ULTIMATE CAPACITY OF SLENDER STEEL REINFORCED CONCRETE COMPOSITE COLUMNS

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ABSTRACT: An experimental study on the behavior of steel reinforced concrete columns and results of a nonlinear numerical analysis are presented. Eight slender steel reinforced concrete composite columns with rectangular section were tested under axial and eccentric loading conditions. Details of the experimental investigation including description of the test columns, testing arrangements, failure modes and mechanism, strain characteristics, load-deformation responses were put forward. Effects of various geometric and material parameters such as concrete strength, slenderness of columns and eccentricity of the applied axial load were studied. The load bearing capacity is reduced with increased slenderness ratio and eccentricity. Significant gains in load capacity are obtained with increased concrete strength for column subjected to axial load, but the capacity is not strongly influenced by the strength of concrete for column subjected to eccentric load. Then this paper presents a numerical method for the analysis of pin–ended slender columns, producing axial force or axial force combined with symmetrical single-curvature bending. This method is applicable for determining the material failure load or buckling failure load of a slender steel reinforced concrete composite column. In this method both material and geometric nonlinearities are taken into account. The results of numerical analysis by proposed method correlate well with the results of the tests.

Keywords: Steel reinforced concrete, Slender column, Capacity, Test, Nonlinear analysis

INTRODUCTION

Steel reinforced concrete （SRC）structures have become a very practical and effective structural system for high rise buildings all over the world ,especially in earthquake area .They provide the required stiffness to limit the story drift of the building to an acceptable limit of lateral displacement, to resist the lateral seismic and wind loads very effectively. The introduction of shaped steel has made it possible to design more slender columns. However, although they can reduce column size, the columns become less ductile due to the brittleness of high-strength concrete. Furthermore, the capacity of slender column is strongly influenced by the second order displacement. Therefore, the structural performance of slender steel reinforced concrete composite columns have recently become a major concern for design engineers.

Many aspects, such as effect of slenderness, amount of shaped steel, ductility, compressive axial force ratio, and eccentricity of the applied load, have to be investigated in order to better understand the structural behavior of the columns. Some researchers, for example Morino et al.(1984), Mirza and Skrabek (1991), Lakshmi and Shanmugam (2000), have studied short steel reinforced concrete composite columns of normal and high-strength concrete subject to axial load. Only a few have studied full-scale composite columns under eccentrically applied axial loading, for example Mirza and Tikka (1999), Mirza and Lacroix (2003). However, the behavior of slender steel reinforced concrete composite columns is not yet fully understood.

ACI318-95 and Chinese standard JGJ138-2001 (Technical specification for steel reinforced concrete composite structures) permit a moment magnifier approach for design of slender composite columns. This approach is strongly influenced by the effective flexural stiffness of the column that varies due to cracking, creep, nonlinearity of the concrete stress-strain curve, slenderness of column, and eccentricity of the applied axial load. This is expected because the ACI and JGJ138 equations were developed for reinforced concrete columns subjected to high axial loads but were modified, without any further investigation, for use in steel reinforced concrete column designs. So this paper describes experimental and theoretical investigations on the behavior of 8 slender steel reinforced concrete composite columns under axial and eccentric loading conditions. Details of the experimental investigation including description of the test columns, testing arrangements, failure modes and mechanism, strain characteristics, load-deformation responses and effects of various geometric and material parameters are presented. In this study, the three parameters varied were the concrete strength, slenderness of columns and eccentricity of the applied axial load. Then this paper presents a numerical method for the analysis of pin–ended slender columns, producing axial force or axial force combined with symmetrical single-curvature bending; this method is applicable for determining the material failure load or buckling failure load of a slender steel reinforced concrete composite column. In the method, both material and geometric nonlinearties are taken into account. In addition, the mechanical properties, such as the compressive concrete and steel strength, the modulus of elasticity, were measured in the experimental investigation. These material properties were incorporated into a model in which the material model for concrete was based on nonlinear fracture mechanics. This model was, in turn, used in a nonlinear numerical program in order to predict the responses of the slender concrete columns. Observations of the failure mechanisms during the tests and the results of the analysis, as well as some reasons for the failure of the columns under axial and eccentric compressive loading, are presented. The predicted failure loads correlate well with the experimental values.

