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Reinforced Concrete Columns Confined with Steel or FRP Grids

Grira, Mongi[1] and Saatcioglu, Murat[2]

ABSTRACT

Experimental investigation was carried out to verify the use of grid reinforcement in concrete columns for improved seismic performance. Large-scale column specimens were tested under simulated seismic loading. The transverse column reinforcement consisted of welded steel grids or fiber reinforced polymer grids. Grid spacing, grid pattern and the volumetric ratio of grid reinforcement were considered as test parameters. The results indicate improved deformability of columns when confined by properly designed grids. The grids provided easy cage assembly, savings in materials, and improved performance, while eliminating the congestion of column cage. Columns reinforced with steel or fiber reinforced polymer grids developed at least 3% drift when current design practice was followed in terms of the amount and spacing of transverse reinforcement.

INTRODUCTION

Reinforced concrete columns are often responsible for overall strength and stability of the entire structure when subjected to strong ground excitations. Flexural hinging of columns, especially at the first storey level, may result in sudden strength degradation, potentially leading to partial or total structural collapse. Therefore, building codes and standards require properly designed and detailed transverse reinforcement to confine concrete. Confinement of column concrete improves strength and deformability, ensuring resistance to seismic forces.

Building code requirements for confinement of circular columns can often be met relatively easily by providing spirals with an appropriate pitch. Circular hoops may also be used if the ends are well anchored into the confined core, or connected by mechanical devices to prevent opening during seismic response. The mechanism of confinement in both cases depends on hoop tension, which can be provided at sufficient magnitude by adjusting the required volumetric ratio of transverse reinforcement. Because the required confinement pressure is provided by the hoop tension, crossties are not needed, leaving the column cage uncluttered for proper placement of concrete.

Most building columns are of rectilinear geometry, having a square or a rectangular cross-section. The mechanism of confinement in these columns is different than that for circular columns. In this case the confinement pressure is not generated by hoop tension, but by transverse forces that are generated in tie legs (Saatcioglu and Razi 1992). Perimeter hoops alone do not result in sufficient confinement pressure. Hence, overlapping hoops and crossties are needed to have well distributed cross reinforcement around the perimeter of the section, tied to well distributed longitudinal reinforcement. The transverse reinforcement must have bends and hooks, with sufficient hook extensions for proper anchorage into the core concrete. The efficiency of confinement pressure provided by this type of transverse reinforcement improves with reduced spacing both along the column height, as well as within the cross-sectional plane. Furthermore, the required volumetric ratio of transverse steel can be quite high, necessitation a closely spaced mesh of reinforcement in both vertical and horizontal planes, with overlaps, hooks and hook extensions. The resulting steel cage often becomes extremely congested, difficult and costly to work with, proving potentials for concrete placement problems.

An alternative to using conventional transverse reinforcement is to use prefabricated grids, consisting of closely spaced reinforcement in two orthogonal directions. The grids eliminate the complications associated with bending and assembling conventional ties, while also minimizing material consumption since the overlaps and hook extensions are not needed. Furthermore, they provide improved dimensional accuracy, providing perfect support to longitudinal reinforcement, while also improving concrete confinement. Cage assembly becomes easy, reducing cost and time of construction.

Experimental research was carried out at the Structures Laboratory of the University of Ottawa to investigate potential use of reinforcement grids as column transverse reinforcement. The results are summarized in this paper.

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[1] Former Ph.D. student, Dept. of Civil Engineering, University of Ottawa, Ottawa, CANADA K1N 6N5.

[2] Professor, Dept. of Civil Engineering, University of Ottawa, Ottawa, CANADA K1N 6N5.

