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Flexural behavior of reinforced lightweight concrete beams under reversed cyclic loading

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Abstract. This paper presents the results of an experimental investigation on the flexural behavior of doubly reinforced lightweight concrete (R.L.C.) beams tested under cyclic loading. A total of 20 beam specimens were tested. Test results are presented in terms of ductility index, the degradation of strength and stiffness, and energy dissipation. The flexural properties of R.L.C. beam were compared to those of normal concrete (R.C.) beams. Test results show that R.L.C. beam with low and medium concrete strength (20, 40MPa) performed displacement ductility similar to the R.C. beam. The ductility can be improved by enhancing the concrete strength or decreasing the tension reinforcement ratio. Using lightweight aggregate in concrete is advantageous to the dynamic stiffness of R.L.C. beam. Enhancement of concrete strength and increase of reinforcement ratio will lead to increase of the stiffness degradation of beam. The energy dissipation of R.L.C beam, similar to R.C. beam, increase with the increase of tension reinforcement ratio. The energy dissipation of unit load cycle for smaller tension reinforcement ratio is relatively less than that of beam with higher reinforcement ratio.

Keywords: reinforced concrete; lightweight aggregate; cyclic loading; ductility; stiffness; energy dissipation

1. Introduction

The use of lightweight aggregate concrete (LWAC) has become more popular in the design of special structures (Helgesen 1995, Sekhniakshivile 1997, Costa *et al*. 2012, Kim *et al*. 2013), such as high-rise buildings, long-span bridge, and off-shore platforms. For the structural design, it is meaningful to understand the behavior of structural members such as beam, shear wall, and column. Ahmad (1991) has studied the flexural behavior of reinforced high-strength lightweight concrete. However, the report related to the behavior of reinforced lightweight beams under cyclic loading is limited.

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Table 1 Summary and details of the test program

	Beam number	fc'(MPa)	Tensile steel	Web spacing	Sizes (mm)	Quantity
Reinforced Lightweight Concrete Beams	L20410M	20	4-#4	100mm	150*200*1500	2
	L20610M	20	4-#6	100mm	150*200*1500	2
	L20415M	20	4-#4	150mm	150*200*1500	2
	L20615M	20	4-#6	150mm	150*200*1500	2
	L20610S	20	4-#6	100mm	120*200*1500	3
	L40410M	40	4-#4	100mm	150*200*1500	2
	L40610M	40	4-#6	100mm	150*200*1500	2
	L40415M	40	4-#4	150mm	150*200*1500	2
	L40615M	40	4-#6	150mm	150*200*1500	2
	L40610S	40	4-#6	100mm	120*200*1500	3
Reinforced Concrete Beams	N20410M	20	4-#4	100mm	150*200*1500	2
	N20610M	20	4-#6	100mm	150*200*1500	2
	N20415M	20	4-#4	150mm	150*200*1500	2
	N20615M	20	4-#6	150mm	150*200*1500	2
	N20610S	20	4-#6	100mm	120*200*1500	3
	N40410M	40	4-#4	100mm	150*200*1500	2
	N40610M	40	4-#6	100mm	150*200*1500	2
	N40415M	40	4-#4	150mm	150*200*1500	2
	N40615M	40	4-#6	150mm	150*200*1500	2
	N40610S	40	4-#6	100mm	120*200*1500	3

Illustration of Symbol: For example L20410M, L: reinforced lightweight aggregate concrete beam. 20: design strength 20MPa. 4: No.4 longitudinal reinforcement, 10: the space of web reinforcement is 100mm, and M: the size of beam is 150*200*1500 mm.

From the viewpoint of seismic resistance, the dynamic properties of structural materials, such as the mass, natural frequency, the damping ratio, have significant effects on the magnitude of the seismic force of buildings (Lee and Song 1999). Since the seismic force is a response of the inertia of mass, a building with lighter LWAC will have smaller seismic force than heavier building with normal concrete under the same ground acceleration (Ishibashi and Okamura 1997, Kim and Park 1998).

The ductility of reinforced concrete member indicates the ability that produces large deformation after the yielding of reinforcement (Marfia 2004, Saptarshi 2011, Constantin 2013, Gunasekaran 2013). It is a significant characteristic and an important index in the seismic design of structures at an earthquake region (Bayasi 1993, Go *et al*. 2012). Results from previous investigations (Ahmad 1995, Fang 1991, Lin 1991, Ziara 1995) have shown that the flexural strength and stiffness of R.C. beam increase with the tensile reinforcement, but the ductility decreases with the increase of tensile reinforcement. The stress-strain characteristics of concrete are often used to simulate the stress-strain distribution of flexural compressive zone in reinforced concrete beam. The varied stress-strain properties of LWAC and normal weight concrete (Wang 1986, Zhang 1991) (NWC) may lead to different flexural behavior of R.C. beam. In addition, the real data on the dynamic properties of LWAC are still insufficient and need further study. This research therefore aims to investigate the flexural behavior of reinforced lightweight concrete (R.L.C.) beam with web reinforcement under cyclic loading. A comparison was made for the test results of R.L.C. and R.C. beam.

