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TESTS OF A REINFORCED CONCRETE FRAME BEAM SUBJECTED TO SEISMIC-TYPE LOADING

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The experimental results from reversed cyclic loading tests on twelve exterior reinforced concrete beam-column joints are presented. The primary variables were the ratio of positive to negative reinforcement and the stirrup spacing of beams. The specimens were subjected to cyclic load reversal at deflection levels intended to represent the levels that could be obtained during a moderate or severe earthquake. The results are compared with the existing design recommendations and investigating the behavior of reinforced concrete beam. A reduced stirrup spacing and an increased ratio of positive to negative steel at the face of the support improves cyclic performance of beams.

Keywords: reinforced concrete, beams, cyclic loads, earthquake-resistant structure, ductility,

1. INTRODUCTION

Beams in special ductile frames designed to resist seismic action are required to contain transverse ties that not only must provide member shear capacity and confine concrete in portions of the frame subjected to repeated quasi static inelastic bending, but also should prevent or delay the buckling of longitudinal reinforcement.

According to Eurocode 8 [1] the design of earthquake resistant concrete building shall provide an adequate energy dissipation capacity of the structure without substantially reduction of its overall resistance against horizontal and vertical loading. Such a global ductile post-elastic behavior is ensured if the local ductility demands appear in critical plastic regions where adequate ductility should be available. In case of the frame system the local ductility require-

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ment of the beams within critical region is deemed to be satisfied if the transverse reinforcement ensures an adequate confinement and prevent local buckling of longitudinal bars, and the additional reinforcement of not less than half of the amount of the actual tension reinforcement placed in the compression zone.

The spacing of the hoops shall not exceed the smallest of the following values [1]:

$s = \min(h/4, 24\Phi_t, 150\text{mm}, 5\Phi_L)$ for ductility class "H" (height),

$s = \min(h/4, 24\Phi_t, 200\text{mm}, 7\Phi_L)$ for ductility class "M" (medium),

spacing according to provisions Eurocode 2 for ductility class "L" (light),

where: h-height of a section, Φ_t-diameter of hoops, Φ_L-diameter of reinforcing bar.

Furthermore EC8 limited the tension reinforcement ratio within the critical region.

A reading of other countries standards indicates the wide differences between the seismic design provisions for reinforced concrete beams. For example the antibuckling role in the New Zealand standard [2] is ensured by limiting the hoop spacing to not more than six longitudinal bar diameter ($6\Phi_L$) and specifying that the tie force is to be at least one-sixteenth of the longitudinal bar force per 100mm length of longitudinal bar, in the US standard [3] spacing of the hoops shall not exceed $8\Phi_L$, and in the French standard [4] spacing of the hoops is up to $12\Phi_L$.

Several researchers have suggested that buckling of reinforcement may be prevented or made inconsequential by using a limiting stirrup spacing in the region anticipated buckling. The column tests of Yeh et al. [10] showed that a greater amount of lateral reinforcement produces a greater maximum strength and ductility factor. Scribner [8], Scribner et al. [9] noticed that large ties did prevent the buckling of longitudinal bars - transverse ties with diameter at least half as large as diameter of longitudinal reinforcement. However these large ties were not able prevent other types of buckling of longitudinal reinforcement, the longitudinal bars could also buckle over a length greater than one stirrup spacing. The results of test Namai et Darwin [7] demonstrate the degree to which the performance of reinforcing concrete beams subjected to cyclic loading can be improved by reducing the flexural reinforcement ratio, and an increased ratio of positive to negative steel at the face of the support improve the cyclic performance of a beam.

Many modern reinforced concrete (RC) structures have suffered damage or have collapsed during recent earthquakes. This indicates that, despite significant improvements in the design of these types of structures, there are still some aspects of the postelastic response of RC structures that are not well understood and further experimental and analytical investigation is warranted.

