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3D crack propagation by the numerical manifold method

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ABSTRACT

A method for three-dimensional crack propagation by the numerical manifold method (NMM) is analyzed. With the help of mathematical cover and physical cover, no Heaviside function is required to describe a crack in the NMM, and so the three-dimensional crack propagation with NMM can be analyzed being similar to that of two-dimensional cases. Mohr-Coulomb criterion with a tensile cut-off is used to analyze failure state of each crack tip line. A simplified method for determining the final propagating direction is described. According to the final propagating direction, a non-local crack tracking method is used to determine the updated crack tip line. Quadrilateral or triangle tracking method is selected according to the situation during propagation. For boundary faces, in order to make the deformed surface remain plane, new generated faces are needed to be triangulated. Three numerical examples are analyzed to validate the proposed 3D crack propagation method. The numerical results are all in good agreement with those results in the existing studies. Furthermore, a concrete gravity dam under water pressure with an overload factor is simulated and the progressive failure process of the concrete gravity dam is obtained, which demonstrates the applicability of the proposed method in practical engineering.

1. Introduction

The study on 3D crack propagation is very meaningful since the prediction of the 3D crack propagation is still very challenging nowadays, such as the determination of crack path and the generation of updated element information. Many researchers have been devoted to the study on 3D crack propagation, and then various numerical techniques have been put forward to overcome the difficulties when predicting 3D crack propagation and great successes have been achieved.

The earlier studies mainly focused on the preset path of propagating crack, however, an actual problem is often complex, and for a cracking simulation of brittle and quasi brittle materials such as rock and concrete cracking, the crack may be extended along the path of arbitrary complexity, namely the so-called moving discontinuities problems in computing mechanics. A crack path was often difficult to know in advance and thus a large number of interface elements were set in the continuous boundary [1] or application of remeshing technique [2] to solve this problem. A large number of interface elements may provide a possible crack path, but the crack propagation path is more sensitive to the shape and size of mesh boundary, and a lot of time will be spent in the calculation of contact. For the remeshing method, much more computational time will be consumed for mapping and transferring between new and old meshes.

Recently, new numerical methods, such as the extended finite element method (XFEM) [3], the meshfree method [4] and the numerical manifold method (NMM) [5], combined with their advantages achieved great success. With the concept of Level Set and by solving the Hamilton - Jacobi equation set around a crack, the propagation of 3 D non planar cracks was studied earlier by Moes et al. [6,7], and then good results were achieved, but it was mainly suitable for the static problem of linear elastic analysis. With this basis, the continuum damage model of viscosity regularization [8] and nonlinear element model [9] were introduced, and then the implicit non-plane crack propagation with Level Set method [10] was discussed. A geometric refinement and a new integration strategy [11] were proposed to improve the calculation accuracy and the stability of results. Subsequently, a cohesive model [12] was applied to the non-plane crack growth, as the initiation and propagation of crack could be regarded as the damage accumulation in the fracture zone. Three-dimensional plane fatigue crack growth [13,14] and non-planar crack growth [15] were simulated with fast forward algorithm. From the perspectives of energy dissipation, an algorithm of crack propagation based on

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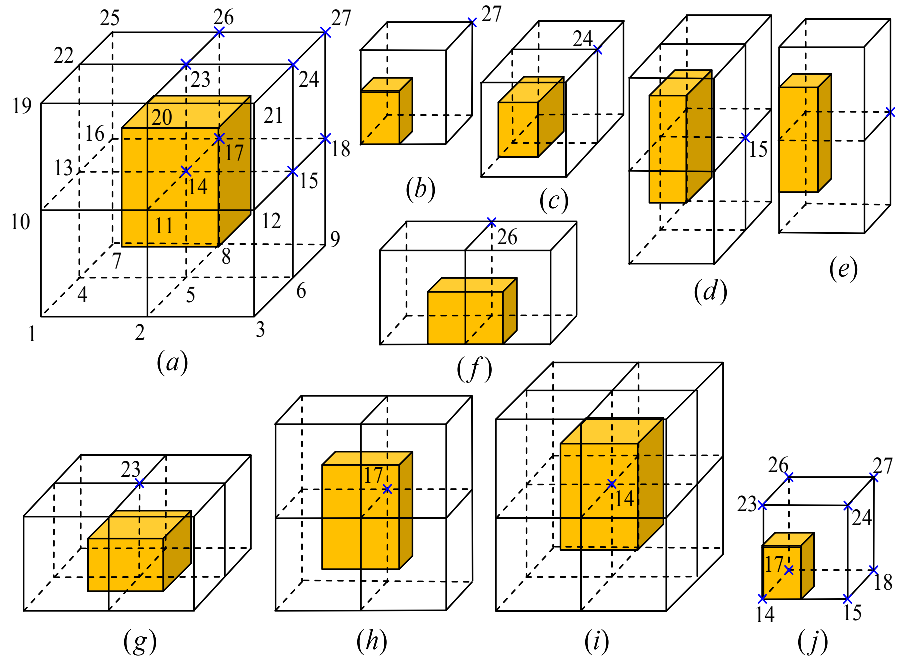