Table 2 Mix proportions of lightweight aggregate concrete (kg/m^3)

Design strength (MPa)	Cement	Water	Natural Sand	Lightweight coarse Aggregate		
				13~19 (mm)	9~13 (mm)	5~9 (mm)
20	297	194	734	179	213	175
40	480	194	664	166	197	162

Table 3 Mix proportions of normal weight concrete (kg/m^3)

Design strength (MPa)	Cement	Water	Sand	Coarse aggregate
20	280	197	781	1056
40	410	196	675	1056

2. Experimental program

A total of 20 flexural reinforced LWAC beams and NC beams were tested. Test parameters included in this research are: concrete type, concrete strength, tensile reinforcement, and spacing of web reinforcement. Table 1 summarizes the detail of specimens. Two concrete strengths of 20 and 40 MPa were adopted for the tests. Three different tension reinforcement ratios ($\rho=A_s/bd$) of 2.88%, 1.03%, and 2.30%, were selected for two beam specimen sizes of 150 mm*200 mm*1500 mm and 120 mm*200 mm*1500 mm. The ratio of compression and tension reinforcement was kept at 1.0. Spacing of No. 3 web reinforcement was 100 and 150 mm.

2.1 Materials

The mix proportions for LWAC and NWC are shown in Tables 2 and 3. Type I Portland cement was used. The natural sand had a fineness modulus of 2.67. The coarse lightweight aggregate used was expanded clay with maximum size of 19 mm. Table 4 gives the properties of the lightweight aggregate.

Two sizes of longitudinal reinforcement, No. 4 and No. 6, were used in the tests. The stirrup used was No. 3 bar. Table 5 gives the mechanical properties of reinforcement.

2.2 Preparation of specimens

The beam specimens were rectangular in cross section, including two sizes of 150mm wide, 200mm deep, and 120 mm wide, 200 mm deep. They are 15000 mm long. The dimension and reinforcement details of the beams are shown in Fig. 1. Freshly mixed concrete was placed with two layers in the form of specimen and followed by controlled vibration. Three control cylinders of ϕ 100 mm×200 mm were also cast with suitable vibration for each mixture. Immediately after casting, specimens were covered with polyethylene sheets to avoid evaporation of moisture. They were de-molded after 24 hours and moved to moist room with 100% RH, 23℃ for curing.

2.3 Test set-up and test procedure

The set-up for the test is shown in Fig. 2. The test beam was 1500mm long, simple supported over a span of 1200 mm and tested under two concentrated loads placed symmetrically 400 mm

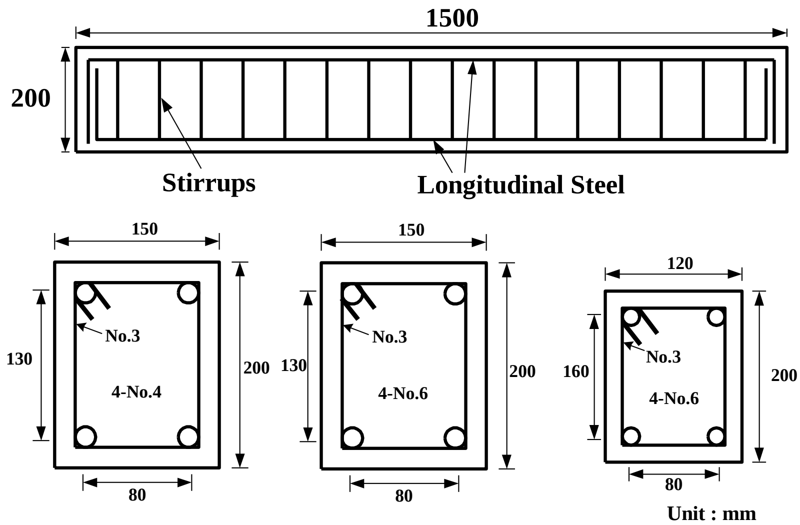


Fig. 1 Specimen details

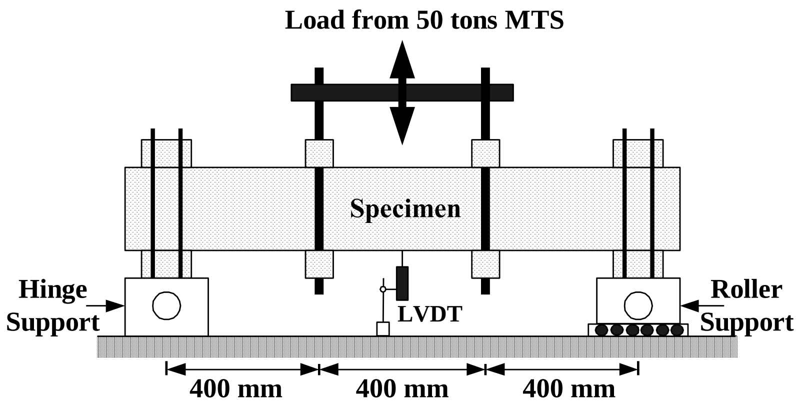


Fig. 2 Test setup

apart. At the two ends of the beam, one hinge support was set available for the beam to rotate freely, and the other was a roller support allowing the beam to rotate and move in horizontal direction. A calibrated load cell was placed between the jack and the spreader beam while two linear displacement transducers (LVDT) were properly placed at mid-span section to measure the deflection during the test. The load was applied by a 5000 kN materials testing machine. A data acquisition system of the model KYOWA UCAM-60A was employed while the load test was conducted. Both the loads and displacements were simultaneously monitored and recorded by way of load cell and LVDT during the loading process.

