論 文 の 内 容 の 要 旨

論文題目　曲げ-せん断-軸力相互作用モデルによる鉄筋コンクリート部材の変形性能評価

Axial-Shear-Flexure Interaction Approach for Displacement-Based Evaluation of Reinforced Concrete Elements

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Abstract

An approach was presented in this manuscript for displacement-based analysis of reinforced concrete elements such as columns, beams and shear walls. The method is based on axial-shear-flexure interaction concept, considering equilibrium and compatibility conditions. The approach is entitled ASFI method, which is stand for axial shear flexure interaction. ASFI element can be considered as an element between two subsequent sections of a reinforced concrete element. The element is a combination of two models, axial-shear model and axial-flexure model. Axial-shear model is an in-plane shear element, applying average stresses and strains considering smeared rotating crack method. Axial-flexure model is based on conventional section analyses at the two end sections of the ASFI element. One-stress-block, two-stress-block and fiber model are three approaches, presented in this study, for axial-flexure model, applicable in ASFI method. Compatibility of axial-shear and axial-flexure models in ASFI method is satisfied when axial strains due to axial mechanism in the two axial-shear and axial-flexure models are identical. In other words, at any steps of an analysis after unloading lateral load to zero, considering the degraded concrete strength, axial strains due to axial load in the two axial-shear and axial-flexure models should become identical. Hence, compatibility of axial deformation for the two models can be simply satisfied by considering identical material properties and material constitutive laws. Total axial strain of ASFI element is obtained based on summation of axial strains due to axial, flexural, and shear mechanisms and total drift ratio is determined based on summation of lateral shear and flexural deformations.

Equilibrium of the two models is satisfied in stress field for normal and shear stresses. As for axial stress, simply equilibrium is satisfied considering the same axial stress in the two models. Moment in axial-flexure mechanism is converted into shear stress to be in equilibrium with shear stress of axial-shear model. It is important to consider that shear stress for axial-flexure mechanism is obtained based on the effective depth of the section, *d*, which is related to an average level arm for the moment, and width of the section, *B*. However, shear stress for axial-shear mechanism is determined based on total depth of the section, *D*, and width of the section, *B*. Studies on analysis by

ASFI method indicated that, *d*, is a proper value for the equivalent level arm of the moment in axial-flexure model for columns and beams sections. However, for shear walls with boundary columns, it is considered equal to the distance between axes of the two boundary columns.

Axial deformation due to flexure is simply determined by considering linear strain distribution between two subsequent sections. Then centroidal strain in the section with lower moment is deducted from the centroidal strain in the section with higher moment and the result is multiplied by 0.5. In another way, axial deformation due to flexure can be determined by obtaining relative centroidal displacement between the two sections divided by the distance between the two sections by means of integration. Axial strain due to flexure can be simply added to the axial deformation in axial-shear model applying flexibility relationships. Stresses in perpendicular directions to the ASFI element plane, or clamping stresses, are considered zero, satisfying the equilibrium between concrete and transverse reinforcement stresses; in columns it is equilibrium between confinement pressure and hoops stresses.

One of the important roles of axial-shear model in ASFI method is to degrade concrete strength in concrete fiber of the axial-flexure model. In case of a reinforced concrete column with dominant flexure behavior, first at the conventional yielding point, axial-shear element is in the pre-crack state. As flexure deformation increases, axial deformation due to flexure mechanism is increased and contributed into axial deformation of the axial-shear element. As the result, shear deformation is increased and compression softening factor is decreased, which follows by degradation of concrete strength in axial-flexure fibers. This phenomenon is continuing until whether a shear-tension or shear-compression failure is dominated. From the onset of the post-peak response, if shear-tension is the dominant failure, axial-shear model rules the ultimate drift. However, if shear-compression failure is dominated, then each of the two models can govern the post-peak responses. Since, axial-flexure model has many sub-elements, fibers, it can give more proper post-peak results comparing to the shear-axial model, which has only one integration point. Applying secant stiffness models in ASFI method, lateral load, axial deformation and drift ratios are estimated for five reinforced concrete columns, a reinforced concrete beam, one bay reinforced concrete frame, and a reinforced concrete shear wall with two boundary columns. Consequently, the analytical results were compared with the experimental data for all the specimens. As the result, consistent correlations were achieved between the analytical results and test outcomes. Experimental results of a reinforced concrete column with bond failure pointed out that bond failure affected the drift-load response of the column and as the result ultimate lateral load capacity was obtained at the lower drift ratio comparing to that of a column with a perfect bond. Therefore modification should be applied on ASFI method to model bond failure mechanism. Based on analytical results by ASFI method, it was found also that slipping and buckling of compression bars (after inclination of post-peak compression strength of concrete in the extreme fibers) have considerable effects on estimation of ultimate drift at the ultimate lateral load capacity. In this study, for elements with high transverse reinforcement ratio, compression stresses of the main bars were degraded after strength of concrete fiber (next to the bars) reached twenty percent of the concrete compression strength. Then it was linearly declined corresponding to degrading compression strength of the concrete fiber. As for columns with low transverse bar ratio, reduction of compression bars was started after concrete fiber strength reached thirty percent of the concrete compression strength.

