Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.IV)

6-6-12

SEISMIC BEHAVIOR OF LIGHTWEIGHT REINFORCED CONCRETE BEAM-COLUMN JOINTS

Tang Jiuru[1] and Xu Xiaolin[2]

[1]Department of Civil Engineering, Nanjing Institute of Technology, Nanjing, China
[2]Guangdong Nuclear Power Joint Venture co., LTD, Shenzhen, Guangdong, China

SUMMARY

This paper describes the experimental results of four exterior beam-column joints of lightweight reinforced concrete under reversed cyclic loading. Emphasis is placed on the shear strength, deformabitity and anchorage of beam bars in lightweight R/C joint core as well as plastic hinge region in beams. Based on the results some design recommendations are presented.

INTRODUCTION

The structural mass can be diminished by using lightweight aggregate concrete in seismic zone, consequently the earthquake response of structure can be reduced. Refered to the experimental building used lightweight concrete in Tianjin city (PRC), the building weight was diminished by 10-20% and the construction cost was cut down 7%. Since the tensile and shear strength and elastic modulus of lightweight concrete are less than of normal weight concrete and the performance of bond in lightweight concrete is poorer than in normal weight concrete, it is necessary to research the behaviours of lightweight R/C frame beam-column joints so as to construct the lightweight concrete structure in seismic zone. Up to now, few data on above subject have been reported (Refs.1,2).

This paper describes the experimental results of four specimens in Nanjing Institute of Technology (Refs. 3,4).

EXPERIMENTAL WORKS

The specimens are beam-column subassembies taken from between points of inflexion of beam and column in plane frame and about one-half scale of the actual structure to simulate the behaviours of the extrior joint of multi-storey frame.

The geometry and details of four test specimens are shown in Fig.1. Among those, the specimen BC2 was casted in normal weight concrete and others in lightweight aggregate concrete. The clay-ceramisite produced on Tianjin was used as lightweight aggregate. Its apparent density was about 600-700kg/m^3 and the tube compressive strength was not less than 4N/mm^2. The density of lightweight concrete was about 1800kg/m^3, the weight batching was 1 (cement) : 1.75 (sand) : 1.375 (lightweight aggregate) and water-cement ratio was 0.40.

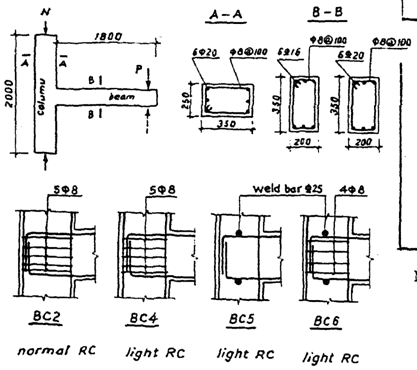

Fig.1

Table 1 Concrete Characteristics

Specimens	Materials	Age (Days)	Cube Compressive Strength f_{cu} (N/mm^2)	Axial Compressive Strength f_c (N/mm^2)	Elastic Modulus E_c (KN/mm^2)
BC2	Normal Weight Concrete	73	26.2	17.55	18.5 Specimens: 10x10x30 cm^3
BC4	Light Weight Concrete	70	29.6	19.83	
BC5	Ditto	67	34.3	22.98	
BC6	Ditto	64	32.8	21.98	

Note: cube specimens: 15x15x15 cm^3; f_c=0.67f_{cu}; 1N/mm^2=1.02kg/cm^2

Table 2 Reinforcement Characteristics

Classification	Diameter (mm)	Yield Strength f_y (N/mm^2)	Ultimate (N/mm^2)	Elastic Modulus (kN/mm^2)
Main Bars of Beam	16	389.8	569.5	191.1
	20	486.7	540.5	187.2
Main Bars of Column	20	486.7	540.5	187.2
Stirrups	8	332.6	———	208.7

The concrete and reinforcement actual strength of four specimens is shown in Tables 1 and 2. During the test, the columns were subjected to constant axial load in a vertical position, its ratio of the axial stress to the concrete compressive strength was about 0.18. The vertical loads were imposed reversely on the free end of beam to simulate the effect of earthquake loading.The loading process is shown in Fig.2.

