EXPERIMENTAL INVESTIGATION ON SEISMIC BEHAVIOUR OF KNEE JOINTS IN REINFORCED CONCRETE FRAMES

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SUMMARY

On the basis of cyclic loading experiments of twenty two knee joints, effect of such factors as reinforcement ratio of the beam and the column, concrete strength, location of lap splices of tensile reinforcement under negative moment, and the lap splice length, on seismic behaviour of the joints, are investigated. The strut mechanism is identified as the main mechanism for shear transfer in the joints under both positive and negative moments. Characteristics of mechanical behaviour and schemes of lap splices are outlined. Finally, critical conditions to avoid diagonal compression failure and bearing failure inside the bend, minimum stirrup detailing requirements and the lap splice length of reinforcement under negative moment are presented.

INTRODUCTION

Within a reinforced concrete frame, Knee joints are different from other types of joints in seismic behaviour. Whenever subjected to negative or positive moments, the beam-column knee joint zone is similar to a broken-line beam with 90°angle. When there is not any external moment imposed on the joint zone, the beam-end moment is equal to the column-end moment under one load combination. Therefore, tensile reinforcement under negative moment at the upper part of the beam and the external side of the column should either continuously cross the zone along the external side of the joint , or reliably be overlapped at different locations in the joint. In addition, the tensile reinforcement under positive moment in the lower part of the beam and the internal side of the column should be anchored in the joint. But in current engineering practice or experimental investigations, however, it is common that the tensile reinforcement in the upper part of the beam is anchored with 90°standard hook in the knee joint, in such a way similar to that of exterior joints in intermediate stories of the frame. As this scheme can't ensure that each section of the broken-line beam, that is, the joint zone, has sufficient flexural capacity, premature flexural failure may occur as a result, thus such kind of practice should be prohibited.

Cyclic loading experiments of 22 knee joint subassemblies are carried out using the test setup shown in Fig.1. Such factors as concrete strength, beam-column reinforcement ratio, lap splices of tensile reinforcement subjected to negative moment at different locations, and the lap splice length, are taken into account. The column section is b_c=300mm, h_c=400mm; and the beam is b_b=200mm, h_b=500mm. As the test rig is statically determinate, the vertical concentrated force at the middle of the beam of the specimen could not change magnitude of moment acting on the joint, but adjust moment gradient in the portion of the beam near the joint. The column section is symmetrically reinforced. As for the beam section, the reinforcement in the lower part is 50% of that in the upper.

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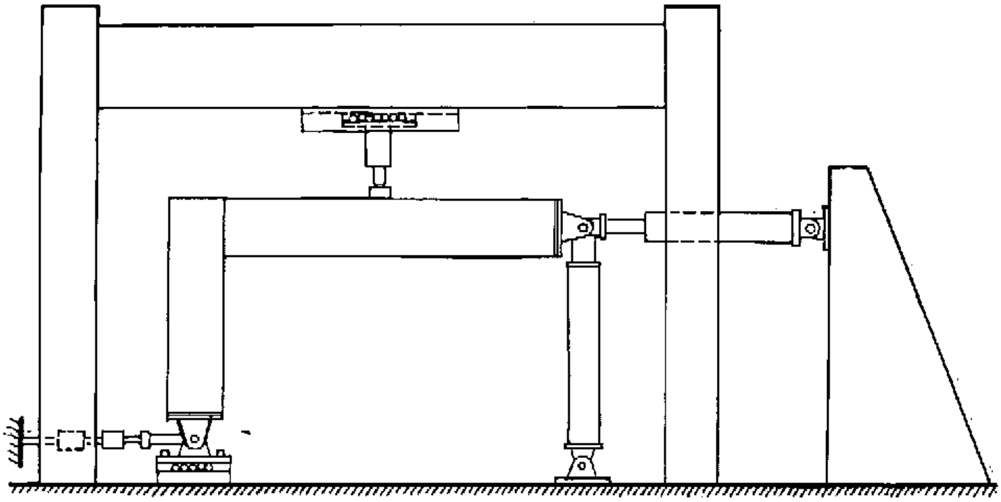