EXPERIMENTAL PROGRAM

Geometry and Configuration

The objectives of the studies were to research the structural behavior of long, slender steel reinforced concrete composite columns subjected axial and eccentric axial loading. The test series consisted of 8 slender columns, with compressive cube (150mm) strength of concrete from 43.3Mpa to 67.0Mpa, and steel shape I10 encased in concrete. The geometric properties of steel shape were shown in Fig.1. The lengths of the columns were 2.8m, 3.2m, 3.5m, or 4.1m, with rectangular cross sections as shown in Fig.2. The thickness of the concrete cover, measured to the outer edge of the stirrup, was 15mm, and measured to the outer edge of the shaped steel flange, was 40mm, for all of the columns. The stirrup spacing was 150 mm; its diameter was 6 mm. The longitudinal reinforcing bar's diameter was 12 mm. The length-to-width ratios, defined as the ratio of the column length, L, to the cross-section dimension, b (applied axial load), or h (subjected eccentric axial loading), were 18, 22 or 26. The eccentricity of applied loading was from 0 to 60mm.The parameters varied in the tests reported here were the concrete strength, eccentricity, and the slenderness of the columns. Table 1 shows the parameters of the test columns.

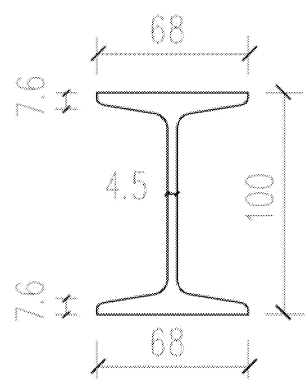


Fig.1 Geometric properties of steel shape

Material properties

The concrete mixes, designed with a target compressive cube (150mm) strength of 40Mpa, 50Mpa or 60Mpa, were produced at the structural engineering laboratory at Inner Mongolia University of Science and Technology. Superplasticizer was used in the concrete mixes to obtain high strength and work ability. The strengths of hardened concrete at 28 days are given in Table 1. The test series consisted of 8 slender columns, with compressive cube (150mm) strength of concrete from 43.3Mpa to 67.0Mpa. The column specimens were cast horizontally in steel forms. The concrete was thoroughly vibrated by means of an internal vibrator. The columns were demolded after approximately seven days and cured under laboratory conditions until tested. The mechanical properties of the shaped steel and longitudinal reinforcement bar are presented in Table 2.

TABLE 1
Details of test columns

No.	Section dimension h×b(mm)	Concrete strength f_{cu} (MPa)	Eccentricity (mm)	Length (mm)	Structural steel ratio %	Ratio of length to width
A1	180×160	65.6	0	2800	5	18
A2	180×160	59.8	0	2800	5	18
A3	180×160	55.7	0	3500	5	22
A4	180×160	50.7	0	3500	5	22
A5	180×160	53.8	0	4100	5	26
A6	180×160	67.0	0	4100	5	26
E1	180×160	43.3	30	3200	5	18
E2	180×160	46.6	40	3200	5	18

TABLE 2
Mechanical properties of structural steel and reinforcement bar

Type	$f_y(MPa)$	$f_u(MPa)$	E(Mpa)
Structural steel	379	507	2.058×10^5
Reinforcement bar	358	471	2.24×10^5

Test setup

The columns were hinged at the ends and were applied with a concentric or an eccentric axial load at both ends. A curved plate of steel and a steel circular bar formed the hinge. The buckling length of the simply supported column is the distance between the bearings at each support. All of the tests were carried out in a universal testing machine with a capacity of 5000KN. The load, which was determined by measurements from a calibrated oil pressure gauge, was increased at a constant rate without interruption. When the load approached the calculated maximum load, the oil pressure gauge was used to indicate how the deformation should be increased in order to capture the post-peak curve.

The deflection in the bending direction was measured by displacement gauge at five locations in order to determine the deflected shape of the column (Fig.3). Another dial gauge was used to check for possible biaxial bending in the perpendicular direction. The vertical displacement of the lower movable plate of the column-testing machine was measured in relation to the laboratory floor by a displacement transducer. For each specimen, 60-mm-long strain gauges were attached to the concrete on each side of the column at mid-height, 6-mm-long strain gauges were attached to reinforcement bars and each flange or web of the shaped steel at mid-height. To ensure that the failure would occur in the instrumented region of the columns, the ends of the test specimens were further confined with stirrups spaced apart 50 mm.