EXPERIMENTAL PROGRAM

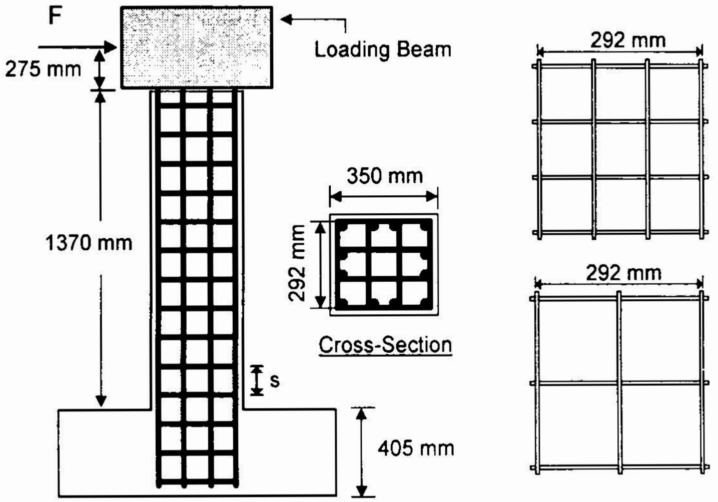
Test Specimens

Six full-size column specimens were designed, constructed and tested. The specimens represented part of a first-story column between the footing and the point of inflection, with a 1645-*mm* shear span. A 350-*mm* square cross-section was used with different configurations of longitudinal reinforcement. Either 8 or 12 #20 (19.5 *mm* diameter) bars were used as longitudinal reinforcement. Two different types of grid reinforcement were used, consisting of either welded steel grids or fiber reinforced polymer (FRP) grids. The grids had either 4-cells or 9 cells, consistent with 8-bar and 12-bar arrangements, respectively, with one longitudinal bar placed in each perimeter corner. Figure 1 illustrates the details of column geometry. Table 1 provides a summary of column and material properties. Columns with steel grids were labeled as "BG" columns and those reinforced with FRP grids were labeled as "FRP" columns.

Table 1 Properties of column specimens and materials

Column Label	f'_c MPa	Reinfor. Arrang.	ρ %	d_b mm	s mm	ρ_s %	P kN	P/P_o %
BG-1	37	8 #20	1.96	9.53	152	1.00	1782	39
BG-2	37	8 #20	1.96	9.53	76	2.00	1782	39
BG-7	37	12 #20	2.94	6.60	76	1.26	1923	38
FRP-1	34	8 #20	1.96	6 x 10	152	0.79	1920	39
FRP-2	34	8 #20	1.96	6 x 10	76	1.59	1920	39
FRP-9	34	12 #20	2.94	6 x 8	76	1.69	1920	39

The columns were cast with heavily reinforced footings, through which they were fixed on the laboratory strong floor for testing. Two 1000kN capacity MTS Actuators were used to simulate gravity loading. A third actuator, with the same capacity and make, was positioned horizontally to apply the simulated seismic loading. The columns were subjected to constant axial compression of approximately 40% of their concentric capacity. The lateral loading was applied in deformation control mode, in increments of lateral drift, consisting of 3 cycles at 0.5%, 1%, 2%, 3% etc., until a significant strength decay was detected. The columns were well instrumented with electric resistance strain gauges placed on reinforcement, and Linear Variable Differential Transducers (LVDT) for displacement measurements. Two sets of LVDT's were also placed in the column potential hinging region to record inelastic rotations due to flexure and anchorage slip. Detailed description of the test set-up and instrumentation are given elsewhere (Saatcioglu and Grira 1999, Grira and Saatcioglu 1996).



(a) Column speciemens (b) Grid reinforcement

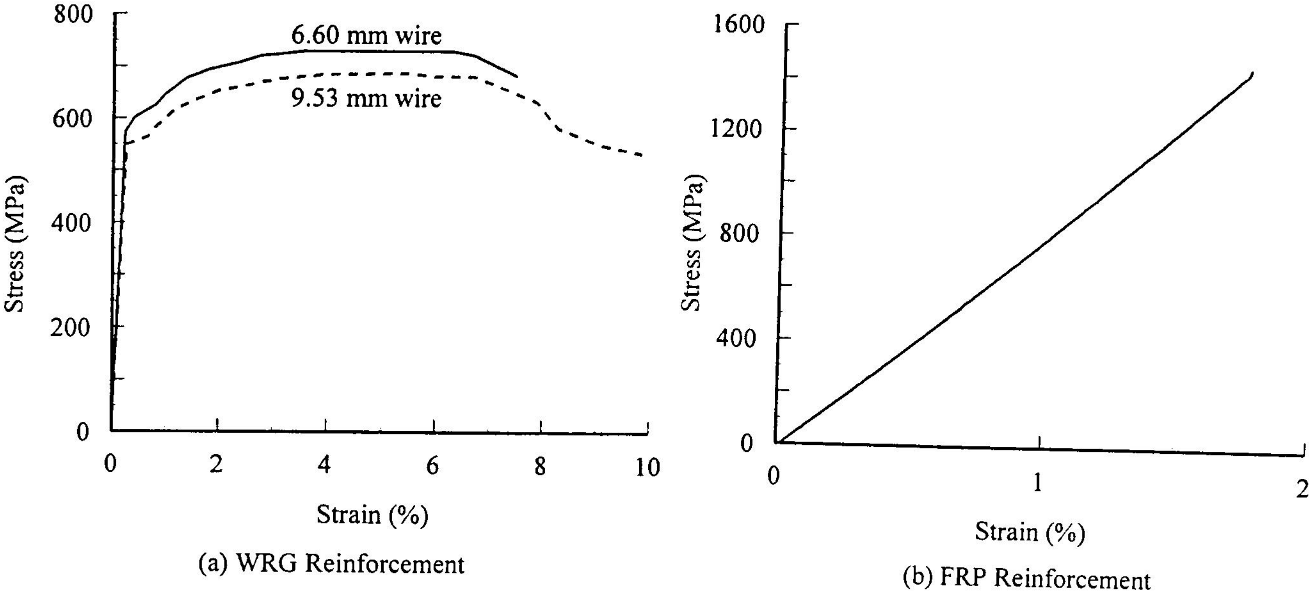
Figure 1 Geometric details of test specimens