Basically, in many cases of analyses by ASFI method, axial-shear and axial-flexure models works mutually until post-peak compression strength in the extreme concrete fiber declines to about thirty percent of the maximum concrete strength. Afterward, post-peak response was governed by the axial-flexure model.

Displacement-based response was estimated by ASFI method for a reinforced concrete frame (with two columns and top & bottom stubs), prior to the test of the frame. Prediction was done also based on AIJ and ACI design equations. Results from both AIJ and ACI indicated that a shear behavior would dominate the performance of the specimen. However, a flexure behavior followed by shear failure was estimated by ASFI method. In the test, experimental results showed a clear flexural behavior followed by shear failure (at the drift ratio almost the same as that of the predicted one by ASFI method), however with 10% lower lateral load capacity. After analysis of the test data, it was found that loading and test setup of the test had also 10% declining effects on the ultimate lateral load capacity (due to displacing inflection point from the center of the columns). This was found from both strain gage and curvature transducer test data. Considering the calculated effective lengths of the columns, satisfactory correlations were obtained between experimental and analytical results for lateral load of the frame as well. The result of this study also indicates highly consideration of preventing shear failures by AIJ and ACI design codes. In the experimental and analytical study of a reinforced concrete frame infilled with a masonry wall, it was found that infill wall reduced the flexural flexibility of the boundary columns, due to interaction of columns and wall in the compression zones. As the result, columns performed as a shorter column with higher shear capacity comparing to that of the column with the original length. However, columns responded a smaller ultimate drift ratio at the ultimate capacity due to forwarding shear failure. A model was described for infill wall and combined with models of ASFI method for the reinforced concrete frame, and lateral load-drift ratio relationship of the specimen was estimated, analytically. Consequently, the analytical results showed acceptable correlation with the experimental data. Based on analytical and experimental results of a shear wall, a modification was applied on the tension constitutive law of concrete for the axial-shear model in ASFI method. Then, displacement-based response of the shear wall was estimated by ASFI approach and compared with experimental outcomes. As the result, a reasonable correlation was obtained between the analytical and experimental results for the shear wall specimen. The modification was done in order to consider the effect of different shear stresses in shear wall and boundary columns due to different thickness. At a loading state in which shear stress in the wall is higher than shear stress in the boundary columns and concrete tensile stress in the columns is lower and in the wall is higher than concrete tensile strength, shear cracks occur first on the shear wall and then its concrete tensile stress starts to decrease. As the result, average tensile strain in the equivalent model is lower than concrete tensile strain in the wall and higher than that in the columns. Hence, in the modified constitutive law, lower peak tension strength at larger strain is applied as average tensile strength and average peak strain, however in the same original constitutive law. Without above modification, ASFI method gives nearly satisfactory results for drift ratio-axial deformation relationship and ultimate lateral load capacity, however higher stiffness is estimated for load-displacement response. In case of reinforced concrete beams, a specimen tested in the University of Tokyo was selected for model verification of ASFI method for beams. In order to apply ASFI method to estimate load-deflection response of a beam, the only consideration in the analysis is to apply an enough negligible axial stress to avoid creating infinitive value in the flexibility matrix. A satisfactory correlation was obtained for displacement-based estimated results by ASFI method with the experimental outcomes of the beam specimen.

FEM analyses were implemented by two programs; VecTor2 program, developed at Civil Engineering Department of University of Toronto and UC-win/WCOMD program, developed at Civil Engineering Department of the University of Tokyo. In order to study on modified compression field theory and to implement FEM analysis by VecTor2 program, the author had a great opportunity to join, as a visiting student, VecTor Analysis Group at the University of Toronto, and hospitalized by Professor Vecchio, who developed Modified Compression Field Theory and VecTor2 program. The author received also valuable advised from Professor Maekawa at the University of Tokyo, who developed UC-win/WCOMD program, in order to do the FEM analysis. FEM analyses were done by the two programs for four reinforced concrete columns with dominant failures of shear, shear-flexure and flexure failure. The analytical results of both programs showed satisfactory correlations with the experimental data in terms of load-drift relationships until ultimate lateral load capacities and drifts. The results of FEM and ASFI analyses were derived as envelope load-drift curves for the four column specimens and compared with the experimental results. Comparable and even more correlated responses to the test data were obtained by ASFI method comparing to the FEM results. ASFI method showed more correlation to post-peak test data comparing to the FEM methods, which might be due to the average strain-stress concept of ASFI method for the entire element. In FEM analysis local collapse mechanisms may occur for the elements in the high stress zone, and leading the analysis to fail before attaining the dominant failure mode.