The 2017 World Congress on
Advances in Structural Engineering and Mechanics (ASEM17)
28 August - 1 September, 2017, Ilsan(Seoul), Korea

Numerical Analysis on Part-CFT Structures with an Improved Bond-Slip Model

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ABSTRACT

CFT column has a lot of structural advantages due to the composite behavior between in-filled concrete and steel tube. Despite of the structural advantages of CFT structure, the economical effectiveness of CFT is much poorer than traditional RC. This paper deals with the development of an effective numerical model which can consider the bond-slip behavior between both components of concrete matrix and steel tube without taking double nodes. This model results in significant savings in the numerical modeling of CFT columns to take into account the effect of bond-slip. Moreover, to reduce the construction cost for CFT structure, part-CFT structures, which is replaced the part of plastic hinge in RC columns to CFT, is suggested. Finally, correlation studies between numerical results and experimental data are conducted to verifying the efficiency of the introduced numerical model.

1. INTRODUCTION

CFT (Concrete-Filled Tube) is a composite structure of rectangular or circular steel tube with in-filled concrete and has a lot of structural advantages due to the composite behavior between in-filled concrete and steel tube. Recently, since the interest of seismic design becomes larger, a CFT column is attracting attention as a good seismic structure. Many researchers (Scheneider ,1998; Huang et al., 2002) have been performed experiments for a change of resistance capacity of CFT columns with various dimensions such as D/t ratio which is the relationship between section diameter (D) and thickness of steel tube (t). To verify the behavior of interface between steel tube and in-filled concrete, Kwon et al. (2005) performed the experiment to check the bond-stress at the interface of CFT. On the other hand, a numerical approach for a CFT column has also been actively conducted to overcome experimental limitations. Hibbitt

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et al. (2000) performed a numerical analysis with the simple friction assumption to interface of a CFT column and Goto et al. (2010) applied the spring element to simulate the composite behavior of steel tube and in-filled concrete at the interface. However, neither of the methods is effective numerical model to explain the composite behavior of a CFT column.

In this paper, numerical approach to a CFT column with an improved bond-slip model is conducted. Also a correlation study between numerical model and experiment was performed to validate the proposed bond-slip model. Finally, the part-CFT structure, which partially replaces a traditional RC column to a CFT structure at the part of plastic hinge, is proposed to improve the resistance capacity of a traditional RC column against seismic damage.

2. NUMERICAL MODEL OF THE PART-CFT

This paper introduces an improved numerical approach that can consider the bond-slip effect without the use of double nodes at the interface between the concrete core and the steel tube by incorporation of the equivalent steel stiffness. Moreover, the part-CFT design of column is proposed to develop the seismic performance of the traditional RC column.

2.1 Bond-slip model

When a concrete filled steel tube column is subjected to a compressive force, both in-filled concrete and steel tube develop the stress in the radial direction as well as the normal stress. The perfect bond assumption at the interface is the most convenient numerical model however it is very different from the actual behavior and difficult to apply to analysis. Differently from perfect bond assumption in which the complete compatibility of strains between the in-filled concrete and the steel tube is based, CTF columns accompany the bond-slip along the interface of both structural components with an increase of the deformations and internal forces delivered through the interaction between the in-filled concrete and the steel tube. Accordingly, to exactly predict the resisting capacity of CFT columns, the bond-slip effect must be taken into consideration, and the bond-link element defined by a spring element connecting a concrete node and an adjacent steel node is usually adopted. Since the link element has no physical dimension, the two connected nodes originally occupy the same location in the finite element (FE) mesh of the structure before deformation.