Properties of Grid Reinforcement

Two types of grid reinforcement were used to confine column concrete. The grids were manufactured either by welding cold-drawn smooth steel wires, or impregnating carbon fibers in epoxy resin in two orthogonal directions. Both grid types were different than the conventional steel used for column confinement, and hence require further elaboration in material properties.

Welded reinforcement grids (WRG) resemble welded wire fabric (WWF) commonly used in the construction industry. Primary differences between the two come from the sizes of wires and grid openings, as well as the stress-strain characteristics. WWF is produced from small diameter wires. Common stocks of WWF include wires of 1.47 mm to 4.2 mm in diameter. Usually, larger size wires are used to produce larger grid sizes, resulting in steel ratios too small for structural applications. Furthermore, the major drawback of conventional WWF is the relatively brittle behavior of material as compared to re-bars. WRG does not have these shortcoming. It is design to be used as transverse reinforcement in structural elements, such as beams, columns, beam-column joints, and shear wall boundary elements. They are produced from cold-drawn smooth wire of relatively large sizes, fuse welded in jigs to obtain grid sizes that result in sufficiently high reinforcement ratios. WRG shows similar ductility characteristics as hot-rolled re-bars, developing 7% to 10% strain at rupture, as illustrated in Figure 2, although they do not exhibit a clear yield plateau and any appreciable strain hardening. The strength of welded joints under laterally expanding concrete, and diagonal tension was monitored during column tests, and are discussed under "Test Results." The WRG used in column tests consisted of either 9.53 mm or 6.6 mm diameter wires, forming either a grid opening of 150 mm or 100 mm square for 8-bar and 12-bar arrangements, respectively, as illustrated in Figure 1.

Long term durability problems observed in many engineering structures and constant deterioration of steel under certain conditions provided impetus for growth of corrosion resistant materials such as fiber reinforced polymers (FRP). A "New Fiber Composite Material for Advanced Concrete" (NEFMAC) grid has been introduced to the market for use in building construction. These NERMAC grids were adopted in the current project as FRP grids, consisting of carbon fibers impregnated with epoxy resin formed into a flat grid. The area of each crossbar was either 6 x 10 mm or 6 x 8 mm, forming grid openings of either 150 mm or 100 mm square for 8-bar and 12-bar arrangements, respectively. Carbon FRP has a high tensile strength, though it has no ductility. Depending on the fiber content, it may also have significantly lower modulus of elasticity. Figure 2 shows the stress-strain relationship of FRP bars used to manufacture the grids. These relationships were obtained by standard coupon tests, coupons of which were obtained from the grids, with crossbar locations in the middle of test coupons. The tests consistently indicated linear behavior up to an average ultimate strength of 1483 MPa corresponding to 1.78% ultimate elongation. The modulus of elasticity was measured to be 83,000 MPa, less than the value of 100,000 MPa specified by the manufacturer. The strength of grid corners was monitored during column tests, as reported under "Test Results."



(a) WRG Reinforcement

(b) FRP Reinforcement

Figure 2 Stress-strain relationships for transverse reinforcement

Test Results

Test results are presented in Figure 3 in the form of hysteretic moment-drift relationships, illustrating strength and stiffness characteristics of columns under constant axial compression and lateral deformation reversals. Column BG-1 was reinforced with WRG, with a volumetric ratio of 1.0% which was approximately equal to 65% of the amount required by the ACI 318 Building Code (1995). The spacing of grids was equal to half the column sectional dimension, which was approximately twice the maximum spacing permitted by the code. Hence, the column did not have sufficient transverse reinforcement based on the current design practice. It sustained deformation reversals at about 1% drift, developing about 17% strength decay, and failed during the second cycle at approximately 2% drift, as depicted in Figure 3(a). The cover concrete had spalled off at this load stage and the failure occurred when the longitudinal reinforcement buckled between the first and the second grids above the base. The second grid from the base deformed excessively and bulged out under the lateral expansion of concrete, while maintaining its integrity. There was no sign of weld failure or fracture of transverse steel even after the buckling of longitudinal reinforcement. The apparent lack of ductility in the columns was caused by lack of transverse reinforcement, rather than the lack of deformability of the welded grids used.

