Beam-Column Connection with Crossed Inclined Reinforcement Bars: An Overview

Vivek V S, Nithin Mohan

Abstract— This paper presents the literature review on beam-column connection with crossed inclined column reinforcement bars.The presence of crossed inclined reinforcement improves the shear strength, the energy dissipation capacity of the joint and the pinching effect of the beam's reinforcement. The specimens with X-bars in the joint area were able to maintain maximum strength for a larger number of post yield cycles. It was also clear from the literatures that the presence of crossed inclined reinforcing bars introduced a new shear transfer mechanism in the joint area, beyond the mechanism of the concrete diagonal strut and the steel truss mechanism of the conventional shear reinforcement (common closed stirrups and vertical bars). The new mechanism due to the addition of the X-bars was called truss mechanism of the crossed inclined reinforcement.

Index Terms—Beam-column connections, X-bars, concrete diagonal strut, shear reinforcement truss, crossed inclined bars truss

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1 INTRODUCTION

Reinforced concrete structures built in zones of low- to-medium seismicity still do not take seismic effect into consideration. The reinforcement details of such structures though
conform to the general construction code of practice may not adhere to the modern seismic provisions. Structural engineers often consider current seismic code details for reinforced concrete framed structures impractical. The behaviour of beam-column joints in existing Reinforced Concrete (RC) structures is often characterized by the lack of ductility, sudden decrease of strength and low energy dissipation capacity.

However, modern design criteria of high ductility RC structures often demand high steel ratio of shear reinforcement that leads to short stirrup spacing. Further, strict durability requirements impose high clear covers between concrete and steel reinforcement. Thus, the combination of these two facts with the recent design trends of small cross-sectional sized structural members induces essential constructional problems due to the dense steel reinforcement. Lack of spacing makes pouring and vibrating of fresh concrete a very difficult task that consequently causes concrete compacting problems, especially in internal beam-column connections that consist of four beams and two columns.

The beneficial use of inclined steel reinforcement in shear-critical RC elements has already been recognised since it directly resists to the principal tensile stresses developing in the diagonal concrete struts due to the applied shear loading. This advantageous remark inspired researchers to investigate the potential application of crossed inclined reinforcing bars, or else X-bars, in the joint area as alternative non-conventional shear reinforcement in RC beam-column connections. The results of the experimental investigations on the cyclic behaviour of beam-column specimens reinforced in the joint region with X-bars only or with the combination of X-bars and common closed stirrups indicated significant improvement of the joint hysteretic behaviour in terms of shear strength, stiffness and energy dissipation capacity over the tests. Nevertheless, the contribution of the crossed inclined bars to the shear capacity of beam-column joints has not yet been included into code provisions.

2 BEAM COLUMN JOINTS

In a moment resisting frame, beam-column joints are generally classified with respect to geometrical configuration and identified as interior, exterior and corner joints (Fig.1). The basic requirement of design is that the joint must be stronger than the adjoining beam or column member. It is important to see that the joint size is adequate in the early design phase; otherwise the column or beam size will have to be suitably modified to satisfy the joint shear strength or anchorage requirements. The design of beam – column joint is predominantly focused on providing joint shear strength and adequate anchorage within the joint.

The joint is defined as the portion of the column within the depth of the deepest beam that frames into the column. When four beams frame into the vertical faces of a column, the joint is called as an interior joint. When one beam frames into a vertical face of the column and two other beams frame from perpendicular directions into the joint, then the joint is called as an exterior joint. When a beam each frames into two adjacent vertical faces of a column, then the joint is called as a corner joint. The severity of forces and demands on the performance of these joints calls for greater understanding of their

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seismic behaviour. These forces develop complex mechanisms involving bond and shear within the joint.

