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Nonlocal damage with evolving internal length: the Eikonal nonlocal formulation

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Integral non-local (INL) formulations [1] are often used to regularize continuum damage models in the presence of strain softening laws. In numerical computations the introduction of an internal length allows for avoiding pathological mesh sensitivities. Some questions concerning the identification of the internal length, its possible evolution during damage process and the need for special treatments of non-locality operators near boundaries (e.g. edges, cracks) are however still open. A physical request is that material points separated by a crack or a highly damaged zone should not interact (despite what is done in standard non-local integral theories). This can be obtained by allowing non-local interactions to evolve depending on mechanical fields (e.g. damage [2], stress [3], etc.).

Different formulations were proposed in the literature for this purpose. In particular, based on the analogy between wave and information propagation within an elastic damaged medium, [4] proposed to reformulate the classic non-local averaging procedure in terms of the ratio of the time needed for an elastic wave to propagate between two material points and the corresponding time in undamaged conditions. Using such an approach in two- and three-dimensional contexts may however reveal complex. In that case, no general analytical solutions for the wave propagation equation through the heterogeneous medium are available, and tedious and time-consuming numerical solution procedures are needed.

Based on the Wentzel-Kramers-Brillouin (WKB) approximation for high-frequency wave propagation in a damaged medium, the Eikonal non-local (ENL) formulation provides a novel interpretation of damage dependent non-local interactions both in isotropic and anisotropic contexts. From a mathematical point of view, interaction distances are computed as solution of a time-independent Eikonal equation (a stationary case of the Hamilton-Jacobi equation) with a damage dependent isotropic/anisotropic Riemannian metric. From a differential geometry viewpoint, this leads to consider that damage induces a curvature of the Riemannian space in which interaction distances are computed. Geodesic interaction distances determined in the curved space are used to compute non-local variables driving damage evolution, thus preserving the general theoretical framework of INL theories. This allows modeling non-local interactions that gradually vanish in damaged zones, leading to a progressive transition from diffuse damage to fracture. From a numerical viewpoint, Fast Marching approaches [5] are used to compute non-local interaction distances between material points. These distances define the kernel of weighting function considered in integral non-local regularization method.

In this work, the theoretical derivation of ENL formulation from wave propagation is discussed and illustrated first. Only the main equations of the theoretical background (fully developed in [4]) are presented. As an illustration, the case of an isotropic damage model is considered for the elastodynamics equations and the WKB approximation, leading to the time-independent Eikonal equation from which interaction distances are computed.

The numerical properties of the ENL regularization technique are investigated then. A numerical formulation [6] for modeling damage dependent non-local interactions within mechanical computations is obtained by coupling Fast-Marching [5] algorithms – for computing interaction distances – and a standard Finite Element (FE) procedure – for solving the quasi-static equilibrium equations. While the method is illustrated with a simple isotropic damage model, the formulation proposed is however general, and can be adapted to more complex models. The extension to anisotropic contexts is also possible without major modifications. In this latter case, the only difference will concern the use of a Fast-Marching algorithm that now should be capable of dealing with anisotropic Riemannian metric fields.

Finally, several numerical results of quasi-static simulations involving the failure of quasi-brittle materials in isotropic/anisotropic media are presented.

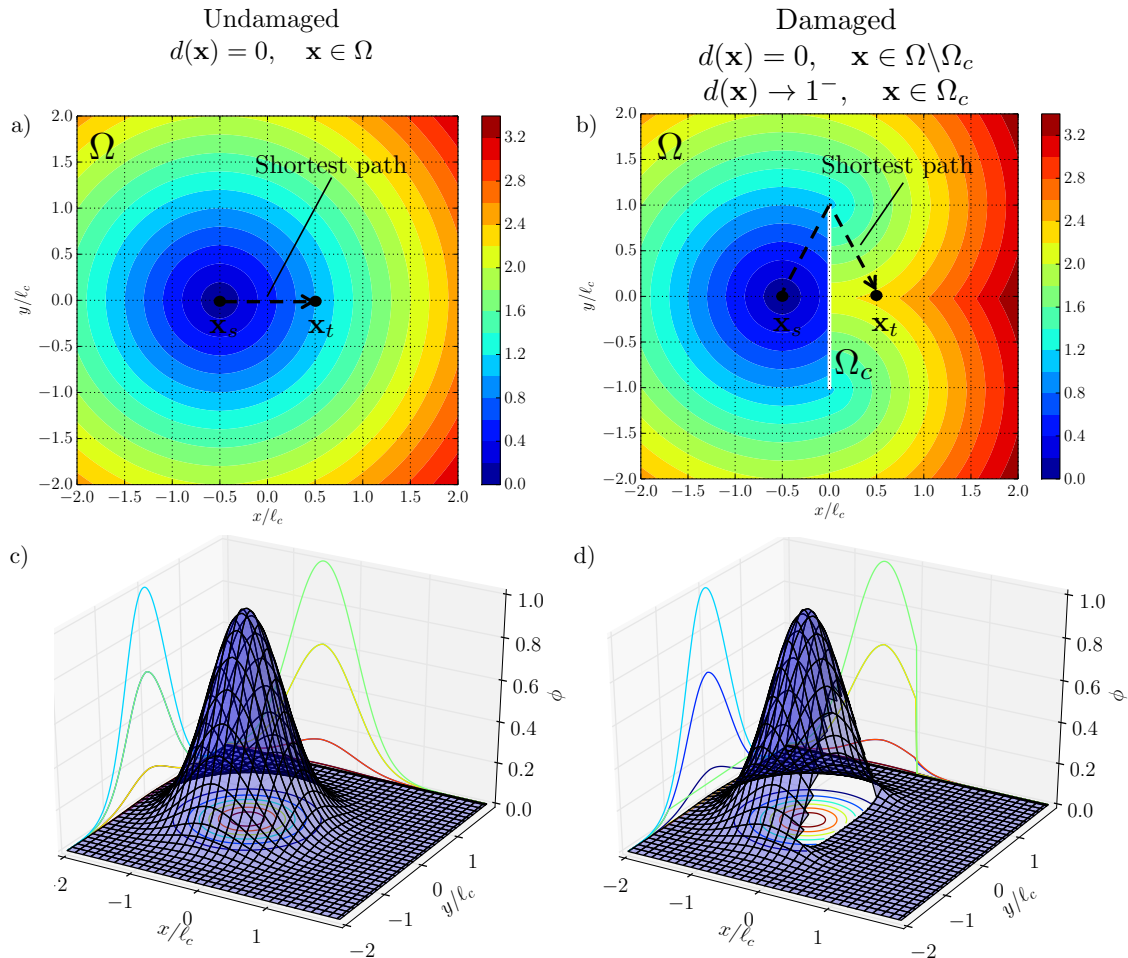


Fig. 1: Geodesic distances field for a square plate and its influence on the Gaussian nonlocal weighting function centered on the point: a) undamaged; b) cracked medium

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