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PARAMETRIC ANALYSIS OF THE DYNAMIC BEHAVIOUR OF RC COLUMNS WITH THE CONFINEMENT EFFECT OF OVERLAPPING HOOPS SUBJECTED TO LATERAL RAPID LOADINGS

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ABSTRACT

To further examine the effect of the strain rate on the behaviour of hoop-confined reinforced concrete (RC) columns, the dynamic behaviour of overlapping hoop-confined RC columns subjected to lateral rapid loadings is investigated by applying finite element analysis. Based on the verified finite element model, the effect of the following five parameters on the dynamic behaviour of RC columns were discussed considering both strain rate effect and confinement effect: the loading rate, axial load ratio, volume ratio of stirrups, shear span ratio and configuration of hoops. The following conclusions were made. The lateral-load-carrying capacity increases and the ductility decreases because of the rapid loadings, but the increase in volume ratio of the stirrups weakens the effect of the loading rate on the ductility. The axial load ratio and volumetric ratio of the stirrups affect the dynamic increasing factor (*DIF*) of the lateral-load-carrying capacity, but the effect of the shear span ratio on the *DIF* can be neglected. The increase in flexural-load-carrying capacity due to the increase in volume ratio of the stirrups under static loadings is higher than that under rapid loadings. The difference in effect of the two configurations of overlapping hoops on the dynamic behaviour of RC columns is notably small.

KEYWORDS

RC columns, Dynamic behaviour, Lateral rapid loadings, Confinement effect of overlapping hoops, Strain rate effect, Finite element analysis

INTRODUCTION

Many studies have demonstrated that the strain rate sensitivity of concrete and reinforcing steel significantly affect the RC members and structures [1-19]. The strain rate sensitivity indicates the change in properties of these materials with the increase in strain rate of concrete and reinforcing steel. Commonly, RC members can acquire the strength gain with increasing strain rate. The increase in strength is not necessarily beneficial to the dynamic response of the structure because it may result in a critical redistribution of forces in the structures or brittle types of failure with less hysteretic energy absorption capacities in some elements [19]. Bad abnormal phenomena have been found in the rapid loading tests. Some tests on RC beams show that the final failure mode shifts from the flexural failure mode at the quasi-static strain rate to the shear failure mode at the high strain rate [12-13], or the opposite transition occurs [14]. Under cyclic loadings, the damage level, stiffness degradation and strength degradation are significantly higher in the RC columns subjected to rapid loadings compared to quasi-static loadings [5-6]. It is believed that code provisions may be non-conservative for long-duration seismic loadings with significant cyclic damage [6]. To appreciate the effect of the strain rate sensitivity of concrete and reinforcing steel on the global seismic response of RC frame structures, Asprone et al. conducted an earthquake evaluation analysis, and the result shows that considering the updated material properties, to account for the earthquake-induced strain rate, a strength reserve of the structural system is experienced when only ductile failure mechanisms are considered; however, the structural capacity decreases when the brittle failure mechanisms are included [7]. Generally, the strain rate of materials in RC structures under earthquake loadings is approximately 10^{-4}-10^{-1}/sec. Thus, it may be more rational to consider the strain rate effect of concrete and steel when one evaluates the dynamic behaviour of RC structures under earthquake action.

