# Capacity of Joints to Resist Impact Loads in Concrete Moment-Resisting Frame Buildings

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## ABSTRACT

Several studies reported that damage due to blast load can be significantly reduced by using seismic detailing because connection design and detailing affect the response of reinforced concrete members in moment resisting frames. Properly detailed connections allow concrete members to develop full flexural capacity resulting in ductile failure in flexural mode instead of brittle shear failure at the connections. The design of such connections emphasizes adequate reinforcement to confine the concrete in the joint and thereby increase the ductility and the shear force resistance of the joint. The ACI 318 Building Code has extensive requirements for the design of joints which are part of special moment resisting frames designed to resist high seismic loads. This paper evaluates the behavior of joints designed for seismic forces in special moment resisting frames.

## BACKGROUND

Moment-resisting frame (MRF) systems have been widely used in building applications throughout the U.S. and the world. Such systems provide resistance to forces primarily by flexural action of frame members. Moment-resisting frames are classified into ordinary (OMF), intermediate (IMF) and special (SMF). This classification leads to different levels of required detailing that are specified in the ACI 318 Code. The terms special, intermediate, and ordinary are indicative of the degree of required toughness for seismic design. For concrete structures, the appropriate design and detailing requirements for intermediate and special moment frames are provided in Chapter 21 of ACI 318 Code. These detailing requirements are related to the type of structural framing system, seismic risk level at the site, level of energy dissipation (or toughness), and occupancy of the structure[2]. These provisions are meant to provide adequate toughness to ensure sufficient deformation capacity. The ACI 318 Code provisions for special moment frame joints cover transverse reinforcement, development length, and shear strength. Details of these provisions can be found in Reference 2.

Although seismic loading is characterized as oscillatory in nature, which is different than blast load effects, special moment frame detailing, specified for seismic design, increases ductility and energy dissipation capability, which are important characteristics in resisting blast loads. While the effect of blast loading is localized compared with an earthquake, the ability to sustain local damage without total collapse is a key similarity between seismic-resistant and blast-resistant design[3]. Similarities between seismic and blast loading include: the dynamic nature of loads, the dynamic structural response and the inelastic structural response. Blast load is characterized by high intensity and short duration. In order to resist such load structural systems require sufficient level of ductility, inelastic rotational capacity and redundancy. When designing structures for blast loads, inelastic deformations are allowed to take place in some critically stressed elements. Similar to seismic design, structural members and joints of moment resisting frames must be properly designed and detailed to satisfy sufficient levels of deformability in order to survive blast load effects without collapse. W. G. Corley[4] reported that with seismic detailing for special moment frames, damage due to blast can be significantly reduced. Corley also reported that if the current detailing for special moment frames had been used in the Alfred P. Murrah Federal Building, the failed columns would have had enough shear resistance to develop a mechanism without failure. In a study by Bilow and Kamara[5] it was reported that satisfying special moment frame code requirements could be beneficial in resisting progressive collapse. Other studies also reported that when using seismic detailing, damage due to blast load can be significantly reduced[6,7].

## OBJECTIVES

The main objective of this paper is to evaluate how reinforced concrete special moment frames behave under the connection qualifying testing procedure recommended by the Federal Emergency Management Agency, FEMA-350[8]. The FEMA-350 provisions follow the requirements of Appendix S of the AISC seismic provisions[9]. The provisions are state-of-the-art guidelines to achieve improved structural performance by controlling inelastic deformations of steel and composite structural steel/reinforced concrete structures.

## FEMA-350 PROVISIONS

In the FEMA-350 Seismic provisions, satisfactory seismic performance levels are achieved by requiring minimum levels of expected inelastic rotation capacity at the joints for the various framing types. The provisions require that beam-column joints and connections of SMF systems used as part of the seismic-force-resisting system be able to undergo an inelastic rotation of 0.03 radians, when subjected to a qualifying cyclic test in accordance with Appendix S in the AISC provisions. In addition to the minimum level of inelastic rotation, the acceptance criteria also focus on the maximum rate of degradation in strength with inelastic deformations. When this rate of degradation is too large, moment demands from P-delta effects can increase significantly, which can lead to frame instability. Figure 1 shows this acceptance criterion. The Figure shows that the flexural strength at 0.03 radians, $M_{0.03}$, must be greater than or equal to $M_p$, where $M_p$ is the nominal plastic flexural strength. The intent of this criterion is for beam-column connections to be able to undergo large inelastic cycles of deformation while maintaining their strength and ductility to dissipate energy generated during seismic events.

