EFFECT OF AXIAL LOAD RATIO ON SEISMIC BEHAVIOUR OF INTERIOR BEAM-COLUMN JOINTS

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SUMMARY

In this paper, effect of axial load ratio on seismic behavior of interior beam-column joints is investigated by means of cyclic loading tests of 10 interior beam-column subassemblies with different levels of shear and axial forces. It is concluded that two different kinds of shear transfer mechanisms are activated before and after yielding of reinforcement in the beam and/or the column crossing through the joint. Favorable and detrimental effects of increasing axial load ratio on behavior of joints during the two stages, that is, before and after yielding, are outlined from the mechanical behavior point of view. On this basis, reasons for effect of axial load ratio on joints with different levels of shear are summarized.

INTRODUCTION

Effect of axial load ratio on seismic behavior of beam-column joints in reinforced concrete frames is debatable even until now among researchers in this field. For exterior beam-column joints, Kaku, et al [Kaku,1991] obtained convincing results by comparison experiments at the late of the eighties, but few is available for interior joints.

Five sets of subassemblies of interior joints (altogether ten specimens) with high, moderate and low shear levels, and different axial compression ratios, are deliberately designed and comparatively tested. Performance of joints under cyclic loading to failure, in the context of $N/f_c b_c h_c$ being equal to 0.05,025 and 0.36 respectively, is investigated. It is hoped that shear transfer mechanisms in the joints and effect of axial compression ratio can be recognized profoundly.

DESCRIPTION OF EXPERIMENTS

The testing setup is shown in Fig.1. The size of the beam section is *b*=250mm, h=400mm; the column is b=350mm, h=350mm. Stirrups in the column and beam ends are spaced as D8@100. The rest data are summarized in table 1. In table 1 f_{cu} is the average compression strength of a set of three standard cubes (say a cube 150mm long). f_c is equal to $0.76f_{cu}$ according to China design code for concrete structures (all are measured values). Except specimens of J-1 and J-2, the rest crash in diagonal compression failure of the strut in the joint core concrete while displacement ductility is relatively high.

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Table 1. Basic Data of Specimens

No.	Concrete Cube Strength, f_{cu} (N/mm^2)	Axial load Ratio $N/f_c b_j h_j$	Upper Reinforcement of the beam, and f_y(N/mm^2)		Lower Reinforcement of the beam, and f_y(N/mm^2)		Column Reinforcement at each side, and f_y(N/mm^2)		Stirrups in joints, and f_{yv}(N/mm^2)		Dispalcement* Ductility when the specimen fails	
											+	−
J-1	46.0	0.05	3D18[1]	397	3D18[1]	397	4D22[1]	363	8D8[1]	298	8.0	7.0
J-2	35.8	0.36	3D18	397	3D18	397	4D22	363	8D8	298	8.5	9.0
J-3	34.3	0.05	3D16	388	3D16	388	3D22	363	5D8	298	6.2	6.0
J-4	36.7	0.36	3D16	388	3D16	388	3D22	363	5D8	298		
J-5	44.2	0.05	3D18 1D16	397 388	3D18 1D16	397 388	4D22	363	6D10	382	6.0	5.5
J-6	30.6	0.36	3D18 1D16	368 378	3D18 1D16	368 378	4D22	364	6D10	344	6.0	5.0
J-7	36.9	0.05	5D18	376	3D18	376	4D20	350	3D18	328	5.0	4.0
J-8	33.6	0.25	5D18	376	3D18	376	3D16	423	6D12	328	4.0	3.5
J-9	35.0	0.05	4D18	376	2D18	376	3D20	350	4D10	382	4.0	4.0
J-10	29.3	0.25	4D18	376	2D18	376	3D14	447	4D10	382	4.0	3.5

* -------*The ultimate displacement is defined as the value when ultimate capacity is 85% of the maximum value.*