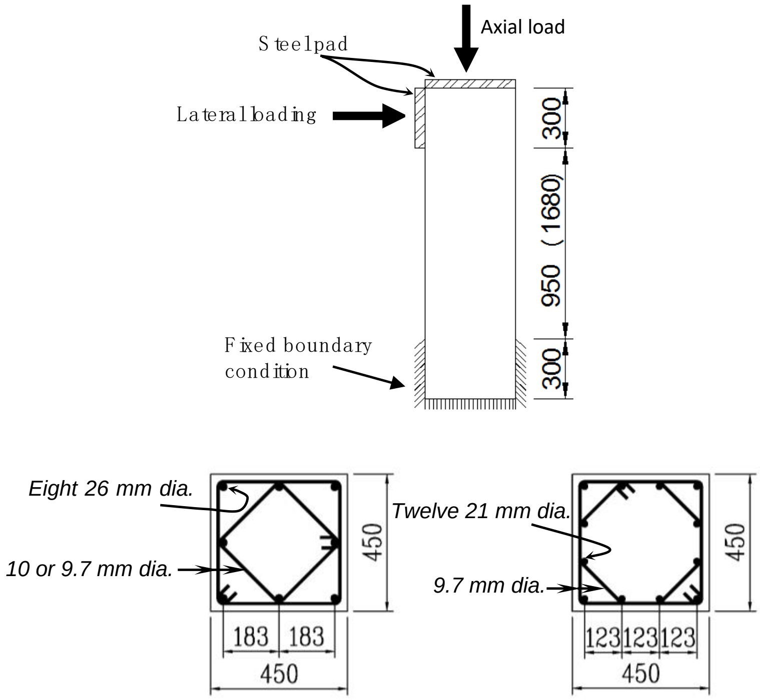
For the dynamic behaviour of RC column considering the strain rate effect, until now, many experimental studies focus on the lightly confined RC columns [2,5-6,15-16]. Fewer experimental studies [17-18] have been conducted on confined RC columns under concentric compressive rapid loadings. To make up for the lack of experimental studies, the finite element analysis method was used to analyse the dynamic compressive behaviour of confined RC columns [1,3,8], but there is no study on the confined RC columns subjected to lateral rapid loadings. Because of the high requirement on loading instrument for the rapid loading test, the FEA modelling becomes a good choice for parametric studies.

In this paper, the objective is to investigate the strain rate effect on the dynamic behaviour of reinforced concrete columns confined by overlapping hoops under lateral rapid loadings using finite element analysis. The finite element model developed by the author [1] is used, which considers the confining effect of the overlapping hoops and strain rate effect of concrete and steel. The effect of the parameters, including the lateral loading rate, axial load ratio, volumetric ratios of transverse reinforcement, shear span ratio and configuration of hoops (type A and type B in Figure 1), on the dynamic behaviour of confined RC columns were investigated.

COLUMN MODEL FOR PARAMETRIC ANALYSIS

The designed column model for the parametric analysis is presented in Figure 1. The center region in the column is 950 mm or 1680 mm, which corresponds to the shear span ratio of 2.7 or 4.5. The columns have a fixed boundary condition at the bottom with 300 mm in length and loading end at the top with 300 mm in length. The spacing of transverse hoops was reduced by one-half at each end of the columns to provide extra confinement and ensure that failure occurred in the central region. All columns have identical cross sections of 450 mm × 450 mm, and the core size measured from the center of the perimeter hoop was maintained constant at 400 mm × 400 mm. Two configurations of hoops (type A and type B in Figure 1) were used. These arrangements are typical for 8-bar and 12-bar columns. The center-to-center spacing of longitudinal bars across the section for type-A and type-B arrangements was 183 mm and 123 mm, respectively. More details of the cross sections in the test regions of different columns are shown in Table 1. All specimens with identical longitudinal reinforcement ratios of 2.65% had identical yielding strength (400 MPa) of longitudinal steel and strength (300 MPa) of the transverse hoops. The concrete compressive cylinder strength f_c was 30 MPa.

Various key parameters in Table 1 were considered, including the lateral loading rate (0.1 mm/s (quasi-static loadings) and 100 mm/s), axial load ratio n (0, 0.2, 0.4, 0.6, 0.8), volumetric ratios of transverse reinforcement ρ_{sv} (1.5% and 3.0%), shear span ratio λ (2.7, 4.5) and configuration of hoops (type A and type B). Table 1 summarizes the specimen characteristics of the simulation matrix. The titles of the specimens in Table 3 describe the varying parameters and have the following meaning. The first letter (A or B) in the titles represents the reinforcement arrangement of type A or type B. The numbers after the first letter indicates the shear span ratio λ (λ=2.7 or λ=4.5). The numbers behind the middle hyphen represent the volumetric ratio $\boldsymbol{\rho_{sv}}$ of the transverse reinforcement. Numbers 3.0 and 1.5 indicate ρ_{sv}=3% and ρ_{sv}=1.5%, respectively. The last character n represents the axial load ratio of 0-0.8.



