学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Development of Rigid Body Coupled Spring discrete model for simulation of cementitious composites and structural elements
(セメント系複合材料および構造要素のシミュレーションのための剛体-バネ連成離散モデルの開発)

INTRODUCTION

Application of discrete modelling technique in the simulation of quasi-brittle materials such as concrete-like which are subject to cracking and discontinuities can be a powerful alternative to Finite Element Method (FEM) which is conventionally base on the theory of continuum mechanics and has some drawbacks when it comes to simulation of opening or closing occurs in the subject of simulation. Also, there are cases that mesoscopic simulation of non-homogeneous volume of concrete or fibrous concrete in FEM does not render the expected properties.

Rigid Body Spring Model (RBSM) technique has been used in mechanical and environmental deterioration of concrete however RBSM also has some drawbacks such as inability to accurately capture the Poisson's effect or to accurately calculate the principal stresses in the model. Therefore, a new discrete model was proposed that can theoretically incorporate the Poisson's effect of the material and calculate the principal stresses or stresses in the desired direction.

Following that material models are developed to simulate nonlinear behaviour of concrete and steel fibre reinforced concrete. The model is tested in various condition to compare the behaviour with the experimental observations.

In final stage the applicability of the method is tested in structural element level by simulating a shear connection in the precast concrete walls and predicting failure of the shear keys in the connection.

METHODOLOGY

The new element referred to as "Rigid Body Coupled Springs" or RBCS is based on the idea of coupling the behaviour of the springs on each ridge to capture the Hooke's law in the model. This coupling is performed by calculating an orthogonal stress for each ridge based on the balance of forces obtained from the stresses of the ridges of the element.

Based on the orthogonal stress, assuming all forces are acting on the ridges of the element, the deformations due to Poisson's ratio on arbitrary ridge j, can be written as a function of the stresses of the element and therefore can be implemented into the stress-strain relationship matrix of the element.

The material models in the element are based on defining nonlinear constitutive laws for the contact springs between rigid bodies.

For the case of fibrous concrete, a novel model was developed for the simulation of Steel Fibre Reinforced Concrete that simplifies the fibre tensile contribution by an average pull-out behaviour defined by three key-points and the shear contribution by accordingly delaying the peak stress of the shear springs resulting in higher energy absorption.

Stress transfer in case of formation of openings and closure, is provided by an algorithm that will create normal forces if separated elements come into touch.

ANALYSIS AND RESULTS

The model was able to capture the Poisson effect even for incompressible materials with Poisson's ration of 0.5. With the new element it was possible to calculate and demonstrate principal stresses.

Various tests such as uniaxial compression, direct tension, splitting tensile, 3-point bending and push-off test on plain and steel fibre reinforced concrete were simulated and the results were compared with the experiment.

To depict the capability of the model in studying fractures in structural elements, a case of keyed shear connection is simulated. Initially the case of shallow shear key was used for the purpose of calibration such as the specification of the Interfacial Transition Zone (ITZ). After this step the failure mode for deep shear keys was predicted and compared with the experimental results using the discrete model.

CONCLUSION

A new element based on the concept of Rigid Body Spring Model (RBSM) that inherently incorporates Poisson effect is developed and utilized to simulate nonlinear behaviour of concrete.

Nonlinear material models are implemented based on the meso-scale modelling technique and do not have the complexity of macroscopic models based on volumetric and deviatoric stress and strain tensors separation. Beside the capability of representing the Poisson's ratio of the material, with the new material models implemented, the new element can represent the compressive, tensile and shear behaviour of concrete as well as the principal stresses in the model.

With further development of the element the capability of simulating fibrous concrete was added to the developed discrete model.

The uniaxial compressive and tensile test beside splitting tensile test on plain concrete specimen were simulated successfully and similar cracking patterns to the experiments were observed in the simulations.

Investigation on the SFRC models performed as uniaxial compression, direct tension, flexural beams tests and direct shear through push-off were conducted to verify the capability of the model.

The new discrete element was also employed into simulation of a prefabricated concrete wall keyed shear connection to show the capabilities of the model beyond material scale.

It was observed that the model could predict the strength of the connection and its failure modes properly for two shear key sizes.

The new ability to visualize stresses and displacement distribution in the model helped clarifying the behaviour of the model and providing a better insight.