1 ---- *D stands for diameter of a rebar or a stirrup.*

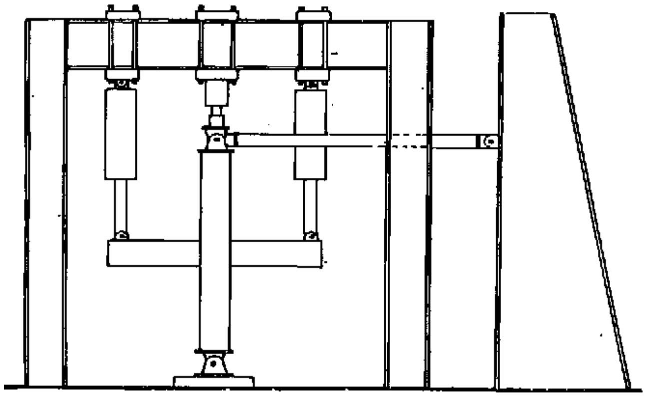


Figure 1: Testing Setup

ANALYSIS OF EXPERIMENTAL RESULTS

Two stages of mechanical Behavior of Joints

Yield first occurs at beam ends for the 10 specimens in this paper. The ratio, d_b/h_c, of the beam reinforcement crossing the joint is only 1/20, satisfying requirements of the China Code, but it is a relative small crossing length. Therefore, no matter how much the shear of a specimen is, substantial bond slip of beam reinforcement occurs when inelastic deformation increases to a certain extent; while the tensile portion of the beam reinforcement extends to the opposite side of the joint, the yield portion penetrates into the joint core. That is to say, bond deterioration is clearly observed. Similar phenomenon happens for the crossing rebars in the column after the longitudinal reinforcement at the column end yields, but it occurs after the beam rebars did so.

On the basis of strain measurements of stirrups both parallel with and perpendicular to loading direction, together with observation of bond deterioration of the crossing portion of the beam reinforcement, some new knowledge is obtained on shear transfer mechanisms and mechanical properties for the joints which finally collapse in diagonal compression failure in the joint core.

The first stage can be defined as just before severe bond deterioration of the crossing portion of beam reinforcement occurs. During this time, as all well known, the compression forces of the beam and the column develop a strut in the joint core concrete after balancing some shears at the beam ends and the column ends. At the same time, forces in the reinforcement of beams and columns form principle tensile and compression field in the core after balancing another portion of shears at column and beam ends. Once diagonal cracks occur in the core, the diagonal tension is transferred to the hoops instead. In subsequent cyclic loading, stresses in hoops parallel with the loading direction increase gradually (Fig.2). At this time, diagonal compression in the core concrete is still small,and lateral expansion is not significant, hence tensile strains in the hoops perpendicular to the loading direction are small (Fig.2).

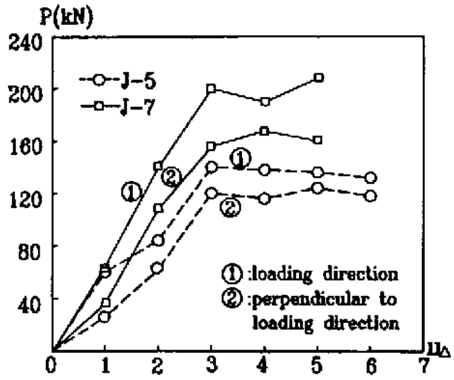


Figure 2 : Tensions in a stirrup parallel with and perpendicular to loading direction

With further significant bond deterioration of the crossing portion of the beam reinforcement occurring, forces of reinforcement in the joint transferred by bond effect decreases, so does the ratio of forces transferred by the truss mechanism. It is defined as the second stage. At this time, as the crossing portion of beam reinforcement is fully in tension, the compression reinforcement of the beam end section opposite to the joint changes into tensile instead , thus the compression forces in the compression zone and that transferred into the core by the strut increase, correspondingly. In this way, the dominant shear transfer mode, the strut mechanism, develops. During this process, cracks along two diagonals of the joint core open and close alternately, and number of crack increase, resulting in severance of the core concrete by the cracks. In the meantime, damage of the joint is accumulating, its stiffness of compression is decreasing gradually, and lateral expansion (including that perpendicular to the loading direction) is also increasing. At this time, confinement on the concrete by the hoops in both directions is developing, hence tensile forces in the confined hoops are increasing. Results of measurement show that one common characteristic of the 10 tested specimens in this stage is that, in the hoops parallel with the loading direction, as the tensile forces in the truss mechanism decrease, the confining tensions increase rapidly; so tensions in the hoops themselves are increasing. On the other hand, tensions in the hoops perpendicular to the loading direction increase rapidly due to the confinement, and the rate of the increasement is greater than that of the hoops parallel with the loading direction (Fig.2). Measured results have also verified once again that obtained by Kitayama, et al [Kitayama,1991] in the late eighties. It is strongly convinced that the role of hoops in the second stage is mainly to confine the concrete. Therefore, it can be described as “confinement mechanism”. This mechanism ensures shear transferring by the diagonal strut mechanism in the core concrete which is severed by cracks.