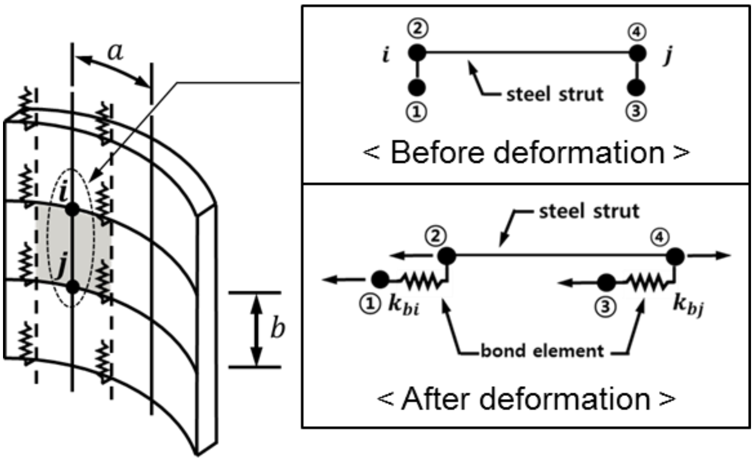


Fig. 1 An idealized steel strut with bond-slip

The use of bond-link element in the FE analysis of RC structures, however, imposes to take a double node to represent the relative slip between the in-filled concrete and the steel tube. In a complex structure, this requirement leads to not only a considerable increase in the number of degrees of freedom but also the complexity of mesh definition. To address these limitations in using the bond-link element, an improved numerical model is proposed in this paper shown in Fig. 1. More details about applied bond-slip algorithm can be found in elsewhere (Kwon et al., 2015).

2.2 The part-CFT design suggestion

Despite the structural advantages of a CFT structure, the high cost of CFT construction, including material costs, remains a problem compared to traditional RC structures. To address this issue, this chapter introduces the part-CFT structure which can optimize construction cost and strength efficiency. Since a CFT structure shows much better performance against bending moment rather than axial force, the optimized column is RC on axial governing section and CFT on bending moment governing section. In practice, the certain part of bending moment governing section for a column is the fixed-end at the surface of ground. Proposed design is that the plastic hinge of a RC column is replaced to CFT, shown as Fig. 4, to secure the sufficient bending moment capacity.

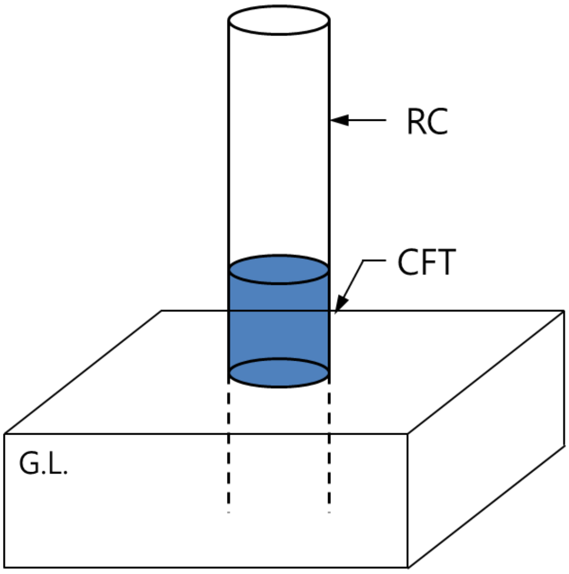


Fig. 2 Design suggestion of the part-CFT column

3. EXPERIMENTAL VERIFICATION

A correlation study for the part-CFT column subjected to double curvature bending is conducted for a specimen that was designed and experimented by the authors. The dimensions and details of the test specimen are shown in Fig. 3. The strengthening by the steel tube was limited to the length of L=270mm+320mm=590mm from both end of the test specimen, because the development of maximum bending moment and plastic deformation accompanied especially after reaching the yielding moment of a RC column section is expected to be concentrated within this range. The ratio of the diameter of the in-filled concrete section (D) to the thickness of the steel tube (t) is D/t=250/3.2=78.1, and the steel ratio by the embedded mild reinforcement is ρ=3.24%. Since the specimen has the clamped boundary condition at both ends, the ratio of L/D=1980/250=7.91 will be equivalent to L/D=3.96 in the cantilevered RC column. In advance, the used material properties are as follows: the compressive strength of concrete f'_c=28MPa, the yield strength of reinforcement f_y=400MPa, and the yield strength of steel tube f_y=235MPa.