The test procedure referred to the process proposed by Priestley and Park (1987). First, it is necessary to determine the yielding displacement Δy for the beam specimen. Specimen was initially subjected to one cycle of bending load at ±0.5 times the ideal flexural strength M_n of the critical section. From this load cycle, the Δy can be calculated by the average value of Δy_1 and Δy_2

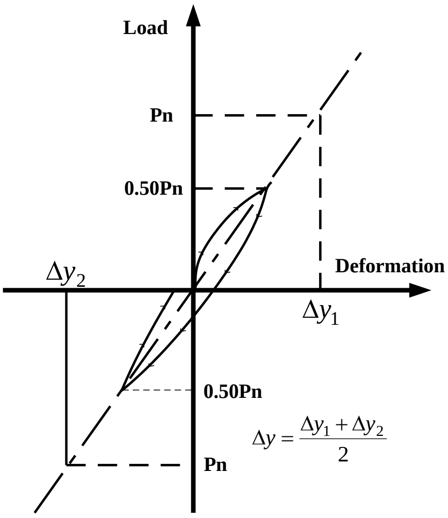


Fig. 3 Determination of yielding displacement Δy

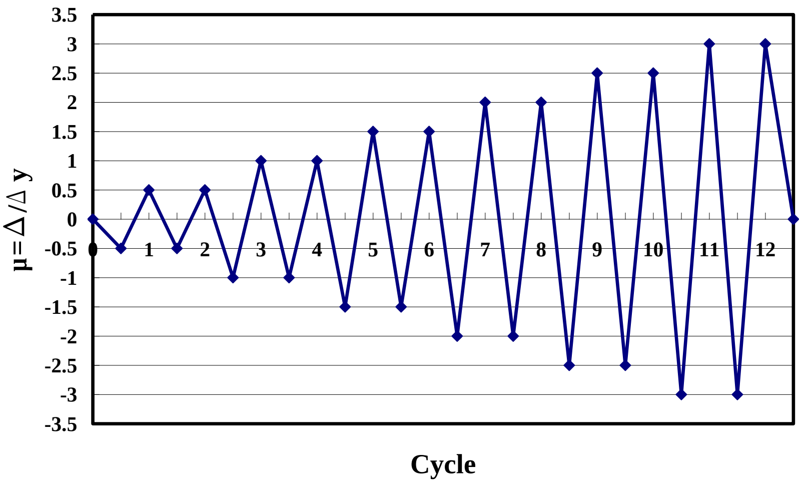
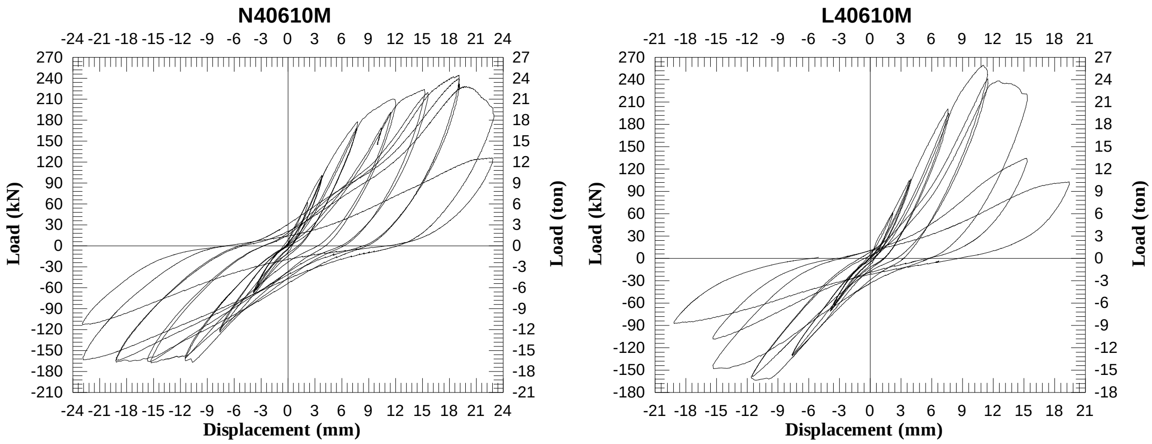


Fig. 4 The loading history

as shown in Fig. 3. And then, subsequent loading was turned to displacement control mode, using displacement ductility factors (μ=Δ/Δy) to control the load. Six μ values of ±1, ±1.5, ±2, ±2.5, and ±3, each two cycles, were selected. The loading history adopted in this study is shown in Fig. 4. The loading test was interrupted when a serious premature failure was occurred.

