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主 論 文 の 要 旨

論文題目　DEVELOPMENT OF COUPLED RIGID BODY SPRING MODEL AND SHELL FEM AND THE INVESTIGATION OF LOCALIZATION OF CONCRETE UNDER CONFINEMENT
(剛体バネモデル－シェル要素 FEM 結合解析手法の開発と拘束コンクリートの破壊局所化挙動に関する研究)

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論 文 内 容 の 要 旨

Due to the observed collapse of structures in past major earthquakes, concerns over the safety of structures against overdesign action have increased. This highlighted the need to model the post-peak behavior of structures in order to accurately predict their redundancy and restorability performance. Recently, the use of concrete confined by steel tubes and fiber-reinforced polymer (FRP) has been increasing both in new construction and in structural retrofitting. These types of structural systems are selected mainly due to the improved ductility that they provide to concrete. The ductility of concrete, however, depends on concrete's post-peak stress-strain behavior which includes strain softening and localization of deformation. These behaviors are influenced, on the other hand, by the level of confinement provided by the confining material. Thus, to understand the post-peak behavior of steel tube confined and FRP confined concrete members, the strain softening and localized behavior of concrete under these confinements must be well-understood. Experimental studies on the post-peak behavior of these structural systems are, however, limited, in particular, in concrete confined by thin-walled steel tube and partial FRP strips. The confinement provided by these systems to concrete is low which makes the localized behavior of

concrete dominates the behavior of the composite. Research to study the influence of these types of confinement on the localized behavior of concrete are likewise scarce, and this may be partly due to the difficulty in visually evaluating the damage in concrete when completely encase by these confinements. Thus, a numerical analysis to study these behaviors is considered a better alternative. However, existing numerical models are also deficient in their ability to simulate these behaviors. Therefore, this study set out to address this limitation.

This study presents the development of a coupled numerical model which combines the use of Rigid Body Spring Model and shell FEM to model concrete and the confining material, respectively, in a steel tube confined and FRP confined concrete member. The objective of the model development is to provide an analysis tool for concrete confined by steel tube or FRP that is able to well-represent their post-peak behavior. Specifically, the model aims to capture the strain softening and localized behavior of concrete under steel tube and FRP confinement. Using the proposed coupled model, it is aimed that it will address the lack of understanding in the localized behavior of concrete under these confinements.

Chapter 1 of presents the background of the study, the review of the related literature, and the study objectives. The organization of the research is also presented in this chapter.

Chapter 2 introduces the development of the coupled RBSM and shell FEM model. In this chapter, the formulation of RBSM and shell FEM were reviewed and their displacement functions were presented. Evaluation of the performance of the developed shell program showed that the element locks (shear) when applied to thin sections. Two solutions to solve the shear locking were proposed: the selective reduced integration (SRI) scheme, and the use of Mixed Interpolation Tensorial Components (MITC shell). Both solutions were found to be effective although the MITC shell showed lower convergence in comparison to the SRI solution. The element was further verified with benchmark models for geometrically nonlinear shell and the comparison showed good agreement. The performance of RBSM was also reviewed and its performance in simulating the strain softening and localized behavior of plain concrete were further confirmed.

Two methods of coupling RBSM and shell FEM identified as Node-to-Surface (NS) method and Surface-to-Surface (SS) method were introduced. The formulation of the NS method was shown to be simple but it provides a less intuitive definition of the contact area. The SS method, on the other hand, requires the use of an inverse mapping algorithm to calculate the interaction between RBSM and shell FEM. The model was found to have a more intuitive definition of contact area but is more computational expensive relative to the NS model. Comparison of the methods showed that the NS model is sensitive to RBSM-to-shell mesh size ratio, whereas the SS method was found to be objective in terms of the mesh size ratio. Both methods, however, provide comparable solutions when the ratio used is at least equal to 1.25.

Chapter 3 presents the application of the model to steel-tube confined concrete members. The material nonlinearity of steel was modeled using a von Mises yield criterion with isotropic hardening. The applicability of this model was confirmed in the simulation of a uniaxial compression test of a bare steel tube where both stress-strain curve and local buckling behavior observed in the test were well-represented by the shell element. Three types of constitutive models for interface elements used to represent the interface interaction between concrete and steel were investigated. It was found that the Mohr-Coulomb friction model is most appropriate among the models considered. The constitutive model parameters such as the friction coefficient and hardening modulus of the shear constitutive model were found to have a minimal influence on the overall performance of the coupled model.

