Three-dimensional finite elementmodeling of ductile crack initiationand propagation

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"This crack is extended when the damage field at its front becomes critical, whereby theorientation is governed by the direction of maximum nonlocal damage driving variable."

**Crack propagation**

"In 2D, the crack-front is a point, whereas in 3D it is a curve. For each node lying onthis curve, a growth direction is determined in a plane perpendicular to the front. By usingthe nonlocal damage driving variable field in this plane, a direction vector is computedfor all nodes lying on the crack-front. Using all these vectors, the extended crack surfaceis constructed."

Crack propagation direction and distance

"Contrary to the 2D case, where a crack is ending in a point called crack tip, here it isdelimited by a curve, the crack-front. The crack-front is either a closed loop or it has twoends called the crack-front corners"



"Using a tetrahedral discretisation of the 3D geometry, crack-front points coincide withfinite element nodes."

"The crackis predicted to grow over a distance which depends on the damage field ahead of the con-sidered crack node and its direction is evaluated differently at the crack-front comparedto the crack-front corners. "

Propagation of a crack-front node

"For each crack-front node, a corresponding growth direction and distance must be deter-mined"

"For each node, a reference plane is defined in which the direction and distance of the crack growth will be computed. The tangent to the crack-front at the desired point o, is used as the normal to this reference plane."



"As shown in Fig.4a, for the crack-front pointo, the vectors v1and v2are the vectorsconnecting the considered crack-front vertex to its neighboring vertices in the discretisedgeometry. The tangent vector is then computed as "

"Having obtained the (normal to the) reference planefor each node reduces the problem to a 2D crack propagation (direction and distance)problem, similar to the one dealt with by Mediavilla et al."

"Motivated by the 2Dprocedure of Mediavilla et al., the nonlocal damage driving variable z is sampled in N points in a semi-circle located in the reference plane. A comparison has shown that using the nonlocal damage driving variable instead of the damage variable as used by Mediavilla et al. avoids abrupt changes in the crack growth direction due to small local (numerical) variations between adjacent nodes."

"Vectors d1 and d2 in Fig.4c are obtained from the intersection of the reference plane with the tetrahedral crack face edges of thediscretised geometry. These two vectors are used to compute the vector d that sets the central direction of the considered semi circle via

"

"The position of a sampling point with respect to the crack-front vertex is given by the vector

where four radii



are used. /Delta a is the maximum crack growth distance which is typically chosen to be a few times the smallest element edge."



"In order to ensure that the crack direction does not fluctuate due to local variations, the obtained crack growth direction vectors are averaged, yielding the following crack propagation direction R for that node.



Propagation of a crack-front corner

"Crack-front corners are the crack-front nodes located on the outer surface of the body."

"The crack direction iscomputed in a similar fashion as for crack-front vertices, albeit on the discretised outersurface rather than the plane Π. Instead of a semi-circular set of sampling points in the plane Π, we therefore consider a set of planes intersecting the outer surface of the body to establish the potential growth directions. Each of these planes contains the crack-front corner node and has a normal nj"



"To determine nj, we first define thecorner vector dc according to Eq. (19), where d1 and d2 are now the vectors along the element edge at the intersection of the outer surface and the two faces of the crack (Fig.5a). We also define a corner vector mc perpendicular to vectors d1 and d2 :

"

Directional smoothing

"Having obtained the averaged growth direction for all crack-front nodes and cornersindependently, these directions are again smoothed"

"The direction vector of anodekon the crack-front is combined with that of the adjacent nodes using the followingsmoothing operation:



This filtering is only applied to the crack-front nodes and not the corners"

Growth distance

"Smoothing the direction of the crack growth paves the path for obtaining a growth dis-tance.At each node k at which the critical damage value ω^c\_p is exceeded, the crack isassumed to grow in the computed direction over a distance L\_k until the damage drops below ω\_p=0.97ω^c\_p. To obtain a smoother crack surface for more stable (re)meshing and computation, we furthermore set a minimum and maximum growth distance as follows: Lmin=0.1Δa ; Lmax=Δa"

"This implies that for a point p^0\_k on the old crack-front, the corresponding position on the new crack-front p^n\_k is obtained as follows:

"

"Before constructing the crack surface and although the crack direction has already been smoothened, the new crack-front is further smoothed by filtering all of itscrack-front positions as follows

"

Construction of the new crack surface

"onstruct a new segment of the crack surface, along whichthe crack will be opened"

**Crack initiation**

"we now turn ourattention to the initiation of cracks based on the computed damage field"

Internal crack initiation

"The initiation points for cracks are the locations where the damage exceeds a predefined critical magnitude. To identify these points, all elements with damage values higher than the critical value are extracted"



"Figure10a shows a cloud of elements with damage values higher than a critical level at the center of a body. The center point of the cloud is calculated using

 where x\_i are the centers of elements within the cloud

 is a damage-dependent weight factor and V\_i is the volume of each element in the cloud; ω^i\_p is its damage value (constant damage elements are used). The weight factor M\_i ensures that larger elements with higher damage values contribute more to the calculation of the center point than small elements or elements with low levels of damage."

"Starting from the center point p, a vector r1 is computed, which is the longest vector connecting point p to any other node in the cloud. A plane (π in Fig.10b) is defined in point p and normal to r1"