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Probabilistic model for failure initiation of reinforced concrete interior beam–column connections subjected to seismic loading

Nilanjan Mitra [a,*], Sudeshna Mitra [a], Laura N. Lowes [b]

[a] Department of Civil Engineering, Indian Institute of Technology, Kharagpur, India

[b] Department of Civil Engineering, University of Washington, Seattle, WA, USA

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ABSTRACT

The results of previous experimental tests indicate that reinforced concrete interior beam column joints may exhibit significant strength and stiffness loss under earthquake loading, and the results of post-earthquake reconnaissance indicate that joint failure may result in structural collapse. Thus seismic evaluation and design of reinforced concrete frames requires accurate prediction of the potential for joint failure. This paper presents a binomial logit model, developed using data from 110 experimental tests, which define the probability that a reinforced concrete interior beam–column building connection, with a specific set of design parameters, will exhibit either a non-ductile joint shear failure prior to beam yielding or a ductile failure that initiates with beam yielding. The calibrated model identifies the relative importance of various design parameters in determining the connection's response mechanism. The model can be used by an engineer designing a new connection, constructed of normal or high-strength materials, to estimate the likelihood of joint failure initiation. The model can also be used by an engineer evaluating an existing structure to estimate the likelihood of joint failure, determine the factors that most significantly affect this likelihood, and, thereby, develop a suitable and efficient retrofit strategy.

1. Introduction

In a reinforced concrete frame subjected to earthquake loading, beam–column joints are critical for developing frame action and ensuring that inertial loads are transferred through the frame to the foundation. Post-earthquake reconnaissance efforts have attributed the collapse of many reinforced concrete frames to the failure of joints [1]. Similarly, analyses of building frames, using models that simulate joint stiffness and strength loss, show that nonlinear joint action reduces lateral load resistance and that joint failure may result in structural collapse [2]. Given the importance of these components, numerous previous experimental investigations have addressed the seismic behavior of beam–column joints, the mechanisms that determine behavior, and the design parameters that affect behavior.

The results of previous experimental investigations show that joints may exhibit significant stiffness and strength loss under lateral loading. The results of previous research suggest also that, in addition to material properties and geometric configuration, a number of different design parameters may affect joint response. These design parameters include joint shear stress demand [3–13], joint transverse reinforcement ratio [3,6,14–17], bond stress demand for beam longitudinal reinforcement passing through the joint [3,7,18–23], and column axial load [7,9,14,17, 24–29]. For joints with sufficient strength to develop the yield strength of the beams framing into the joint, experimental data indicate also that drift history affects strength deterioration of the joint [30,31]. Experimental investigations at the University of Washington [30,31] also indicate that drift has minimal impact on connection strength.

The ACI Committee 352 [32] defines a beam–column joint as "that portion of the column within the depth of the deepest beam that frames into the column", and a connection as "the joint plus the columns, beams and slabs adjacent to the joint". The strength of a beam–column connection may be determined by the flexural yield strength of the beams or columns framing into the joint, or by the joint region. The results of previous research provide a basis for the current ACI Code [33] requirements that are intended to ensure that connection response is determined by flexural yielding of beams and that connection strength is determined by beam flexural strength. These requirements include a minimum volume of transverse reinforcement, a minimum anchorage length for beam longitudinal reinforcement, a minimum column-to-beam flexural strength ratio, and a limit on the joint shear stress demand. Joints designed prior to 1967 [18,27,30,34,35,31] typically do not comply with the current ACI Code [33] requirements and may

* Corresponding author. Tel.: +91 3222 283430.
E-mail addresses: nilanjan@civil.iitkgp.ernet.in (N. Mitra), sudeshna@civil.iitkgp.ernet.in (S. Mitra), lowes@u.washington.edu (L.N. Lowes).

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result in connections that exhibit joint failure or column yielding prior to beam yielding.

Very limited guidance is provided by the ACI Code [33] for design of structures with high-strength materials; however, high-strength materials have been used in recent construction project. Joints designed using high-strength materials may result in connections for which seismic behavior is determined by joint failure and not beam yielding [12,14,16,19,36–40]. In recent years, high strength concrete (concrete with compressive strength in excess of 59 MPa (8.6 ksi), as specified by ACI-363 committee [41]) has been used successfully to reduce member sizes in cast-in-place concrete buildings and high-rise structures [39]. However, research studies by Noguchi et al. [37] report that the use of smaller, high-strength concrete column increases the potential for joint shear failure prior to beam yielding. High strength reinforcing steel has been used also in recent construction to reduce the congestion of reinforcing bars in slender members [16,19,38]. However, research studies by Fujii and Morita [14] concluded that high strength reinforcing steel in beams may increase beam flexural strength and joint shear demand such that joint shear failure precedes beam yielding.