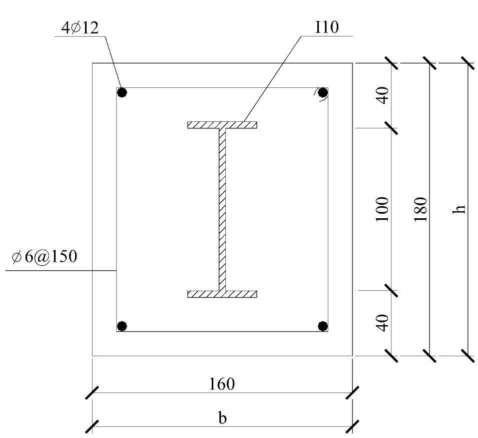


Fig. 2. Geometry and Details of Configurations

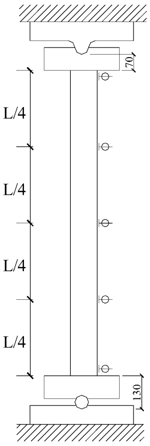


Fig.3. Test setting

Test results

All concentrically loaded columns failed due to spalling of the concrete cover at the mid-height for test specimens ; spalling of concrete cover and tensile cracks were not observed until reaching the maximum load. The columns exhibited a rather sudden and explosive type of failure, especially for columns with a length-to-width ratio of 26. For the columns subjected to an eccentric load, tensile cracks were observed at about 90% the maximum load. The failure is due to concrete spalling at the mid-height. The column failure location was within 500mm from the column mid-height. Furthermore, horizontal bending cracks developed on the tension face. On the compressed side, vertical cracks extending about 2.5 times the column width were observed at maximum load. The loss of the protecting cover combined with a high load level finally led to buckling of the flange of steel shape at the end of the test（Fig.4）

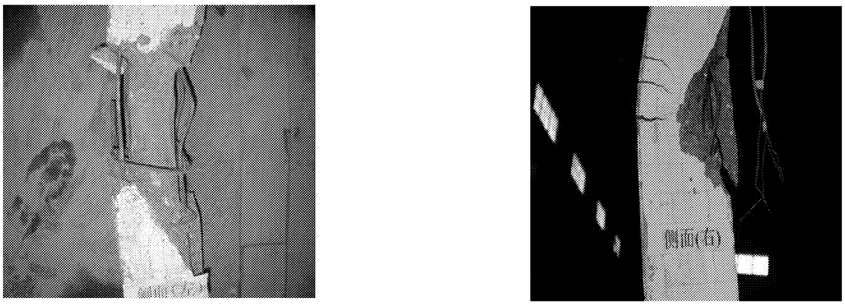
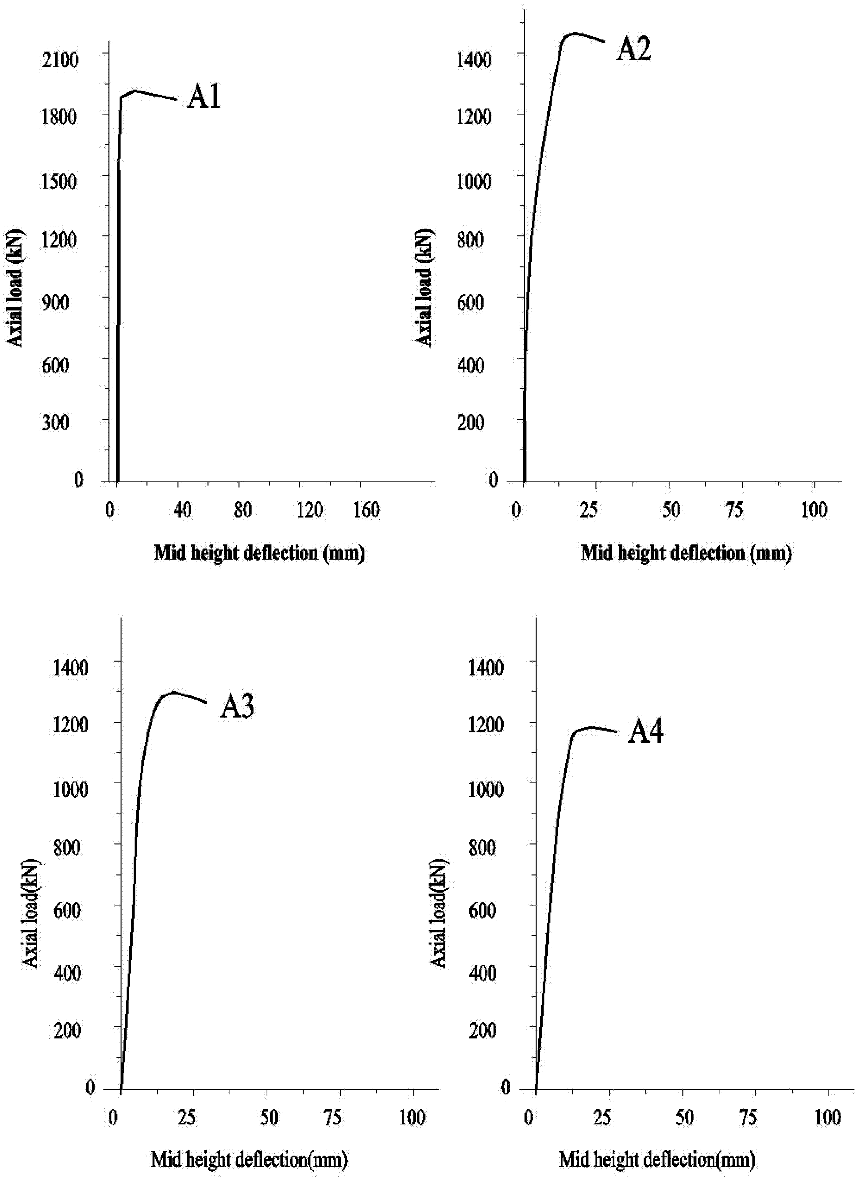