3. Results and discussions

The flexural behavior of doubly reinforced lightweight concrete beams with web reinforcement under cyclic loading was investigated based on the load-displacement characteristics, displacement



(a) R.C. beam (b) R.L.C. beam

Fig. 5 Cyclic responses of concrete beam

Table 4 Basic properties of lightweight aggregate

Grading	Particle Density (kg/m^3)	Absorption (30 minutes, %)	Absorption (24 hours, %)
13 ^{mm} ~ 19 ^{mm}	1460	8.77	13.47
9 ^{mm} ~ 13 ^{mm}	1300	3.13	7.76
5 ^{mm} ~ 9 ^{mm}	1430	5.12	8.92

Table 5 Mechanical properties of steel bars

Numbers	Diameter (mm)	Yielding strength (MPa)	Ultimate strength (MPa)
No.3	9.5	281	476
No.4	12.7	283	482
No.6	19.0	420	611

Table 6 Test results of concrete compressive strength

Curing days	20 MPa level				40 MPa level			
	LWAC (MPa)		NC (MPa)		LWAC (MPa)		NC (MPa)	
	19.6		19.5		39.9		37.8	
7	23.1	(21.7)	19.1	(20.0)	39.8	(39.6)	41.3	(39.4)
	22.5		21.5		38.9		39.2	
	26.9		24.6		43.2		44	
28	27.5	(27.4)	23.7	(23.1)	44.6	(43.5)	44.6	(43.7)
	27.8		22.4		42.9		42.9	

LWAC: Lightweight Aggregate Concrete; NWC: Normal Concrete
(21.7): the value is an average value

ductility index (μ_Δ), degradation of strength and stiffness, and the capability of energy dissipation of the specimens. The tested compressive strength of LWAC, as shown in Table 6, was close to that of NWC at two strength levels of 20MPa and 40MPa.

Fig. 5 shows the typical load-deflection curves of R.L.C. and R.C. beams. From the load-deflection curve, various indexes of beams can be determined or calculated, such as the displacement ductility index (μ_Δ), degradation of strength and stiffness, and the capability of energy dissipation of the specimens. These results were adopted for comparing the performance of the beams.

3.1 Displacement ductility

Ductility is a significant parameter for the seismic resistance of structural members. This research intended to investigate the displacement ductility of R.L.C. beam. The displacement ductility index (μ_Δ) was defined as the ratio of maximum deflection (Δ_{max}) to the yielding displacement (Δ_y). Table 7 shows the results of average value μ_Δ for all specimens. It is seen that μ_Δ of reinforced lightweight concrete beams with concrete strength level of 20MPa varies from 2.0 to 3.0 and from 1.47 to 3.07 for normal reinforced concrete (R.C.) beams. And both the R.L.C. and R.C. beams with concrete strength levels of 40MPa have the similar results of μ_Δ. This implies that the R.L.C. beam performs approximately similar displacement ductility as the R.C. beam. As also shown in Table 7, for similar tension reinforcement ratio (ρ), the spacing of transverse reinforcement has not any noticeable effect on the displacement ductility of beams. The spacing of web reinforcement varied from 100 to 150mm demonstrates a similar confinement effect for both R.L.C. and R.C. beams. And also, Fig. 6 shows the crack patterns of the beams. It is seen that the beams with stirrup spacing varied between 100 mm and 150mm presented a similar flexural-shear crack patterns due to sufficient confinement effectiveness.

Table 7 Test results of displacement ductility of concrete beams

Concrete strength level		20 MPa					40 MPa				
Web spacing		100 mm			150 mm		100 mm			150 mm	
Tension reinforcement ratio ρ (%)		1.03	2.30	2.88	1.03	2.30	1.03	2.30	2.88	1.03	2.30
$(\mu_\Delta)_{Avg}$	R.L.C	2.89	2.51	2.00	3.00	2.57	2.95	2.95	2.47	2.99	2.99
	R.C	3.07	2.50	1.47	3.02	3.05	3.01	2.98	2.51	3.01	2.31

