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SIMULATION OF FRACTURE IN HETEROGENEOUS MATERIALS WITH THE COHESIVE SEGMENTS METHOD

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Summary. *In the cohesive segments method, the nucleation, growth and coalescence of cracks is modelled by incorporating multiple cohesive zones in continuum elements by using the partition-of-unity property of finite element shape functions. In this contribution, the possibility of simulating crack branching is demonstrated by a small example.*

1 INTRODUCTION

In the cohesive approach to fracture, the region in which the separation and the dissipative process take place is concentrated in a single plane with zero thickness: the cohesive zone. The opening of this cohesive zone is governed by an additional constitutive relation which characterises the fracture process of the material. The cohesive and bulk constitutive relations, together with the appropriate balance laws and boundary conditions completely specify the problem. Fracture, if it takes place, emerges as a natural outcome of the deformation process.

Cohesive zones can be incorporated directly in continuum elements as a jump in the displacement field by exploiting the partition-of-unity property of the finite element shape functions [1]. The magnitude of the displacement jump is governed by additional degrees of freedom that are added to the nodes that support the element that contains the cohesive zone. In this technique, a cohesive zone can be extended during a simulation in any direction, irrespective of the structure of the finite element mesh.

A drawback of the current implementation of the partition of unity approach to cohesive fracture is that the crack is regarded as a single entity. Crack propagation is simulated by extending an existing discontinuity. In the cohesive segments method [2, 3], which is based on the partition of unity approach, crack nucleation can be simulated by inserting multiple cohesive zones of finite length, in any position in the mesh. Since each cohesive segment is supported by a unique set of degrees of freedom, the coalescence of multiple cracks and crack branching can be accounted for as well. As a result, the method can be used to simulate diffuse fracture phenomena which arise for example in heterogeneous materials.

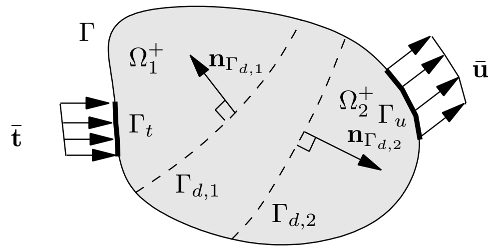


Figure 1: Domain Ω with two discontinuities, $\Gamma_{d,1}$ and $\Gamma_{d,2}$ (dashed lines). It is assumed that the discontinuities do not cross.

2 KINEMATIC RELATIONS

The key feature of the cohesive segments approach is the possible emergence of *multiple* cohesive zones in a domain. Consider the domain Ω with boundary Γ as shown in Figure 1. The domain contains m discontinuities $\Gamma_{d,j}$, where $j = 1...m$. It is assumed that the discontinuities do not cross. Each discontinuity splits the domain into two parts, which are denoted accordingly as Ω_j^- and Ω_j^+. The displacement field in the domain Ω consists of a continuous regular displacement field $\hat{\mathbf{u}}$ plus m additional continuous displacement fields $\tilde{\mathbf{u}}_j$:

$$\mathbf{u}(\mathbf{x}, t) = \hat{\mathbf{u}}(\mathbf{x}, t) + \sum_{j=1}^{m} \mathcal{H}_{\Gamma_{\mathrm{d},j}}(\mathbf{x})\tilde{\mathbf{u}}_j(\mathbf{x}, t)\,, \tag{1}$$

where $\mathbf{x}$ denotes the position of a material point, t is time and $\mathcal{H}_{\Gamma_{\mathrm{d},j}}$ is a Heaviside step function associated to the discontinuity $\Gamma_{d,j}$, which is equal to 1 when the material point resides in Ω_j^+ and 0 otherwise.

The strain field in the bulk can be found by taking the spatial derivative of the displacement field (1). The magnitude of the displacement jump at the discontinuity $\Gamma_{d,j}$, which represents the opening of the cohesive zone, is equal to the additional displacement field $\tilde{\mathbf{u}}_j$. The stress field in the bulk material and the tractions at the cohesive zone can be obtained using regular constitutive relations in combination with the strain field and displacement jump, respectively. The discontinuous displacement and strain fields can be discretised in the space domain by using the partition-of-unity property of the finite element shape functions [4].

3 IMPLEMENTATION

In the current implementation of the cohesive segments method, a distinction is made between different stages of crack growth, such as the nucleation of a new crack, the extension of an existing crack and the coalescence of cracks. It will be demonstrated that according to this scheme, crack branching is accounted for automatically.

In all situations, the same criterion is used to determine when and in which direction a cohesive segment must be created or extended. In this criterion, an equivalent stress is determined for arbitrary orientations in the domain [5]. The orientation for which