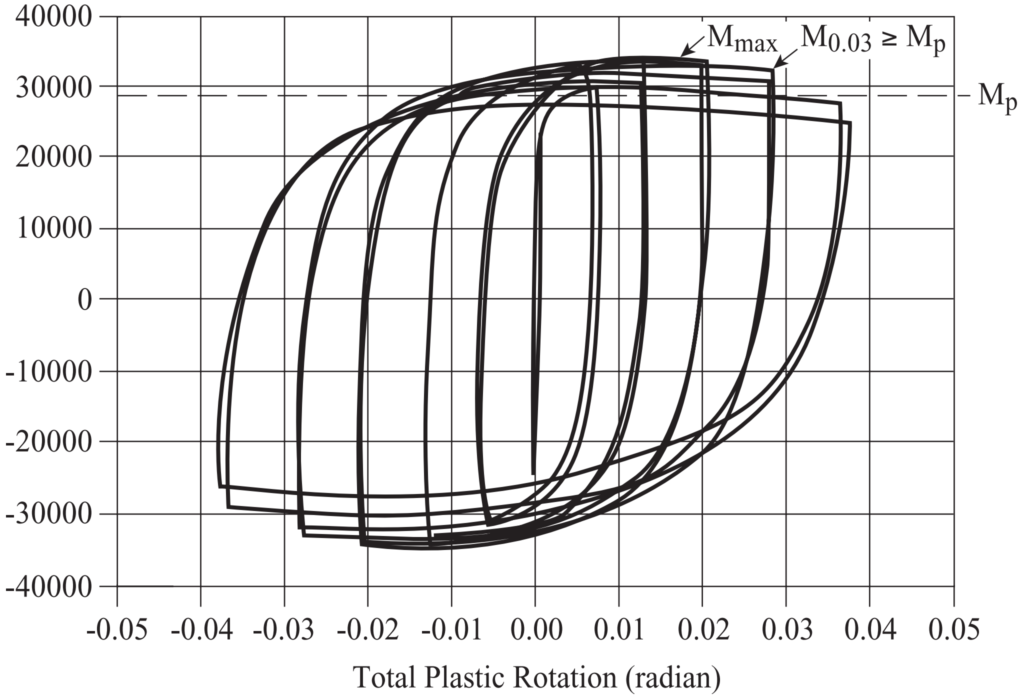


FIGURE 1
ACCEPTABLE STRENGTH DEGRADATION ACCORDING TO AISC-97 SEISMIC PROVISIONS

## PROCEDURE

Test results available in the literature on reinforced concrete moment frames joints were compiled and analyzed by S. K. Ghosh Associates[10]. The significant design variables that were examined and evaluated for reinforced concrete systems in regards to the performance criteria are joint shear stress, beam-column flexural strength ratio, transverse reinforcement ratio in the joint, and beam length-to-depth ratio. The results of a total of 28 experiments were examined in detail. The 28 specimens were classified as SMF joints based on the requirements in Chapter 21 of ACI 318-02[1].

A procedure based on plastic rotation capacity as a function of cycles of inelastic deformation is used to evaluate joint performance in reinforced concrete buildings. The inelastic rotation is defined as total rotation measured in the specimen minus the elastic rotation. The inelastic rotations calculated at the face of the column are used in this study to evaluate joint performance. Most test specimens consist of columns and beams. In some cases, transverse beams and slab were also included to model corner or interior connections of a reinforced concrete structure. Figure 2 shows a test setup for a typical exterior joint with transverse beams and slab. The beam length is measured from the face of the column to the loading point. The total rotation is determined by dividing the tip deflection by the beam length. In these tests, the total rotation is a function of both the elastic and the plastic flexural deflection of the specimen. To account for the nonlinearity