Fig. 1. Covers and manifold element in 3D NMM ((a) physical domain and mathematical covers; (b) P_{27}; (c) P_{24}; (d) P_{15}; (e) P_{18}; (f) P_{26}; (g) P_{23}; (h) P_{17}; (i) P_{14}; (j) manifold element produced by P_{14}, P_{15}, P_{17}, P_{18}, P_{23}, P_{24}, P_{26} and P_{27}).

driving force [16,17] was proposed and then an hp adaptive method for non-planar 3D crack [18] was proposed. Similar research on adaptive method can be found in [19–21]. In addition, the parallel computation of 3D crack propagation [22] was also studied, and then the numerical integral and calculation of crack stress intensity factor [23] were discussed without considering the extension of crack. With the meshfree method and the level set method, the basic formula of three-dimensional crack propagation was obtained by Zhuang et al. [4], and then the relevant non-planar crack growth was simulated. Similar research has been done by Peng et al. [24,25]. The fatigue propagation of multiple cracks in the structure, combined with remeshing technology, was put forward to deal with plane crack and non-planar crack problems [26]. The three-dimensional multi-crack propagation problems [27], mainly for tensile and shear fracture, was studied by using the XFEM, and then it was applied to excavation of an underground engineering with a good feasibility. With the level set method and the singularity at the crack tip line, non-planar crack propagation [28] was introduced to simulate the gradual extension of planar and non-planar crack. In the meanwhile, crack propagation simulations with the NMM and Discontinuous Deformation Analysis (DDA) [29–33] have been described and the comparisons between the NMM and XFEM in crack propagation simulations have also been carried out. Similar to the XFEM, the NMM is able to simulate both continuum and discontinuum in a unified manner. It has the advantage to simulate heavily fractured solids using a regular or irregular cover system and it has been widely applied to simulate blocky rock mass deformation and stability under different static and dynamics loads. Different from the FEM and its extended versions which approximate the displacement field in a finite element using the node displacements, the NMM calculates the displacement fields in a manifold element using quantities at associated physical covers. Detail introduction of the NMM can be found in [30,34]. However, the research work of 3D NMM has just started and mainly focused on the study of basic theory, such as the proposed 3D NMM with 3D-CAD [35], the derived basic formula of 3D NMM with tetrahedral mesh and hexahedral mesh [36,37], the contact problems of 3D NMM [38–40] and the linear

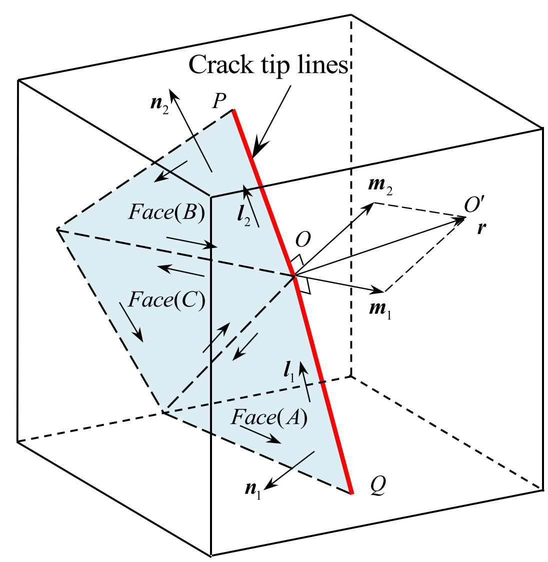

Fig. 2. Determination of propagating direction for a point on crack tip line.

dependence problem of high-order NMM when modifying the finite element partition of unity (PU) into the flat-top PU [41]. Little research has been done on how 3D crack propagates with the three-dimensional numerical manifold method [5].

In the present paper, a non-local tracking method with the NMM is proposed to simulate 3D crack propagation. Only physical covers, manifold elements and crack loop shells are required to be updated. Mohr-Coulomb criterion with a tensile cut-off is used to analyze failure state of each crack tip line. A simplified method for determining the final propagating direction is described in the present paper. According to the final propagating direction, a non-local crack tracking method is used to determine the updated crack tip line. Quadrilateral or triangle tracking method is selected according to the situation during propagation. For boundary faces,