Type A *Type B*

Fig. 1 - Details of the column model for the parameter analysis

Tab. 1 - Columns for the parameter analysis

Specimen	Longitudinal reinforcement diameter (mm)	Transverse reinforcement			Axial load ratio *n*	Lateral loading rate
		Diameter (mm)	Spacing (mm)	Volumetric ratio ρ_{sv}		
A2.7-1.5-n	26	10	86	1.5%	0,0.2,0.4, 0.6,0.8	0.1 mm/s (Quasi-static)、100 mm/s
A2.7-3.0-n	26	10	43	3.0%		
A4.5-3.0-n	26	9.7	43	3.0%		
B2.7-3.0-n	21.2	9.7	43	3.0%		

EXPLICIT DYNAMIC FEA MODELLING

The finite element model was developed by the author [1], which has been verified by the experiment on axial compression RC column confined by type-A and type-B overlapping hoops at low and high strain rates, was used to investigate the strain rate effect on the behaviour of the RC column under lateral rapid loadings. As shown in Figure 2, a half model with symmetric boundaries on the Y-Z plane was used based on the symmetry, which reduced the computation cost. A fixed boundary condition was applied at the bottom of the columns with 300 mm in length. The steel plates in Figure 1 were modelled with analytical rigid plates, which is reasonable to save the computing cost. The motion of the rigid plate was constrained to the motion of the reference point, which implies that the translational and rotary motions of the rigid plate are consistent with the corresponding reference point. Thus, the axial load was applied to the top reference point RP with an allowable translational motion in direction Z and an allowable rotational motion around the X-axis, and the lateral load was applied to the side reference point RP-1 with an allowable translational motion in direction Y and an allowable rotational motion around the X-axis.

