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Modeling of interior beam-column joints for nonlinear analysis of reinforced concrete frames

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ABSTRACT

Beam-column connections undergo significant shear deformations and greatly contribute to story drifts during earthquake loading, yet their response is typically neglected in traditional frame analyses through the use of rigid end offsets. Although local joint models are available in the literature for the investigation of single, isolated joints, there is a lack of holistic frame analysis procedures simulating the joint behavior in addition to important global failure modes such as beam shear, column shear, column compression, and soft story failures. The objective of this study is to capture the impact of local joint deformations on the global frame response in a holistic analysis by implementing a joint model into a previously-developed global frame analysis procedure. The implemented joint element simulates the joint shear deformations and bar-slip effects. Concrete confinement effects are also considered so that both older and modern joints can be modeled. The developed procedure successfully captures the local load-deflection response of joints within a global frame analysis procedure. The ratio of predicted and observed peak load had a mean of 1.25 before the modification, and a mean of 1.05 after the modification.

1. Introduction

According to the U.S. Geological Survey, at least 850,000 people were killed and more than 3 million buildings collapsed or were significantly damaged during the 26 major earthquake events that occurred over the past two decades [1]. Reinforced concrete frame structures constituted a large percentage of those buildings. Common failure modes observed after those earthquakes included beam-column joint shear, column shear, beam shear, column compression, reinforcement bond slip, foundation failures and soft story failures.

While most of the failure modes are commonly considered in typical frame analyses, the joint failure mode is often neglected. It is crucial to consider all modes since any one of them may govern the failure of the structure. The interaction among the failure modes should also be considered. In the traditional analysis of reinforced concrete frame structures subjected to seismic loading, beam-column joints are assumed rigid. This assumption implies that the joint core remains elastic and deforms as a rigid body throughout an earthquake event, even if the beams and columns undergo significant deformation and sustain severe damage. On the contrary, tests on seismic performance of non-ductile beam-column joints conducted by Walker [2] have demonstrated that joint deformations due to shear cracking and bond slip are major contributors to lateral story drifts as shown in Fig. 1.

Although joint shear failure is a local failure mechanism, it often leads to progressive collapse of buildings. Insufficient anchorage lengths of reinforcing bars, unconfined connections, and deterioration of reinforced concrete materials are the main contributors to this type of failure, as illustrated in Fig. 2. Frame joints designed prior to the 1970s according to older design standards, with little or no transverse reinforcement, exhibit a non-ductile response and are more vulnerable to joint shear failures. Older design codes did not specify a limit on the joint shear stress or required joint transverse reinforcement prior to the pioneering experiment of Hanson and Connor [3]. As a result, joints in these frames exhibit high joint shear, which contribute to greater story drifts and higher bond stresses with potential bar slippage under seismic loading. Joints in newer buildings possess better reinforcement detailing with transverse reinforcement as specified in modern building design codes such as CSA A23.3-14 [4]. Nonetheless, tests have demonstrated that even newer joints exhibits shear cracking under strong seismic loading, significantly contributing to story drifts of the global structure [5].

Since the pioneering experiment of seismic resistance of beam-column joints conducted by Hanson and Connor in 1967 [3], there

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Nomenclature

A	transformation matrix that converts the nodal displacements to component deformations
A_b	nominal bar area
d_b	nominal bar diameter
E_c	tangent modulus of elasticity of concrete
E_s	modulus of elasticity of steel
E_{sec}	secant modulus of elasticity of concrete
E_{sh}	hardening modulus of steel
f'_{cc}	compressive strength of confined concrete
f_i	component force
f_s	stress in the reinforcing steel at the interface of the joint
f_y	yield stress of steel
F	external nodal resultant
$\hat{h}$	distance between the bar slip springs on the beam side
k	confinement effectiveness coefficient
r	parameter that is a function of the tangent and the secant modulus of elasticity of concrete
u	external displacements and rotations
v	internal nodal displacement
$\hat{w}$	distance between the bar slip springs on the column side
x	parameter that is a function of the strut strain
α_{strut}	angle of inclination of the strut
Δ	component deformations
Δ_{slip}	slip of the reinforcing bar at the joint interface
ε_{cc}	strain of the confined concrete at the peak stress
ε_t	principal tensile strain of concrete in the shear panel
φ	interior nodal resultant
τ_{EC}	bond stress of elastic steel in compression
τ_{ET}	bond stress of elastic steel in tension
τ_{YC}	bond stress of post-yielding steel in compression
τ_{YT}	bond stress of post-yielding steel in tension
w_{strut}	in-plane width of the strut

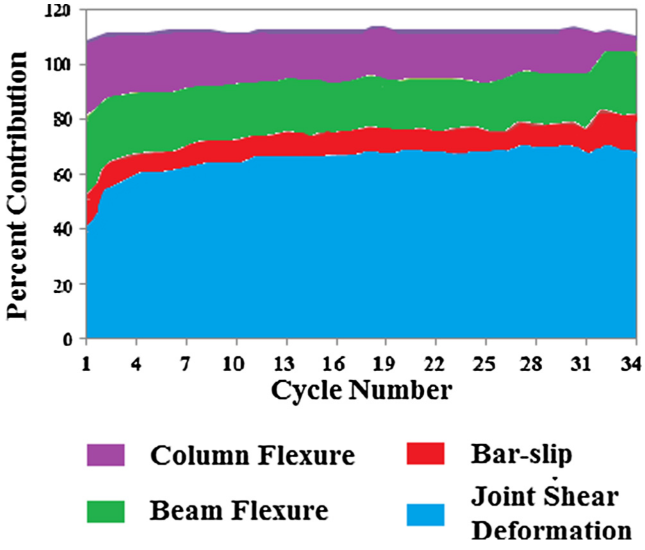

Fig. 1. Contributions of displacement factors to story drift for an older type joint, Specimen CD15-14, subjected to reversed cyclic loading [2].

has been an ongoing effort in understanding the behavior of beam-column joints under seismic actions, and in creating numerical simulation methods to model and determine joint response under various loading conditions. Researchers have proposed a variety of beam-column joint models. These models can be categorized into three classes: rotational hinge models such as by Alath and Kunnath [6], Altoontash [7] and Shin and LaFave [5]; component models such as by Youssef and Ghobarah [8], Lowes and Altoontash [9] and Mitra and Lowes [10]; and finite element models [11]. Each model has its advantages and limitations, and there is no scientific consensus on a model that is optimal for all applications. Rotational hinge models require calibration for each specific type of joint. Finite element models are complex and require significant computational resources; therefore, they are not suitable for holistic frame analyses. Component models provide a good balance between simplicity and accuracy. They are generally based on experimentally calibrated parameters, and they are suitable for analyzing large frames. They use mechanics-based formulations and generally do not require calibration for each particular joint type. However, the results obtained usually depend on the material models used for the joint element.

While existing joint models are effective for the investigation of single isolated joints, they do not consider the interactions between the joints and the other parts of the structure within a global frame analysis procedure. Therefore, there is a need to develop a holistic analysis procedure incorporating the joint response. The primary focus of this current study is to capture the impact of local joint deformations on the global frame response subjected to monotonic loading by implementing a new joint model into a previously-developed global frame analysis proce-

(a) Insufficient anchorage length (b) Unconfined connection (c) Poor coverage

Fig. 2. Different joint failure modes in reinforced concrete frames under earthquake loading (Google Images).