Fig.4. Buckling of the flange of steel shape and crack of column

In Fig.5, the measured load versus mid-height deflection relations are shown. In the ascending branches, the mid-height deflection of the columns were linearly increasing with load until reaching 90% of the maximum load. When the load is about 90% of the maximum load, the mid-height deflections increased rapidly. This implies that the flexural stiffness of columns started to be reduced. The load-carrying capacities was decreased with an increase of the slenderness. As can be observed from the Figure 5, the load-deflection curves are approximately the same for columns with same slenderness ratio at the initial stage.



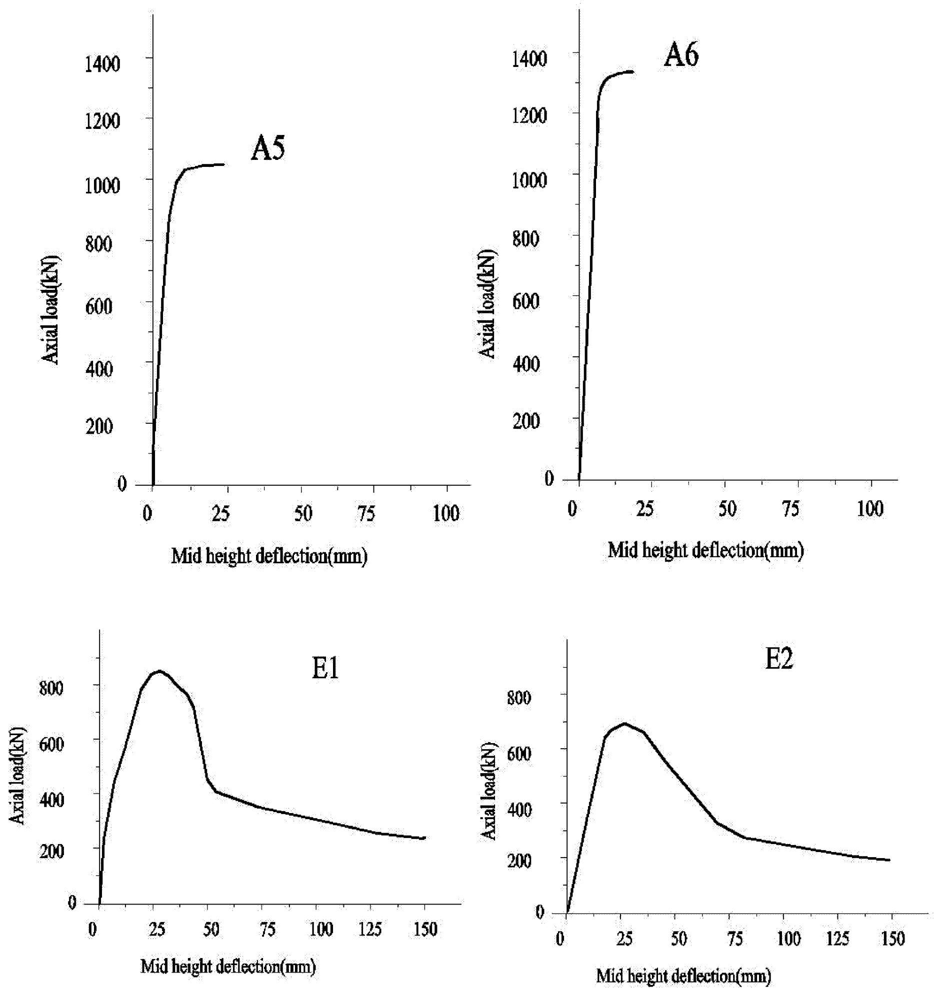


Fig. 5. The measured load versus mid-height deflection relation

Numerical Analysis of the composite columns

For computations of strength, the following assumptions were used: (1) the strain in the cross section was proportional to the distance from the neutral axis, (2) there was no slip between the structural steel or reinforcing bars and the surrounding concrete, (3) the concrete and steel stresses were calculated as functions of the strains, (4) the effects of residual stresses in structural steel section(Fig. 6) were included, (5) the concrete confinement provided by lateral ties and structural steel section flanges was considered. The composite steel-concrete cross section was assumed