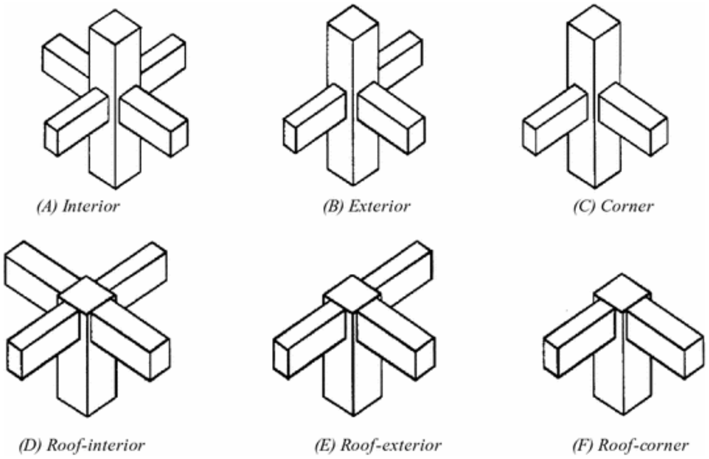


Fig 1: Types of joints

The pattern of forces acting on a joint depends upon the configuration of the joint and the type of loads acting on it. The effects of loads on the three types of joints are discussed with reference to stresses and the associated crack patterns developed in them.

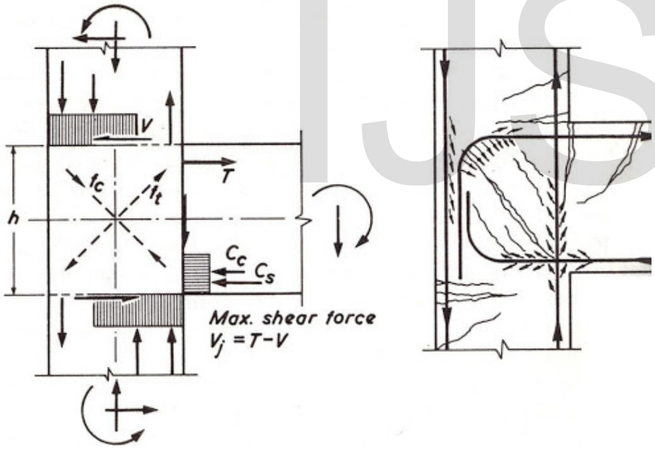


Fig 2: Forces acting on a Joint

The forces acting on an exterior joint can be idealized as shown in Fig.2. The shear force in the joint gives rise to diagonal cracks thus requiring reinforcement of the joint. The detailing patterns of longitudinal reinforcements significantly affect joint efficiency. The bars bent away from the joint core result in efficiencies of 25-40 % while those passing through and anchored in the joint core show 85- 100% efficiency. However, the stirrups have to be provided to confine the concrete core within the joint.

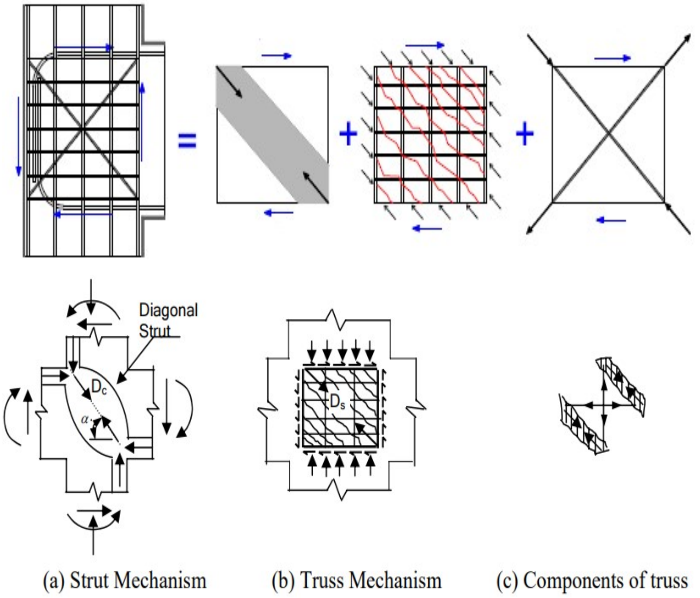
3 JOINT MECHANISMS

In the strong column-weak beam design, beams are expected to form plastic hinges at their ends and develop flexural over strength beyond the design strength. The high internal forces developed at plastic hinges cause critical bond conditions in the longitudinal reinforcing bars passing through the joint and also impose high shear demand in the joint core. The joint behavior exhibits a complex interaction between bond and shear. The bond performance of the bars anchored in a joint affects the shear resisting mechanism to a significant extent.