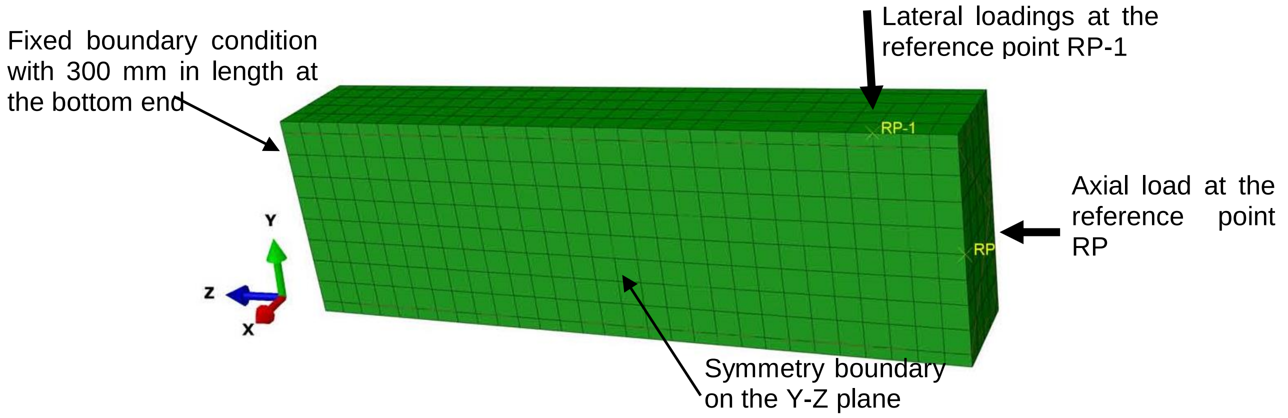


Fig. 2 - Illustration of the finite element model

INFLUENCE ANALYSIS OF INVESTIGATED PARAMETERS

Effect of loading rate

At the loading rate of 100 mm/s, the strain rates reach to the order of magnitude of 10^{-1}/s and 10^{-2}/s for columns with shear span ratio 2.7 and 4.5, respectively, which is in the range of strain rate of RC structures under earthquake action. As shown in Figure 3, the loading rate has an obvious effect on the lateral load *F* versus displacement Δ curves. The lateral bearing capacity increases with the increase in loading rate. The dynamic increasing factor (*DIF*) of the lateral bearing capacity, namely, the ratio of dynamic bearing capacity to quasi-static bearing capacity at a loading rate of 0.1 mm/sec, is commonly used to describe the effect of the loading rate on the bearing capacity. In these cases, the maximum *DIF* is 1.2 when the loading rate reaches to 100 mm/s. Figure 3(a) shows the descending branches of F-Δ curves become obviously steeper with the loading rate increasing when the axial load ratio is 0.8. However, increasing the volumetric ratio of stirrups the effect of loading rate on the slope of the descending branches of F-Δ curves becomes weaker, which is shown in Figure 3(b).

Influence of axial load ratio and volumetric ratio of stirrups

(1) Lateral load F versus displacement Δ curves

Figure 4 shows the similar influence of the axial load ratio *n* and volumetric ratio of stirrups ρ_{sv} on F-Δ curves for quasi-static and rapid loadings. When the axial load ratio *n* is between 0.0 and 0.6, the lateral bearing capacity of columns increases as the axial load ratio increases, but the ductility decreases. When the axial load ratio is in the low range of 0.0 to 0.2, the columns behave with good ductility and increasing the volumetric ratio of stirrups from 1.5% to 3.0% has little influence on the F-Δ curves. As the axial load ratio increases to 0.6, the ductility decreases obviously. However, increasing the volumetric ratio of stirrups is able to enhance the lateral bearing capacity and obviously improve the ductility in the range of axial load ratio from 0.4 to 0.6. The reason is that the compressive area of the core concrete confined by the overlapping hoops increases as the axial load ratio increases, and then the confining effect of overlapping hoops on

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the core concrete becomes stronger, which enhances the strength and ductility of the core concrete.

When the axial load ratio *n* reaches to 0.8, the descending branches of *F-Δ* curves drop more remarkable for the columns with volumetric ratio of stirrups 1.5%. In addition, the lateral bearing capacity drops obviously for the columns under quasi-static loading. However, the lateral bearing capacity for the columns under rapid loading drops a little. That is because the strain rate effects increase the strength of concrete and steel. As the axial load ratio increases, that the lateral bearing capacity falls down means the failure model of the RC sections changes from a tension failure to a compression failure. When raising the volumetric ratio of stirrups to 3.0% at *n*=0.8, the lateral bearing capacity drops slightly under quasi-static loading or increases slightly under rapid loading.