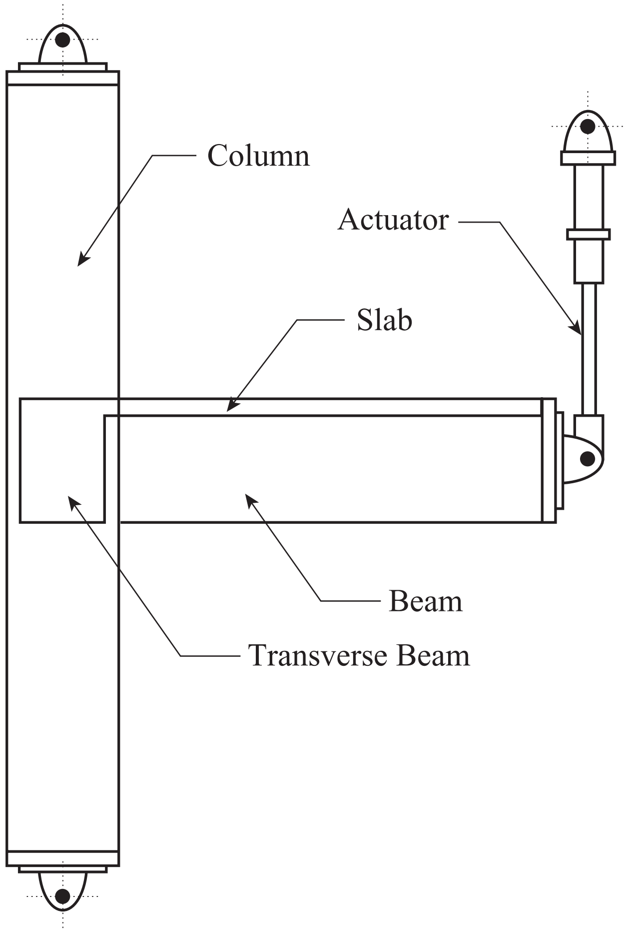


FIGURE 2
TYPICAL EXTERIOR JOINT WITH TRANSVERSE BEAMS AND SLAB

of the elastic response, a procedure recommended by Cheung et. al.[11] and in ATC 24[12] was used to define the yield values. The procedure is graphically illustrated in Figure 3. This procedure is based on the secant of the force-displacement relationship passing through the point where 75% of the computed ultimate strength $Q_y$ of the test structure is attained. $Q_y$ in this report was calculated by the strength equation derived from ACI 318 provisions using the measured material yield strengths. A line from O to A is used to define the test structure's effective stiffness, $K_e$. The yield displacement, $d_y$, for the test structure is then determined by extending the line from A to B. The corresponding rotation is determined by dividing the yield displacement by the length from the face of a column to the loading point of a beam. The required total rotation for SMF structures is the total of the inelastic rotation of 0.03 radians and the elastic rotation of 0.01 radians due to the displacement at yield.

