Reinforcement Modeling in Nonlinear Analysis of RC and RCFT Columns Subjected to Axial Compression

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ABSTRACT

In numerical simulations of reinforced concrete (RC) columns with ADINA, when the REBAR element model is applied to simulate the reinforcement, the load-displacement curve of RC is similar to that of concrete, without reflecting the contribution of reinforcement. Therefore, employing another element model-BEAM element model for reinforcement, nonlinear analyses of RC columns are carried out and compared against the REBAR element model. The nonlinear analysis of reinforced concrete filled steel tubular (RCFT) columns, then, is performed with the BEAM element model. Meanwhile, the axial compression tests of concrete, RC and RCFT columns are also conducted to validate the nonlinear analysis. Comparing the results of nonlinear analysis against the results of experiment, it is concluded that the BEAM element model can simulate the reinforcement more reasonably than REBAR element model and can be applied to the nonlinear analysis of RCFT columns.

Keywords: *numerical simulation, ADINA, reinforcement, RC column, RCFT column*

キーワード：数値シミュレーション， ADINA，鉄筋，鉄筋コンクリート柱，RCFT柱

1. Introduction

Currently most of the researchers who are performing nonlinear analysis of reinforced concrete (RC) structures with ADINA are employing the REBAR element model (REBAR model)[1)-4)] which is specific to simulate the reinforcement in ADINA. However, through the analysis of RC structures with REBAR model in ADINA, it is found that the load-displacement curve of RC column is similar to the load-displacement curve of pure concrete column. This means that the result of analysis cannot reflect the effect of reinforcement in load-displacement curve.

Besides, reinforced concrete filled steel tubular (RCFT) structures are attracting structural engineers due to its excellent shear-resistance and anti-seismic capacity than concrete filled steel tubular (CFT) structures [5)-7)]. Because the RCFT structures are composite of steel tube and RC, the behavior of inside RC affects the performance of all structures [7)], therefore proper modeling of inside RC is important when perform

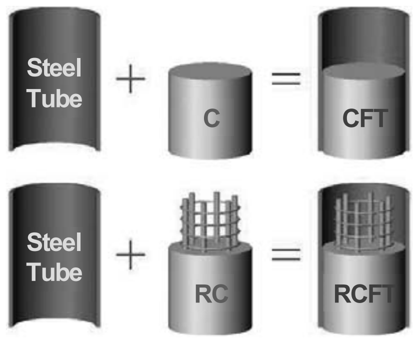

Fig.1 Model of CFT and RCFT

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numerical analysis. The **Fig.1** shows the model of CFT and RCFT.

Therefore, in this paper, nonlinear analyses of RC columns are conducted with ADINA using another kind of element model-BEAM element model (BEAM model) and compared with REBAR model on the basis of experiment. The decided RC model, then, is applied to the nonlinear analysis of RCFT column and compared with results of corresponding experiment. Meanwhile, axial compression tests of concrete, RC and RCFT columns are carried out to provide a comparison standard for numerical results.

2. Compression test

2.1 Test outline

To validate the results of the numerical analysis, axial compression tests of concrete, RC and RCFT columns were carried out.

The diameter and height of all specimens was 150mm and 450mm, respectively. Material of steel tube was SS400 (Japanese Industrial standard: JIS). Material of axial reinforcement was SD295 (JIS) and number was 6, diamete r was D= 6mm. Spiral reinforcement were used in transverse direction and material was SS400 (JIS), diameter was D= 3mm.

Specimens were divided into 3 groups (concrete, RC and RCFT) and 3 same specimens were prepared for each group. **Table 1** shows the detailed information about the specimens.

The items measured from the experiment were load, axial deformation and strains. 4 deformation transducers were installed on the top of specimens to measure axial deformation. Strains of steel tube were measured by 8 strain gauges placed circumferentially longitudinally at the outside longitudinal center of specimens. Only 2 strain gauges were placed symmetrically for 2 of 6 axial reinforcements at the longitudinal center. To measure the Compressive strain of the concrete, a mold strain gauge was placed inside of the concrete at longitudinal center. **Fig.2** and **Fig.3** shows the installation of specimens.

Table 1 Outline of the specimens

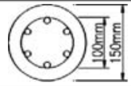
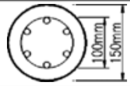
Specimen type Labels	Concrete C-T-(1,2,3)	RC RC-T-(1,2,3)	RCFT RCFT-T-(1,2,3)
Cross section			
Steel tube	none	none	SS400 t=1.2mm
Axial reinforcement	none	6 SD295 D=6.0mm	6 SD295 D=6.0mm
Spiral reinforcement	none	SS400 D=3.0mm Pitch 30mm	SS400 D=3.0mm Pitch 30mm

Fig.2 Setup of the specimen

Fig.3 Reinforcement cage

2.1 Test results

The results of the tests are listed in **Table 2**.