On the basis of the aforementioned analysis, it is reasonably concluded that the first stage is relatively longer to play its role when bond of the crossing portions of beam and column reinforcement keeps well. In addition, when the amount of hoops is considerable, redundancy of strains, which can be used to develop confinement, is aboundingly available.

Observations from the experiment show that when the shear is relatively small, bond deterioration of the crossing portion of beam rebars increases the compression force in the diagonal strut in core concrete. Despite many cycles of loading, the core concrete is free of crash. So the joint does not fail until considerable ductility is reached. Its behaviour of energy dissipation is not so satisfactory, however, as it is shown in Fig.3. As the shear is greater, the joint fails in crush of the strut in the core concrete, when some ductility is reached.

Effect of Axial Load Ratio on Behaviour of Joints

Effect of axial load ratio on behaviour of joints relates closely to two main factors, one is the bond of crossing portions of beam and column reinforcement, the other is the level of shear. From the point of bond effect of the beam reinforcement, it is recognized from comparison experiments that no matter what the relative $(V_j / f_c^{'} b_j h_j)$ shear is, penetration of yield of the beam reinforcement into the joint core slows down when the axial load ratio increases, therefore slip of the crossing portion of beam reinforcement decreases, and pinch effect of the hyseretic loops is not so significant. Under the same ductility, joints with high axial load ratio have better energy dissipation capacity than those with low axial load ratio. It is demonstrated that increase of axial load ratio is favorable for the bond behaviour in the joint zone when the joint is in the first stage.

But from the point of effect on overall seismic behavior of the joint zone, two cases are classified.

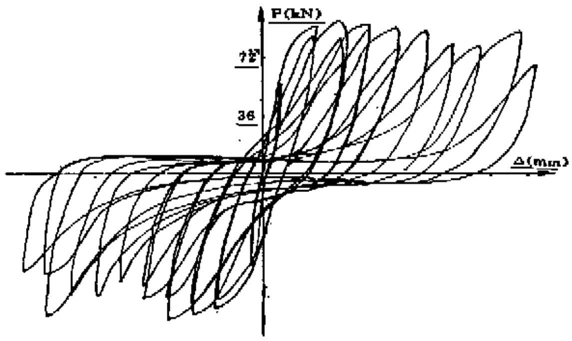
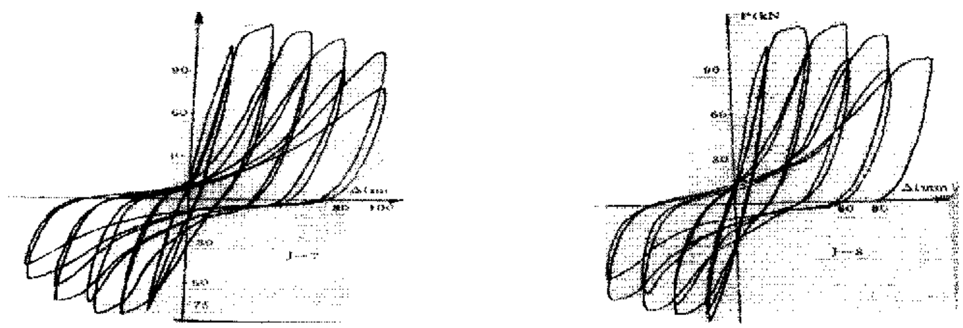