The purpose of this investigation is to study the inelastic behavior of reinforced concrete beams subjected to cyclic loading. The primary variable were the ratio of positive reinforcement and the stirrup spacing of beams. Specimen's performance is compared based on ductility index and total dissipation energy. In this paper we present the results of the investigation described in report [5].

2. EXPERIMENTAL PROGRAM

2.1. Specimens

Twelve half-scale beam-column subassemblies were constructed and tested. Specimen configuration is shown in fig.1a with corresponding details listed in table 1.

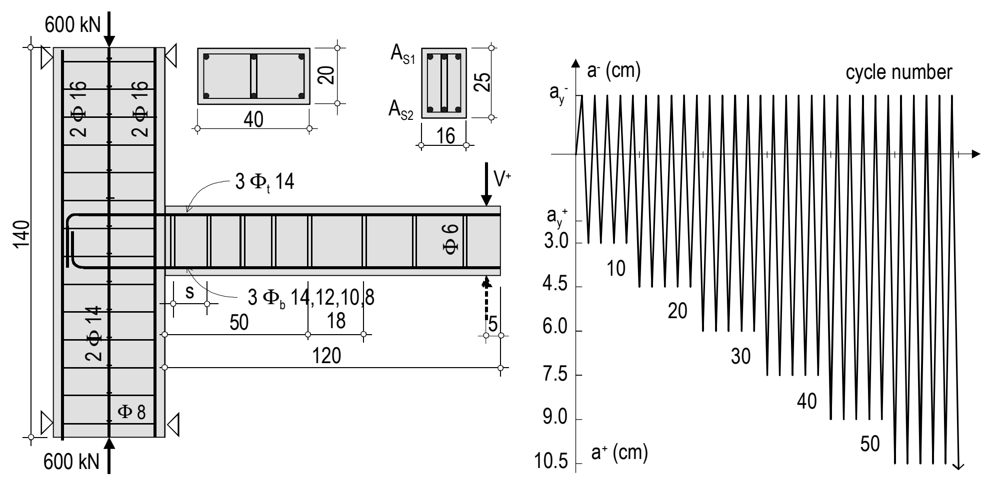


Fig.1. a) Details of test specimens, b) Loading history

All specimens were designed to have: the same section and the same longitudinal column reinforcement, the same section and the same top longitudinal beam reinforcement (ρ_{Lt}=1.26%). The parameters studied were the bottom longitudinal reinforcement ratio of beam (ρ_{Lb}=1.26-0.41%) and the spacing of stirrups (s=4.5-18cm).

Table 1. Properties of specimens

Speci-men	f_c (MPa)	Longitudinal reinforcement				Transverse reinforcement		
			f_y (MPa)	f_u (MPa)	ρ_{Lt} ρ_{Lb}	f_y (MPa)	s (mm)	ρ_T
D6 D12 D18	31,9	top 3#14 bottom 3#14	499 499	750 750	0,0126 0,0126	520	60 120 180	0,0118 0,0059 0,0039
C6 C12 C18	33,0	top 3#14 bottom 3#12	499 544	750 623	0,0126 0,0092	520	60 120 180	0,0118 0,0059 0,0039
A6 A12 A18	36,7	top 3#14 bottom 3#10	499 504	750 717	0,0126 0,0064	520	60 120 180	0,0118 0,0059 0,0039
B4 B9 B14	31,3	top 3#14 bottom 3#8	499 560	750 640	0,0126 0,0041	520	45 90 140	0,0157 0,0078 0,0050

2.2. Test program

The specimen was mounted in a vertical position. During the test, the axial load applied to the column was held constant at 600 kN (7.5MPa). At the free end of the beam, the specimen was loaded by hydraulic jacks. The shear span ratio was 4.6. By reversing the direction of the vertical beam loads, the effect of a horizontal earthquake function was simulated.

The typical loading history is show in fig.1b. After the beam yielding the applied loading was controlled by deflections of the beam according to the displacement a=3.0cm, 4.5cm, 6.0cm, … till complete failure. Under each deflection level, ten cycles were imposed. During the test, the applied loads, the deflection of the free end of the beam were measured.