4 CROSSED-INCLINED REINFORCEMENT BARS

A typical conventionally reinforced beam-column joint resists to the applied joint shear stress with two main mechanisms; the concrete diagonal strut and the steel conventional shear reinforcement truss mechanism. The presence of cross inclined reinforcement improved the shear strength, the energy dissipation capacity of the joint and the pinching effect of the beam's reinforcement. The specimens with X-bars in the joint area were able to maintain maximum strength for a larger number of post yield cycles. It was also observed that the presence of crossed inclined reinforcing bars introduced a new shear transfer mechanism in the joint area, beyond the mechanism of the concrete diagonal strut and the steel truss mechanism of the conventional shear reinforcement (common closed stirrups and vertical bars). The new mechanism due to the addition of the X-bars was called truss mechanism of the crossed inclined reinforcement.

X-bars as the only shear reinforcement was insufficient to restrict joint cracking, but the combination of crossed inclined bars and closed stirrups enhanced the joint shear strength, the strength and stiffness degradation and prevented cracks at the beam-column joint area.



(a) Strut Mechanism (b) Truss Mechanism (c) Components of truss

Figure 3: Shear force transfer mechanisms in a joint with crossed inclined reinforcement bars

The failure of a joint with X-bars is governed by the failure of the strut and truss mechanisms, whereas the contribution of the crossed inclined reinforcement to the ultimate shear strength of the joint should be estimated as an additional shear force component. Fig.3 illustrates the horizontal shear force transfer mechanisms in the joint area. The total horizontal shear force carried by the developed three mechanisms of (a) the concrete diagonal strut (b) the steel conventional shear reinforcement truss and (c) the crossed inclined bars truss.

5 OBJECTIVE OF THE STUDY

This objective of this paper is to study published literatures related to the on beam-column connections with cross inclined reinforcement bars.

6 LITERATURE REVIEWS ON WIDE BEAM COLUMN CONNECTIONS

Chalioris Constantin et al [1] conducted an experimental study was conducted to investigate the effectiveness of crossed inclined bars (X-bars) as joint shear reinforcement in exterior reinforced concrete beam–column connections under cyclic deformations. Test results of 20 joint subassemblages with various reinforcement ratios and arrangements including X-bars in the joint area are presented. The X-type, non-conventional reinforcement is examined as the only joint reinforcement and in combination with common stirrups or vertical bars. The experimental results reported herein include full loading cycle curves, energy dissipation values and a categorization of the observed damage modes. Based on the comparisons between the overall hysteretic responses of the tested specimens, it is deduced that joints with X-bars exhibited enhanced cyclic performance and improved damage mode since a distinct flexural hinge was developed in the beam–joint interface. Further, the combination of crossed inclined bars and stirrups in joint area resulted in enhanced hysteretic response and excellent performance capabilities of the specimens. They concluded that the application of crossed inclined reinforcement enhance the shear strength and stiffness deterioration of the tested specimens. Further, the joint specimens with X-bars developed distinct plastic hinges in the beam-joint interface. However, specimens that had only crossed inclined reinforcement demonstrated mixed failure modes with cracks in the joint region, spalling of the concrete cover at the back of the joint area due to deformation of the bent anchorage of the reinforcing bars of the beam and plastic hinge in the beam. Thus, although the specimens with crossed inclined bars as the only shear reinforcement in the joint area showed great ability to undergo high shear stresses, their use could be limited to structures of low and medium ductility ratio due to the slip of beam reinforcing bars anchorage.

Chalioris Constantin et al [2] carried a new analytical approach for the evaluation of the shear strength of reinforced concrete beam-column joints with crossed inclined reinforcement is developed. The proposed model considers that a joint member resists to the applied shear via three mechanisms, the concrete diagonal strut, the steel conventional shear reinforcement truss and the X bars truss. Failure criteria are adopted in order to quantify the contribution of the crossed inclined bars to the shear capacity of the joint. The joint shear strength is calculated using a simple expression as a function of the shear resistance of the joint without X-bars. The developed procedure is applicable to beam-column joint elements with crossed inclined reinforcement as the only shear reinforcement in the joint region or with the combination of X-bars and conventional horizontal or/and vertical shear reinforcement.