A total of 39 published test results of concrete-filled steel tube (CFST) were used in the validation of the model. The validation included tests of CFST in uniaxial concentric load, eccentric load, pure bending, and combined axial and bending load. The performance of the developed model, in general, was found to be in good agreement with the test results. The performance of the model in simulating the ductile responses observed in the uniaxial concentric test of thick-walled CFST, pure bending, and combined axial and bending of CFSTs puts the model in equal performance with existing numerical models. However, the ability of the model to simulate the strain softening observed in thin-walled CFST subjected to uniaxial concentric and eccentric load makes the model superior over existing numerical models. It also addresses the limitations of these existing numerical models in simulating this behavior. Moreover, simulation of fracture behavior of concrete in CFST compares well with those observed in the test and the quantitative comparison of the lateral expansion of CFST between test and the simulation also showed good agreement. The validation performed has confirmed the applicability of the RBSM-shell model in simulating the post-peak strain softening behavior of concrete confined by a thin steel tube.

Chapter 4 presents the application of the developed coupled model to FRP confined concrete members. The FRP material was modeled as a linear elasto-brittle material which is essentially elastic up to its ultimate tensile strength and beyond this load, the material was assumed to suddenly fail in a perfectly brittle manner. Two types of interface constitutive models to simulate the concrete-FRP interaction were investigated. It was found that the Mohr-Coulomb model is once again applicable to simulate the interaction between concrete and FRP, and the model properties were also found to have a minimal influence in the overall performance of the coupled model.

A total of 20 published test results of FRP confined concrete columns were used in the validation. The validation included columns subjected to uniaxial compressive load and columns subjected to eccentric loading. Comparison of axial stress-strain behavior between test and simulation results, in general, showed a good agreement. In particular, the coupled model was able to represent the ductile response observed in columns fully confined by FRP. This, once again, places the performance of the coupled model comparable to existing numerical and analytical models in the literature. The advantage of the coupled model, however, is in its ability to simulate the strain softening behavior of concrete partially confined by FRP strips which showed a good agreement with test results. Simulated deformation of concrete in partial FRP confined concrete columns were also found to compare well with those observed in the test. This further makes the model superior over existing numerical models. The validation confirms the applicability of the coupled RBSM-shell model in representing the post-peak strain softening behavior of partial FRP confined concrete columns.

Chapter 5 presents the numerical analysis performed to investigate the localized behavior of concrete under steel tube and FRP confinement using the coupled RBSM-shell FEM model. For concrete confined by steel tubes, the applicability of the model was first presented by simulating geometrically similar CFST columns with increasing steel tube thickness (steel ratio). Comparison of concrete stress-strain curve between test and simulation shows a good agreement and in particular, the simulation results were able to represent the transition of the stress-strain curve from softening into a ductile response. The simulated deformation of concrete was found to be consistent with this observed transition which showed that the length of localized damage in concrete increases with increasing steel ratio. The comparison has confirmed the applicability of the coupled model in simulating the localized behavior of concrete confined by a steel tube.

For concrete partially confined by FRP, comparison of axial stress-strain behavior between test and simulation showed that the simulation results over-estimate the axial ductility of columns observed in the test. This was found to be due to the simulation models overestimating the length of localized damage of concrete observed in the test. The observed discrepancy may be due to the difference in the rupture strains of FRP observed in test and simulation.

Numerical analysis performed to investigate the localized behavior of concrete under steel tube showed that the compressive behavior of steel-tube confined concrete column is also localized, and the length of the localized zone was found to be affected by the shape of the cross-section and column slenderness. The length of the localized zone increase with increasing confinement and this behavior is also affected by the column slenderness. Similarly, the numerical analysis performed to investigate the effect of partial FRP confinement in the localized behavior of concrete shows that the length of localization zone is always a function of both the level of confinement and column slenderness.

Chapter 6 presents the conclusions derived from the study and recommendations for future research.

The developed coupled RBSM-shell model has addressed the limitations of existing numerical models in simulating the post-peak behavior of steel tube confined and FRP confined concrete members, in particular, in columns with low confinement, where strain softening and localization of deformation of concrete dominates the behavior the of the composite. The performance of the coupled model was validated with published test results of CFST and FRP confined concrete members with good agreement. The coupled model was used to understand the localized behavior of concrete under steel tube and FRP confinement. It confirms that the compressive behavior of concrete confined by steel tube and FRP is also localized and therefore the consequences of localization must be recognized particularly when improving the ductility of concrete using these confinements.

An improvement in the coupled model is due to its application to simulate the cyclic behavior of steel tube confined and FRP confined concrete columns. The improvement requires new constitutive models for interface elements between concrete and steel, and concrete and FRP. The constitutive models must include a hysteresis model to capture the unloading and reloading response under cyclic action. The material models for steel tube and FRP must also be adjusted accordingly such as the use of kinematic hardening in the von Mises model for steel tube. The application of the coupled model to FRP confined concrete columns has also been limited to a circular cross-section which is partly due to the limitations in the meshing code of the RBSM which limits the generation of rounded corners necessary to accurately investigate rectangular cross-section of FRP confined concrete columns. An improvement in the RBSM mesh program would be invaluable.