3. EXPERIMENTAL RESULTS

3.1. General observation

Figure 1 shown load-deflection curve for specimen A6 subjected to load reversal. Similar curves were obtained for the other specimens.

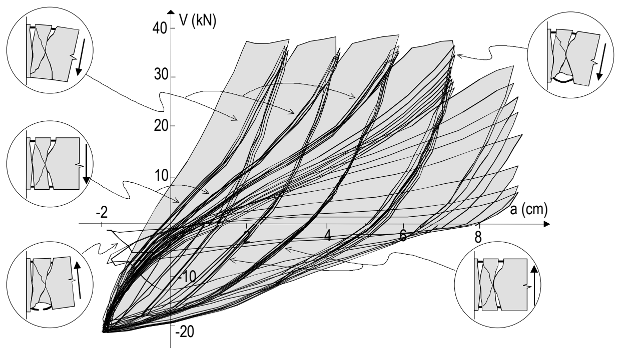
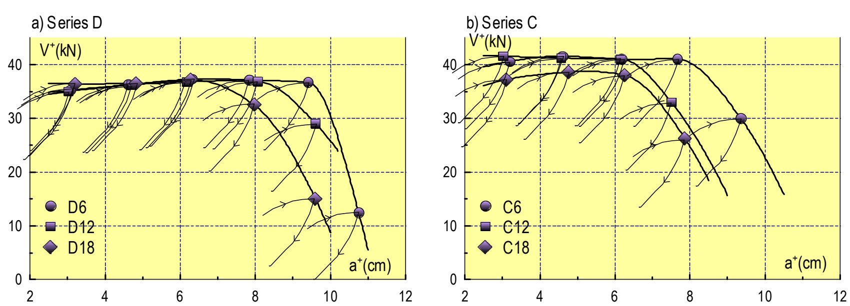


Fig.2. Experimental results for specimen A6

All specimens experienced failure or major deterioration as a result of cracking a crushing of concrete in hinge zone, although the nature, extent , and rate of deterioration varied from one specimen to another. Fig.2 shows also the type of cracking which resulted from reversed loading. Vertical and inclined cracks which formed during positive half-cycle were intersected by similar types of cracks which originated from the opposite side of the beam during loading reversal. The integrity of the hinging zone was influenced primarily by the ability of the reinforcement to limit sliding and degradation of concrete along cracks and to limit the mobility of discrete concrete blocks or pieces formed by such cracks. The flexural cracks penetrate the whole section and do not close, hence the bending moment is carried only by the steel in this portion of the loop. The loop has a pinched shape after closing the flexural cracks. Each specimens experienced severe loss of the flexural strength due to buckling and accompanying spalling of concrete cover of compression reinforcement during the latter stages of loading.



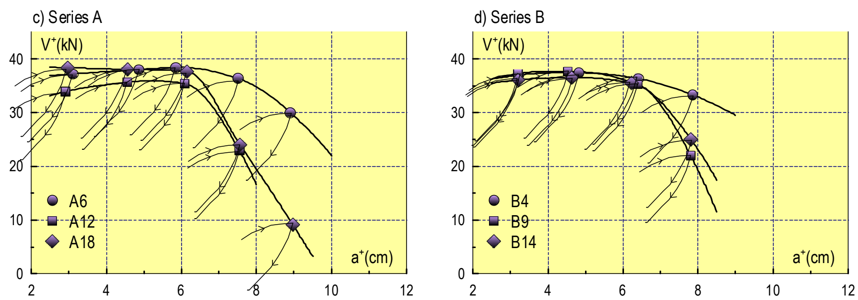


Fig.3.Experimental load-deflection curves (envelope of peak loop for c=1,11,21,…)