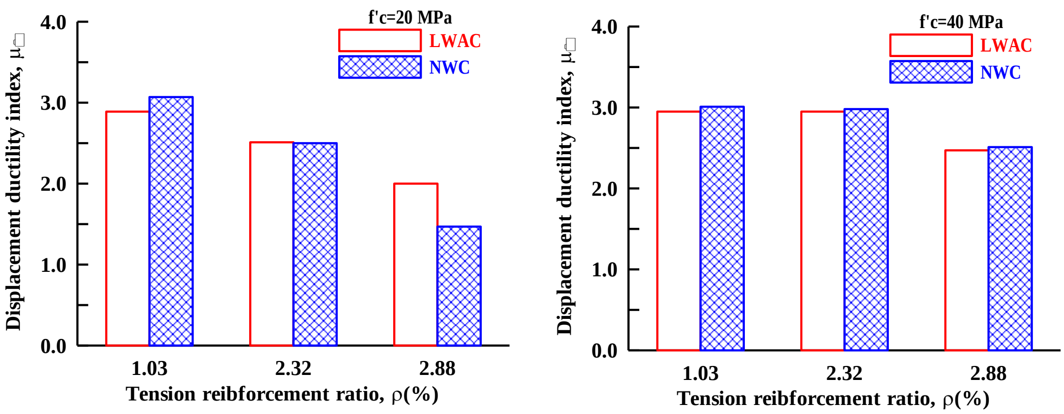


Fig. 7 Displacement ductility index versus tension reinforcement ratio

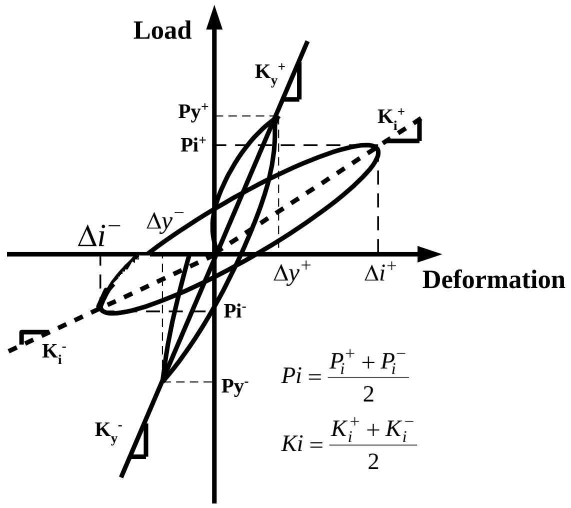


Fig. 8 Definitions of strength and stiffness

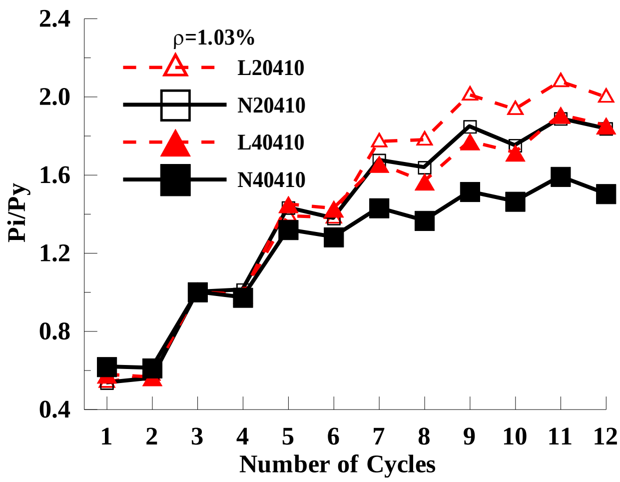


Fig. 9 Effect of concrete strength on the degradation of the flexural strength of beam

Fig. 7 illustrates the relations between μ_Δ and tension reinforcement ratio in relation to the concrete strength of R.L.C. and R.C. beams. It is seen that the μ_Δ for both concrete beams decreases with the increase of tension reinforcement ratio, but increases with the increase of concrete strength. This indicates that the R.L.C. beam, similar to R.C. beam, may improve the displacement ductility by enhancing the concrete strength or decreasing the tension reinforcement ratio.

3.2 Strength and stiffness degradation

Structural member with adequate seismic resistance should have not only higher ductility, but also a gradual reduction in strength and stiffness. This research experimentally investigates the

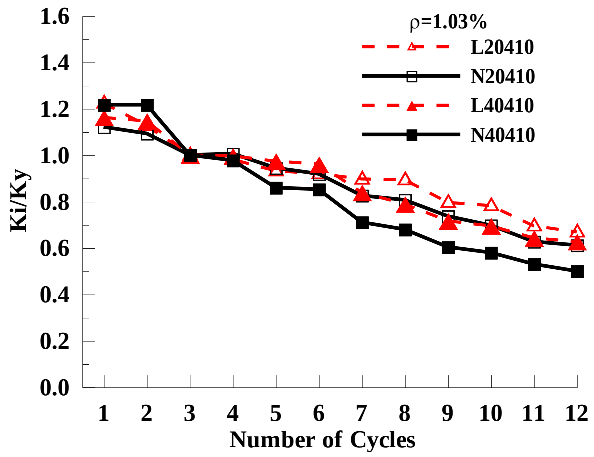
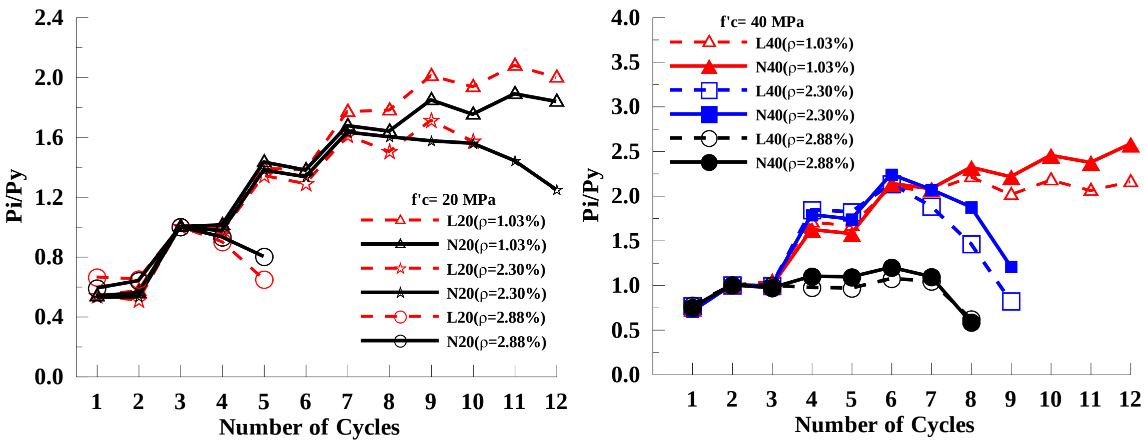


