IN-PLANE BAR BUCKLING IN RC COLUMNS IN EXTREME SEISMIC EVENTS

A. Nojavan¹, A.E. Schultz², and S-H. Chao³

ABSTRACT

A clear understanding of resistance mechanisms in reinforced concrete (RC) columns under extreme earthquakes is crucial as column failure can lead to structural collapse. To enhance such understanding, seven full-scale reinforced concrete columns were tested under distinct monotonic and cyclic loading protocols, similar to those that RC columns experience during large earthquakes. The columns were representative of columns in mid- or high-rise buildings, located in high seismic zones, and were designed according to seismic provisions of ACI 318-11 [1]. Transverse ties were placed at close spacing along column height to prevent reinforcing bar buckling and to enhance ductility. However, during the tests, longitudinal bars were observed to buckle in-plane (i.e., parallel to column compression face); a failure mechanism that has not been addressed in previous RC column tests. While transverse ties could prevent or postpone out-of-plane bar buckling, they were found to have no effect in restraining the bars from in-plane buckling. The observed in-plane bar buckling phenomenon is investigated analytically using three-dimensional (3D) nonlinear finite element (FE) models of the tested columns. The FE model was validated with experimental results and was used to study the effect of several parameters that can affect in-plane bar buckling including concrete compressive strength ($f'_c$), longitudinal bar size and spacing, transverse tie spacing, and cross sectional size. The analysis shows that RC columns that feature a larger cross section with larger longitudinal bar sizes and are built with a lower strength concrete are more susceptible to in-plane bar buckling.

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A clear understanding of resistance mechanisms in reinforced concrete (RC) columns under extreme earthquakes is crucial as column failure can lead to structural collapse. To enhance such understanding, seven full-scale reinforced concrete columns were tested under distinct monotonic and cyclic loading protocols, similar to those that RC columns experience during large earthquakes. The columns were representative of columns in mid- or high-rise buildings, located in high seismic zones, and were designed according to seismic provisions of ACI 318-11 [1]. Transverse ties were placed at close spacing along column height to prevent reinforcing bar buckling and to enhance ductility. However, during the tests, longitudinal bars were observed to buckle in-plane (i.e., parallel to column compression face); a failure mechanism that has not been addressed in previous RC column tests. While transverse ties could prevent or postpone out-of-plane bar buckling, they were found to have no effect in restraining the bars from in-plane buckling. The observed in-plane bar buckling phenomenon is investigated analytically using three-dimensional (3D) nonlinear finite element (FE) models of the tested columns. The FE model was validated with experimental results and was used to study the effect of several parameters that can affect in-plane bar buckling including concrete compressive strength ($f'_c$), longitudinal bar size and spacing, transverse tie spacing, and cross sectional size. The analysis shows that RC columns that feature a larger cross section with larger longitudinal bar sizes and are built with a lower strength concrete are more susceptible to in-plane bar buckling.

Introduction

Structural performance of RC columns subjected to seismic loads can be significantly affected by reinforcement bar buckling as this mechanism can impact the displacement ductility and is often followed by large stiffness degradation and strength reduction. Bar buckling is a complicated phenomenon that depends on the behavior of concrete cover, expansion of core

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concrete, transverse tie spacing, and characteristics of the applied loads. To better understand the bar buckling failure mode, many previous experimental and analytical studies were focused on the behavior of isolated bars. The studies showed that the bars exhibit distinct behavior under tension and compression \[2\], \[3\]. Therefore, some studies investigated the constitutive relations of bars under compression \[4\]–\[6\]. Prior studies also showed that the ratio of unsupported length of the bars to bar diameter \((s/d_b)\) as well as the ratio of their eccentricity to bar diameter \((e/d_b)\) affect the plastic behavior of reinforcing bars \[3\], \[7\]. Additionally, some analytical studies idealized the bar buckling problem as a system of bar and linear springs to investigate the role of transverse ties in restraining bar buckling.

A common assumption in prior studies on bar buckling is that the bars only buckle outward (i.e., perpendicular to the nearest column face) with transverse ties acting as the main restraint. However, recent tests that were carried out at the Multi Axial Subassemblage Test (MAST) Laboratory of the University of Minnesota on full scale RC columns under extreme seismic loads revealed a failure mode in which reinforcing bars buckled parallel to the compression face of the column (i.e., in-plane bar buckling) (Fig. 1). During in-plane bar buckling, transverse ties were observed to have little or no impact on controlling in-plane bar buckling while they were still effective in restraining outward (i.e., out-of-plane) buckling.