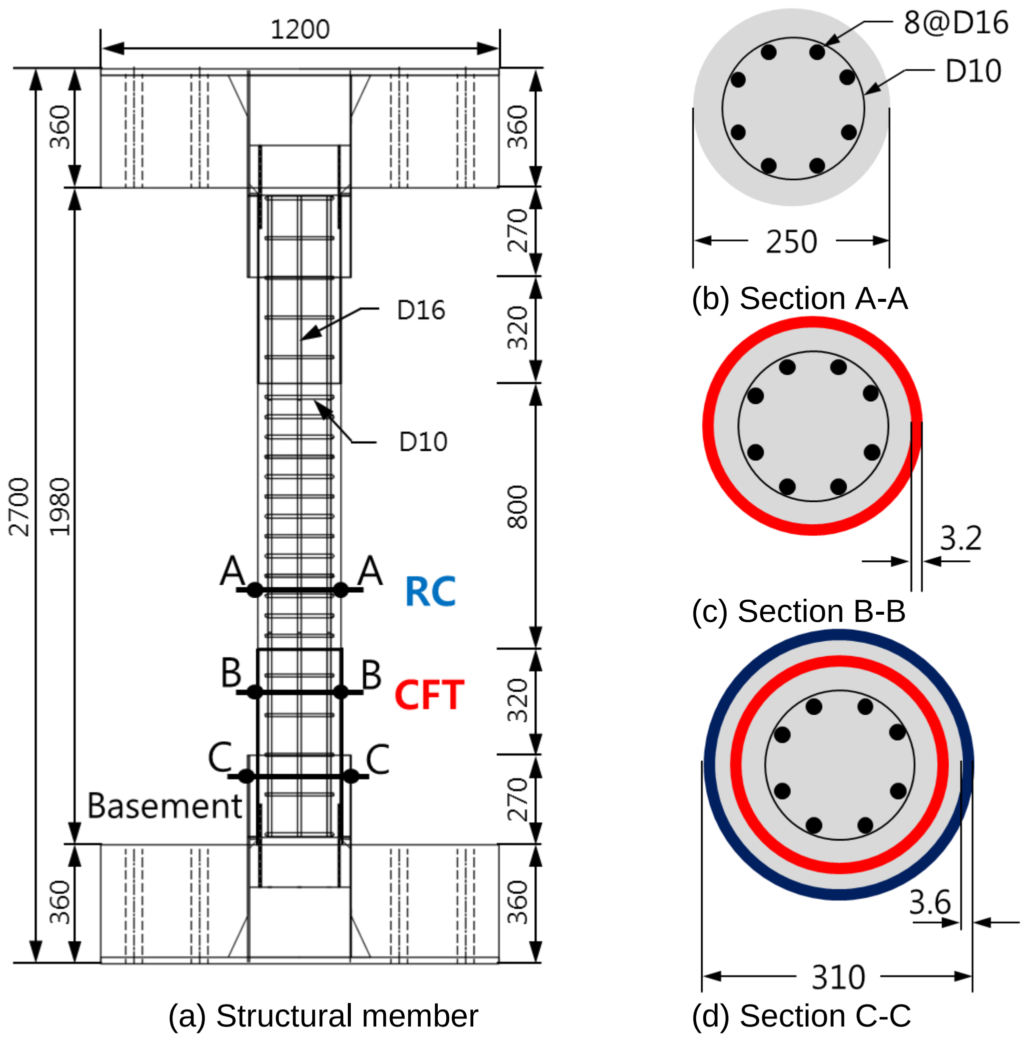
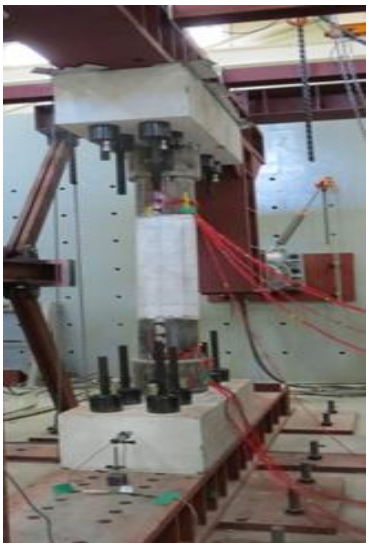
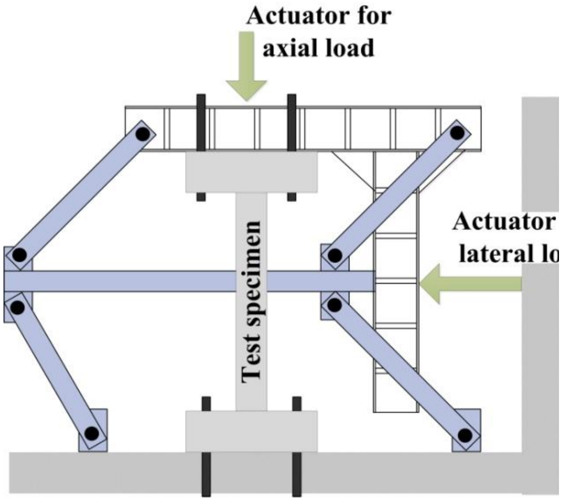


