Design of beam-column connections for composite-framed structures

Design of Beam-Column Connections for Composite-Framed Structures

Conception des assemblages entre poutre et poteau pour des structures à ossature mixte

Entwurf von Rahmenknoten in Verbundbauweise

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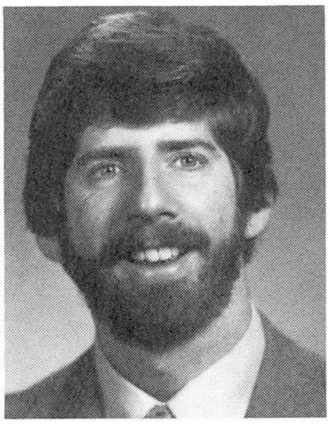

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SUMMARY
This paper addresses the design of composite beam-column joints which have been used in tall buildings with perimeter frames consisting of structural steel beams and reinforced concrete (or composite) columns. The connection behavior is described based on an experimental research program in which specimens were tested to failure under monotonic and cyclic loads. Mechanisms for evaluating the joint shear strength are proposed which consider interaction of the structural steel and reinforced concrete joint panels.

RÉSUMÉ
Cet article décrit la conception des assemblages entre poutres en acier et poteaux en béton armé (ou mixtes), qui sont utilisés dans des bâtiments élevés avec portiques extérieurs. La description du comportement de ce système est décrite sur la base d'un programme de recherche expérimentale dans lequel des échantillons furent soumis à rupture sous l'action de forces monotones et cycliques. Des mécanismes sont proposées pour calculer la résistance au cisaillement des assemblages, avec prise en considération des interactions entre l'ossature en acier et les dalles en béton armé.

ZUSAMMENFASSUNG
Dieser Artikel behandelt den Entwurf und die detaillierte Bemessung von Rahmenknoten in Verbundbauweise. Seite einigen Jahren werden solche Verbindungen in hohen Gebäuden mit Aussenrahmen, die aus Stahlriegeln und Stahlbeton- oder Verbundstützen bestehen, eingesetzt. Das Verbindungsverhalten wurde in einem Forschungsprogramm untersucht, in dem Versuchsstücke unter monotoner und zyklischer Belastung bis zum Versagen getestet wurden. Bemessungsgrundlagen wurden entwickelt für die Berechnung der Gesamttragfähigkeit unter Einschluss der Wechselwirkung zwischen den Stahlträgern und den Stahlbetonverbindungsscheiben.

1. INTRODUCTION

Increasingly, composite and mixed steel-concrete construction is being used to build more efficient structures than either material alone could provide. However, due to the traditional separation of structural steel and reinforced concrete design, there are pressing research needs to develop design guidelines for composite components and systems. One such need is in the design and behavior of connections which are an integral part of composite-framed structures.

As used herein, the term "composite frame" describes a moment resisting frame consisting of steel beams and reinforced concrete (or composite columns). To date, such frames have been employed for lateral load resisting perimeter tube systems for buildings in the 40 to 70 story height range. Typically, such structures are built by first erecting a frame of light steel erection columns and deep steel beams. The steel columns are later encased by reinforced concrete to create the composite frame [1].

In this paper, the behavior of composite beam-column joints is presented based on recent research in which seventeen large-scale specimens were tested under monotonic and cyclic loads. The internal force mechanisms are described using familiar concepts from current design standards for structural steel and reinforced concrete joints. A more detailed discussion of the research and recommendations for design are presented by Sheikh et.al. [2] and Deierlein et.al. [3].

