論文 EFFECT OF HYSTERETIC REVERSALS ON LATERAL AND AXIAL CAPACITIES OF REINFORCED CONCRETE COLUMNS

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ABSTRACT: The combination of loading frequency and loading magnitude of lateral loadings on buildings due to earthquakes are always not constant, but are variables within the duration of a single earthquake. This fact is more pronounced and results are more scattered when dealt with different earthquakes. To analyze the structural response to such kind of excitations and understand the effect of hysteretic reversals on lateral and axial capacities, seven reinforced concrete column specimens were tested under different lateral loading histories. The experimental results are presented and discussed and finally results of a trial on shear-friction model are summarized.

KEYWORDS: reinforced concrete column, near field earthquake, loading frequency and magnitude, hysteretic reversals, Lateral and axial capacity deterioration, shear-friction model

1. INTRODUCTION

In order to secure societies from earthquake disasters, post-earthquake campaigns, analytic and experimental works pointed to the need of a minimum limit performance of the construction patrimony and extended it to new developed ones. Studies showed that the seismic performance of individual structural elements in moderately tall reinforced concrete buildings depends on the mechanical and geometric characteristics of loaded elements, as well as on the type of loadings[1,2,3]. While effects of different types of axial loading had previously been investigated[3], this paper presents experimental results of columns subjected to constant axial loading and different types of unidirectional cyclic lateral loading, simulating near and far field earthquake shakings. The testing program included 16 specimens, seven of them are the subject of this paper while other specimens are oriented to strengthening studies. Analysis of the experimental results tried to reach conclusions as to the effect of hysteretic reversal type on columns' response for instance, deformability, axial stiffness and shear strength degradation.

2. TESTED SPECIMENS AND EXPERIMENT SETTINGS

The tested specimens are scaled to 1/3 of actual columns, considered representative of those occurring in the first story of moderately tall building systems located in seismic regions. The cross section of all columns is square (300x300mm²). Geometric details and material mechanical properties are depicted and listed in **Fig.1** and **Table 1**, respectively. The principal variables of the testing program are, mainly, transverse reinforcement ratio and lateral loading type, while the axial load is constant for all specimens. The presumed axial load ratio based on a concrete strength of 24 MPa is 0.25, which corresponds to a constant axial load of 540 kN actually applied on all specimens, though cylinder concrete tests revealed later higher strength.

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 Table 1 Material and characteristics of specimens

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	Height	Shear	Concrete	Axial	Longitudinal	Transverse	Lateral
Specimen	meight	span	strength	load ratio	reinforcement	reinforcement	loading
	(mm)	ratio	σ_{B} (MPa)	η	(MPa)	(MPa)	type
No.1	600	1	27.7	0.22	12-D13	2-D6@50	Type-1
					ρ _g =1.693%	ρ _w =0.43%	
No.11			28.15	0.21		2-D6@150	Type-1
No.12	900	1.5	20.15	0.21		ρ _w =0.14%	Type-2
No.13			26.1	0.23	16-D13	2-D6@50	Type-1
					ρ _g =2.258%	ρ _w =0.43%	
No.14					σ _y =447	σ _{wy} =398	Type-2
No 15						4-D6@50	Type_2
110.15						ρ _w =0.85%	Type-2
No.16	600	1			12-D13	2-D6@50	Type-2
					ρ _g =1.693%	ρ _w =0.43%	

The columns were tested in a vertical position. Independent axial and lateral loads were applied simultaneously to specimens. Laterally, columns were subjected to an anti-symmetric double curvature bending where the loading path was controlled by displacement. In order to simulate the action of near and far field earthquakes, two types of lateral loading were selected. Till a certain level, the total maximum deflection for both loading types is the same, while the difference resides in the number of



Fig.2 Lateral displacement loading patterns

intermediate hysteretic reversal peaks as shown in Fig.2, then Type-2 becomes monotonic.