Fig. 3 Configuration of test specimen (unit : mm)

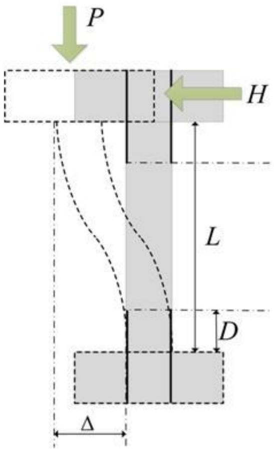
The loads were applied to the specimen by actuators placed at the top face and at the mid-span of the specimen, as shown in Fig. 4(b) (Moon, 2014). Then the load at the mid-span is transformed to the lateral load at the top face of the specimen through the parallelogrammatic apparatus, which was designed to prevent the rotational deformation accompanied by the horizontal drift at the top face of the specimen (see Fig. 4(c)). The applied axial load maintained a constant value of P=200kN, but cyclic loading was applied for the lateral load H with the displacement control up to reaching the failure of specimen. Fig. 4(d) shows the horizontal displacement history introduced at the top face of the specimen.



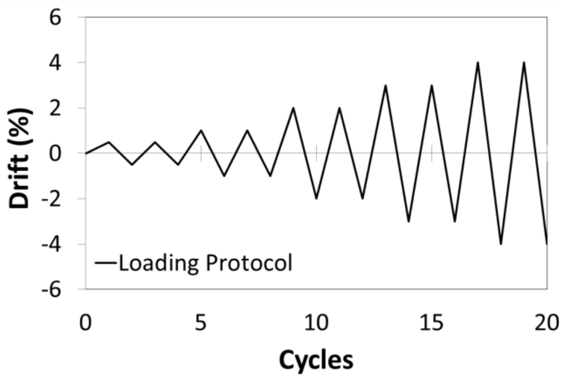
(a) Test set-up



(b) System configuration of actuator



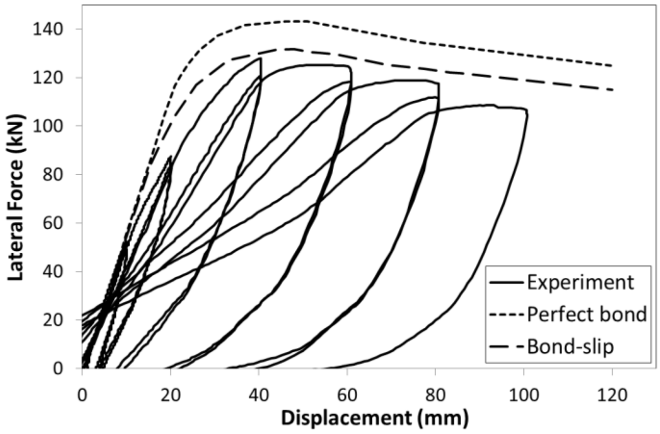
(c) Free body diagram



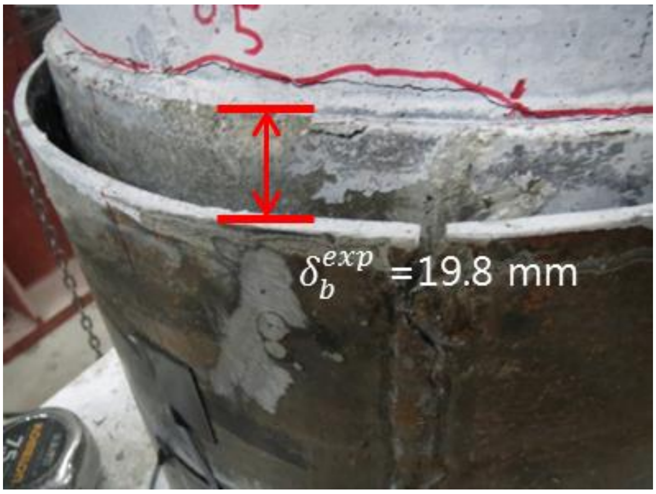
(d) Applied displacement history

Fig. 4 Test set-up details with actuator and cyclic load

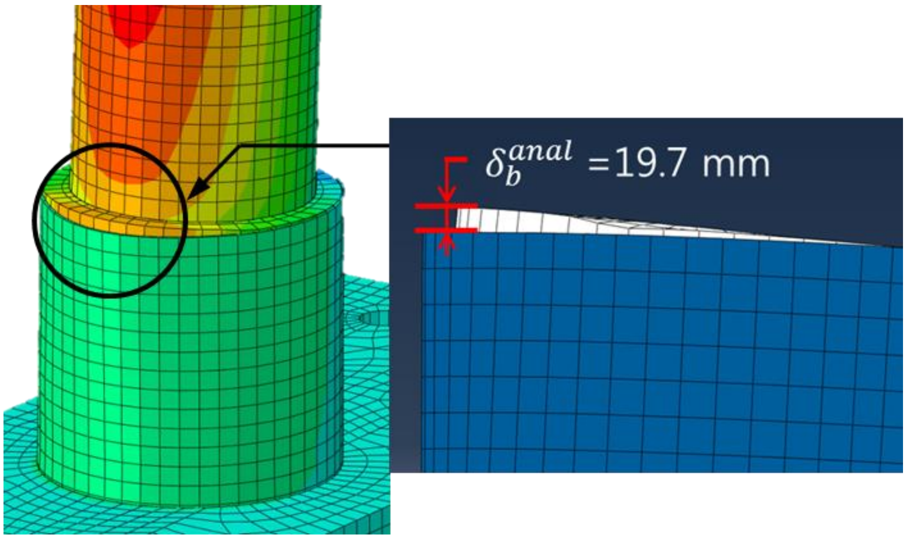
Full modeling of the experimental specimen by ABAQUS (2013) is considered and fixed end boundary conditions are introduced at both end faces. Upon the introduction of the self-weight and a constant axial force of P=200kN, the lateral load is imported with the designed displacement history in Fig. 4(d). Fig 5(a) shows the obtained numerical results, presenting very good agreement with the monotonic envelope developed by the experimental data. However, the numerical results, in which the bond-slip effect is ignored, still overestimates the ultimate resisting capacity of the CFT column, even in a CFT column subjected to double curvature bending. Moreover, the slip behavior at the interface between the in-filled concrete and the steel tube can be found in Fig. 5(b) and (c). Because of the slip, the in-filled concrete was lifted up above the steel tube in the tensile region with the slip amount of $\delta_b^{exp} = 19.8\,mm$. The slip amount calculated by the proposed analytical bond model is $\delta_b^{anal} = 19.7\,mm$, which is almost the same as that obtained from experiments, and this means that the proposed model can effectively simulate the bond-slip behavior of CFT columns subjected to arbitrary loading type.