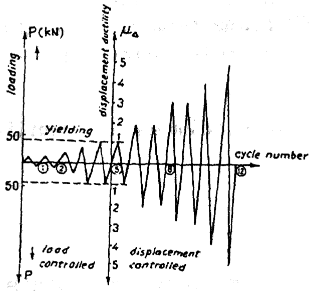

Fig.2

The applied loads, deflections of free beam end, average rotations in beam plastic hinge region, shear deformations in joint core and the width of cracks were measured and the strains of beam main bars, beam stirrups and joint core transverse stirrups were readed during the test.

The main experimental results are shown in Table 3. The flexural-shear failure was occurred in beam plastic hinge regions of both specimens BC2 and BC4 (Fig.3a). Since the specimen BC4 was constructed with lightweight concrete, its first inclined crack strength and performance of bond were poorer than that of specimen BC2.

The shear-compressive failure was occurred in the joint core of both specimens BC5 and BC6 (Fig.3b). The joint core concrete of specimen BC5 which provided no stirrups in joint was severely spalled and the failure appeared obvious brittleness.

BEHAVIOURS OF BEAM PLASTIC HINGE REGION

Table 3 Test Results

Specimens	Materials	First Inclined Crack (KN)	Main Diagonal Crack (KN)	Specimens Yielded (KN)	Ultimate Load (KN)	M_u^t/M_u^c	μ_Δ	Failure
BC2	Normal-weight Concrete	44.1	Not Occurred	43.12	50.96	1.08	5.06	The flexural-shear failure was occurred in beam plastic hinge region.
BC4	Light-weight Concrete	40.18	Ditto	43.0	51.94	1.02	4.15	
BC5	Ditto	39.20	58.8	78.4	81.34	0.98	2.97	The concrete in joint core was fractured and severly, spalled.
BC6	Ditto	41.16	68.6	79.38	82.32	0.97	2.92	

Fig.3a

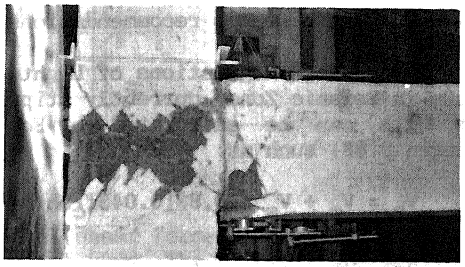

Fig.3b

Beam Flexural Strength The beam fixed end is subjected to, in many cases, maximum internal forces (M,V) in frame. There are cracks in the beam compressive zone under reversed loading. After beam bars yielded, the moment produced by the tension of beam bars and the resultant force of compressive concrete is equilibrium with imposed moment, so that the beam ultimate flexural strengths of both lightweight concrete and normal weight concrete are similar as long as both concretes have about same compressive strength. The overstrength of beam bars and decrease of concrete compressive zone after yielding should be taken into account to determine the flexural strength in beam plastic hinge region.

The ultimate flexural strength in plastic hinge region for normal weight R/C beam is expressed in New Code of PRC as following:

$$M_u = 1.25A_sf_y(h_o-a_s') \qquad (1)$$

Based on experiment, the calculating flexural strength of four specimens by Eq. (1) was very near the test strength (see Table 3). It indicates that flexural strength of lightweight RC beam can be also calculated by Eq.(1) as normal weight RC beam.

Beam Shear Strength Under reversed loading, there were many diagonal and vertical cracks in the plastic hinge region of frame beam, so the concrete shear resistances in the beam compressive zone was reduced. Due to bars yielded, the shear deformation was increased and the effect of beam bar dowel was very small. With the cracks opened and closed by reversed loading, the effect of aggregate interlock, particularly lightweight concrete, was reduced. So the shear force of beam was mainly transferred by the transverse stirrups.