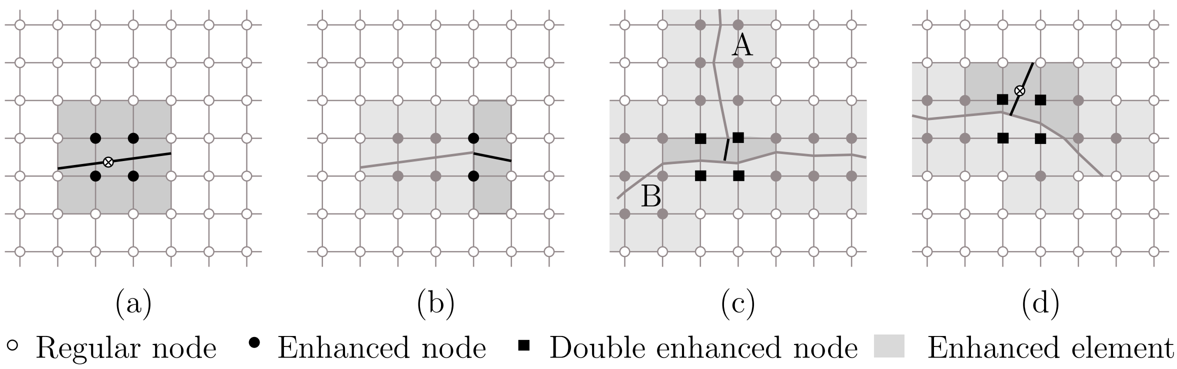


Figure 2: (a) Nucleation of a single cohesive segment. The segment (bold line) passes through the integration point (⊗) where the fracture criterion is violated. (b) Extension of a cohesive segment. (c) Coalescence of two cohesive segments. Segment A is extended until it touches segment B. (d) Crack branching. A new segment is added trough an integration point where the fracture criterion is violated.

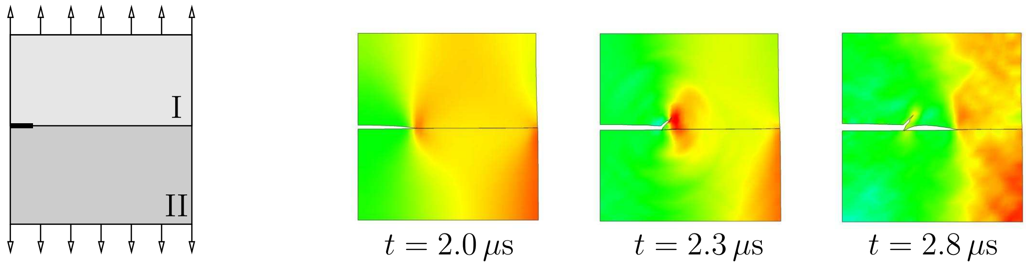
the equivalent stress reaches a maximum is obtained by solving a minimisation problem. When this maximum equivalent stress exceeds the ultimate value, the cohesive segment is created or extended in the direction of the corresponding direction. An important advantage of this criterion over a principal stress criterion is that the contribution of the shear stress can be scaled and that compressive normal stresses can be excluded.

When the stress state in an integration point in the bulk material violates the fracture criterion, a new segment is created. The segment is taken to extend throughout the element to which the integration point belongs and into the neighbouring elements, see Figure 2(a). The magnitude of the displacement jump is determined by a set of additional degrees of freedom which are added to all nodes whose support is crossed by the cohesive segment. The nodes of the element boundary that is touched by one of the two tips of the cohesive segment are not enhanced in order to ensure a zero opening at these tips [1]. Subsequently, the evolution of the separation of the cohesive segment is governed by a decohesion constitutive relation in the discontinuity. When the criterion for the initiation is met at one of the two tips, the cohesive segment is extended into a new element, as demonstrated in Figure 2(b).

The possibility of coalescing cracks is demonstrated in Figure 2(c). Segment A is only extended until it touches segment B, which can be regarded as a free edge. This implies that there is no crack tip, so that all four nodes of the element in which the two segments meet are enhanced twice. Crack branching will follow automatically from previous scenario's. When the criterion for crack nucleation is met in the vicinity of an existing crack, a new cohesive segment is created, taking into account the special regulations for coalescing segments, see Figure 2(d).

4 NUMERICAL EXAMPLE

The cohesive segments method has been implemented in both a quasi-static and an explicit dynamic model [3]. The latter model is used to analyse the problem shown in



(a) (b) (c) (d)

Figure 3: (a) Geometry and loading conditions of specimen. (b)-(d) Deformed specimen.

Figure 3. A specimen composed of two different isotropic elastic materials is subjected to a pulse load in vertical direction, Fig. 3(a). The stiffness of material II is four times as big as the stiffness of I. The ultimate traction of the relatively weak interface is 0.75 times the ultimate traction of material I. The interface, which is modelled by a cohesive segment that is placed in the mesh a priori, has partially debonded over a small distance.

Upon loading, the interface crack starts to grow. At a given moment, the stresses in material I have built up such that a new crack is nucleated, see Figure 3(c). This branch arrests soon after and the interface continues to debond away from the point where the branch was formed.

5 CONCLUSIONS

The cohesive segments method allows to simulate complex fracture phenomena, including coalescence and branching of cracks in a mesh-independent way. The method has been demonstrated by an example in which the branching of an interface crack is simulated.

REFERENCES

[1] G.N. Wells and L.J. Sluys, A new method for modeling cohesive cracks using finite elements, *International Journal for Numerical Methods in Engineering*, **50**, 2667–2682, 2001.

[2] J.J.C. Remmers, R. de Borst and A. Needleman, A cohesive segments method for the simulation of crack growth, *Computational Mechanics*, **31**, 69–77, 2003.

[3] R. de Borst, J.J.C. Remmers and A. Needleman, Mesh-independent discrete numerical representations of cohesive-zone models, to appear in: *Engineering Fracture Mechanics*.

[4] I. Babuska and J.M. Melenk, The partition of unity method, *International Journal for Numerical Methods in Engineering*, **40**, 727–758, 1997.

[5] G.T. Camacho and M. Ortiz, Computational modeling of impact damage in brittle materials, *International Journal of Solids and Structures*, **33**, 2899–2938, 1996.