2. JOINT BEHAVIOR AND DETAILING

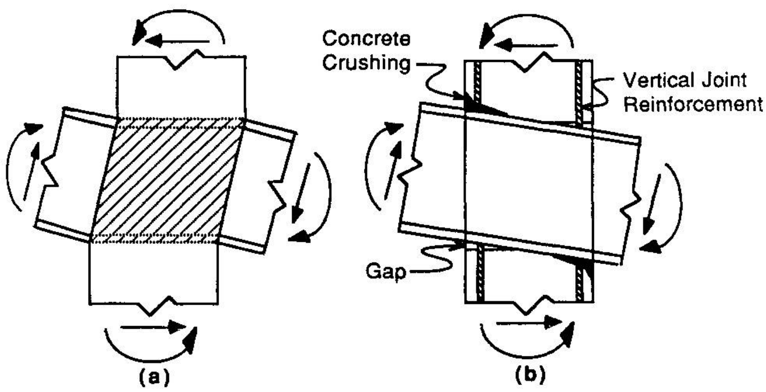

Fig. 1. Primary Failure Modes: (a) Panel Shear, (b) Vertical Bearing

In a frame subjected to lateral loading, the moments and shears imposed on the beam-column joint are shown in Figs. 1(a-b). In composite frames, typically the steel beam is continuous through the joint, and where used the steel erection column is interrupted by the beam. As shown in Figs. 1(a-b), joint behavior is characterized by two primary modes of failure. Panel shear failure is similar to that usually associated with structural steel or reinforced concrete joints, but in composite joints the relative contribution from each material should be considered. Vertical bearing failure occurs in regions of high compressive stresses and permits rigid body rotation of the steel beam within the concrete column. Vertical joint reinforcement, as shown in Fig. 1(b), is one means of strengthening for bearing failure.

Three mechanisms for joint shear resistance are shown in Figs. 2(a-c). In these figures, beam and column moments are shown as horizontal and vertical force couples, respectively. The joint shear mechanisms can be visualized by considering how they resist the beam flange forces and thus prevent horizontal movement of the beam flanges through the joint.

The steel web panel, shown in Fig. 2a, acts similarly in composite and structural steel joints. The web is idealized as carrying pure shear stress over an effective panel length, *jh*, which is dependent on the location and distribution of vertical bearing stresses.

The concrete compression strut, shown in Fig. 2b, is similar to the mechanism used in U.S. practice to model the shear strength in reinforced concrete joints [4]. In composite joints, the concrete strut is mobilized by vertical stiffener plates attached to the beam that bear against the concrete. The location and width of the stiffener plates determine how effectively the inner region of concrete is mobilized in resisting joint shear.

The concrete compression field, shown in Fig. 2c, consists of multiple struts that act together with horizontal reinforcement to form a truss mechanism similar to that used for modeling shear in reinforced concrete beams. The compression field is developed in the region outside the steel beam. As shown in Fig. 3, shear is transferred into the compression field by horizontal struts which form through bearing against either: embedded steel columns, stiffener plates extended above and below the beam, and shear studs or other attachments welded to the beam flanges.