3. OBSERVED BEHAVIOR, VISIBLE DAMAGE AND FAILURE MODE

Changing lateral loading did not come up to expectations. The results exhibited some differences among tested specimens, while few differences were noticed among specimens with

low transverse steel ratio or low shear span ratio. However, visible damages were more noticed under loading Type-1. Also, collapse of columns was less brittle under the previous loading type than under lateral loading Type-2.

Disregarding the type of loading, all specimens failed as predicted by design: except specimen No.15, all specimens were designed to fail in shear. Also, except specimen No.15, shear cracks characterized the crack patterns development and conditioned the failure mode of columns. While failure in specimens with low transverse steel ratios or low shear span ratio (No.1, No.16, No.11, No.12) was due to clear diagonal tension cracks, failure in other specimens with higher transverse steel ratios and higher shear span ratio (No.13, No.14) was based on truss mechanism. Specimen No.15 experienced the formation of truss mechanism after yielding of longitudinal reinforcement. Bond splitting and spalling of concrete cover were observed on specimens during the last loading cycles. Actually, evolution of cracks and their widths depended closely on the type of lateral loading. Their number was higher and their width was lower under lateral loading Type-1 than under lateral loading Type-2. Finally, collapse was reached when columns were unable to sustain any more the applied axial load, which corresponded at the time when shear strength decay consumed nearly the whole lateral capacity of columns. Also, in good accordance with conclusions of previous experiments on nearly similar columns[3], collapse occurred along inclined planes. For all specimens, plane inclinations were slightly steeper under lateral loading Type-2 than under loading Type-1.

4. COLUMNS RESPONSES

The data analysis of tested specimens indicated the dominance of shear deformation during loading as to the flexural one. The curvature-lateral drift responses of all specimens, except in specimen No.15, showed a fast increase in the lateral deformation rather than in the curvature. Also, except on specimen No.15, no a single longitudinal bar yielded before shear failure in all specimens. Yield was reached for almost all stirrups depending on the position of the stirrups to the major cracks. All steel strains, generally, reached slightly higher maximum values under loading Type-1 than under loading Type-2. Buckling of steel bars, which occurred simultaneously when stirrups' hooks opened was one of the conditions that lead to collapse.

4.1 LATERAL LOAD-LATERAL DISPLACEMENT RESPONSES

As observed on specimens with same shear span ratio, though a small difference in concrete strength, high transverse reinforcement ratio provided high shear resistance and allowed large lateral deformability. Also, shear strength reached high levels for specimens with low shear span ratio, however their lateral deformability was low.

Compared to loading Type-1, the application of loading Type-2 resulted in higher shear strength on the first loading direction and in lower shear strength on the opposite direction. Higher values were obtained because of absence of low amplitude reversals, which would induce some damage. Lower values were obtained in the opposite direction because of the cracks imposed by the large amplitude of the first loading direction. Those cracks induced a drop in the shear strength on the first loading direction that influenced the shear strength in the opposite direction. Also, shear strength degradation was more pronounced under loading Type-1 than under loading Type-2, which can be explained by the development of more cracks in the first loading type than in the second one.

As for lateral deformability, while specimens No.1 and No.16 or No.13 and No.14 that responded differently relatively to the lateral loading type where loading Type-2 induced higher

lateral deformability, specimens No.11 and No.12 did not show any difference toward applied lateral loading type. To illustrate these mentioned observations, tested columns' lateral load-lateral drift ratio responses are depicted in **Fig.3**.



Fig.3 Lateral load-lateral drift responses

4.2 VERTICAL DISPLACEMENT RESPONSES

Concerning the vertical deformation responses shown in **Fig.4**, experimental data showed that degradation of column axial stiffness was comparable from a certain level of testing for both lateral loading types, though degradation was faster at the beginning of loading for specimens subjected to loading Type-1. Finally, collapse occurred at the same level of vertical deformation for each pair (No1 and No.16, No11 and No.12, and No.13 and No.14). Furthermore, transverse steel content

18 400 Specimen No. 15 300 200 (kN 100 force 0 ateral -100 -200 -300 -400 -6 -3 0 3 6 9 12 15 18 Lateral drift ratio (%)

and shear span ratio influenced differently the evolution of axial stiffness. For columns with same shear span ratio, providing more stirrups delayed degradation in the axial stiffness, consequently collapse occurred at higher vertical deformation. However, for columns with same transverse steel ratio, shear span ratio difference resulted in the same limit vertical deformation and collapse.