to consist of four different materials, each represented by a different stress-strain curve. These materials include the unconfined concrete outside the transverse tie reinforcement, the partially confined concrete with the transverse ties, the longitudinal reinforcement, and the structural steel section as indicated in Fig .7.

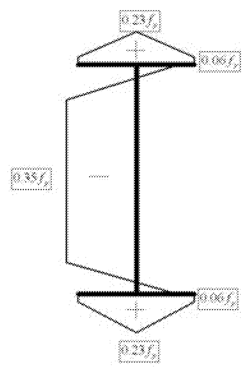


Fig.6. Residual stresses in structural steel section

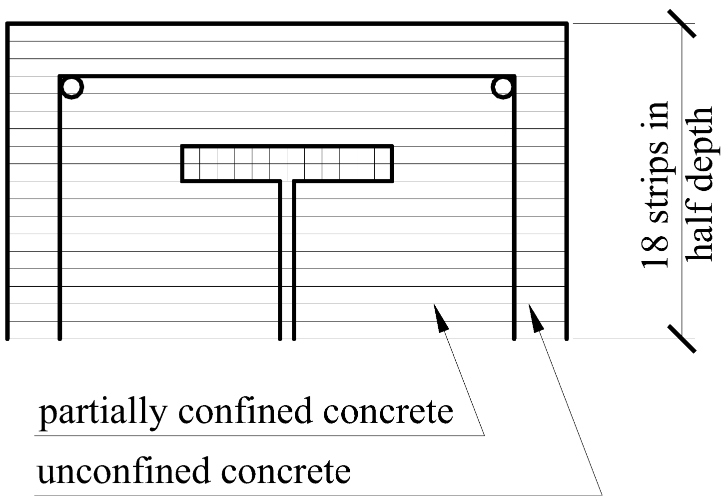


Fig. 7. Discretization of composite one-half cross section for computing strength

Fig. 8. Modeling of a composite column

The modeling of a composite steel-concrete column subjected to symmetrical single curvature bending is illustrated in Fig.8. For the purpose of analysis, the symmetry about the mid-length permitted the use of an equivalent column that was one-half the length of the original column. A column was loaded by introducing a small-applied axial load and a small bending moment at the top node, reflecting the end eccentricity used in the physical test of the column specimen. The applied axial load and bending moment were then increased in increments of constant proportions, using a second-order analysis procedure, until failure occurred. For the analysis of columns subjected to pure axial load, an imperfection was added to the initially straight element model in order to ensure a smooth transition from column stability to column instability.