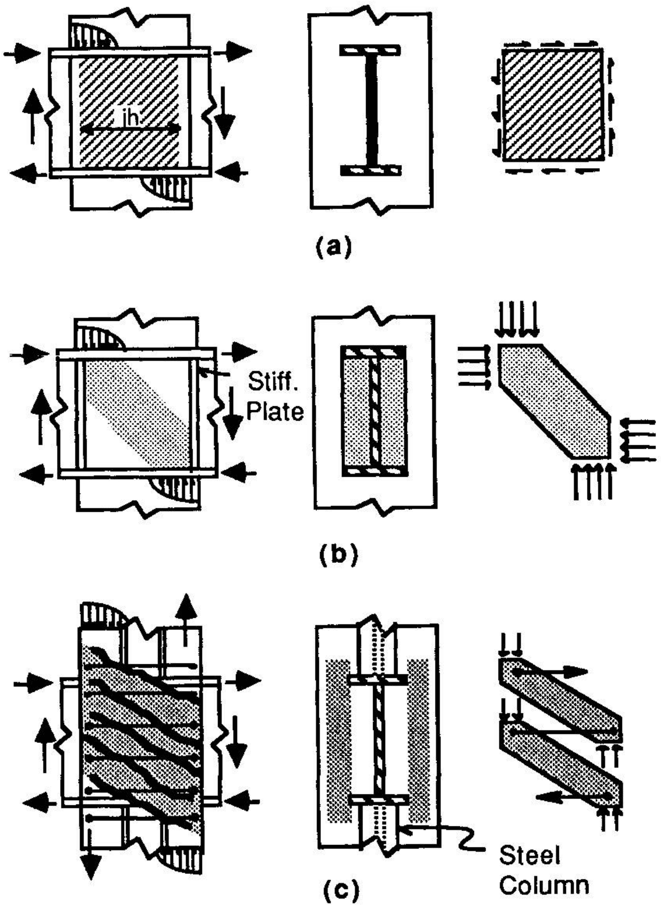

Fig. 2: Joint Shear Mechanisms: (a) Steel Web Panel, (b) Concrete Compression Strut, (c) Concrete Compression Field

3. EXPERIMENTAL RESEARCH PROGRAM

To evaluate the effectiveness of various joint details in mobilizing the internal force mechanisms, an experimental program was undertaken where seventeen beam-column joint specimens were built and tested [2,3]. In this paper, results from five tests are presented to illustrate the relative effectiveness of various details in mobilizing internal joint mechanisms.

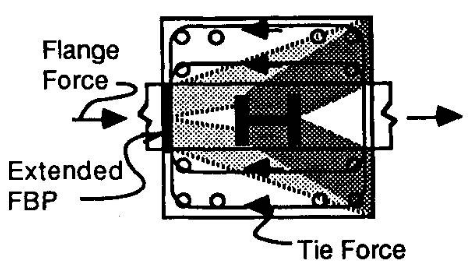

Fig. 3 Horizontal Force Transfer

3.1 Specimen Description: The cruciform shaped joint specimens consisted of 510 mm square concrete columns and built-up steel beams 460 mm deep which were continuous through the joint. The connections were loaded to replicate in-plane joint forces from lateral loading as shown previously in Figs. 1(a-b). For experimental purposes, both the steel beams and concrete columns were overdesigned in shear and flexure to force failure in the joint, however, in actual design the members should be proportioned so that yielding occurs in the beams before the joint or column strength is reached.

corners to allow clear passage of the steel beams through the column. Horizontal ties were provided within the beam depth to confine concrete in the joint and carry tension forces associated with the compression field mechanism. These ties were U-shaped stirrups which passed through holes drilled in the beam web. Above and below the beam, three layers of closed rectangular hoops confined the concrete in the region where high bearing stresses developed and where there were tension forces associated with the strut and tie mechanism shown in Fig. 3. Concrete compressive strengths ranged between 24.8 to 34.5 MPa (3.6 to 5.0 ksi). As described below, various attachments to the steel beam were used to investigate the strength of the joint shear mechanisms of Fig. 2.

3.2 Load-deformation response: The response for a test which is representative of the cyclic behavior is shown in Fig. 4. The vertical axis indicates the applied beam load which is proportional to the beam moments adjacent to the connection. The total joint distortion on the horizontal axis is a measure of the relative angular rotation between the steel beam and column.

