Comparison of Irreversibility Strategies in Phase-Field Fracture Simulations

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The phase-field fracture model is extensively used for the simulation of crack propagation in various materials. Within the phase-field model the discrete crack is approximated by a smeared function, the phase-field function. For proper simulation results especially in cyclic loading the treatment of the irreversibility condition $\dot{z} < 0$ is crucial. This physical condition, in which the material is not allowed to heal, can be handled by various methods. The most common choice here is the history-field approach by Miehe et al. [1]. Here, the tensile strain energy Ψ^+ in the crack driving force Y is substituted by the history function $\mathcal{H}^n$ - the maximum tensile strain energy of all previous time steps. However, this strategy requires small time step sizes to capture the crack initiation point, and thus simulations might become computationally expensive. Since phase-field fracture simulations are already computationally expensive, especially for complex structures, adequate improvements should be employed. Besides different strategies of adaptive spatial refinement [5] or adaptive temporal refinement, the choice of maintaining irreversibility can also be considered.

In this presentation, we would like to adresse the comparison of different irreversibility strategies according to the correctness of the simulations and their performance. Common irreversibility strategies are the History previous approach, the History current approach, the Damage formulation [2], the Dirichlet-type approach [3], and the penalization approach [4]. For the History current approach the history value $\mathcal{H}^{n+1}$ is computed as the maximum tensile strain energy up to the current time step. Furthermore, in the staggered solution scheme, the displacement equations are solved before the phase-field equations. In the Damage formulation, the irreversibility condition is checked for each degree of freedom after the phase-field equations have been solved. If the irreversibility condition is violated, the nodal phase-field value is changed to its value of the previous time step and constrained in the next time step. For the Dirichlet-type approach, the phase-field variable is fixed to the broken state $z = 0$ if the phase-field variable falls below a given threshold and is constrained from there on. Since the phase-field solution is actively changed within the last two approaches the solution is not in an equilibrium state anymore. Thus a combined convergence check is necessary followed by an equilibration step in case of non-convergence. A suitable limit of the number of outer loops for the combined convergence check is necessary. In the penalization approach, the phase-field equations are extended by adding a penalty term to the energy functional, resulting in an equality to be solved. This term vanishes if the irreversibility condition is not violated.

For the comparison, a cyclic shear test is conducted where each strategy is tested for proper physical simulation results and performance.

References

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