The behavior of concrete material has important effect on correctness of numerical analysis. Therefore, in the numerical analysis, experimental material parameters only for concrete have been used. According

Table 2 Maximum load and corresponding displacement

Group name Specimen label	C-T-1	Concrete C-T-2	C-T-3	RC-T-1	RC RC-T-2	RC-T-3	RCFT-T-1	RCFT RCFT-T-2	RCFT-T-3
Max. load (kN)	619.3	568.3	677.5	599.7	527.1	656.0	870.5	818.2	852.2
Average Max. load (kN)		621.7			594.3			847.0	
displacement (mm)	1.28	1.34	1.34	1.36	2.61	1.33	2.70	2.57	2.67
Average displacement (mm)		1.32			1.77			2.65	

to stress-strain results of concrete specimen, experimental stress-strain relationship of concrete is drawn as **Fig.4**.

3. Numerical modeling

3.1 Material model for concrete

Uniaxial stress-strain relationship of the concrete used in this analysis for pure concrete and RC columns is shown as **Fig.5**,where σ_c is maximum uniaxial compressive stress, ε_c is uniaxial strain corresponding to σ_c, σ_u is ultimate uniaxial compressive stress, ε_u is ultimate uniaxial compressive strain corresponding to σ_u, σ_t is uniaxial cut-off tensile strength; σ_{tp} is post-cracking uniaxial cut-off tensile strength(if σ_{tp}=0, ADINA sets $\sigma_{tp}=\sigma_t$, shown as oblique dotted line in **Fig.5**), ε_t is uniaxial strain corresponding to σ_t, E_{ct} uniaxial tangent modulus at zero strain (must be greater than σ_c/ε_c [2])).

In this analysis: σ_u was determined by experiment (according to Ref. 2), this value can be $0.8\sigma_c$. In addition, confined concrete can be modeled using close values for σ_u and σ_c [8]), $\sigma_t=0.23(\sigma_c)^{2/3}$ [9]), $\sigma_{tp}=0$ [8]). Values of σ_c, ε_c, ε_u, E_{ct} can be determined through the material tests.

3.2 Material model for steel tube and reinforcement

Bilinear stress-strain relationship is used for reinforcement and steel tube. Constitutive law for bilinear material is shown as **Fig.6**, where σ_y is yield stress, ε_y is yield strain, σ_p is ultimate strength; ε_p is strain corresponding to σ_p, E_s is Young's modulus, E_{st} is strain hardening modulus. Values of these can be determined by material tests or material property.

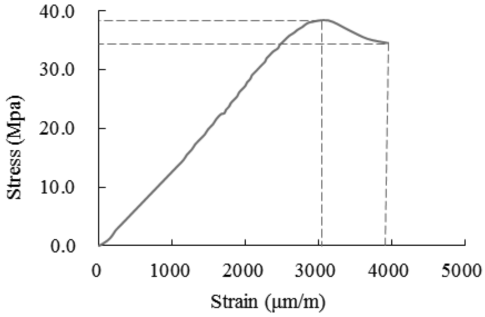


Fig.4 Experimental stress-strain curve of concrete

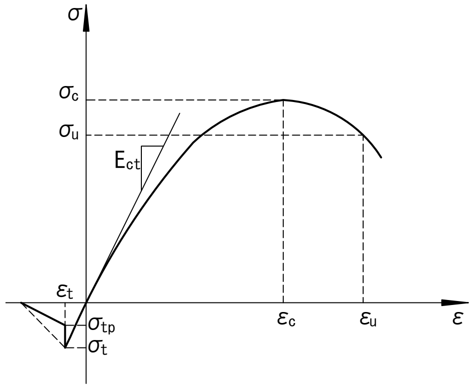


Fig.5 Constitutive law for concrete

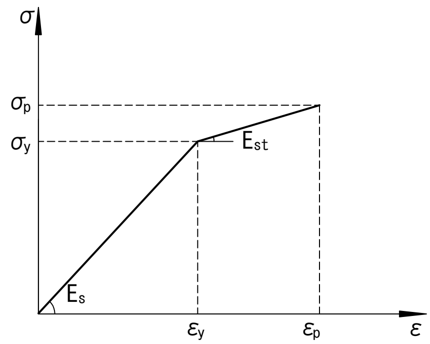


Fig.6 Constitutive law for steel

4. Nonlinear analysis of RC column

Three columns corresponding to the compression test in Sec.2 were analyzed: 1) pure concrete column, labeled C-A; 2) RC column with REBAR element model, labeled RC-R-A; 3) RC column with BEAM model, labeled RC- B-A.