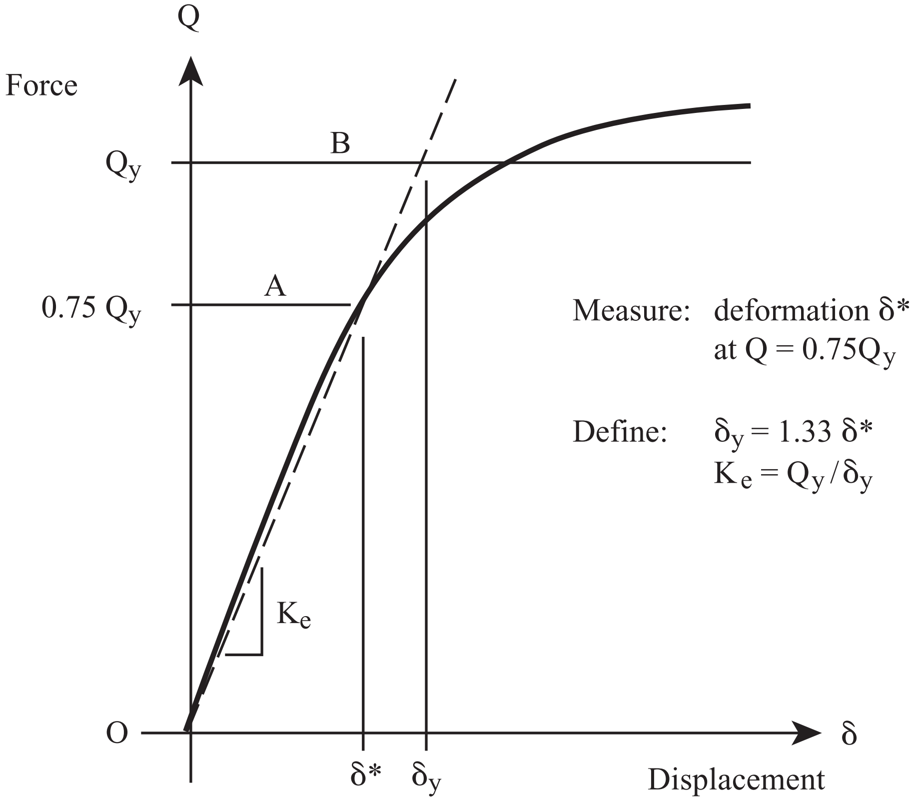


FIGURE 3
GRAPHICAL PROCEDURE TO ESTABLISH YIELD POINT (ATC, 1992)

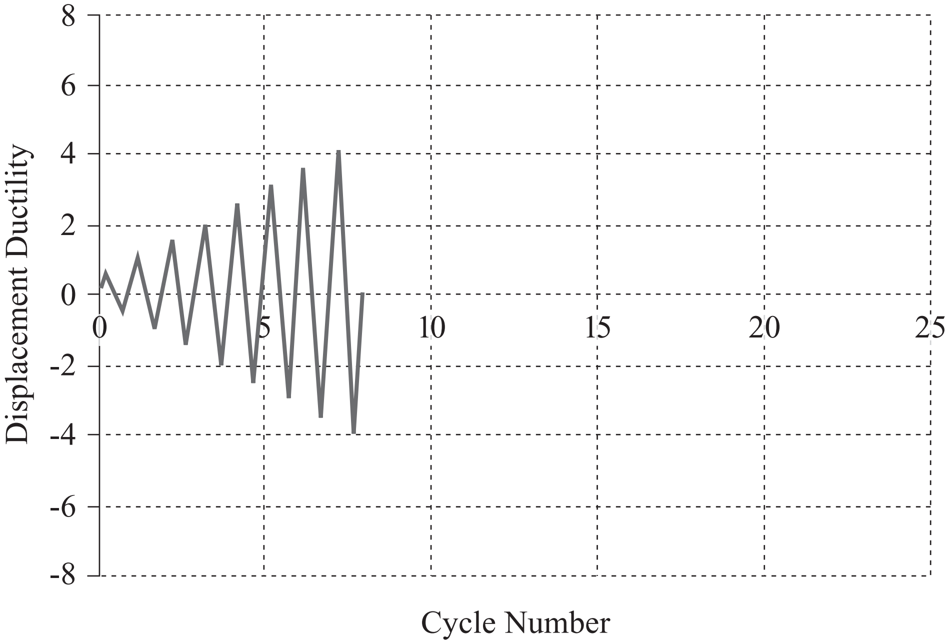


FIGURE 4
CYCLIC LOADING HISTORY USED IN ACTUAL TESTS

## DISCUSSION OF EXPERIMENTS ON CONCRETE BEAM-COLUMN JOINTS

Laboratory tests and lessons learned from previous earthquakes have revealed that the key to satisfactory seismic performance is overall integrity of a structure during inelastic deformations. For moment-resisting frames, beam-column joints must exhibit a suitable level of inelastic deformation without significant loss in strength. Degradation of beam-column joints can result in large lateral deformations, which can lead to excessive damage or even failure[12]. Numerous research studies have been undertaken to examine the cyclic inelastic behavior of beam-column joints of reinforced concrete moment frames. Studies on beam-column joints were performed by Hanson and Connor[13], Celebi and Penzien[14], Bertero et. al.[15], and Foranzi et. al.[16], and Meinheit and Jirsa[17,18]. The results of these studies indicated that adequate energy dissipation could be achieved near the joint if proper attention was given to anchorage of beam bars, shear resistance, and confinement of the joint. No significant influence of dynamic loading on the stiffness degradation and energy absorption of specimens within a deflection ductility range of 1 to 4 were reported. The dynamic loading appeared to increase the yield strength of the joint by as much as 20%. The tests showed that a column-to-beam flexural strength ratio greater than 1.4 greatly improved the behavior of the joint. Also, a significant improvement in exterior joints was observed when the joint shear stress was limited to 12 $\sqrt{f'_c}$ (ps