Au et al [3] introduces a new detail especially developed for low to medium seismicity, which involves the use of additional diagonal bars in the joint. Six half-scale interior beam–column assemblies with different joint details, namely 'empty', nominal transverse reinforcement and diagonal bars, tested under reversed cyclic loading are reported. The empty joint is not suitable even under moderate seismicity. The test results show that the joints containing the newly proposed detail, with or without axial compressive load present in the column, exhibit better behaviour at the lower range of ductility factors in terms of higher load-carrying capacity, greater stiffness and less strength degradation. Therefore, the newly proposed joint detail is suitable for beam–column joints of reinforced concrete buildings located in regions of low to medium seismic risk.

Tsonos et al [4] carried out an experimental investigation of the behavior of external beam-column joints with inclined reinforcing bars under seismic conditions is presented. A simple technique to prevent these elements from failing in premature, explosive cleavage shear fracture was implemented for the first time. Twenty full-scale reinforced concrete exterior beam-column subassemblies were tested. The primary variables were the amount of inclined bars, the ratio of the column-to-beam flexural capacity, and the joint shear stress. Test results showed that use of crossed inclined bars in the joint region is one of the most effective ways to improve the seismic resistance of exterior reinforced concrete beam-column joints.

Tsonos et al [5] have presented results which were obtained during a theoretical and experimental investigation of the influence of the P−Δ effect that was caused by the simultaneous changing of the axial load P of the column and the lateral displacement Δ in the external beam-column joints. The increase or decrease of Δ was simultaneous with the increase or decrease of the axial compression load P and caused an additional influence on the aseismic mechanical properties of the joint. A total of 12 reinforced concrete exterior beam-column subassemblies were examined. A new model, which predicts the beam-column joint ultimate shear strength, was used in order to predict the seismic behaviour of beam-column joints subjected to earthquake-type loading plus variable axial load and P−Δ effect. Test data and analytical research demonstrated that axial load changes and P−Δ effect during an earthquake cause significant deterioration in the earthquake-resistance of these structural elements. It was demonstrated that inclined bars in the joint region were effective for reducing the unfavourable impact of the P−Δ effect and axial load changes in these structural elements. Test results were very interesting and promising for the case of the non-conventionally reinforced joint specimens since these joints exhibited ameliorated performance with respect to the conventionally reinforced ones. It was stressed that the amelioration of the overall hysteretic response due to the application of X-bars was even greater than the corresponding improvement observed in the joints with 70% higher percentage of conventional shear reinforcement (common closed stirrups and/or vertical bars).

Bakir [6] attempts at improving beam-column joint performance has resulted in non-conventional ways of reinforcement such as the use of the crossed inclined bars in the joint area. Despite the wide accumulation of test data, the influence of the crossed inclined bars on the shear strength of the cyclically loaded exterior beam-column joints has not yet been quantified and incorporated into code recommendations. In this study, the investigation of joints has been pursued on two different fronts. In the first approach, the parameters that influence the behaviour of the cyclically loaded beam-column joints are investigated. Several parametric studies are carried out to explore the shear resisting mechanisms of cyclically loaded beam-column joints using an experimental database consisting of a large number of joint tests. In the second approach, the mechanical behaviour of joints is investigated and the equations for the principal tensile strain and the average shear stress are derived from joint mechanics. It is apparent that the predictions of these two approaches agree well with each other. A design equation that predicts the shear strength of the cyclically loaded exterior beam-column joints is proposed. The design equation proposed has three major differences from the previously suggested design equations. First, the influence of the bond conditions on the joint shear strength is considered. Second, the equation takes the influence of the shear transfer mechanisms of the crossed inclined bars into account and, third, the equation is applicable on joints with high concrete cylinder strength. The proposed equation is compared with the predictions of the other design equations. It is apparent that the proposed design equation predicts the joint shear strength accurately and is an improvement on the existing code recommendations.