The failure strength of a column was defined as the peak strength reached on the load-deflection response curve when the column was subjected to pure axial force or axial force combined with bending moment. Thus, this analysis can be applied to short up to very long steel reinforced concrete composite columns, which may fail in material failure or buckling failure.

The elastic-perfectly plastic stress-strain curves defined by measured values of yield strength and modulus of elasticity were used for structural steel section and reinforcing steel bars. The descriptions of both the unconfined and the partially confined concretes in compression outside and inside the lateral ties, respectively, were taken from Park et al (1982).

Analysis and discussion of results

The analytical method described above was applied to investigate the behavior of pin-ended rectangular slender steel reinforced concrete composite columns; the different ratios of length-to-depth, concrete strengths, and eccentricities of applied loading were analyzed. The analytical values are compared with the corresponding experimental results in order to assess the accuracy of the proposed method.

Comparisons of tested and computed strength

The tested strengths and the calculate strengths by non-linear analysis method are presented in Table 3. A comparison of tested and computed response is shown in Fig.9. The calculated values in all cases are close to the corresponding experimental results. The mean value of the ratio of experimental load P_{test} to calculated load P_{calc} is 1.13, it's standard deviation is 0.05. Therefore it can be concluded that the proposed method provides an accurate solution.

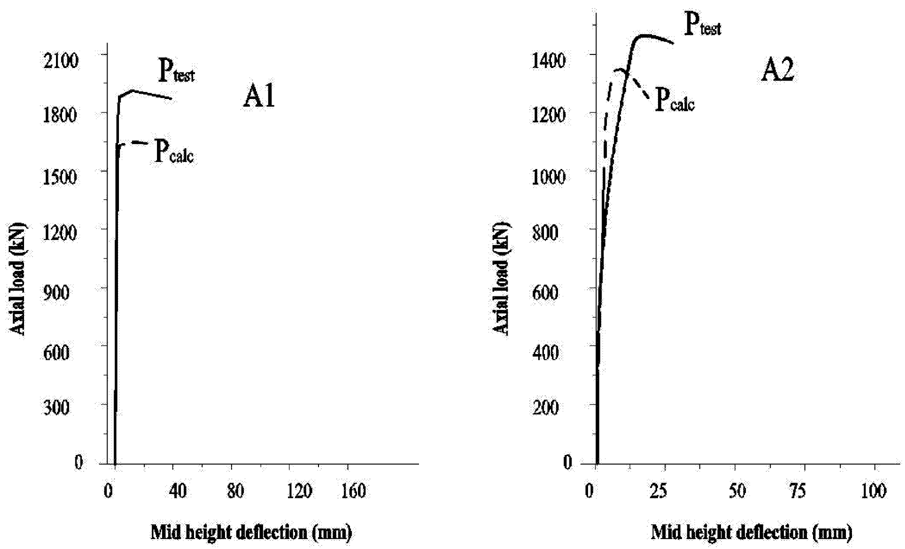
TABLE 3

Comparison of tested and computed strengths

No.	A1	A2	A3	A4	A5	A6	E1	E2
$P_{test}(kN)$	1900	1457	1270	1183	1040	1330	820	678
$P_{calc}(kN)$	1633	1341	1067	993	863	1233	739	647
P_{test}/P_{calc}	1.16	1.09	1.19	1.19	1.20	1.08	1.11	1.05

Load-deflection response

To enable a comparative study of the influence of different eccentricity ratios, length-to-depth ratios and concrete strengths on columns behavior, three different eccentricity ratios, length-to-depth ratios and concrete strengths were chosen. Fig .10(a) presents the relation between axial and mid height deformation obtained by