The load-strain curves of the beam stirrups of BC2 and BC4 are shown in

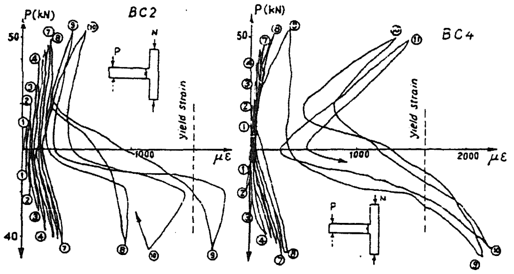

Fig.4

Fig.4. It indicated that the strains were rapidly increased after beam bars yielded either normal weight R/C specimen BC3 or lightweight R/C specimen BC4. Among those, BC4's strains were more than BC2's, so it can be infered that the capacities of shear resistance in lightweight concrete were less than in normal concrete.

In New "Code for the Design of Concrete Structures" (PRC), the shear strength in beam end of normal weight R/C frame in seismic zone can be calculated by(Ref.5)

$$V_b = V_c + V_s = 0.045 f_c b h_o + f_y (A_{sv}/s) h_o \qquad (2)$$

But there are no recommendations for lightweight concrete in this Code.

In "Design Regulations of Lightweight Aggregate (clay ceramisite) R/C Structure in Seismic Zone" currently stipulated in Tianjin city (PRC), the beam shear strength can be calculated by Eq. (2) multiplied the reduction coefficient (taken 0.83) such as:

$$V_b = V_c + V_s = 0.83[0.045 f_c b h_o + f_y A_{sv} h_o / s] \qquad (3)$$

By comparsion, the beam shear strength (V_b) at ultimate load is less than calculations by Eq.(2) and (3). It indicated that under reversed loading the calculated shear strength in general are more higher and become not good for safety. Therefore, it is necessary to further study the calculating method for shear resistance strength of beam in plastic hinge region of lightweight concrete.

BEHAVIOUR OF JOINT CORE

Shear Resistance Strength in Joint Core The shear-compressive failure was occurred in the joint core of both lightweight R/C specimens BC5 and BC6. No transverse bars and 4ϕ8 stirrups were provided in BC5 and BC6's joints respectively. The failure processes of two specimens were developed in four stages -- first inclined crack, main diagonal crack, ultimate load and failure.

Because of lower tensile strength of lightweight concrete, the first inclined crack was occurred early in joint core. The small strains of transverse bars were found and the joint shear force was mainly transferred by concrete in this stage. When a pair of the main diagonal cracks across the joint were occurred, the load was about 75% of the ultimate load, but the joint shear deformation was obviously increased and the joint stiffness became also obviously reduced. So that the shear strength of beam-column joint could be taken as this stage as a design criterion.

The joint shear strength is consist of the effect of concrete shear resistance, which is still affected by the column axial loads and confinement of transverse beams, and shear resistance of transverse bars. In this test, the concrete shear resistance capacities could be directly obtained by specimens BC5 which wasn't provided transverse bars . The shear resistance capacies of transverse stirrups could be obtained by specimen BC6 in comparsion with BC5. Based on above, the shear resistance strength of lightweight concrete joint can be expressed by:

$$V_j = V_c + V_s = 0.1\omega(1 + \frac{N}{b_c h_c f_c}) b_j h_j f_c + f_y \frac{A_{sh}}{s}(h_o - a_s') \qquad (4)$$

where V_j — the joint shear resistance capacities;
V_c — the concrete shear resistance capacities.
V_s — the shear resistance capacities of transverse bars.
ω — the strength reduction coefficient (Based on this test, taken ω=0.8).

The test results are compared with the calculations by Eq.(4) in Table 4, in which the test data of Tianjin Building Design Institute had been quoted. It can be found that the test conclusions are all more than the calculations and the mean ratio is 1.12.