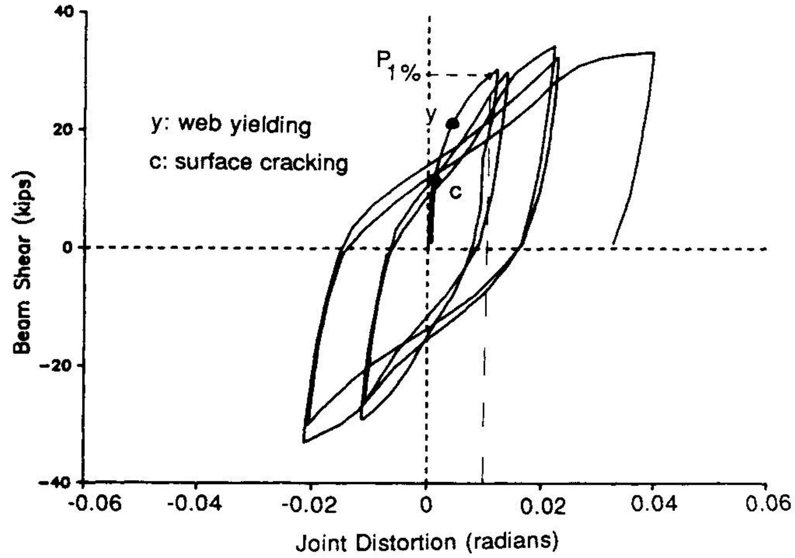

Fig. 4 Typical Load-Deformation Response

The load-deformation curve indicates that the joints failed in a "ductile" manner and displayed a fair degree of toughness under cyclic loading. In the figure, the points, *c* and *y*, indicate when cracks were first observed on the column face and when the steel web inside the joint yielded in shear. Web yielding was detected through electronic strain gages attached to the web. The joint continued to carry increasing load beyond web yielding, thus demonstrating participation of the concrete shear mechanisms. As indicated in the figure, the joint capacity measured at 0.01 radians distortion was chosen as the strength for comparison between tests and represents a reasonable measure of the nominal strength for use in design.

3.3 Visual Damage: The typical surface cracking and concrete crushing is shown in Fig. 5. Diagonal cracks on the column face indicated the formation of compression field struts which carried joint shear. In specimens where plain beams were used without attachments, the concrete panel was not mobilized and these cracks did not form. Cracks on the side of the column revealed the dissipation of compression forces beneath both the top and bottom beam flanges. Bearing was concentrated directly below the beam flanges, and at high loads

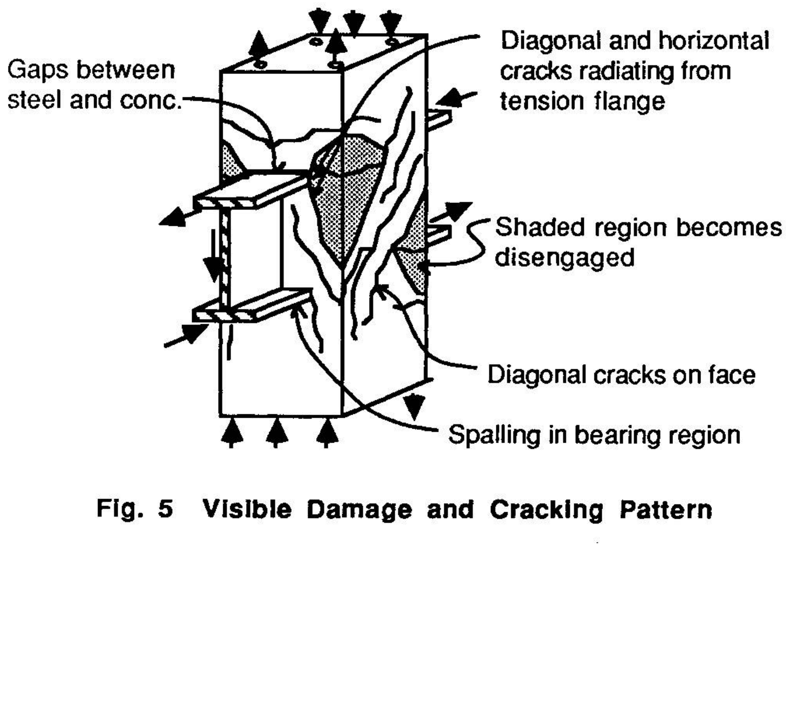

Fig. 5 Visible Damage and Cracking Pattern

concrete spalling was observed in this area. Once joint cracking progressed to a certain point, the concrete regions shown shaded became disengaged from the joint core. This decreased the transfer of vertical force to the longitudinal column bars through the joint region since the bars were located in the corners of the column.

<u>3.4 Comparison of nominal joint strengths</u>: In Fig. 6, the relative strengths are summarized for five test specimens with the details shown in Fig. 7. The results reveal how effectively each detail mobilized shear resistance in the steel web, concrete compression strut, and concrete compression field. The reported joint strengths were all measured at deformations of 0.01 radians and are normalized with respect to specimen 1.