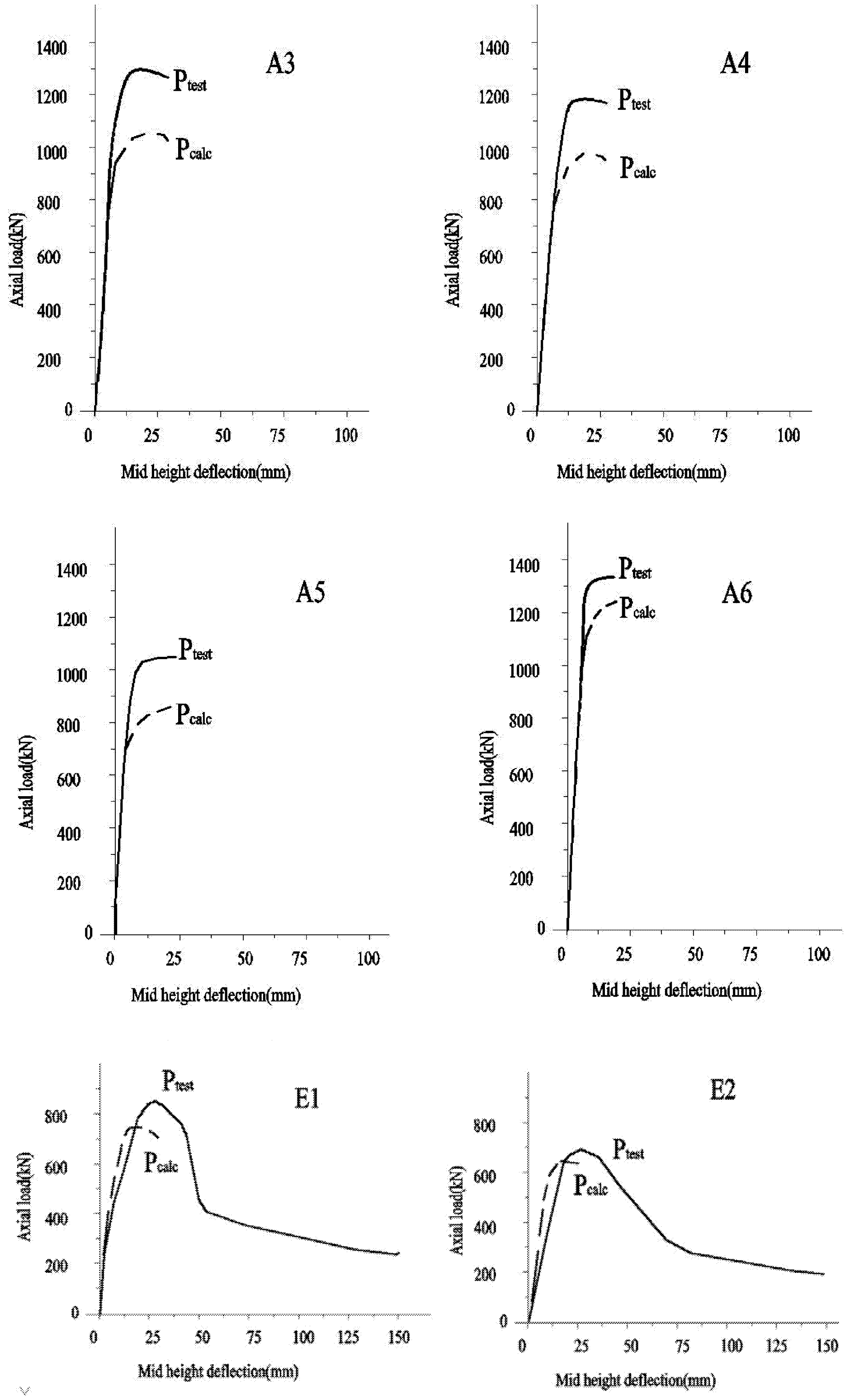


Fig. 9. Comparison of tested and computed relation of axial and mid height deformation

the proposed analytical method for the columns subjected to different initial load eccentricities, the eccentricity varies from e/h=0.1 to 0.3 about the major axis. These columns of length 3.6m pinned at the ends are subjected to single curvature bending. It is clear that column capacity is strongly affected by the amount of eccentricity. Fig.10 (b) shows the results of the simulations for three length-to-depth ratios columns subjected to an initial eccentricity of 18mm. When the length-to-depth ratio increases, the load bearing capacity is decreased. Fig.10(c) shows the relations between the load and the mid-height deflection for three different concrete strength columns subjected to an initial eccentricity of 18mm. The advantage of using a higher compressive concrete strength is not obvious. Comprehensive parametric studies show that the two main parameters that influenced the force-deflection response are column slenderness and eccentricity of the applied load. It can be seen from the Figure 5 that the load-deflection response remains very stiff even up to the ultimate load in the case of columns subjected to axial load. As the eccentricity increases the load-carrying capacity drops significantly and the initially stiffness decreases.