Figure 1 : Testing setup

CHARACTERISTICS, FAILURE MODES AND CHECK CRITERIA OF JOINTS

Experimental results show , that under negative moment, after fan-like diagonal cracks develop in the joint zone due to flexure and shear (Fig.2a), stresses of tensile reinforcement at the two ends of the bend of the joint are close to that at joint faces (it is similar to redistribution of tensile forces in reinforcement due to diagonal cracks in beams). Therefore, only a few tensile forces are transferred into the joint core by bond effect along horizontal and vertical portions of the reinforcement under negative moment in the joint. The compression forces in the compressed reinforcement and concrete are also transferred into the joint core after balancing shears of column and beam at joint faces. The diagonal compression on the concrete in the joint core due to the tensile forces in rebars by the 90° bend is in equilibrium with the resultants of compression forces from the beam and column sections, and the dominant strut mechanism is thus developed (Fig.2a). A few shear stress flows transferred into the joint through bond effect of peripheral reinforcement form very weak truss mechanism.

Under positive moment, if the beam has the same width as the column, from the interior end of the diagonal, one dominant diagonal crack will develop into the joint ; but if the width of the joint is greater than that of the beam, flexural cracks will develop at the ends of the beam and the column, respectively (Fig.2b). After balancing shears of column and beam at joint faces respectively, some of the tensile forces in reinforcement of the beam and the column under positive moment is transferred into the joint core by bond, the rest constitutes the resultant diagonal compression force in the joint , combining with the compression forces transferred from the compression zones of the beam and the column. In this way, a strut perpendicular to that under negative moment develops, together with some principle tensile cracks in the region outside of the diagonal of the joint, resulting in a tendency to push away the concrete in the exterior corner of the joint (Fig.2b). The compression forces in compressed rebars in the beam and the column are transferred into the joint core by bond effect. After the longitudinal reinforcement in the upper part of the beam or at the exterior side of the column yields in the previous cycle of loading under negative moment , and wider flexural cracks develop afterwards, under subsequent positive moment, the bonding forces resulting from the upper and exterior portions of the reinforcement in the joint are not sufficient to balance the compression forces in the reinforcement before the cracked concrete contacts, and the compression forces are sustained mainly by the rebars. In this context, the compression forces transferred in the exterior upper corner of the joint thus push the bend aside, resulting in cracks along the bend.

(a) Negative moment **(b)** positive moment

Figure 2 : The strut mechanism in the joint

Under the action of negative moment, if the characteristic value of tensile reinforcement in the beam and the column, that is, is too high, the concrete in the strut mechanism will fail in diagonal compression. According to experimental results, if the tensile reinforcement of the beam and the column at joint faces yields to a limited extent, the critical condition for the diagonal compression failure can be expressed as:

$$A_s f_y \,/\, f_c bd \le 0.35 \qquad (1)$$

if the reinforcement steps into post-yield state substantially, the critical condition is modified as follows,

$$A_s f_y \,/\, f_c bd \le 0.27 \qquad (2)$$

If the characteristic value is relatively high and the radius of the bend of the reinforcement in the exterior upper corner is too small, bearing failure may occur in the concrete inside the bend. As the experimental results show, if $r/d \geq 0.15$, (d is effective height of the beam), then this kind of failure can be avoided.

Under positive moment, the exterior upper corner of the joint contributes little to transfer forces. Moreover, the level of positive moment in these experiments is relatively low. These are believed as the reasons why the joint doesn’t fail under positive moment.

The ratio of forces transferred by the truss mechanism in the joint core under negative moment is small. Under positive moment, although the ratio is increasing a little bit, the truss mechanism does in induce obvious damage in the joint core due to the fact that the relative value of the positive moment is small. From this context, stirrups in the knee joints of a RC frame can be determined with respect to minimum codified requirements, other than specific calculation. If there are lap splices of the tensile rebars in the joint zone under negative moment, just as expressed as the following, the stirrup spacing should be further moderately reduced.