Table 2. Experiment results

Speci-men	$\alpha = A_{S2}/A_{s1}$	$\beta = s/\Phi_b$	a^+_y (cm)	a^-_y (cm)	a^+_u (cm)	V^-_y (kN)	V^+_y (kN)	$\mu = a^+_u/a^+_y$	Number of cycle	Total E (kJ)	E/cycl
D6		4,3			10,3			4,29	44	62,9	1,43
D12	1,00	8,6	2,4	2,4	10,1	36,0	36,0	4,21	40	50,3	1,26
D18		12,9			8,6			3,58	32	31,9	1,00
C6		5			10,5			4,20	42	49,9	1,19
C12	0,75	10	2,5	1,8	8,2	32,2	39,0	3,28	25	18,8	0,75
C18		15			8,0			3,20	25	16,8	0,67
A6		6			8,2			3,90	33	23,3	0,71
A12	0,50	12	2,1	1,5	6,5	20,3	35,0	3,10	21	10,8	0,52
A18		18			6,5			3,10	20	10,0	0,50
B4		5,6			7,7			3,67	30	16,3	0,54
B9	0,33	11,2	2,1	1,4	6,4	13,9	37,0	3,05	21	9,3	0,44
B14		17,5			6,6			3,14	21	8,5	0,41

The performance details of the specimens under incrementally cyclic loading are shown in table 2 and fig.3. Fig.3 shows the envelope of peak loop hysteresis experimental load-deflection curves.

3.2. Energy dissipation

One the most important aspect of structural performance under seismic loading is the ability of the structure to adequately dissipate energy. The following criteria for evaluation beam performance such as total number of cycles, and energy dissipation are used. The energy dissipated by the beams is assumed to be an area enclosed by the load-deflection curves. Only cycles before buckling of reinforcement longitudinal considered in the computation of the dissipated energy *E* and of the total number of cycles.

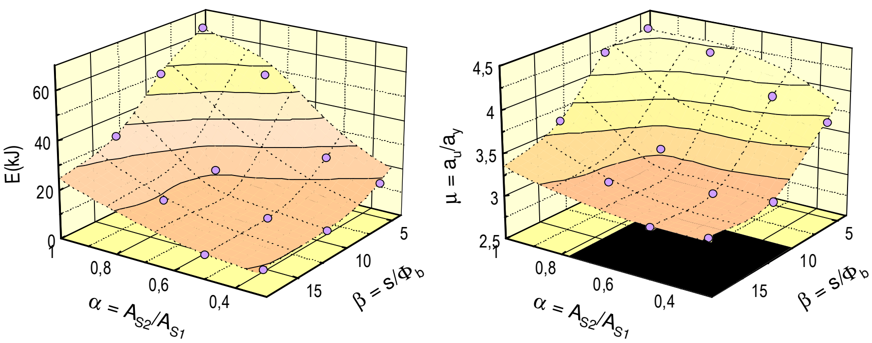


Fig.4. a) Energy dissipation E, b) Ductility factor μ: versus α and β

The effect of stirrup spacing can be analyzed by comparing beams each series (table 2, fig.4a). Beams series D had stirrup spacing of $4.3\Phi_b$, $8.6\Phi_b$ and $12.9\Phi_b$. Beams D6 dissipated more energy, 62.9kJ, than beams D18, which dissipated 31.9kJ. The similar effect may be observed for the other series, a decrease in the stirrup spacing increase the dissipated energy, greater than 100% between the maximal and minimal spacing of stirrup. The main effect of smaller stirrup spacing is to provide greater concrete confinement. Smaller stirrup spacing also improves energy dissipation by dealing buckling of the bottom reinforcement.

An increase in the ratio of positive to negative steel ($\alpha=A_{S2}/A_{S1}$) increases the moment capacity in positive bending, and thus, increase the area energy closed by load deflection curves. In addition, an increase in A_{S2} reduces the concrete compressive stresses under negative bending, delaying compressive spalling. Hence, an increase in the α ratio will increase the dissipated energy. For example this is illustrated (table 2) by beams D6 which had a α ratio of 1.0. Beams D6 survived fourteen more cycles of inelastic loading than beam B4 (α=0.33) and dissipated 62.9kJ compared to 16.3kJ for beam B4.

