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Analytical study of in-plane buckling of longitudinal bars in reinforced concrete columns under extreme earthquake loading

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ABSTRACT

Seven full-scale reinforced concrete (RC) columns were tested at the Multi-Axial Subassemblage Testing (MAST) Laboratory of the University of Minnesota to investigate their performance under extreme seismic events. The specimens were designed according to seismic provisions of *ACI 318-11* (ACI Committee 318, 2011) and incorporated closely-spaced transverse hoops at their base. However, at large drift ratios during these tests, longitudinal bars were observed to buckle parallel to the face of the columns with transverse ties having little effect. This previously unobserved bar buckling phenomenon is investigated numerically to gain a better understanding of the column characteristics that affect it. First, a bar-spring mechanical model is used to understand the conditions needed to prevent buckling of longitudinal bars by means of restraints with finite stiffness. Second, a three-dimensional (3D) nonlinear finite element analysis of the lower portion of the specimen subjected to monotonic loading was formulated in ABAQUS and validated with test data. The analysis reveals that columns with larger cross-sectional dimensions that incorporate larger longitudinal bar sizes (No. 8 and above) and lower strength concrete are more prone to in-plane bar buckling.

1. Introduction

Reinforcing bar buckling is a complex phenomenon that can reduce ductility of RC columns and lead to significant stiffness reduction and strength loss. The complexity of this phenomenon is attributed to the fact that the reinforcing bar buckling in RC columns involves both material and geometric nonlinearities and depends on several parameters including tie spacing and effectiveness, spalling of cover concrete, expansion of concrete core, and loading history. Due to the complexity of the problem, many prior experimental and analytical studies were carried out on isolated bars under compression to investigate bar buckling behavior. Experimental investigations showed that the behavior of bars in compression is generally different from that in tension [2,3] and hence analytical formulations were proposed to capture the constitutive relations of compression bars including buckling [4–6]. Additionally, the investigations revealed that the post-yield behavior of reinforcing bars under compression is generally controlled by the ratio of their unsupported length to bar diameter (s/d_b) as well as their eccentricity to bar diameter ratio (e/d_b) [3,7]. Berry and Eberhard [8] utilized experimental results of a dataset of RC columns to develop an equation for estimation of the drift ratio at the onset of bar buckling. However, their proposed equation seems to overestimate the drift ratio at the onset of bar buckling as they calibrated their equation with reported drift ratios corresponding to initiation of bar buckling that were mostly based on visual inspections at or near the end of the tests [9,10]. Considering the major role of transverse ties in controlling bar buckling, some research studies idealized the bar buckling problem as a system of bar and springs with the springs representing the axial stiffness introduced by transverse ties [2,11]. Kashani et al. [12] used this concept to calculate the buckling length of longitudinal bars and employed a nonlinear fiber element modeling technique to investigate bar buckling phenomenon in RC bridge piers. Using fiber-based model of circular RC columns, Feng et al. [13] investigated the strain limits at the onset of bar buckling.

In all the former studies of bar buckling in RC columns, it is assumed that the bars will buckle outward, that is perpendicular to the nearest column face, and the transverse ties are essential in restraining them from buckling. However, recent tests carried out at the MAST Lab in the Department of Civil, Environmental and Geo- Engineering of the University of Minnesota on full scale RC

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columns subjected to extreme loading conditions similar to what the columns experience during extreme seismic events revealed another buckling mode in which the bars buckled parallel to the compression face of the columns (in-plane bar buckling). In several instances, the ties were observed to still be effective in restraining the bars from outward buckling. However, after extensive damage to the concrete surrounding the bars, the reinforcing bars buckled over a height equal to twice the tie spacing and exhibited large lateral deformations parallel to compression face of the columns.

The main restraint against in-plane buckling is the concrete surrounding the bars, especially the concrete residing between adjacent bars (i.e. the concrete "teeth"). This concrete, while being within the column core, tends to be the portion of the core that gets damaged earliest and to a greater extent during a load test. Extensive damage to the concrete surrounding the bars would typically happen under large seismic loading conditions during which concrete exhibits severe inelastic behavior. The unique control and loading capabilities of the MAST Lab provided the opportunity to continue loading of the specimens far beyond the extent of loading in previous tests on RC columns. During these tests, the loading continued until the specimens lost more than 80% of their lateral load capacity whereas in almost all previous tests, loading was terminated after approximately 20% strength loss. In the authors' opinion, such an extended loading regime provided the chance to observe a failure mechanism in RC columns that was not addressed in previous tests.