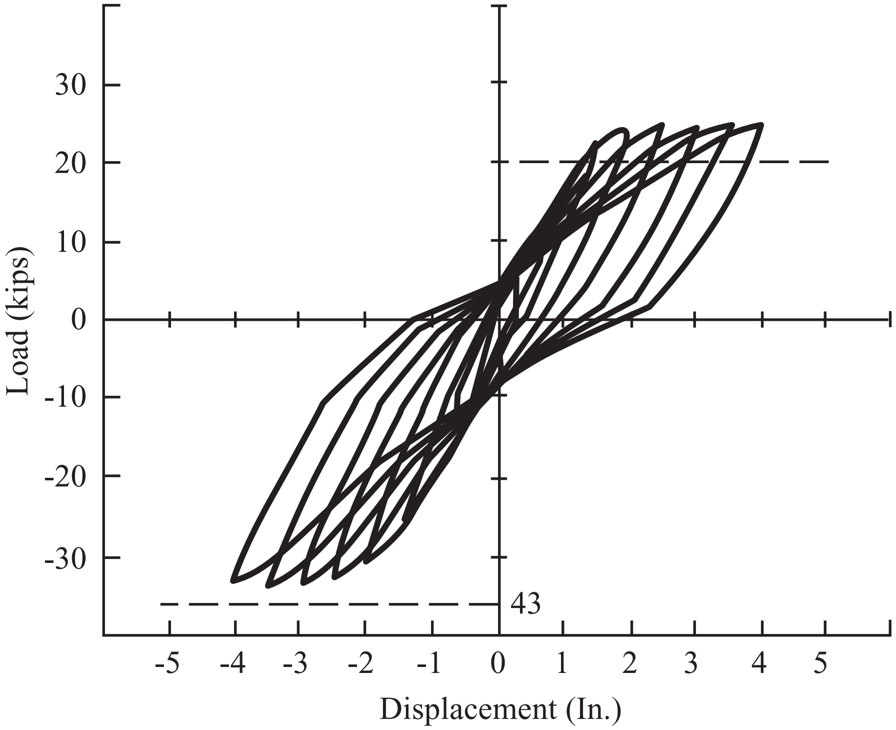
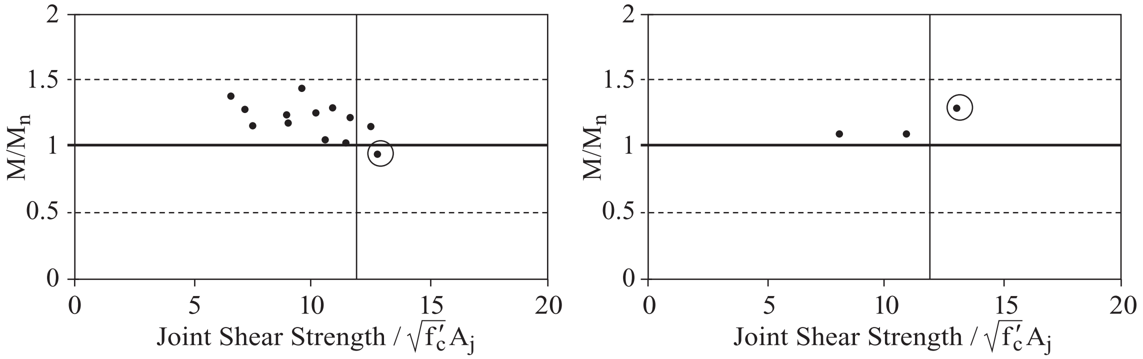