3.3. Ductility

The ductility by beams in thus study is taken as the displacement ductility factor μ i.e. the ratio of the maximum displacement $a_{.u}$ to yield displacement a_y. The definition of yield deflection a_y based on first yielding and only cycles for which the peak load V was greater or equal to 75% of initial yield load V_y are considered in the computation of maximum displacement. Though somewhat arbitrary, $0.75V_y$, may be considered to represent the lower limit of the usable capacity of a beam. The performance of the specimens under incrementally increasing cyclic loading is shown in table 2 and fig.4b.

From the comparison of the available ductility factor of specimen each series it is concluded than a decrease in the stirrup spacing β increases the displacement ductility factor μ. In case that the stirrup spacing is less than $5\Phi_b$ and the ratio positive to negative steel α is more or equal than 0.75 (specimen D6 and C6) the available ductility factor μ exceed 4, it is 4.29 and 4.20 respectively. For specimen A6 (α=0.50, β=6.0) and A4 (α=0.33, β=5.6) the ductility factor is less, 3.90 and 3.67 respectively. If the ratio of positive to negative steel is less than 0.75 the stirrup spacing, more than $10\Phi_b$, has very small influence on ductility. In this case displacement ductility factor is equal from 3.58 to 3.05.

An increase in the ratio of positive to negative steel α increases the displacement ductility factor μ. In case that the stirrups spacing is major that ten diameter of bottom reinforcement Φ_b the influence of amount positive steel of ductile behavior is not too great. For example, specimens D18, C12, C18, A12, A18, B9 and B14 shown similar ductile behavior, the ductility factor μ is 3.58, 3.28, 3.20, 3.10, 3.10, 3.05 and 3.14 respectively. More significant effect of positive steel on availably ductility factor is observed when stirrup spacing is less than $10\Phi_b$ (fig.4b). This effect have connection with stability of bar. In all beam of specimens tested during their experimental work longitudinal bottom bar buckling was observed during the last cycles of the test, thus the ductility of beam depend on stability these bar. Test performed by Monti and Nuti [6] on the inelastic buckling of reinforcing bars show that for ratios between length and diameter bar L/D>10-11, a soon as the yield point is reached buckling start. For L/D<10, the bars still maintains a rectilinear configuration after yielding.

4. CONCLUSIONS

From these tests, the following conclusions may be drawn.

Instability of longitudinal reinforcement it marks the limit of usable ductility and energy dissipation capacity of the reinforced concrete beams subjected to cycling loading. The ductility and energy dissipation capacity of beams will improve with a decrease in stirrup spacing in hinge zone and an increased ratio of positive to negative steel at the face of the support.

The stirrup spacing more than $10\Phi_b$ and ratio of positive to negative steel is less than 0.75 has very small influence on ductility and energy dissipation capacity of the reinforced concrete beams.

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BADANIA RYGLI RAM ŻELBETOWYCH PODDANYCH OBCIĄŻENIOM TYPU SEJSMICZNEGO

S t r e s z c z e n i e

Wyniki badań dwunastu zewnętrznych węzłów ram żelbetowych poddanych obciążeniom cyklicznym są przedstawione. Celem badań było określenie wpływu ilości zbrojenia podłużnego i poprzecznego rygli ram na ich odporność na obciążenia sejsmiczne. Badanymi parametrami były stopień zbrojenia w strefie ściskanej i rozstaw strzemion w strefie przywęzłowej rygla. Elementy badawcze były poddane obciążeniom cyklicznym wywołującym duże przemieszczenia plastyczne, odpowiadające tym które występują podczas średnich i dużych trzęsień ziemi. Wyniki badań porównano z zaleceniami normowymi i dostępnymi wynikami badań. Zmniejszenie rozstawu strzemion oraz zwiększenie ilości zbrojenia w strefie ściskanej belek zwiększają ich odporność na obciążenia cykliczne.