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Scale interaction and ordering effects at fracture

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Abstract

Many technical and natural systems are characterized by presence of inherent or loading induced series of length scales. The fracture processes in such systems have many features and are adjusted by scale interaction. In particular, ordered systems of faults or cracks can be formed. Different scenarios of fracture process ordering are analyzed (in particular, the possibilities of ordered multiscale crack systems formation accompanied by increasing or decreasing the scales of the sequentially formed cracks sub-systems are illustrated). The problem of providing safety and reliability of the hierarchical technical systems is discussed accounting for the possibilities of energy redistribution between the scales of the system at fracture and probabilistic aspects of fracture processes in such systems. Examples of prevention of catastrophic failure in a hierarchical system are also given. The paper is based on the studies performed by the author and his team as well as on the available publications of other specialists.

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1. Introduction

Progress in fracture prediction and prevention, evaluation of the residual lifetime of structures and design of new materials with high fracture resistance is in many respects related to understanding the mechanics of scale interaction at deformation and fracture. By the scales we mean here the scales inherent to the materials and media, structures and natural objects as well as the scales induced by the processes occurring in the technical or natural systems.

Experimental studies, analytical and numerical modeling of fracture transition from one scale to another accompanied by stress–strain and energy redistribution and localization in complex technical

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systems belong to actual directions of activity in solid mechanics and fracture mechanics. That is why various aspects of the problem of scale interaction at deformation and fracture are permanently considered on representative International Conferences and Symposia (see, e.g. [1, 2] where further references are given).

The given review paper is aimed at attraction of attention to several primary problems of linking scales at fracture which continue to be or become actual because of their importance for fracture mechanics and its applications.

In connection with fracture by means of crack growth at least two situations different from the point of view of scale interaction need to be considered: (1) Single crack formation and growth; (2) Multiple cracking at fracture. Modeling and analysis of the first situation leads to the development of the concept of scale separation at crack growth. An interaction between the scales (length and force) of the process zone and crack in the whole determines the criterion (or criteria) of the crack limit state and growth. In Sect. 2 this concept and its further development for modeling other fracture processes characterized by formation and extension of a cracklike violation of continuity elongated and large as compared to an active zone, where fracture preparing and realization occur, is considered.

Among the processes of multiple fracture one can separate very important class of processes characterized by sequential formation of ordered systems of cracks and/or cracklike defects. These systems usually are referred to "structures of fracture". Formation of such structures often leads to catastrophic fracture of technical and natural systems. Models and mechanisms of structures of fracture formation are analyzed in Sect. 3 with attention to the key role of scale interaction in the appropriate processes.

Echelons of cracks represent the typical example of structures of fracture.

Formation of a structure of fracture is based on the mechanisms and conditions of nucleation, growth and arrest of an element of the structure; redistribution of the stresses near this element; initiation, growth and arrest of the adjacent element of the structure; repeating this cycle up to finishing the formation process for the structure of fracture of the given level (scale). In turn this structure of fracture can serve as an element of the structure of fracture of the next larger scale.

Similar ideas lead to a discrete – continual approach for modeling catastrophic fracture in hierarchical complex technical systems. This approach is discussed in Sect. 4 where a probabilistic model of a fracture process in a hierarchical system (of a binary-tree type) is also described. It is demonstrated that within the framework of this model one can formulate and solve the problems on optimal protection of the hierarchical system by sharing the protection resources of the given volume through the specific levels of the system structure.

2. Concept of scale separation in crack modeling

Presence in the system several characteristic length scales often allows to simplify an analysis of its deformation and fracture (note, that presence in the material at least one structural scale generally leads to occurring a hierarchy of characteristic scales at its deformation and fracture. As a typical example one can mention nanostructural objects. For instance, transverse sizes of such nanostructural formations as nanotubes have a nanoscale while their length has micron or millimeter scales. Larger structural scales occur at joining nanotubes in bundles, fibers, etc. Similarly in modern materials hierarchies of structures of different scale levels are created. Adjusting these levels one can provide the required combinations of deformation and strength characteristics as well as fracture resistance and wear resistance). A simplification is attained in those cases if it is possible to introduce adequate small parameters such that one can separate the problems which model the processes related to adjacent scales. After solving these problems and accounting for that their solutions represent the solution of the complete problem within the