In this study, first the required lateral restraint to prevent bar buckling is investigated numerically using FEM modeling of isolated bars. In practice, the lateral restraint can be provided by transverse ties in the case of outward deformation, or by concrete surrounding the bars (i.e. the "teeth") in the case of in-plane deflection. Results from analysis of the isolated bars are then utilized in a nonlinear finite element model in ABAQUS/Explicit to investigate the observed failure mechanism in the longitudinal bars of tested column specimens. The model was validated with experimental data and was employed to explore the influence of several parameters that can affect in-plane buckling of the bars.

2. Experimental program

The columns tested at the MAST Lab represent the lower portion of typical columns on the ground floor of a moment resisting frame in a high-rise building. The column specimens were designed according to seismic provisions of *ACI 318-11* [1] and featured two distinct cross sectional dimensions: 36×28 in. and 28×28 in. (914×711 mm and 711×711 mm). The specimens were built using normal-strength, normal-weight concrete with 28-day nominal compressive capacity (f'_c) of 5000 psi (34.47 MPa), *ASTM A706* [14] Grade-60 No. 8 and No. 9 steel reinforcing bars confined by ASTM *A615* [15] Grade-60 No. 5 steel hoops. Transverse hoops were placed at close spacings in the base of the columns to prevent outward bar buckling and ensure ductile behavior (Fig. 1).

At the beginning of each test, a constant axial load was applied on top of the specimens (Fig. 1(a)) and kept constant and vertical during the tests. To simulate behavior at near-collapse conditions during extreme seismic excitation, the column specimens were then subjected to either a monotonic or one of several progressively increasing displacement reversals until they lost more than 80% of their lateral loading capacity. Further details regarding these tests can be found elsewhere [16].

3. Test observations

When the lateral loading was applied to the column specimens, flexural cracks formed on tensile face of the columns (Fig. 1). Flexural cracking initiated at approximately 0.2% drift level, which was equal to 6 mm of the cross-head displacement. Additionally, flexure-shear cracks formed in the lower portion of the other two faces of the columns and longitudinal cracks were observed along the corners on the compression sides. Following concrete cracking, the longitudinal bars started to yield at approximately 0.5% drift ratio (15 mm of cross-head displacement). However, the columns exhibited further lateral load capacity due to confining pressure from the transverse reinforcement and strain hardening of longitudinal reinforcement. An increase in lateral load was accompanied by more crack development and propagation. Finally, the specimens started to lose flexural strength due to crushing of the cover concrete and buckling of the longitudinal bars. The columns exhibited severe strength loss by the end of the test (more than 80% of their peak lateral load capacity) following the fracture of the buckled bars and extensive damage to the concrete around the perimeter.

While it is commonly assumed that longitudinal bars in an RC column would buckle in the outward direction (i.e. perpendicular to the compression face of the column), investigation of the buckled bars at the end of the tests conducted at the MAST Lab indicated that this assumption is not necessarily true in all cases. Instead, it was observed in all tested specimens that some of the bars buckled parallel to the compression face of the columns (Fig. 2). More specifically, when only the two middle bars on compression faces of the columns in monotonic and cyclic uniaxial tests at the MAST Lab are considered, 10 out of 24 bars (i.e. 42% of the total observed buckling cases) revealed either a complete or a dominant in-plane buckling mode. A buckling mode is considered to be completely in-plane when no out-of-plane translation is observed in the buckled region whereas if a small outward translation is present in conjunction with large in-plane translation, it is considered a dominant in-plane buckling mode.

Another observation is related to the axis of bending in the buckled bars. Since reinforcing bars incorporate ribs along their length, they have strong and weak axes of bending. In practice, longitudinal bars are typically oriented in a way that their outward deformation (i.e. deflection perpendicular to the column face) mobilizes flexural rigidity corresponding to the weak axis while their in-plane deflection (i.e. deflection parallel to the column face) occurs about their strong axis of bending. In many of the observed cases of buckled bars, in-plane buckling occurred about the strong axis of bending of the bars, which is contrary to the common assumption, that is supported by experimental results from isolated bars, that the bars would only buckle about their weak axis.

4. Analytical investigation using bar-spring model

A bar and spring model is used to investigate the demands on lateral restraints that have finite stiffness to prevent buckling of longitudinal reinforcing bars. For outward (i.e. out-of-plane) buckling, these restraints are the hoops or ties that are also used as shear reinforcement and reinforcement for confinement. For in-plane buckling, the restraints are provided by the concrete that bears against the longitudinal reinforcement.

4.1. General description of the bar-spring system

The buckling behavior of bars can be simply modeled with a bar-spring system as illustrated in Fig. 3 where springs represent the axial stiffness of the ties preventing the bars from buckling. Dhakal and Maekawa [2] employed such model to estimate the required tie stiffness for a stable buckling mode and to determine the buckling length of the bars. Based on their investigation, Dha-