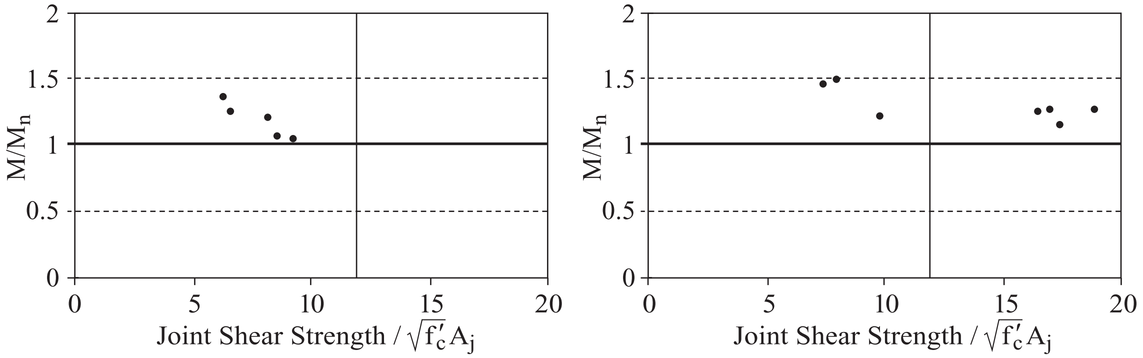
FIGURE 5
HYSTERETIC BEHAVIOR OBTAINED FROM TEST

## SPECIAL MOMENT FRAMES (SMF)

A total of 28 specimens were classified as SMF joints based on the requirements specified in Chapter 21 of ACI 318-02. The test results for all the connection specimens were analyzed and plotted based on the joint shear stress, the column-to-beam flexural strength ratio, and the transverse reinforcement ratio. Figures 6 through 8 show the test results for SMF structures. The data were analyzed and plotted based on different design parameters. $M/M_n$ was calculated by dividing the measured moment ultimate strength from the test by the nominal moment strength. The measured moment strength corresponds to a plastic rotation of 0.03 radians. A ratio of $M/M_n$ larger than 1.0, indicates that the measured moment strength at a 0.03 radians plastic rotation is larger than the nominal strength of the beam. In such cases, the test specimen satisfies the minimum acceptance criteria based on FEMA-350. Of the 28 test specimens, 27 specimens have a $M/M_n$ ratio larger than 1.0, which means that they pass the criteria for acceptance according to the FEMA-350. Figure 6 shows that the performance of beam-column joints deteriorated as the joint shear stress increased. Figures 7 (a) and (b) show the performance of the beam-column joints as a function of flexural strength ratios. The Figures indicate that, as the flexural strength ratio increases, $M/M_n$ ratios also increase, which means that up to a 0.03 radians

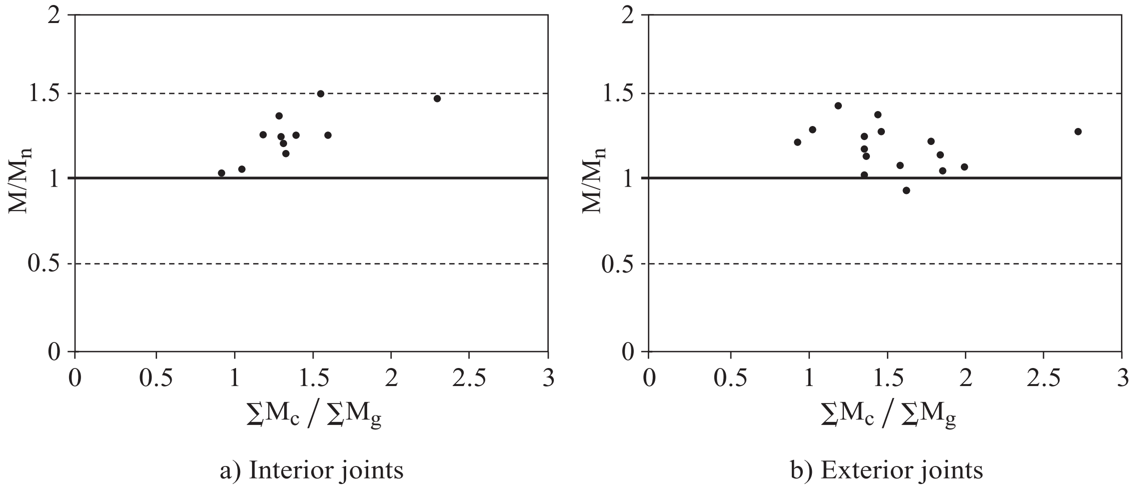


a) Exterior joints without transverse beam b) Exterior joints with transverse beams



c) Interior joints without transverse beam d) Interior joints with transverse beams

