^{ini}	initial TSL parameter
T_n^{full},T_1^{full}	fully degraded TSL parameter
T_n^{unl},T_1^{unl}	normal and tangential traction at unloading
$\boldsymbol{T}_{cz}$	cohesive traction
$\boldsymbol{T}_{ext}$	external traction
T^{eff}	effective cohesive traction
$T^{eff,ini}$	initial maximum effective cohesive traction
T_{max}^{eff}	maximum effective cohesive traction
$T_{max,n},T_{max,n}$	maximum cohesive traction, normal and tangential
T_χ^{eff}	effective cohesive traction at critical separation
$T_{\chi,n},T_{\chi,1}$	cohesive traction at critical separation, normal and tangential
$u,\ddot{u}$	displacement, acceleration
W	width of specimen
x,y	Cartesian coordinates
$\alpha^{ini},\alpha^{full},\alpha_\chi$	normal softening parameter
β^{ini},β^{full}	tangential softening parameter
$\delta_n^{ini},\delta_n^{full}$	normal separations
$\delta_1^{ini},\delta_1^{full}$	tangential separations
$\delta_{nc}^{ini},\delta_{nc}^{full}$	normal critical separations
$\delta_{1c}^{ini},\delta_{1c}^{full}$	tangential critical separation
δ^{eff}	effective separation
δ_c^{eff}	critical effective separation
$\delta\boldsymbol{u}$	variation of displacement
$\delta\boldsymbol{E}$	virtual Green-Lagrange strain
$\delta\Delta$	virtual separation
Δ_{eff}	current effective separation
$\Delta_{\max}$	largest effective separation
Δa	crack extension
ΔT_n	traction change
$\Delta u_n,\Delta u_1$	current normal and tangential mid-plane separation
$\Delta u_n^*,\Delta u_1^*$	current scaled normal and tangential mid-plane separation
η_{deg}	degradation parameter
η_T	damage parameter
η_T^{old}	damage parameter from previous step
$\lambda_n^{ini},\lambda_n^{full},\lambda_{\chi,n}$	normal initial slope indicators
$\lambda_1^{ini},\lambda_1^{full},\lambda_{\chi,n}$	tangential initial slope indicators
μ	cohesive strength reduction factor
ν	Poisson's ratio
$\Pi_a,\Pi_{int},\Pi_{ext}..$	virtual work
ρ,ρ_c	density, density in current configuration
σ	Cauchy stress
σ_Y	yield stress
χ	degradation parameter
ϕ,ϕ_n,ϕ_1	fracture energy, normal and tangential
$\phi^{deg},\phi_n^{deg},\phi_1^{deg}$	degraded fracture energy, normal and tangential
$\phi^{full},\phi_n^{full},\phi_1^{full}$	fracture energy at full degradation, normal and tangential
$\phi^{ini},\phi_n^{ini},\phi_1^{ini}$	initial fracture energy, normal and tangential

into a computational concept by Hillerborg [13]. The cohesive description is a method to mimic the complex physical behaviour of crack growth. The cohesive element is an interface description in which the element is described with two linear faces, and the cohesive properties are governed by the separation between these two linear faces. The separation is then translated into traction by differentiation of the potential of the cohesive law, this traction separation curve is called the Traction Separation Law (TSL). The area inside the TSL at every cohesive element is the Griffith's energy [14] and also the elastic part of the J-integral [15]. The formulation enables a zero thickness 2D-element, it introduces a length scale in the model and it removes the singularity present in Linear Elastic Fracture Mechanics (LEFM). There are however some inherent challenges with the cohesive elements, which must be kept in mind when using them: the lack of balance of angular momentum is one, thermodynamic consistency is another and material frame indifference is a third [16].

There are many different shapes of the traction-separation curves, the most popular are the polynomial [17], the trapezoidal [18], the linearly decreasing which is also called triangular [19], the exponential [20,21], bilinear [22–24] and the discrete cohesive model [25]. A comparison between different TSL shapes was performed by Alfano [26].

A degradation process due to environmental exposure can be implemented by altering the fracture energy and the ultimate strength in the TSL. The fracture energy in a cohesive element can be obtained from the area enclosed by the TSL. The ultimate strength is the maximum traction the cohesive interface can provide. The degradation processes is usually implemented by lowering the maximum cohesive strength while keeping the final separation fixed in a triangular shaped TSL [27,28] or other TSL shapes [29,30]. Neither of these methods can be varied to describe a material that changes the ductility throughout the degradation process. In cyclic cohesive zone models (CCZM) complex degradation phenomena has been developed, thought for fatigue crack growth. A review on this subject is found in Kuna and Roth [31].

The present work focused on creating a versatile tool for the mechanical modelling of the degradation processes of IGSCC and HE. To be able to model more complex environmental effects, a more general TSL than the ones described in the literature was desired, for instance to control the plastic zone at fixed cohesive strength and fracture energy or changing the ductility throughout the