The main restraint against in-plane bar buckling was found to be the portion of the concrete that is located surrounding the bars and which resides between adjacent bars. This portion of RC columns gets damaged under large-amplitude seismic loading conditions that produce severe inelastic behavior. Such extreme loading conditions were achieved using the unique loading capability of the MAST Lab, and they provided the chance to observe the in-plane bar buckling mode of failure that has not been addressed in previous tests of RC columns.

**Experimental Program**

Seven full-scale RC columns, representing those located at the lower portion of typical columns on the ground floor of high-rise buildings were tested at the MAST Lab. The columns featured cross-sectional dimensions of either 36×28 in. or 28×28 in. and were designed according to seismic provisions of ACI 318-11 \[1\] with closely spaced transverse ties to enhance ductility. The column specimens were constructed using normal weight concrete with 28-day compressive strength \((f'_c)\) of 5000 psi, No. 8 and No. 9 ASTM A706 \[8\] Grade 60 steel reinforcing bars confined by ASTM A615 \[9\] Grade 60 steel hoops bent from No. 5 bars. The columns were subjected to an axial load followed by a lateral loading protocol. The axial load was maintained constant and vertical during the test while the lateral loading scheme followed either a monotonic protocol, or one of several cyclic loading protocols with progressively increasing displacement cycles until the specimens lost nominally 80% of their lateral loading capacity. More details regarding these tests can be found elsewhere \[10\].

**Test Observations**

The first form of damage to the specimens appeared as flexural cracks at approximately 0.2% drift ratio, approximately 12 in. above the column-footing interface, followed by flexure-shear cracks formed on the other two faces of the columns and longitudinal cracks along the corners on
the compression side of the columns. Application of larger drift ratios to the columns was accompanied by more crack development, yielding of the bars, spalling of the concrete cover, and buckling of the longitudinal bars until the specimens exhibited significant strength loss (i.e., nominally 80% of the peak lateral loading capacity) by the end of the test. In-plane bar buckling was observed in 10 out of 24 longitudinal bars located on the compression face of the specimens that were subjected to monotonic and uniaxial cyclic tests (i.e., all specimens except the one which was subjected to a biaxial loading protocol).

Figure 1. In-plane bar buckling in: (a) tested specimen (b) 3D FE model [11].

**Finite Element Modeling of Tested Column Specimens**

To better understand the in-plane bar buckling mechanism in the tested columns, a three-dimensional (3D) nonlinear finite element model of the lower portion of the columns was developed and analyzed in ABAQUS/Explicit. The model was validated with experimental data and used to investigate several parameters that affect in-plane bar buckling. The 3D nonlinear finite element model of the tested column specimens was subsequently used to qualitatively assess the observed in-plane bar buckling and the main parameters that affect it. To reduce analysis cost, the model represented only the lower 25-in. portion of the specimen under monotonic loading (SP1). Fixed boundary conditions were introduced at the nodes at the column base. Concrete and reinforcing steel elements were modeled using 8-node brick elements with reduced integration (C3D8R) and 2-node shear flexible beam-in-space (B31) elements, respectively. The model was validated with experimental results and used to investigate the effect of several parameters including concrete compressive strength, longitudinal bar size and spacing, tie spacing, and cross-sectional dimensions on the in-plane buckling mechanism. Further details on the FE model can be found elsewhere [11].

**Results and Observations**

The lateral displacement-top rotation behavior of the benchmark FE model was compared to that from other FE model variants with distinct concrete compressive strength, longitudinal bar size and spacing, tie spacing, and cross-sectional dimensions. Results from these analyses indicate that a higher concrete compressive strength ($f'_c$) is beneficial in preventing the in-plane bar buckling by delaying the onset and rate of strength decay and stiffness reduction (Fig. 2(a)). Additionally, it was found that columns with larger bar sizes are more susceptible to in-plane bar
buckling due to the higher restraint demands on the concrete that prevents them from buckling. However, the effect of longitudinal bar spacing and transverse tie spacing was found to be insignificant. Finally, RC columns featuring larger cross-sectional dimensions that often incorporate larger longitudinal bar sizes exhibit an earlier and faster strength loss and stiffness reduction (Fig. 2(b)), and hence are more prone to in-plane bar buckling [11], [12].

![Diagram](image)

**Figure 2.** Effects of concrete compressive strength (2a) and cross-sectional dimensions (2b) on in-plane bar buckling [11].

### References