FIGURE 6
PERFORMANCE CRITERIA AS A FUNCTION OF JOINT SHEAR STRESS FOR SMF JOINTS



a) Interior joints

b) Exterior joints

FIGURE 7
PERFORMANCE CRITERIA AS A FUNCTION OF COLUMN-TO-BEAM FLEXURAL STRENGTH RATIO FOR SMF JOINTS

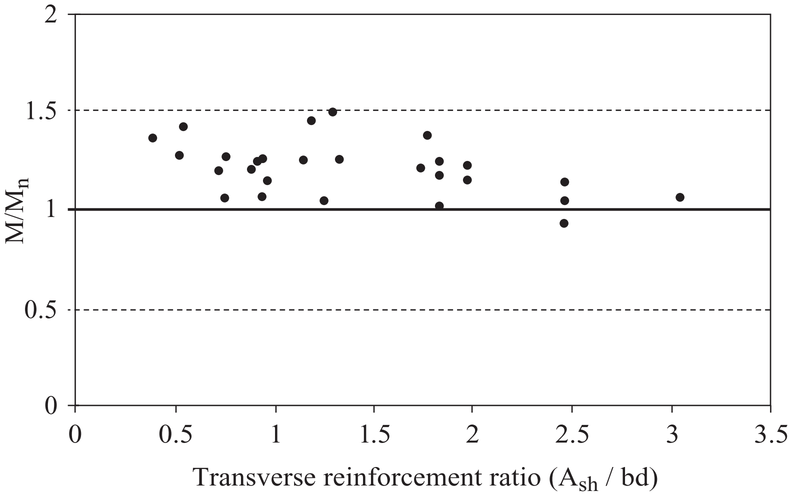


FIGURE 8
PERFORMANCE CRITERIA AS A FUNCTION OF TRANSVERSE REINFORCEMENT RATIO FOR SMF JOINTS

plastic rotation, the joint is able to maintain higher flexural strength than the nominal flexural strength of the beam. For the exterior joints, the flexural strength ratio and the performance of the connection are not directly correlated. This is primarily due to the different geometric configurations.

Other factors affecting the performance of beam-column joints are the transverse reinforcement ratio, the beam span-to-depth ratio, and the column axial load. In general, the SMF joints exhibited satisfactory performance. Twenty seven out of the 28 test specimens provided sufficient strength and ductility up to the inelastic rotation level of 0.03 radians. Joint shear stress, column-to-beam flexural strength ratio, transverse reinforcement ratio in a joint, development lengths of the beam flexural reinforcement and compliance with ACI 318 SMF joint requirements all play a key role in producing good performance of the joints.

## CONCLUSIONS

This paper has examined and compared the experimental results from inelastic cyclic deformation tests on reinforced concrete beam-column joints. All of the test specimens were classified as SMF joints based on the design and detailing requirements in ACI 318-02. The acceptance criteria, originally defined for steel moment frame connections in the FEMA-350 Seismic provisions, were used to evaluate the joints of concrete moment frames. The following conclusions can be drawn from this study.

1. In general, most of the joints that satisfy the design requirements for SMF structures in ACI 318-02 show a high $M/M_n$ ratio, which indicates that, these connections are ductile up to an inelastic rotation of 0.03 radians without any major degradation in strength. This is mainly due to the stringent ACI 318-02 requirements for SMF joints.
2. The presence of transverse beams increases confinement and shear resistance of joints, and results in better performance than for joints without transverse beams. All of the SMF joints that satisfy the ACI 318-02 limitations on joint shear stress meet the acceptance criteria.
3. As expected, a high column-to-beam flexural strength ratio increases the performance of interior joints. The same effect, however, was not observed in exterior joints. It is believed that the configuration of the interior joint (2 columns and 2 beams) versus that of the exterior joint (2 columns and 1 beam) offers the necessary explanation.
4. Based on conclusions from reviewed reports and studies it is believed that using seismic detailing for special moment frames, damage due to blast can be significantly reduced.