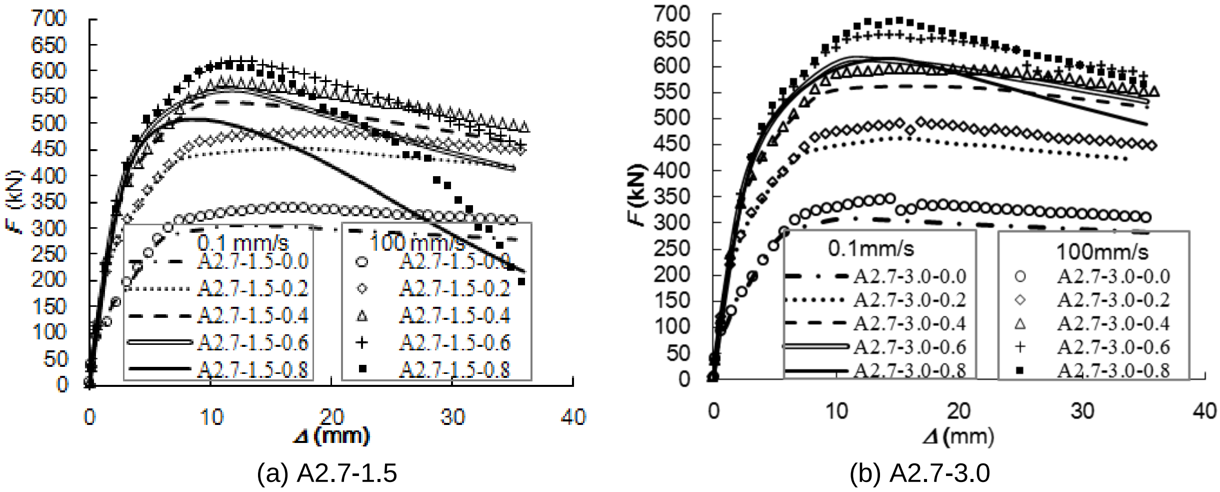


Fig. 3 - Effect of the loading rate on the F-Δ curves

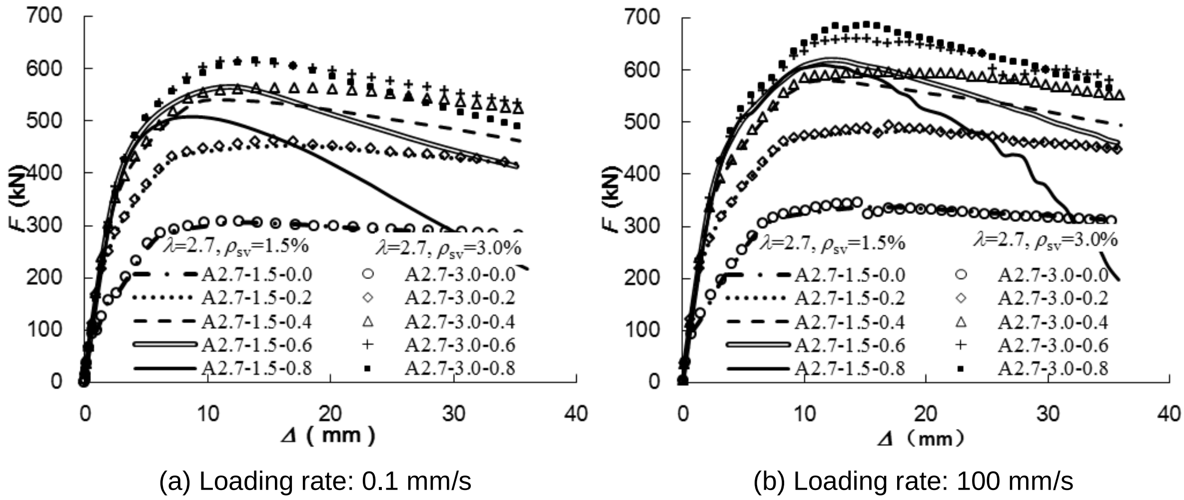


Fig. 4 - Influence of axial load ratio and volumetric ratio of stirrups on F-Δ curves

(2) Dynamic increasing factor (DIF) of the lateral bearing capacity

As shown in Figure 5, the *DIF* decreases with the axial load ratio *n* increasing at first, and then inversely ascends with *n* increasing. Figure 6 depicts the influence of volumetric ratio of stirrups ρ_{sv} on *DIF*. In Figure 6, $R_{DIF,sv}$ means the ratio of the *DFI* with ρ_{sv} of 3.0% to the *DFI* with ρ_{sv} of 1.5% for the columns with shear span ratio of 2.7 at the same axial load ratio. It can be seen that increasing the volumetric ratio of stirrups reduces the *DIF*, and $R_{DIF,sv}$ becomes smaller with the axial load ratio increasing. Raising the volumetric ratio of stirrups from 1.5% to 3.0% makes the *DIF* reduce 7% at an axial load ratio of 0.8. After the axial load ratio increasing, the compression area of the section broadens, which is beneficial to the confining effect. The phenomenon of *DIF* reducing has been explained by the researches [20-21] that as the confining effect of stirrups on concrete strengthens, the increase in strength of concrete due to strain rate effect reduces.

