論文 / 著書情報
Article / Book Information

題目(和文)	拡張節点勾配型有限要素法とその破壊力学問題への応用
Title(English)	Extended nodal gradient finite elements and their application to fracture mechanics problems
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種別(和文)	論文要旨
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（博士課程）
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論 文 要 旨

THESIS SUMMARY

専攻： Department of	情報環境学 専攻	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of （工学）
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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Defects or cracks greatly affect the performance and strength of engineering structures and materials in many technical areas including civil, infrastructures, aerospace, automotive, and marine. A better understanding of fracture behaviors of engineering structures and materials is essential in the design, development and maintenance of engineering applications. Solutions of fracture problems are usually derived from experiments, analytical, and numerical methods. Experiments however often require a high cost while the analytical methods are valid only for problems with simple configuration and boundary and loading conditions. The numerical methods like the finite element method (FEM) are often chosen for practical purpose. Although the FEM has shown to be an effective method in solving problems with smooth solutions, mesh refinement is necessary along the crack which makes the FEM very time-consuming and ineffective in dealing with the evolution of cracks. Extended finite element method (XFEM) becomes a powerful computational method for modelling discontinuities without remeshing.

This research presents an effective finite element approach based on enrichment and consecutive-interpolation procedure (CIP) for solving fracture issues in 2D elastic. The approximation functions constructed based on the CIP, which differs from the traditional methods, involve both nodal values and averaged nodal gradients as interpolation conditions. The difficulty of meshing issues and the post-processing of stress recovery are hence no longer required. The accuracy and performance of the proposed XCQ4 and its numerical properties are illustrated through numerical examples, considering both single and mixed-mode problems with complicated configurations. Compared with reference solutions available in the literature and the conventional XFEM results, it is found that the accuracy of the XCQ4 is higher and the XCQ4 can manage the relative error below 1% even though the coarse mesh discretization. Studies on the convergence rate of the stress intensity factors (SIFs) in relative errors also reveal a better performance of the XCQ4 over the classical XFEM. The fracture parameters are found to be stable for different areas of integration paths around the crack tip. Further applications of the developed XCQ4 to other complex problems are potential.

Upon the achievement of the performance of XCQ4 in mixed mode fracture problem, the implementation of the XCQ4 for crack propagation is evaluated. In this work, the discontinuous Heaviside function is taken to treat the discontinuity cut by crack, while the asymptotic crack-tip branch functions are embedded into the approximation functions to capture the singular field at the crack tips. As an alternative way of capturing the singular field at the crack tip, another version of enrichment function, called the ramp function, along with the Heaviside function is taken into account. We consider to integrate the ramp functions into both the standard XFEM using 4-node quadrilateral element (XQ4) and the developed XCQ4. The SIFs calculated by using both approaches, the ramp function with XCQ4 and with XQ4, are validated against reference solutions and can be found in the numerical examples. We integrate the interaction integral in terms of J-domain to estimate the fracture parameters, and adopt the maximum hoop stress criterion to determine the direction of crack evolution. Several representative examples in 2D elastic solids are considered to show the accuracy and performance of the present approach. Compared with the reference solution, the proposed XCQ4 method is capable of achieving high precision in SIFs calculation and predicting the crack paths accurately.

To develop the XCQ4 algorithm to analyze the dynamic fracture response in isotropic and anisotropic materials, the prediction of dynamic SIFs (DSIFs) time history for both single and mixed-mode fracture problems is investigated in this work based on the previous achievements. For orthotropic material, versatile crack tip enrichment functions spanning all possible displacement states are adopted and fracture mechanics for two-dimensional orthotropic material is briefly introduced. In addition, the time-dependent discrete equations are solved using Newmark time integration without considering damping matrix. The numerical values of DSIFs are extracted according to interaction integral taking into account inertial effect. The time history of DSIFs derived from XCQ4 for isotropic and anisotropic solids are verified with respect to reference solutions reported in open literature.

The new approach is further extended to the numerical analysis of fluid flow in fractured porous media. The coupled deformation and fluid flow in fractured porous media has been simulated by the present XCQ4 approach. Through introducing the transfer function that mathematically demonstrates the flow interaction between the porous matrix and existing fracture, the pore fluid pressure is simulated in terms of Biot's theory which accounts for the fluid flow inside both matrix and fracture domain, and the numerical results show the robustness of XCQ4 for solving fracture behavior in saturated fractured porous media.

The applicability of developed XCQ4 technique was successfully verified through several numerical validations. It is found that the new numerical method is suitable for solving the fracture problems and the satisfactory numerical results can be achieved, which reflects the value and reliability of XCQ4.