## REFERENCES

[1] ACI Committee 318, *Building Code Requirements for Structural Concrete and Commentary,* American Concrete Institute, Farmington Hills, MI, 2002.

[2] Fanella, D. A., *Seismic Detailing of Concrete Buildings,* Publication SP382, Portland Cement Association, Skokie, IL, 2000, 69 pp.

[3] Carino, N. J., and Lew, H. S., Editors “Summary of NIST/GSA Workshop on Application of Seismic Rehabilitation Technologies to Mitigate Blast-Induced Progressive Collapse,” National Institute of Standards and Technology, NISTIR 6831, September 2001.

[4] Corley, W. G, *Applicability of Seismic Design in Mitigating Progressive Collapse,* CTL Group, Skokie, IL, 2004.

[5] Bilow, D. N., and Kamara, M. E., *U.S. General Services Administration Progressive Collapse Design Guidelines Applied to Concrete Moment-Resisting Frame Buildings,* ASCE Structures Congress, Nashville, TN, May 2004.

[6] Baldridge, S. M., and Humay, F. K., *Preventing Progressive Collapse in Concrete Buildings,* Concrete International, November 2003.

[7] Munshi, J. A., *Seismic Versus Blast Loading,* Concrete International, May 2004.

[8] *Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings,* Federal Emergency Management Agency, FEMA-350, June 2000.

[9] AISC, *Seismic Provisions for Structural Steel Buildings,* American Institute of Steel Construction, Inc., Chicago, IL, 1997, 2002.

[10] Inelastic Rotation Capacity of Beam-Column Joints of Reinforced Concrete Moment Frames, Unpublished Report submitted by S. K. Ghosh Associates Inc. PCA R&D Serial No. 2698, August 2004.

[11] Cheung, P., Park, R., and Paulay, T., "Seismic Design of Reinforced Concrete Beam-Column Joints with Floor Slab," *Research Report 91-4,* Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, 1991.

[12] Applied Technology Council, ATC-24, *Guidelines for Cyclic Seismic Testing of Components of Steel Structures,* Redwood City, CA, 1992, 57 pp.

[13] Hanson, N., and Conner, H., "Seismic Resistance of R/C Beam Column Joints," *Journal of the Structural Division,* ASCE, Vol. 93, No. ST5, October 1967, pp. 533, 560.

[14] Celebi, M., and Penzien, J., "Experimental Investigation into the Seismic Behavior of Critical Regions of Reinforced Components as Influenced by Moment and Shear," *Report No. EERC 73 4,* University of California, Berkeley, CA, 1973.

[15] Bertero, V., and Popov, E., "Hysteretic Behavior of Ductile Moment Resisting Reinforced Concrete Frame Components," *Report No. EERC 75 16,* University of California, Berkeley, CA, 1975.

[16] Foranzi, B., Popov, E., and Bertero, V., "Hysteretic Behavior of Lightweight R/C Beam Column Subassemblages," *Report No. EERC 79 01,* University of California, Berkeley, CA, 1979.

[17] Meinheit, D., and Jirsa, J., "Shear Strength of R/C Beam-Column Connections," *Journal of the Structural Division,* ASCE, Vol. 107, No. 11, November 1981, pp. 2227 – 2244.

[18] Meinheit, D., and Jirsa, J., "The Shear Strength of Reinforced Concrete Beam-Column Joints," *CESRL Report No. 77-1,* Department of Civil Engineering, The University of Texas, Austin, TX, January 1977.

## NOTATIONS

$A_j$ = effective cross-sectional area within a joint in a plane parallel to the plane of the reinforcement generating shear in the joint.

$A_{sh}$= total cross-sectional area of transverse reinforcement (including crossties) within spacing s and perpendicular to dimension b

b = width of compression face of member

d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement

$f'_c$ = specified compressive strength of concrete

$M_c$ = column moment strength

$M_g$ = beam moment strength