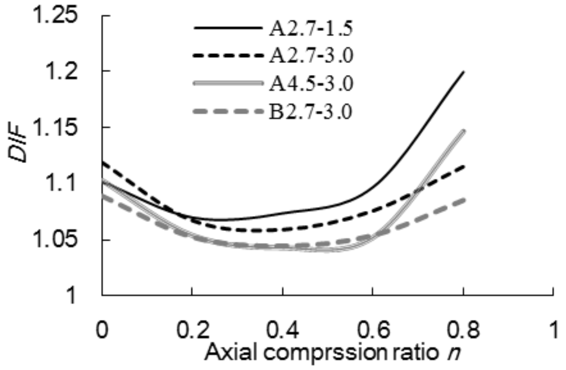


Fig 5 - Influence of axial load ratio n on DIF

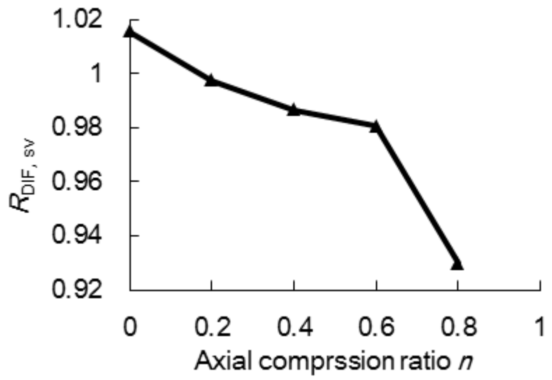


Fig. 6 - Influence of volumetric ratio of stirrups on DIF

(3) Moment (M)-Axial load (N) interaction diagram for RC column section

Figure 7 shows the similar influence of volumetric ratio of stirrups ρ_{sv} on *M-N* interaction diagrams of RC columns section for quasi-static and rapid loading. Increasing the ρ_{sv} makes the axial load at balance failure increase. The ρ_{sv} has little influence on the interaction diagrams when the axial load ratio *n* is in low range. As the *n* rises, the increase in ρ_{sv} enhances the flexural capacity. It seems that Figure 8 shows the influence of ρ_{sv} on flexural capacity at a certain *n* for different loading rate. There $M_{3.0}/M_{1.5}$ means the ratio of flexural capacity with ρ_{sv}=3.0% to flexural capacity with ρ_{sv}=1.5% at the same loading rate and axial load ratio. It is seen that increasing the ρ_{sv} makes the percentage of increase in flexural capacity larger with the axial load ratio increases and the effect is stronger under quasi-static loading than under rapid loading.

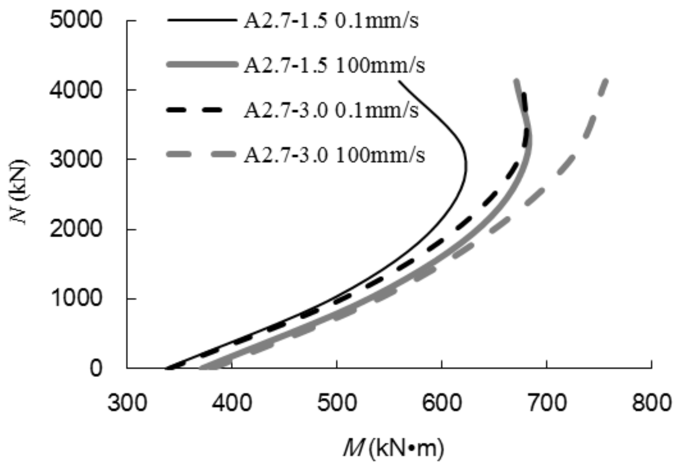


Fig. 7 - Influence of volumetric ratio of stirrups and loading rate on M-N interaction diagrams