4.3 DISSIPATED ENERGY

Depending on the loading type and the reinforcement amount, the total dissipated energy, obtained from lateral and vertical loads, as shown in **Fig.5**, varied from one element to another. Higher values were obtained for higher confinements, for higher shear span ratios and *also for higher numbers of hysteretic reversals*. Loading Type-1 induced higher total dissipated energy than loading Type-2. Also, while not depicted by a figure, a tentative to assess the part of energy dissipated by reinforcements and concrete was carried out. Ramberg-Osgood model was used to

assess stresses in the reinforcements and approximate their corresponding amount of dissipated energy. The part of energy dissipated by concrete was deduced from the total one. It was found that during loading concrete dissipated far higher amount of energy in all specimens, compared to steel. This fact calls attention to the effect of friction and its contribution to dissipate energy.



Fig.4 Vertical deformation-lateral deformation responses

5. SHEAR-FRICTION MODEL

The shear-friction model[2,4] shown in Fig.6, based on an assumed diagonal failure plane, was applied to the tested specimens in order to find some convenient relationships that

might allow assess the ultimate limit of columns failing in shear in terms of the axial load N and its corresponding lateral drift ratio R. The ultimate stage is attained when the resulting sliding force S along the failure plane reaches the plane tangent component of the compression force Cby mean of friction μ . Actually, the inclined plane angle θ is a very crucial parameter that has not a negligible effect on the aimed results. Inclination of observed failure planes during testing, applied axial load and forces developed by stirrups crossing the presumed planes were the basis to express the variation of friction along the presumed plane. Fig.7, which includes other experimental results[2,3], is a trial to relate the observed failure plane inclination to some main parameters by mean of a simple function. The figure shows an assumed variation function of plane inclination where data errors were taking as a half of the calculated standard deviation (σ_{tan} $_{\theta}=0.282, \ \overline{\tan \theta}=0.753).$

As to friction variation, considering or neglecting the dowel action of longitudinal reinforcement resulted in differences as to required friction values at columns' ultimate stage. The formulation of the friction, after some trials, was expressed relatively well by combination of different parameters than by a single one, to name the lateral drift ratio (R). The friction, when dowel action was considered is shown in Fig.8 including data of previous experiments and data reported by other authors[2].

7. CONCLUSIONS

Changing the lateral loading pattern, in this testing program, did not exhibit much differences as expected. However, the following conclusions can be drawn:



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(1) Evolution of cracks and their widths depends closely on the type of lateral loading. Their number is higher and their width is narrower under Type-2 loading (few-hysteretic-reversals).

(2) Shear strength degradation is more pronounced under Type-1 loading (many-hysteretic-reversals).

(3) For low transverse reinforcement ratio, lateral loading type has negligible effect on the attained maximum lateral drift, however it has an effect on the maximum shear strength in the negative loading direction, where maximum shear strength is higher under loading Type-1 than under Type-2.
(4) For high transverse steel ratio or low shear span ratio, lateral loading Type-2 induces larger lateral deformability than loading Type-1.

(5) Axial stiffness degradations under both loading types are comparable. Limit vertical deformations are also comparable and collapse of columns occurs at the same level of vertical deformation despite the loading type difference.

(6) Total energy dissipated under loading Type-1 is higher than under loading Type-2.

(7) Friction along failure plane at column's ultimate stage is well formulated by combining different parameters, including lateral drift ratio.

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Fig.6 Shear-friction model



Fig.7 Observed angles of critical cracks



Fig.8 Shear-friction formulation

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