Fig. 10 Effect of concrete strength on the stiffness degradation of beam



(a) *fc'*=20MPa (b) *fc'*=40MPa

Fig. 11 Effect of tension reinforcement on the degradation of the flexural strength of beam

degradation of flexural strength and stiffness of concrete beam. The yielding load P_y and the corresponding yielding stiffness K_y are defined as shown in Fig. 8, where P_y is an average of the maximum and minimum loads (absolute value) at the load cycle when the first yielding displacement occurs. The K_y is defined as $K_y=P_y/\Delta_y$. Similarly, $K_i=P_i/\Delta_i$, where Δ_i is the maximum displacement at i-th cycle. Figs. 9 and 10 show the effects of concrete strength on the degradation of the flexural strength and the stiffness of R.L.C. and R.C. beams, respectively, in relation to the tension reinforcement ratio (ρ) of 1.03%. It can be seen from Fig. 9 that the beam made with medium concrete strength (40 MPa) present the greater strength degradation than that of beam with low concrete strength (20 MPa) for both lightweight concrete and normal concrete. This tendency is more evident after 6th load cycles. Moreover, the degradation of the strength for R.L.C. beam is smaller than that of R.C. beam. These results imply that an increase in concrete strength will increase the flexural strength degradation of beam, while the R.L.C. beam can perform less flexural strength degradation than that of R.C. beam.

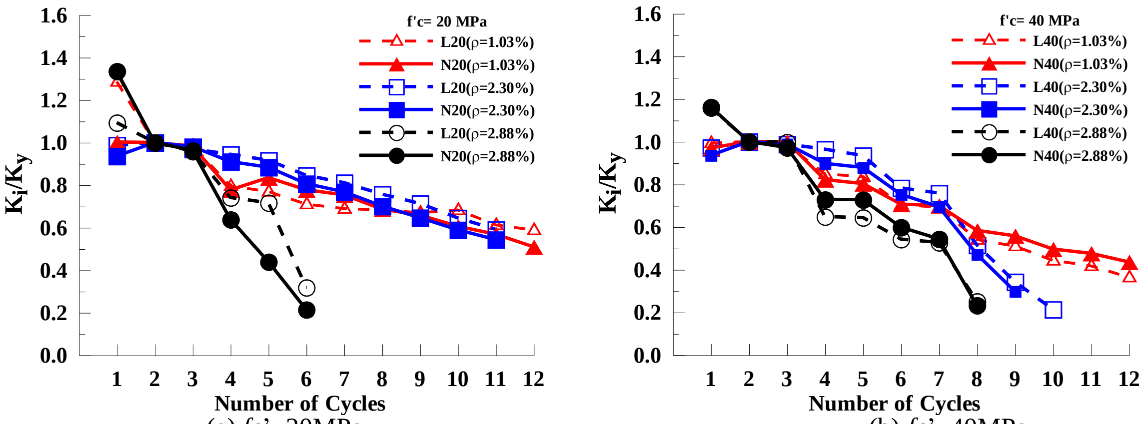
Compare the stiffness degradation of R.L.C. beam with that of R.C. beam, it is found in Fig. 10, the former has stable and less stiffness degradation than the later. Both concrete beams show a similar tendency of stiffness degradation. The beam with medium concrete strength (40 MPa) presents greater stiffness degradation than that of beam with low concrete strength (20 MPa). This signifies the use of lightweight aggregate in concrete may improve the dynamic stiffness of concrete beam, while increase the concrete strength will increase the stiffness degradation of beam.

Fig. 11 shows the effects of tension reinforcement ratio (ρ) on the degradation of the flexural strength of R.L.C. and R.C. beams. The two concrete present similar tendency for the degradation of flexural strength. Higher ρ exhibits greater strength degradation. This tendency is move evident after 3rd load cycles. The results imply that, similar to R.C. beam, the increase of ρ of R.L.C. beam may result in the increase of flexural strength degradation. It is also found in Fig. 11 that the R.L.C. beams perform smaller strength degradation than that of R.C. beams at low concrete strength (20 MPa), but the greater strength degradation at medium concrete strength (40 MPa).