EFFECT OF LAP SPLICES OF TENSILE REINFORCEMENT UNDER NEGATIVE MOMENT ON BEHAVIOUR OF JOINTS; AND CHARACTERISTICS OF LAP SPLICED REINFORCEMENT

Three schemes of lap splices of tensile reinforcement under negative moment are tested in this paper, which are shown in Fig.5a,b, and c. The scheme in Fig.5a can ensure that plastic hinges of negative moment occur at beam ends. When the width of the joint is not equal to that of the beam, bond split cracks caused by compression in reinforcement of positive moment due to remaining cracks of previous negative moment develop ; and the cracks along the bend in the exterior upper corner of the joint, when inelastic deformation is large, occur at the edge of the top of the joint. In the meantime, the joint core remains undamaged (Fig.3a). Hysteretic characteristics of the subassemblies are similar to beam hinges; that is, ductility and energy dissipation capacity are very satisfactory (Fig.4a).

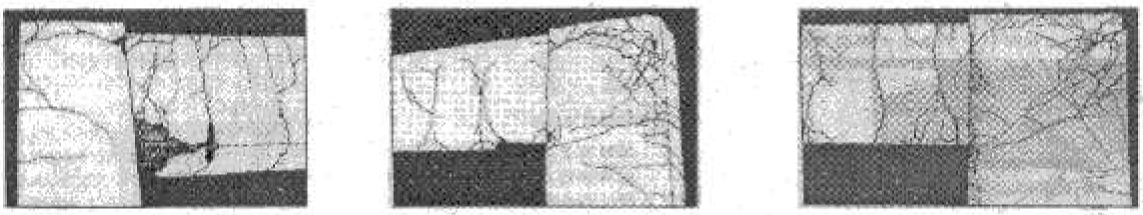
For the second scheme shown in Fig.5b, the plastic hinge occurs at the end of the column. Cracks under both negative and positive moments develop well in the joint when the inelastic deformation is large (Fig.3b). Hystertic behaviour is not so good as that of the first scheme, but it is still very satisfactory (Fig.4b). In this scheme , when the column width is greater than the beam width, rebars in the corner of the exterior side of the column can not be stretched in the beam, but be cut off in the interior side of the column or be stretched into the cast-in-place slab at the side of the beam, but in any case, the beam reinforcement area stretched into the exterior side of the column should not be less than 60% of the total reinforcement area.

In these two schemes, the lap spliced rebars under negative moment all have 90° bend. As the friction of the bend is heavy and the forces can be transferred well, tensile forces in the rebars at the end of the bend reduce sharply, thus the lap splice length can be shorter than that of direct lap splices.

The third scheme in Fig.5c can avoid congestion due to lap splices of reinforcement. As the reinforcement is lap spliced in a straight line, when the depth of the column is less than depth of the beam , the weakest section of the subassembly may be formed along the diagonal of the joint crossing cut-off ends of the exterior rebars at the top of the column (Fig.3c), so the plastic hinge under negative moment develops in the joint zone. Cracks in the joint develop seriously when inelastic deformation is large, and the hysteretic behaviour is a little poor (Fig.4c). In such a case, the lap splice length should not be discounted due to the fact that there are not 90° bend in the lap spliced portion.

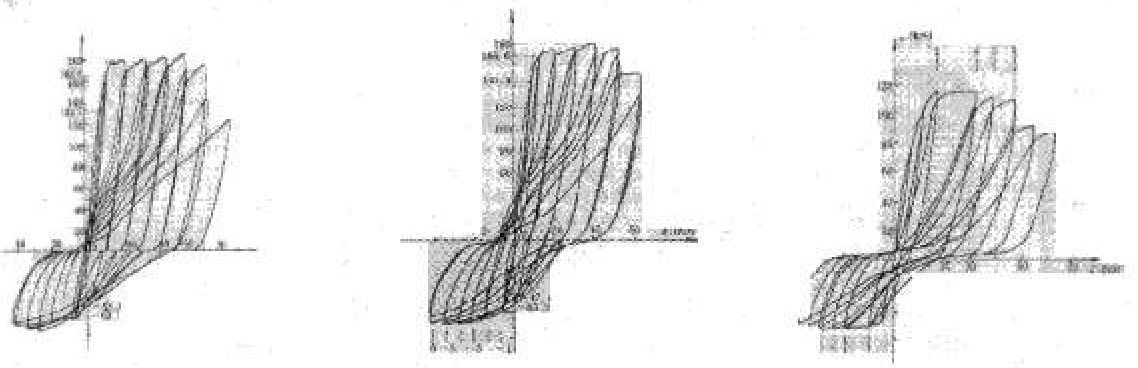
In the above three schemes, plastic hinges of positive moment all occur at beam ends.