(a) Load-displacement relationship



(b) Slip resulted by experiment

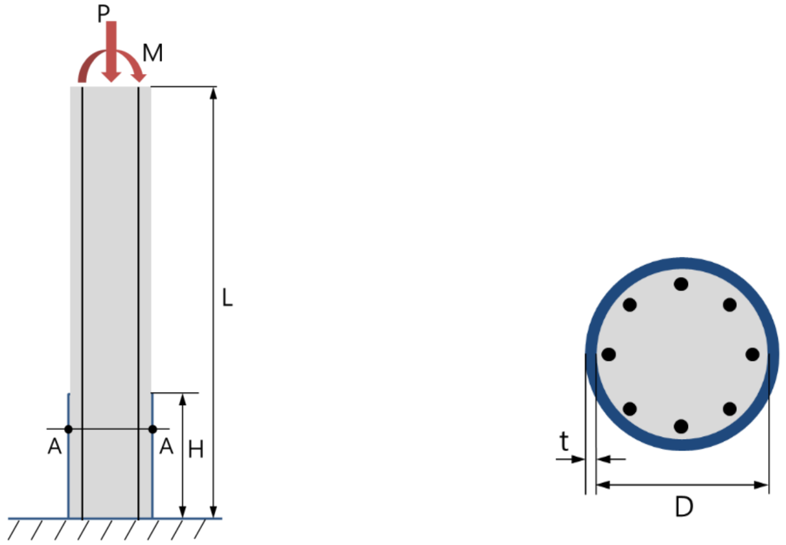


(c) Slip resulted by numerical anlaysis

Fig. 5 Load-displacement relationship and slip behavior of test specimen

4. APPLICATIONS

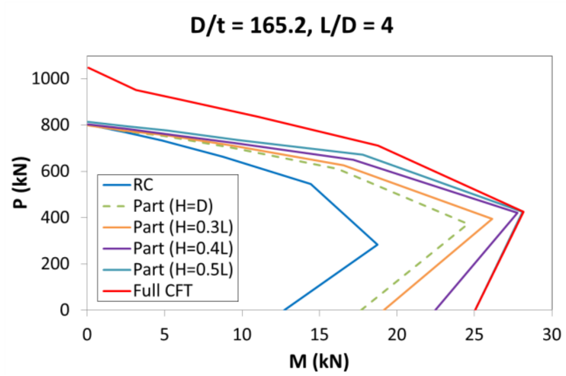
To determine the most effective wrapping length of steel tube, part-CFT columns with section diameter of 165.2*mm* are considered as shown in Fig. 6(a), and assumed material properties of concrete and steel have the following values: the compressive strength of concrete is $f_c' = 35MPa$ and the yield strength and modulus of elasticity of steel are $f_y = 400MPa$ and $E_s = 2.1 \times 10^5 MPa$, respectively. Parametric studies are conducted with variation of the length-diameter ratio of $L/D=$4, 15, and 30, thickness of steel tube, *t*= 0.5 and 1 *mm*, and the length of steel tube, H=0.3L, 0.4L, and 0.5L, producing 18 cases. Since the failure of the thicker part-CFT column occurs at the RC section, the thickness of steel tube is considered less than 1mm. The vertical and lateral forces are applied at the top face of the column (see Fig. 6(b)).



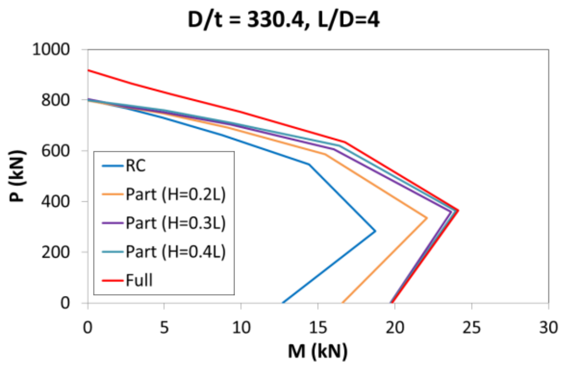
(a) Structural member (b) Section A-A

Fig. 6 Configuration of part-CFT column

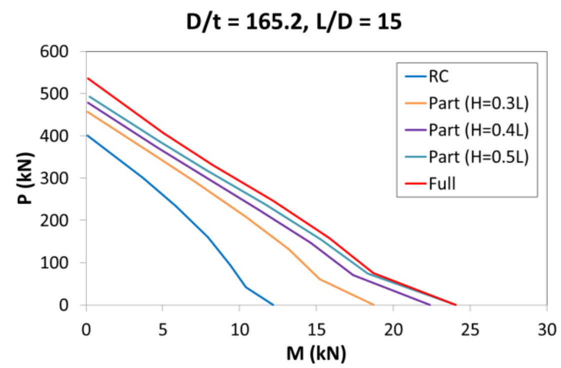
From the P-M diagram as shown in Fig. 7, which represents the obtained numerical results, reduction of resistance capacity by CFT length has similar trends for every slenderness ratio. In case of t=1mm, which has D/t ratio of 165.2, the moment resistance shows similar to full CFT when the H is larger than 0.4L. Meanwhile, the moment resistance shows similar to full CFT when the H is larger than 0.3L with thinner steel tube when D/t ratio of 330.4.