According to **Fig.4**, material parameters for concrete are: σ_c=38.5Mpa, σ_u=34.0Mpa, $\sigma_t=0.23\times(40)^{2/3}$=2.69Mps, ε_c=3133μm/m, ε_u=3933μm/m, $E_{ct}=1.73\text{x}10^4$ Mpa.

Material parameters for reinforcement are used from material properties. σ_y=295Mpa, $E_s=2.0\text{x}10^5$ Mpa, $E_{st}=0.01\ E_s$ =2000Mpa [11])

The analyses results are drawn in the **Fig.7**, **Table 3** and **Fig.8**, based on these results, discussions are

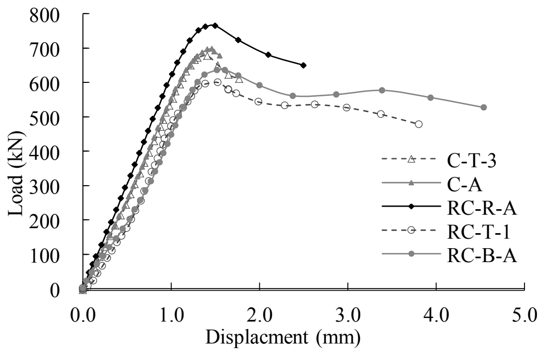
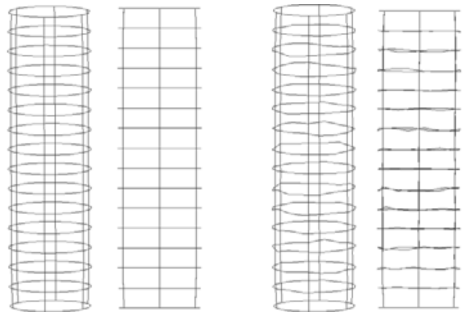


Fig.7 Load-displacment curves



(a) RC-R-A　(b) RC-B-A

Fig.8 Deformation shape of reinforcement

conducted as follows:

(1) In the **Table 3**, results of maximum load and corresponding displacements are in good agreement except the results of REBAR model (RC-R-A).

(2) In **Fig.7**, the analytical curve of REBAR model (RC-R-A) is similar to that of pure concrete (C-A) and have larger difference compared with experimental curve (RC-T-1). On the contrary, the analytical the curve of BEAM model (RC-B-A) is difference from that of pure concrete (C-A) and in a good agreement with experimental curve (RC-T-1).

(3) From the **Fig.8**, when the columns are in maximum load, not so significant deformations of reinforcement cage can be observed with REBAR model (RC-R-A) while the changes are apparent with BEAM model (RC-B-A). This means BEAM model (RC-B-A) are more close to actual state of the column.

Why are there so big differences between REBAR model (RC-R-A) and BEAM model (RC-B-A)? This is because: when we simulate the reinforcement with REBAR model, reinforcements are acting like truss (only with axial forces without bending), meanwhile, ADINA will treat the reinforcement as a strengthened fiber of the concrete. On the contrary, when we simulate the reinforcement with BEAM model (RC-B-A), ADINA will treat the reinforcement as beam (with axial forces and bending) implanted into the concrete which is more close to actual conditions and can simulate the reinforcements more correctly.

In addition, it can be noticed from the **Table 3** and **Fig.7** that maximum load of concrete column is greater than that of RC column, in case of both experiment and numerical analysis except REBAR model. This may be explained as follows: on the same loading stage, bond-failure between reinforcement and concrete will cause cracks on the bonding area of concrete while there are no cracks with pure concrete columns, with the increase of loading, bond-failure-cracks will help concrete of RC develop cracks more rapidly and force the RC column reach maximum load in advance of pure concrete column but with more ductility. Some other research results [12] also indicate that this kind of phenomena is related to reinforcement ratio of stirrups and cover thickness of concrete, higher the reinforcement ratio of stirrups or smaller the cover thickness of concrete is, the more significant this phenomena is [12].

5. Nonlinear analysis of RCFT column

RCFT column corresponding to compression test in Sec.2 was analyzed. Material parameters for concrete cannot be used same values as RC columns are used

Table 3 Max. load and corresponding displacement

label	Max. Load(kN)	Displacement(kN)
C-T-3	677.50	1.34
C-A	697.60	1.46
Differences	2.88%	8.22%
RC-T-1	599.70	1.40
RC-R-A	764.70	1.65
Differences	21.58%	15.15%
RC-B-A	636.00	1.52
Differences	5.71%	7.89%