Identification of the mechanism that determines connection strength and seismic behavior (i.e., beam yielding, column yielding, joint failure) provides insight into the performance of the connection. Previous research indicates that connections that exhibit joint failure prior to flexural yielding of beams and columns exhibit minimal ductility and minimal drift capacity [5,7,9,12,14,16,19,38]. Connections for which strength is determined by column yielding may develop a soft-story mechanism leading to structural collapse at relatively low drift demands [18,35]. However, connections in which joints exhibit minimal stiffness loss and for which strength is determined by beam yielding typically exhibit a ductile response and significant drift capacity [3,6,12,16,22,23,40,42,43].

In evaluating and retrofitting existing structures and designing new structures, it is appropriate to assess the potential for beam–column connections to exhibit a non-ductile response as well as the impact of inelastic joint action on frame response. To address this issue, a number of previous studies have focused on the development of mechanistic models for simulation of connection response. Simple mechanistic models [44–47] are computationally efficient, but require the engineer to make a number of assumptions about beam, column and joint behavior, including the mechanism that determines connection strength and drift capacity. A detailed discussion of examples of relatively simple models can be found in Mitra [48]. Previous research has resulted also in more sophisticated models [49–55] that provide improved prediction of the mechanism that determines the connection's behavior. These models require far fewer assumptions by engineers, but are typically both computationally intensive as well as time consuming to calibrate for a particular connection with specific design parameters. The reader is referred to Mitra and Lowes [53] for an example of one of these sophisticated models and Mitra [48] for a detailed discussion of the models referenced above.

The above models enable the engineer to assess the potential for non-ductile connection response *as well as* the impact of inelastic joint action on frame response. However, use of the above models typically requires a significant investment of an engineer's time. The objective of the research present here was to develop a simple, easily applied, computationally efficient model that the engineer can use to assess the potential for non-ductile connection response and thereby the need for further investigation using more sophisticated and time consuming analysis methods.

2. Research objectives, motivation and activities

The research presented here seeks to fill the need for a simple and efficient tool for preliminary assessment of connection performance. Specifically, the objectives of the research are to

1. Use existing experimental data to develop a simple model that will define the probability of failure initiation of reinforced concrete interior beam–column connection, either by a non-ductile joint failure mechanism or a ductile, beam-yielding mechanism, subjected to seismic loading.
2. Quantify the impact of various design parameters on the likelihood of the connection exhibiting joint failure.

It is expected that this model will provide

1. An engineer designing new connections with the ability to estimate the likelihood of joint failure controlling connection response. With this model, an engineer can determine the parameters determining the connection's response and, thereby, modify a new design to reduce the likelihood of a joint failure mechanism for a strong-column-weak-beam building frame subjected to earthquake loading. While the building code provides guidance for design of connections using normal-strength materials, it provides very limited guidance for design using high strength materials.
2. An engineer evaluating or retrofitting as existing structure with the ability to assess the likelihood of joint failure controlling connection response as well as improved understanding of the design parameters in determining the increased likelihood of joint failure. This information could be used to develop a suitable, efficient retrofit scheme.
3. A researcher with an estimate of the relative importance of various design parameters to the likelihood of a connection exhibiting a brittle joint failure as well as an example of the application of logistic models for prediction of the behavior of structural components and systems.

To accomplish the above objectives,

1. A large experimental data set was assembled that includes data characterizing the response of building frame connections, with a wide range of design parameters, subjected to simulated earthquake loading.
2. These experimental data were used to calibrate a binomial logit model which determines the probability of initiation of connection failure initiation due to either joint failure or beam yielding.
3. Statistical goodness-of-fit tests were employed to validate the logit model.
4. The calibrated logit model was used in example applications to assess the relative importance of various connection design parameters on the likelihood of joint failure.

3. Experimental data set

An extensive experimental data set was used to support development of the statistical model. The data set comprises 110 laboratory tests of two-dimensional interior beam–column connections conducted by 20 research teams from around the world during the last 40 years [3,5,7,9,12–14,16,19,21–23,30,34,31,36,38,40,42,43,56]. Mitra [48] provide a detailed presentation of the data set, including material, geometric and design parameters for each test specimen. The specimens in the data set span a wide range of joint design parameters. However, the data set is limited to two-dimensional connections in which a continuous column intersects a continuous beam and specimen response is determined by flexural yielding of beams at the beam-joint interface and/or joint failure. Too few tests were found in the literature in which connection failure was determined by column hinging to enable use of these data in the analysis. To improve the accuracy of the model, connections with slabs, eccentric beams