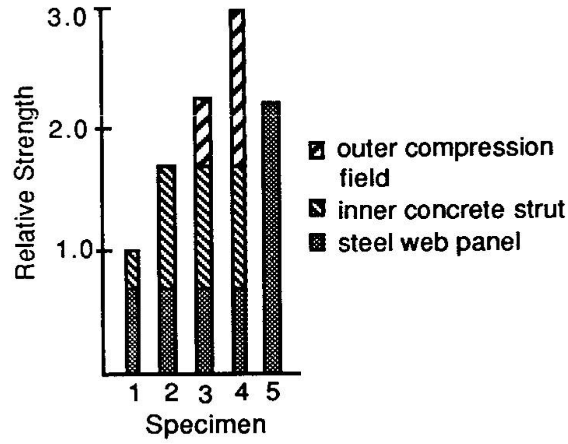

Fig. 6 Comparison of Joint Strengths

The strength of specimens 1 to 4 was limited by the shear capacity of the joint. In specimen 1, which consisted of a plain steel beam, most of the shear was carried by the steel web with only a small contribution from the concrete that was developed through adhesion and friction between the steel and concrete. In specimen 2, the face bearing (stiffener) plates mobilized the diagonal compression strut directly and the additional concrete contribution increased the total strength to 1.67 times that of specimen 1. In specimen 3, the addition of a W5 (130 mm) steel column increased the total strength to 2.25 times that of specimen 1 by mobilization of the outer panel through the strut mechanism of Fig. 3. Similarly, in specimen 4 which had a strength of almost 3 times specimen 1, the extended face bearing plates mobilized the outer concrete panel to an even greater degree. As shown in Fig. 3, the bearing plates at the face of the column result in a more effective transfer mechanism than with the steel column due to the shallower compression strut angles. In specimen 5, thick doubler plates were welded to the steel web in the joint to preclude yielding and thereby eliminate the shear failure mode. In this case, failure occurred by vertical bearing which provided a measure of the crushing strength for concrete bearing against the flanges. This test showed that for design the maximum concrete bearing stress above and below the flanges may be taken as 2 F'_c [3]. It is interesting to note that where the outer compression field was mobilized (specimens 3 & 4), concrete crushing did not control the strength even though the applied load was larger than in specimen 5. Presumably, this was due to the fact that when the concrete compression field was mobilized the total effective joint width (and bearing zone width) was increased.

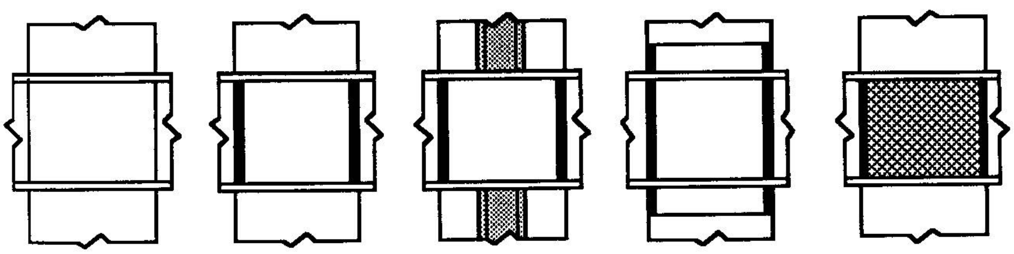

Fig. 7 Specimen Details

4. SUMMARY

Test results have shown that composite beam-column connections are reliable details which provide adequate stiffness at service loads, fail in a ductile manner at ultimate limit loads, and exhibit reasonable toughness under cyclic loading. Further, the strength of such connections can be increased significantly by simple details which mobilize the concrete panel in resisting joint shear. Such details can be designed using models derived from basic mechanics which are similar to those used for structural steel and reinforced concrete joints. These tests demonstrate the potential for composite joints as an attractive design alternative to structural steel or reinforced concrete.

ACKNOWLEDGMENTS

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