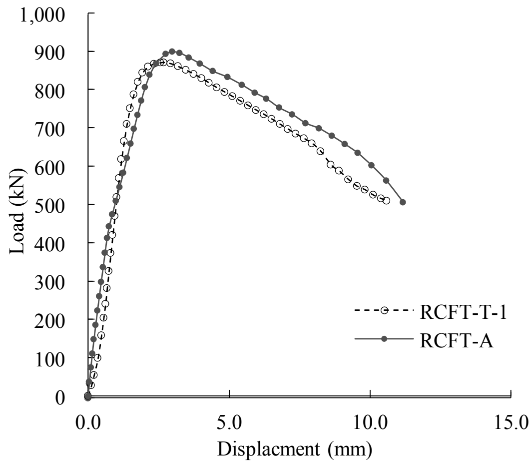
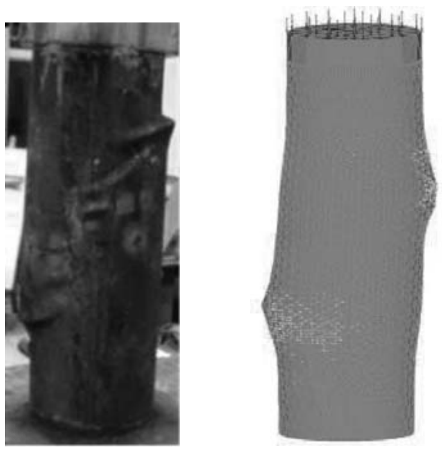


Fig.9 Load-displacement curves of RCFT



(a) RCFT-T-1 (b) RCFT-A

Fig.10 Comparison of failure shapes

due to the confinement effect of steel tube and reinforcements to concrete core. In this study, the study results of Ref.10) on confined concrete have been adopted to model the concrete core. Material parameters for steel tube and reinforcements are used from material properties, namely, σ_y=400Mpa, E_s=2.0x10^5 Mpa, E_{st}=0.01 E_s =2000 Mpa [11]. BEAM model mentioned in Sec.3 was used for inside RC.

As to modeling the contact between concrete and steel tube, according to some research results with CFT, it is assumed that the steel tube and concrete is completely bonded, meanwhile the effect of shrinkage and creep of concrete and local buckling of steel tube to the CFT structure can be neglected [13]. Therefore, in this analysis, bonded contact model in ADINA, is used to model the contact between steel tube and RC.

Results of analyses are drawn in the **Fig.9** and **Fig.10**, according to the results, following statements may be applicable:

(1) In **Fig.9**, maximum load of experiment and analysis is 870.5kN and 898.6kN respectively, the difference is 3.1%. Displacement corresponding to the maximum load is 2.70mm and 2.99 mm respectively, the difference is 9.7%. Load-displacement curve of analysis (RCFT-A) is also similar to the curve of experiment (RCFT-T-1). These show that the results of experiment and analysis are in a good agreement.

(2) In **Fig.10**, failure shape of analysis is almost similar to the experiment but more distorted than experiment. This is maybe due to the boned contact model between steel tube and RC. With the boned contact model, steel tube and RC deformed together until final failure state, but in the experiment, steel tube and RC was separated in the certain stage of loading and not worked together. Thus, the numerical model is differed from the experiment.

In addition, it can be noticed that the difference of displacement is a little larger than that of load. This is maybe also duo to the difference of contact between numerical model and test.

6. Conclusions

According to study results above, conclusions are drawn as follows:

(1) When RC structures are analyzed with ADINA, BEAM element model simulate the reinforcement better than REBAR element model. In addition, from the view point of modeling operation in ADINA, BEAM element model has more flexibility than REBAR element model. But, in case of solution convergence, REBAR element model have advantage over BEAM element model.

(2) A RCFT column is analyzed using the BEAM element model and applicable results are achieved.

Moreover, in case of RCFT, contact modeling between steel tube and concrete core is worth of further study. Achieving a converged solution also is a prominent problem in nonlinear analysis, especially when model the concrete and contact. In most cases, we do interested in descending stage of load-displacement curves, but this will become a troublesome problem in nonlinear analysis because of the convergence problem. Therefore, it is also worthy of further studies on convergence of solution with ADINA.

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要　旨

現在、非線形解析ソフトとして多くの研究者が利用している ADINA による鉄筋コンクリート（RC）構造解析では、多くの場合、利便性から REBAR 要素モデル（REBAR モデル）を使用している。REBAR モデルは、ADINA で鉄筋をシミュレートする際の専用要素と言える。しかし、REBAR モデルを使って RC 構造を解析すると、RC の荷重-変位曲線はコンクリートのそれに似ているが、最大荷重以降の荷重-変位曲線は、実験結果と大きく異なっている。これは、少なくとも荷重-変位曲線に鉄筋の影響を反映していないことを意味する。そこで、本論文では、円筒形断面を有する RC 柱を例に、コンクリートおよび RC 柱の軸圧縮試験と、BEAM 要素モデル（BEAM モデル）および REBAR 要素モデルの解析結果と比較考察し、RCFT 柱のモデル化に適用した。

キーワード : 数値シミュレーション， ADINA，鉄筋，鉄筋コンクリート柱，RCFT柱