In Fig.5, proposed three schemes of lap splices and recommended lap splice length for the revising “Design Code for Concrete Structures” of China are presented.



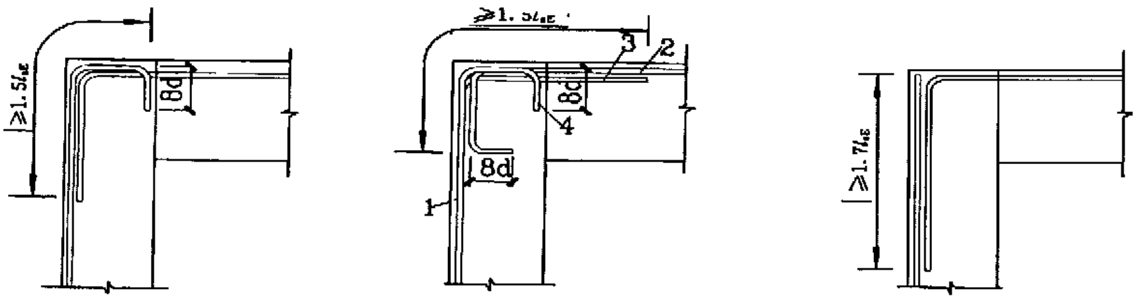
a. Fig.5a lap splices scheme b. Fig.5b lap splices scheme c. Fig.5c lap splices scheme

Figure 3 : Cracking Patterns in joints with different lap splices scheme



a. Fig.5a lap splices scheme b. Fig.5b lap splices scheme c. Fig.5c lap splices scheme

Figure 4 : Typical Hysteretic Curves for subassemblies with different Lap Splices Schemes[Bai,1994] When inelastic deformation is substantial



Note: l_{aE} is the basic development length of reinforcement

1. Rein. of the column at the exterior side section area is A_{cs}
2. Upper rein. Of the beam
3. Rein. Of the column stretched into the beam,the area is not less than $0.65A_{cs}$
4. Rein. Of the column which can not be stretched into the beam

a. The Lap splices are at the edge of the joint and the column end

b. The Lap splices are at the edge of the joint and the beam end

c. The Lap splices are at the exterior side of the joint and the column end

Figure 5 : Proposed Lap Splices Schemes for Reinforcement Under Negative Moment

CONCLUSION

1. The strut mechanism is dominant in shear transfer in knee joints under both negative and positive moments, while the struss mechanism is insignificant. In seismic design, diagonal compression failure and bearing failure within the bend should be avoided.

2. As the truss mechanism in knee joints is very weak, minimum requirements for stirrups are proposed. The stirrups can sustain the diagonal tension in the core concrete after cracking, and confine the core concrete and lap splices of reinforcement of negative moment as well.

3. It is not appropriate to anchor the beam reinforcement with 90° standard hook under negative moment in knee joints. Reinforcement of the beam and the column under negative moment should be reliably lap spliced to ensure flexural capacity on each section of the joint zone as a broken line with 90° angle beam.

REFERENCES

Shaoliang, Bai, et al, “Static and Seismic Behavior of Knee Joints in a Reinforced Concrete Frame”, *Research Report of Concrete Structures*, Vol.3, Edited by China Academy Building Research, June, 1994(in chinese),pp184-216.