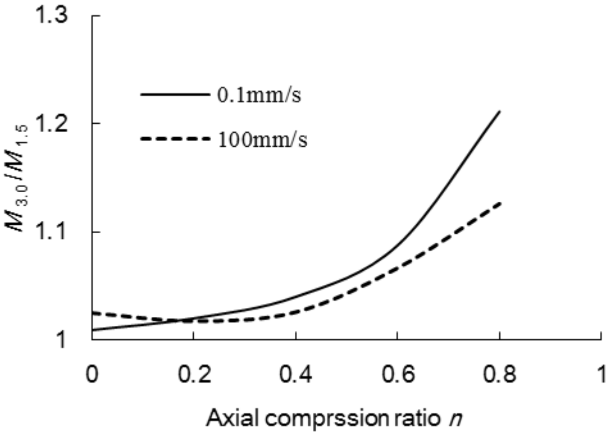


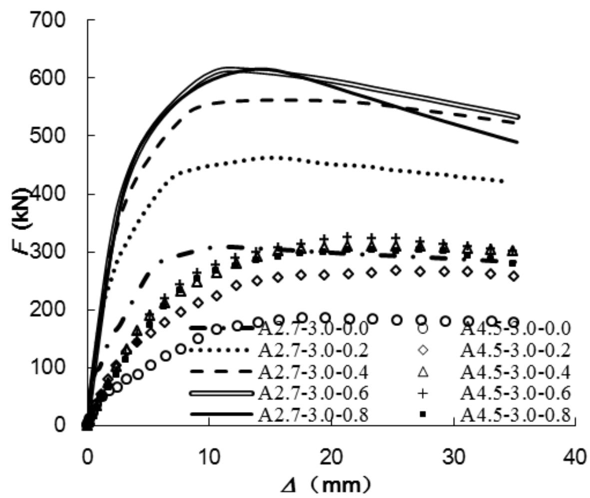
Fig. 8 - Influence of volumetric ratio of stirrups on flexural capacity for column with shear span ratio of 2.7

Influence of shear span ratio

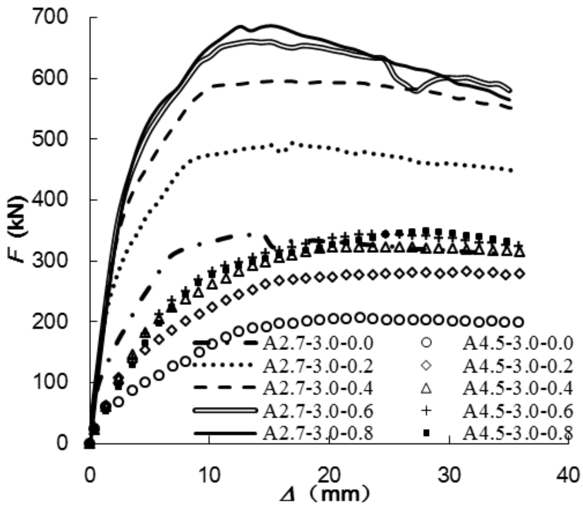
Figure 9 shows the similar influence of shear span ratio λ on *F-Δ* curves for quasi-static and rapid loading. As the shear span ratio increases, the lateral stiffness and lateral bearing capacity fall obviously, but the ductility becomes better. Figure 10 shows the influence of shear span ratio λ on the *DIF* of lateral bearing capacity. In the figure, $R_{DIF,\lambda}$ means the ratio of the *DFI* with λ of 4.5 to the *DFI* with λ of 2.7 for the columns with the same axial ratio and volumetric ratio of stirrups. It seems that the influence of shear span ratio on the *DIF*, which is less than 3%, can be negligible.

Influence of configuration of stirrups

When investigating the influence of configuration of stirrups, the longitudinal reinforcement ratio, the volumetric ratio of stirrups and the spacing of overlapping hoops keep the same for the contrast columns, only the configuration of stirrups is different from each other. From Figure 11, it is seen that the type A and type B reinforcement arrangements have little different influence on the *F-Δ* curves for different loading rate.