Table 4 Shear Strength in Joint Core

Specimens	Test Measured V_j^t	Calculated V_j^c	V_j^t/V_j^c	Note
BC5 BC6	231.65 339.65	189.8 314.9	1.22 1.08	Failure in joint core [4]
A1-3 A1-4 B1-3 B1-4 B1-5 B1-6	239.4 280.5	208.4 270.2	1.15 1.04	Major diagonal cracks across the joint [2]

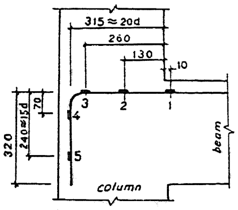

Fig.5a

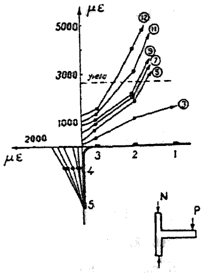

Fig.5b

Anchorage of Beam Bars in Joint The horizontal shear force is transferred by the bond between reinforcements and concrete in joint core. The strength and stiffness of joint are directly affected by the performance of bond and anchorage of beam bars in joint.

In this test, the anchorage failure of beam bars was not occurred in both specimens BC2 and BC4. The details of beam bars and the locations of gauges in the beam bars are shown in Fig.5a. The strain variation are shown in Fig.5b.

From Fig.5b, it is indicated that the tensile force of beam bars was mainly transferred by bond stresses of the longitudinal anchorage in joint core before beam bars yielded and then the tensile force was gradually transferred by both the longitudinal anchorage and the hook. Since the yield scopes were penetrated into joint core, the bond of the longitudinal anchorage became deterioration. With the loading cycles developed, the effect of the hook became more important for anchorage. By the specimens failure, the beam bars were yielded into 10d (d - diamater of beam bar and hereinafter) away from the face of column and the tensile force transferred by the hook was about half of total horizontal shear force. Under ultimate load the average bond stress was about 3N/mm^2. Besides, the strains of the hook end (the fifth gauges in Fig.5b) were very small from start to finishing, near zero.

DUCTILITY AND ENERGY DISSIPATION CAPACITIES

Because of poorer stiffness and more deflection in yielding, the ductility coefficient of lightweight concrete specimen BC4 was less than that of normal weight concrete specimen BC2 in same stage and the total energy dissipation and the energy-power coefficient of BC4 were 82% and 89% of BC2's respectively. Since the lightweight concrete specimen BC6 had been failed in the joint core, its effective ductility was more less than that of BC4 failed in beam hinge region and its energy-power coefficient was 66% of BC4's. It also indicated that it is disadvantageous for both ductility and energy dissipation if failure occurred in the joint core. Therefore, in actual structure the joint should be provided with transverse reinforcement to avoid such brittle failure.

CONCLUSIONS

1. In new code of PRC, the formula to calculate the ultimate flexural strength of normal weight concrete frame beam in seismic zone could be acceptable for calculating on lightweight concrete, but the beam shear resistance calculated using this code is not good for safety.

2. The shear strength of lightweight R/C frame beam-column joint could be expressed as:

$$V_j \leqslant 0.1\omega(1+N/b_c h_c f_c)b_j h_j f_c + f_y \frac{A_{sh}}{s}(h_o - a_s')$$

where, ω — strength reduction coefficient (taken $\omega=0.8$) other symbols can be found in reference (5).

3. Under reversed loading, the development length for straight anchorage of beam bars in lightweight R/C extrior beam-column joint should not be less than 20d and also should be greater 5-10d than that of normal weight R/C joint and the 90° standard hook developed 15d could be compatible with the anchorage requirement.

4. Under reversed loading, the effective displacement ductility and energy dissipation capacities of the lightweight concrete specimens are less lightly than that of normal weight concrete specimens.

REFERENCES

1. Bertero, V. V., Popov, E. P., Forzani, B., "Seismic Behaviour of Lightweight Concrete Beam-Column Subassemblages", ACI proc. Vol.77, No.1, Jan.Feb., 44-52, (1980).

2. Gao Yong Fu, Chen Zenghua, "Experimental Report of Clay-Ceramsite R/C Frame Beam-Column Joints Under Low Cyclic Reversed Loading", Tianjin, China, (1986).
3. Tang Jiuru, "Shear Strength of R/C Frame Joint", "Building Structure", No.6, (1987).
4. Xu Xiao Lin, "Experimental Study and Nonlinear Finite Elements Analysis of Lightweight R/C Beam-Column Joints", (master degree paper), Nanjing Institute of Technology, China, (1987).
5. State standards of the People Republic of China, "Code for the Design of Concrete Structures", (1988).