Figure 3: Measured hysteretic curve of tested specimen J-1 when shear is relatively small

For the joints with moderate or high relative shear, increase of axial load ratio will better bond of crossing portions of beam reinforcement, and retard development of cracks in the first stage. Although the bond deter10 ration is postponed, it is still serious. When the joint enters the second stage, the strut and the confinement mechanisms develop in the joint core, higher axial load ratio would further enhance the compression force in the diagonal strut, resulting in a tendency for the core concrete to crush. Although increase of axial load ratio is favorable in the first stage, it is unfavorable in the second stage. And it postpones the demarcated condition of the two stages as well. At the meantime, overall behaviour (that is, ductility at failure, energy dissipation index, and stiffness deterioration) of the joint has little difference, as shown in Fig.4, in which hysteretic curves of J-7 and J-8, with axial load ratios are 0.25 and 0.05 respectively, are presented.



(a) The specimen J-7 (b) The specimen J-8

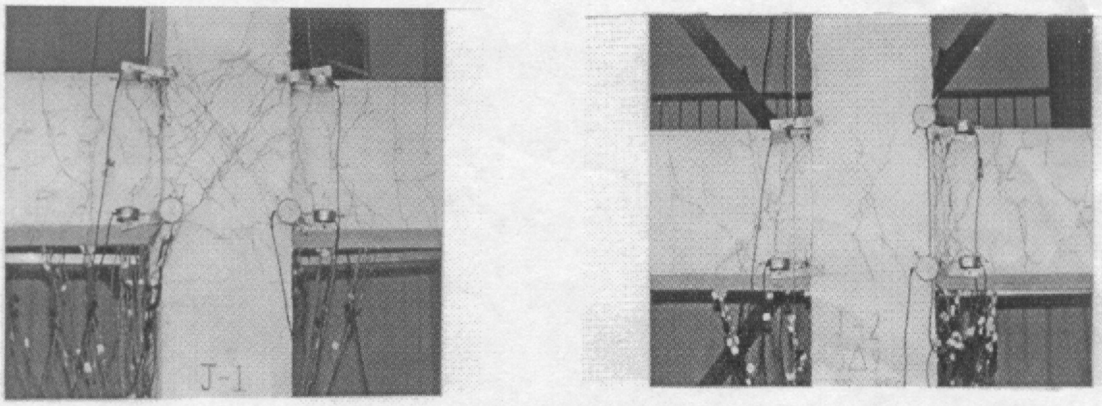
Figure 4 : Hysteretic behaviour of specimens with different axial load ratios and moderate shear

It can be suggested that if the shear is much higher, the displacement ductility the specimen may reach would decrease correspondingly due to the reason that the more the increase of axial compression ratio, the more unfavorable effect on the second stage. In a word, increase of axial load ratio is unfavorable as a whole.

When the shear is small, besides its favourable effect on both bond of the crossing portion of the beam reinforcement and retarding cracks inside the joint in the first stage（Fig.5）, the increase of axial load ratio will not have significant unfavorable effect on the second stage, hence overall favourable effect remains as a whole.

CONCLUSION

On the basis of comparison experiments of the interior beam-column subassemblies under cyclic loading, two distinct stages of behaviour of joints are clearly classified. The first stage is characterized by two activated shear



(a) J-1 (b) J-2

Figure5 : Damage Patterns of specimens with different axial load ratios and small shear

transfer mechanisms, one is the truss model, the other is the strut model. The second stage is distinct from the first stage by the corresponding strut and the confinement mechanisms. Classification of the two stages depends on bond of crossing portions of the beam and the column reinforcement, acting shear level and volumic stirrup ratio. Therefore, it is found from previous literatures that specimens of New Zealand with excellent bond mainly show characteristics of the first stage, while the specimens of other countries with poor bond present much similar properties to that in the second stage.

Experimental results show that, while increase of axial load ratio is favorable to energy dissipation capacity of joints with small shear; no significant effect is observed on the joints with moderate shear; and unfavorable effect is noticed on the joints with high shear, resulting in premature shear failure, that is, crush of the joint core concrete.

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