(a) Loading rate: 0.1mm/s



(b) Loading rate: 100mm/s

Fig. 9 - Influence of shear span ratio on F-Δ curves

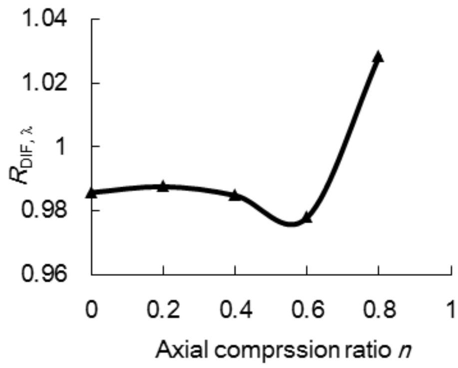
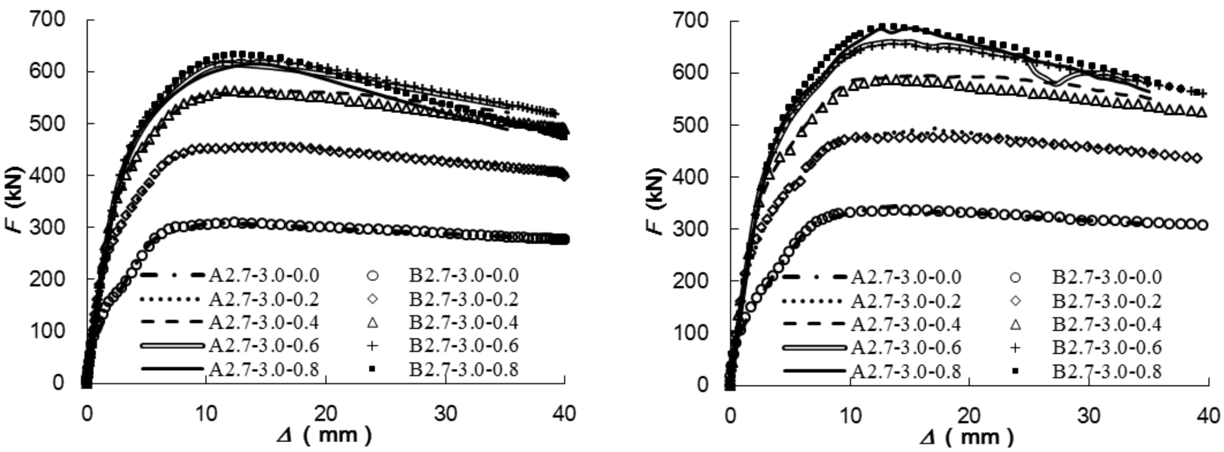


Fig. 10 - Influence of shear span ratio on DIF



(a) Loading rate: 0.1mm/s

(b) Loading rate: 100mm/s

Fig. 11 - Influence of configuration of stirrups on F-Δ curves

CONCLUSION

Based on the three-dimensional nonlinear finite element analysis model, a parametric analysis of dynamic behaviour of RC columns with confinement effect of overlapping hoops subjected to lateral rapid loading in this paper. The following conclusions were drawn.

(1) Increasing the lateral loading rate increases the lateral bearing capacity, but decreases the ductility and makes the descending branches of *F-Δ* curves become steeper. However, increasing the volumetric ratio of stirrups is able to weaken the effect of loading rate on the slope of the descending branches of *F-Δ* curves. Raising the axial load ratio makes the descending branches of *F-Δ* curves become steeper for different loading rate.

(2) The influence of axial load ratio, volumetric ratio of stirrups and shear span ratio on the behaviour of RC columns is similar for different lateral loading rate.

(3) The dynamic increasing factor (*DIF*) of lateral loading carrying capacity decreases with the axial load ratio increasing and then inversely develops. Increasing the volumetric ratio of stirrups reduces the *DIF* and the larger the axial load ratio is, the more the *DIF* reduces. The influence of shear span ratio and configuration of hoops on the *DIF* can be negligible.

(4) The volumetric ratio of stirrups has similar influence on the interaction diagram of RC column section for different lateral loading rate. However, the increase in volumetric ratio of stirrups enhances flexural capacity larger under quasi-static loading than under rapid loading and that is influenced by the axial load ratio.

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(5) With the identical longitudinal reinforcement ratio, volumetric ratio of stirrups and spacing of overlapping hoops, the change of configuration of hoops between type A and type B slightly affects the behaviour of RC columns for different lateral loading rate.

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