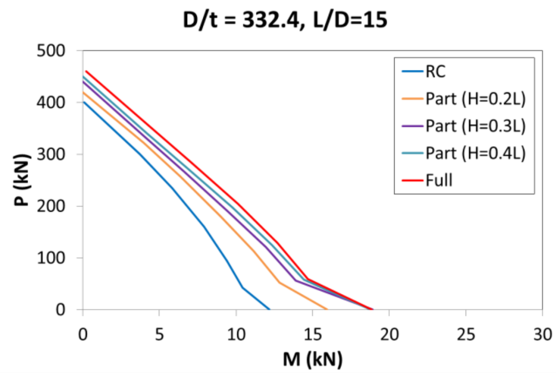
(a) *t*=1*mm*, *L/D*=4



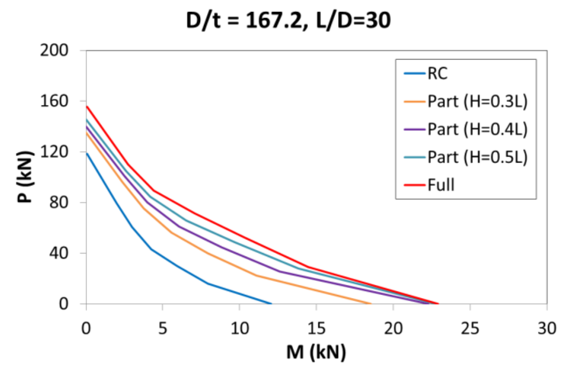
(b) *t*=0.5*mm*, *L/D*=4



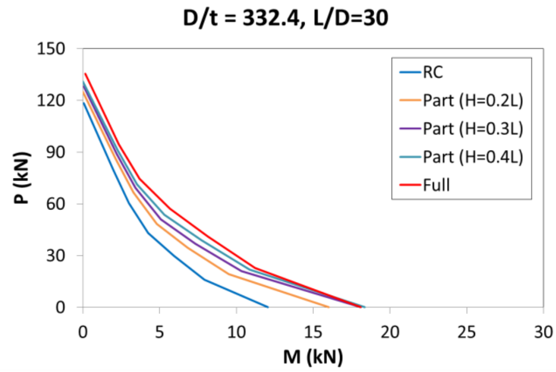
(c) *t*=1*mm*, *L/D*=15



(d) *t*=0.5*mm*, *L/D*=15



(e) *t*=1*mm*, *L/D*=15



(f) *t*=0.5*mm*, *L/D*=15

Fig. 7 P-M interaction diagrams of part-CFT columns

5. CONCLUSIONS

This paper introduces numerical analysis of the part-CFT column applying bond-slip model at the interface of in-filled concrete and steel tube and the proposed model is verified by a comparison with results from experiment. The numerical model shows similar results with experiment not only the load-displacement relationship but also the slip behavior at the interface of in-filled concrete and steel tube. The moment resistance of part-CFT column has similar performance with full CFT structure with less amount of steel. Moreover, parametric studies are performed to figure out optimized length of part-

CFT which can show the moment resistance of full CFT. To bring the occurrence of plastic hinge at CFT section, D/t ratio of part-CFT should be larger than 165.2. The effective length of CFT section is obtained as 0.4L for D/t=165.2 and gets shorter when the thickness of steel tube becomes thinner. Additional parameter studies to identify the elaborate relationship between the effective length and D/t ratio.

ACKNOWLEDGEMENT

This research was supported by a grant(13SCIPA01) from Smart Civil Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport(MOLIT) of Korea government and Korea Agency for Infrastructure Technology Advancement(KAIA) and Korea Agency for Infrastructure Technology Advancement (KAIA) and Korea Minister of Ministry of Land, Infrastructure and Transport (MOLIT) as “U-City Master and Doctor Course Grant Program”.

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