Fig. 12 shows the effects of ρ on the degradation of the stiffness of R.L.C. and R.C. beams. The R.L.C. beams have a similar stiffness degradation tendency under cyclic loading as that of R.C. beams. Increase of ρ leads to the increase of stiffness degradation of beams. This is more evident for the beams with higher reinforcement ratio, such as ρ=2.88%. In addition, beam with medium concrete strength (40 MPa) exhibits greater stiffness degradation than the beam with low concrete strength (20 MPa). These results implicate that the R.L.C. beam performs similar stiffness degradation under cyclic loading as that of R.C. beam with various tension reinforcement ratio and concrete strength.

3.3 Energy dissipation capacity

To realize the energy dissipation of beams under cyclic loading, this research uses the hysteric energy to evaluate the capacity of energy dissipation. The energy dissipation is defined as the area enclosed by the load-deflection hysteresis loop, as showed in Fig. 13. From the test load-deflection curve, the calculated value of energy dissipation for a single cycle load is shown as Fig. 14 and Fig. 15. Also, the accumulative values of energy dissipation are shown as Fig. 16.



(a) *fc*'=20MPa (b) *fc*'=40MPa

Fig. 12 Effect of tension reinforcement on the stiffness degradation of beam

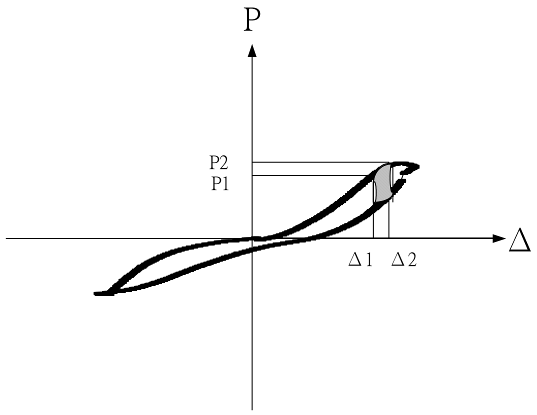


Fig. 13 Calculation of the energy dissipation capacity

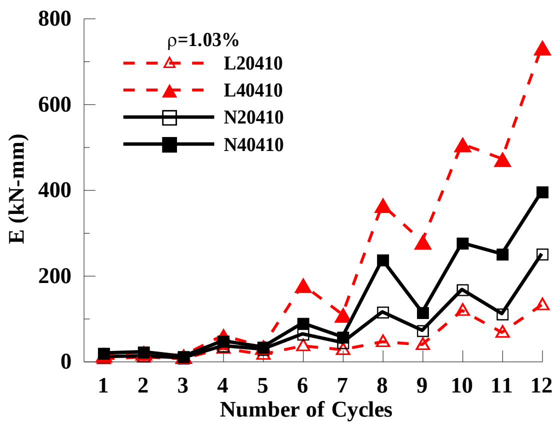


Fig. 14 Energy dissipation versus load cycles (ρ=1.03%)

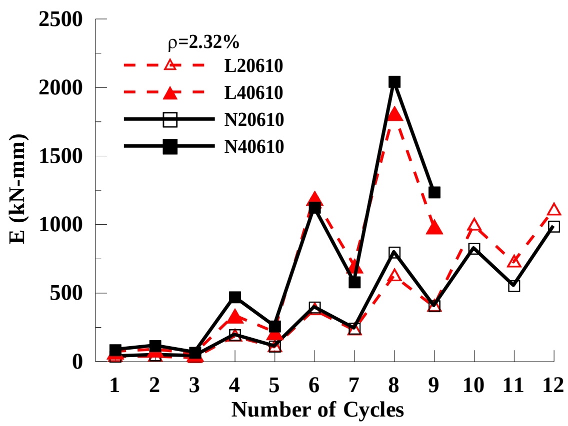
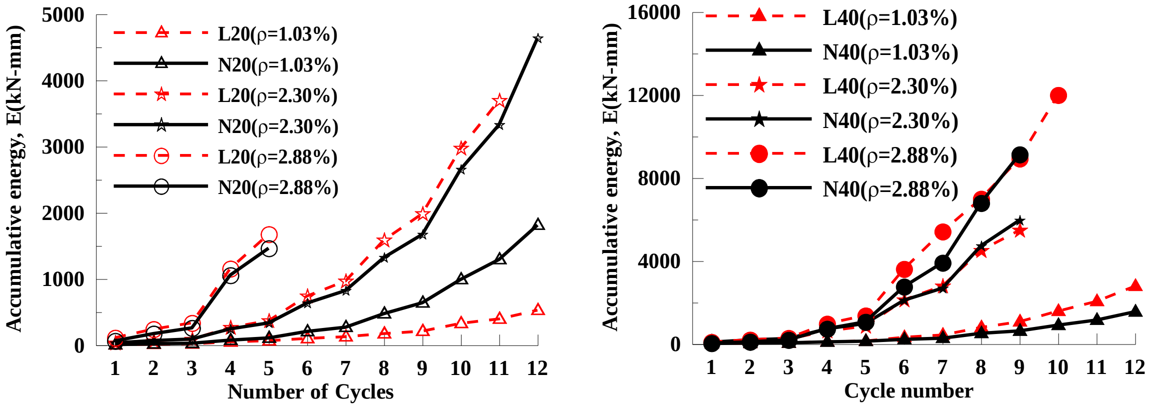