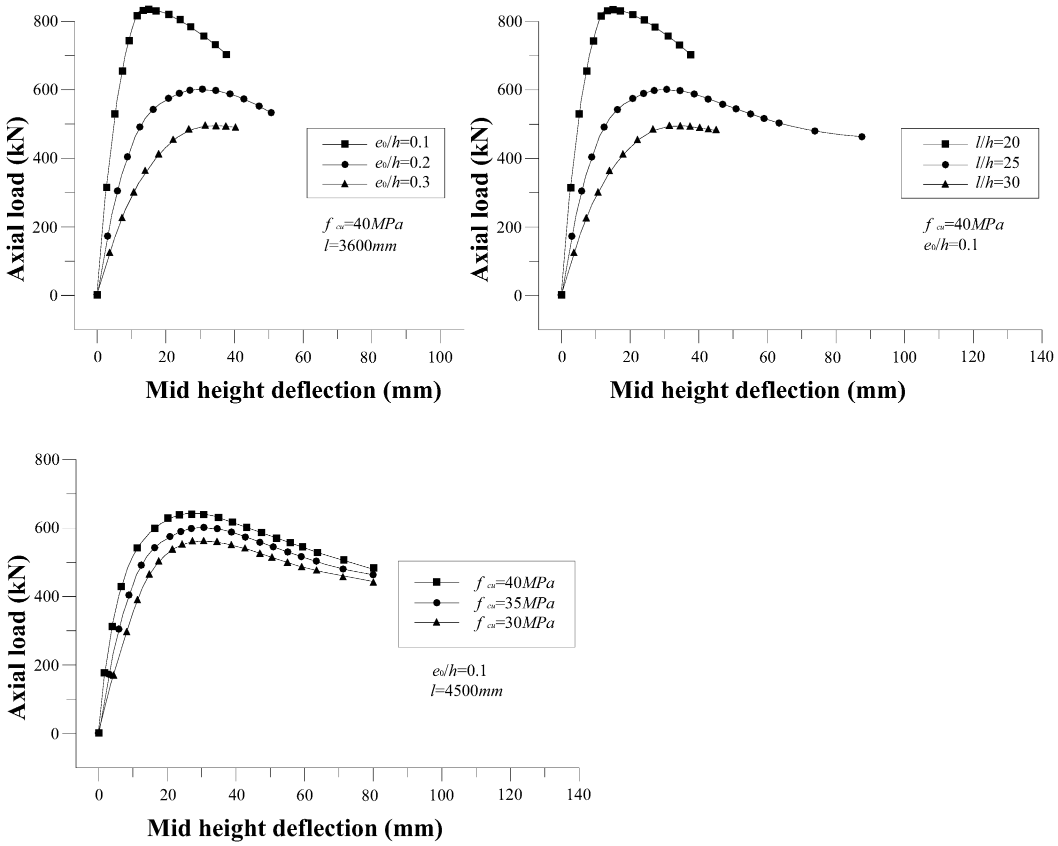


Fig.10. Computed relation of axial and mid height deflection

Conclusions

The influence of different eccentricity ratios, length-to-width ratios and concrete strengths on slender steel reinforced concrete column strength was studied. The results of tests and the numerical analysis on the columns presented here allow the following conclusions to be drawned. The buckling capacity is reduced with the slenderness ratio increase. For the eccentrically loaded columns, load carrying capacity is found to drop significantly with an increase of eccentricity, but that is not strongly influenced by the concrete strength. For column subjected to axial load, the buckling capacity is increased with an increase of concrete strength. An analytical method to compute the ultimate strength of slender steel reinforced concrete composite columns has been proposed. Comparison of ultimate strength, which was obtained by using the proposed method with the corresponding experimental results for column, has proven the accuracy of the described method.

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