Chalioris et al [7] experimentally investigated the use of crossed inclined bars in external beam-column connections under cyclic deformations. For this purpose, test results of four Reinforced Concrete (RC) joint subassemblages subjected to constantly increasing pseudo-seismic loading are presented. The shear reinforcement in the joint area for two specimens was two pairs of inclined bars that formed a pair of X-type reinforcement. The other two specimens were conventionally reinforced joints (control specimens). The effectiveness of this X-type, non-conventional reinforcement on the overall seismic performance of the tested joints is examined. The beam and the columns of all the specimens were designed according to the requirements of ACI 318-02 and the recommendations of ACI-ASCE 352-02 (Type 2 exterior connections). The design of the joint area for one control specimen was also carried out according the ACI Design Codes and the required amount of steel stirrups (5Ø8) was added in the joint body. The other control specimen had no stirrup at the joint area. Comparisons between the test results of the examined specimens indicated that the cyclic behaviour of the joints with X-bars was ameliorated with respect to the response of the control specimen without stirrups. Further, load capacity and hysteretic energy dissipation values of the joint with 2X-bars Ø14 were slightly lower than the values of the control specimen which joint area had stirrups (5Ø8) according to the specifications of ACI Design Codes.

Golias et al [8] experimentally investigated the use of crossed inclined bars as shear reinforcement in external beam-column connections subjected to cyclic loading . The presented experimental work consists of full-scale specimens with different reinforcement arrangement in the joint area as follows: (a) A control specimen without shear reinforcement in the joint area, (b) a specimen with only one stirrup in the joint area, (c) a specimen with inclined bars that form two pairs of X-type reinforcement. The effectiveness of this X-type, non-conventional reinforcement on the overall seismic performance of the tested joints is examined. Comparisons between the test results of the examined specimens indicated that the cyclic behavior of the joint with X-bars was drastically improved in comparison with the one of the control specimen in terms of load carrying capacity and hysteretic energy dissipation. Further, load capacity and hysteretic energy dissipation values of the joint with the X-reinforcement were alike with the corresponding values of the specimen with one stirrup and two vertical side bars in the joint area.

Golias et al [9] studied the behavior of beam-column joints in moment resisting frame structures is susceptible to damage caused by seismic effects due to poor performance of the joints. A good number of researches were carried out to understand the complex mechanism of RC joints considered in current seismic design codes. The traditional construction detailing of transverse reinforcement has resulted in serious joint failures during earthquakes. This paper introduces a new design philosophy involving the use of additional diagonal bars within the joint particularly suitable for low to medium seismic effects in earthquake zones. In this study, ten full-scale interior beam-column specimens were constructed with various additional reinforcement details and configurations. The results of the experiment showed that adding additional bars is a promising approach in reinforced concrete structures where earthquakes are eminent. In terms of overall cracking observation during the test, the specimens with additional bars (diagonal and straight) compared with the ones without them showed fewer cracks in the column. Furthermore, concrete confinement is certainly an important design measure as recommended by most international codes.

7 CONCLUSION

The presence of crossed inclined reinforcement improves the shear strength, the energy dissipation capacity of the joint and the pinching effect of the beam's reinforcement. The specimens with X-bars in the joint area were able to maintain maximum strength for a larger number of post yield cycles. It was also clear from the literatures that the presence of crossed inclined reinforcing bars introduced a new shear transfer mechanism in the joint area, beyond the mechanism of the concrete diagonal strut and the steel truss mechanism of the conventional shear reinforcement (common closed stirrups and vertical bars). The new mechanism due to the addition of the X-bars was called truss mechanism of the crossed inclined reinforcement.

The literature shows reveals that the application of crossed inclined bars in the joint region is a promising construction alternative reinforcement scheme in RC beam-column joint regions. Although there is a rather broad collection of experimental data, the theoretical research on this area is extremely limited. Bakir [6] was initially based on the first theoretical approach of the inclined reinforcement truss mechanism that has been introduced by Tsonos et al. [4] and proposed a design equation that has been adjusted and verified on the available test data. The lack of various and updated analytical expressions for computing the contribution of the crossed inclined bars on the shear strength of RC beam-column joints and the influence of several interacting phenomena that have not been fully clarified are the main reasons that there is not yet a framework covering the design of joints with X-bars or crossed inclined bars.

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