Fig. 15 Energy dissipation versus load cycles (ρ=2.32%)

The test results of the energy dissipation for each load cycle of R.L.C. and R.C. beams are illustrated in Figs. 14 and 15, where the energy dissipation is plotted against number of cycles for beams with a tension reinforcement ratio (ρ) of 1.03% and 2.32%, respectively. As can be seen in Fig. 14, when the ρ value is 1.03%, for low concrete strength (20 MPa), the maximum unit energy dissipation of R.L.C. beam is around 100kN-mm, and 200kN-mm for R.C. beam. For medium concrete strength (40 MPa), the maximum unit energy dissipation of R.L.C. beam is around 700 kN-mm, and 400 kN-mm for R.C. beam. Before 5th load cycles (μ=1.5), beams with low and medium concrete strength present a similar tendencies of energy dissipation. After the 5th load cycle, the R.L.C. beam with low concrete strength has smaller energy dissipation than that of the R.C. beam, but in reverse for the energy dissipation of the beams with medium concrete strength. Moreover, as seen in Fig. 15, when the ρ value is 2.32%, for low concrete strength (20 MPa), the maximum unit energy dissipation of R.L.C. beam is around 1,000 kN-mm, and 990 kN-mm for R.C. beam. For medium concrete strength (40 MPa), the maximum unit energy dissipation of R.L.C. and R.C. beams are around 1,800 kN-mm and 2,000 kN-mm, respectively. The two concrete beams present a similar tendency of energy dissipation in relation to the load cycles.



(a) *fc'*=20MPa (b) *fc'*=40MPa

Fig. 16 Effect of tension reinforcement on the energy dissipation of beam

In regard to the effects of tension reinforcement ratio on the accumulative energy dissipation of beams, as shown in Fig. 16, the energy dissipation of both R.L.C. and R.C. beams increases significantly with the increase of reinforcement ratio. For both low and medium concrete strength, the beams with a reinforcement ratio of 1.03% may consistently dissipate the energy and resist the load until 12-th load cycle (μ=3.0), nevertheless, the dissipated energy at each cycle is less than that of the beam with higher reinforcement ratio (2.03%) that has smaller ductility.

It is also interestingly found in Fig. 16 that, after 5-th cycles, the R.L.C. beam with reinforcement ratio of 1.03% and low concrete strength (20 MPa) presents the smaller energy dissipation than that of R.C. beam, while in contrast, a reverse situation is found in the beams with medium concrete strength (40 MPa). This may be attributed to the facts that lightweight aggregate concrete of medium strength exhibits larger bond strength than that of beam with low concrete strength, which results in the higher load resistance capability and greater energy dissipations corresponding to a similar deflection.

In comparison of the R.L.C. beams with various tension reinforcement ratios, the energy dissipation of unit load cycle for smaller tension reinforcement ratio is relatively less than that of the beam with higher reinforcement ratio, because the former has smaller yielding load and deflection. Consequently, beam with higher reinforcement ratio needs greater loading than the beam with lower reinforcement ratio to form a similar μ value. It will be therefore fractured at a lower μ value.

4. Conclusions

(1) The R.L.C. beams with low and medium concrete strength (20MPa and 40MPa) perform similar displacement ductility as that of R.C. beams. The displacement ductility of R.L.C. beam may be improved by enhancing the concrete strength or decreasing the tension reinforcement ratio.

(2) The increase of concrete strength will increase the flexural strength degradation of R.L.C. and R.C. beams, while the R.L.C. beam can perform less degradation than that of R.C. beam. The increase of ρ of R.L.C. beam may, similar to R.C. beam, lead to an increase of flexural strength degradation.

(3) Using lightweight aggregate in concrete may improve the dynamic stiffness of concrete beam. Enhancement of concrete strength and increase of ρ may lead to increase of the stiffness degradation of beam. This is more evident for the beam with higher ρ, such as ρ=2.88%.

(4) R.L.C. and R.C. beams with low ρ (1.03%) and medium ρ (2.32%) for low and medium concrete strength present a similar energy dissipation tendencies, except that after the 5th load cycles the R.L.C. beam with ρ of 1.03% and low concrete strength display smaller energy dissipation than that of R.C. beam, but in reverse for the energy dissipation of the beam with medium concrete strength.

(5) The energy dissipation of R.L.C. beam, similar to R.C. beam, increase with the increase of reinforcement ratio. The energy dissipation of unit load cycle for smaller tension reinforcement ratio is relatively less than that of the beam with higher reinforcement ratio.

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