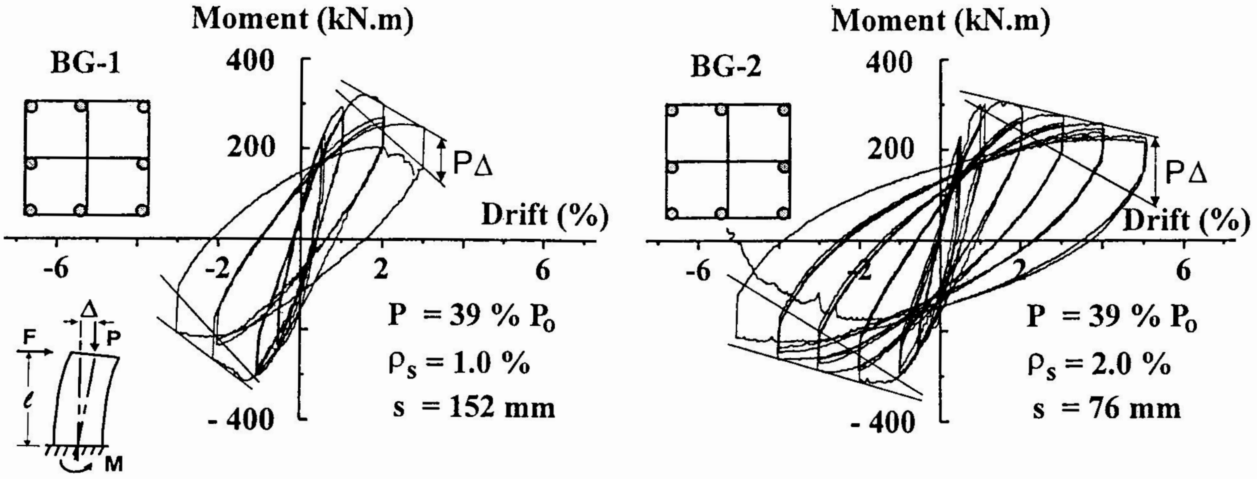
Column BG-2 was companion to BG-1, except the grid spacing was reduced by one half to 76 mm. This resulted in increased volumetric ratio of transverse steel, equal to 2.0%, exceeding the amount required by the building code (ACI 318 1995) by about 30%, while confirming to the maximum spacing requirement. The hysteretic relationship shown in Figure 3(b) indicates ductile behavior and stable hysteresis loops up to 3% lateral drift, with little degradation thereafter, and failure at approximately 4% drift. The grids provided excellent confinement to the core concrete, maintained their integrity up to 5% drift in one direction, at which load stage one of the longitudinal bars ruptured in tension, followed by the rupturing of one of the grids near a weld location. Though the rupturing of one of the grids was observed in this column test, this did not occur until after the rupturing of longitudinal reinforcement.

Column BG-3 had an improved reinforcement arrangement, because of the use of 9-cell grids, which resulted in a 12-bar arrangement. The area of individual wires that made up the grids was smaller than the 4-cell grids used in the previous two columns. Consequently, although the total number of crossbars increased, the volumetric ratio of steel decreased to 1.26% relative to Column BG-2. This amount of transverse steel was equal to 83% of that required by ACI 318 (1995), based on the actual recorded steel yield stress. The hysteretic behavior, depicted in Figure 3(c), clearly indicates improved column performance, showing a lateral drift capacity of 4% with little or no strength decay. The failure was initiated by longitudinal bar buckling during the second cycle at 5% lateral drift. The improved ductility observed in Column BG-3, in spite of the reduced volumetric ratio, was attributed to the reduced spacing of cross reinforcement both in cross-sectional and vertical planes. The welded grids remained intact until after the test was completed, with no sign of distress in either the welds or the steel, though they deformed excessively while stabilizing the longitudinal bars and confining compression concrete.

Column FRP-1 was companion to BG-1, with the same grid spacing. The volumetric ratio of FRP was 0.8%, which was somewhat lower than the 1.0% used in BG-1. The hysteretic behavior shown in Figure 5(d) illustrates similar response to that of BG-1, with stable hysteresis loops up to 1% drift, followed by a strength decay of about 27% at 2% drift. The column developed a sudden loss of resistance during the first cycle at 3% drift, when the FRP grids failed prematurely at the joints, allowing the longitudinal bars to buckle under compression. The strain gauges placed on grids indicated a maximum tensile strain of 0.5%, which corresponded to 415 MPa stress in transverse direction. This is about the same level of stress that would be developed by conventional tie reinforcement, though the FRP had a much higher strength of 1483 MPa.

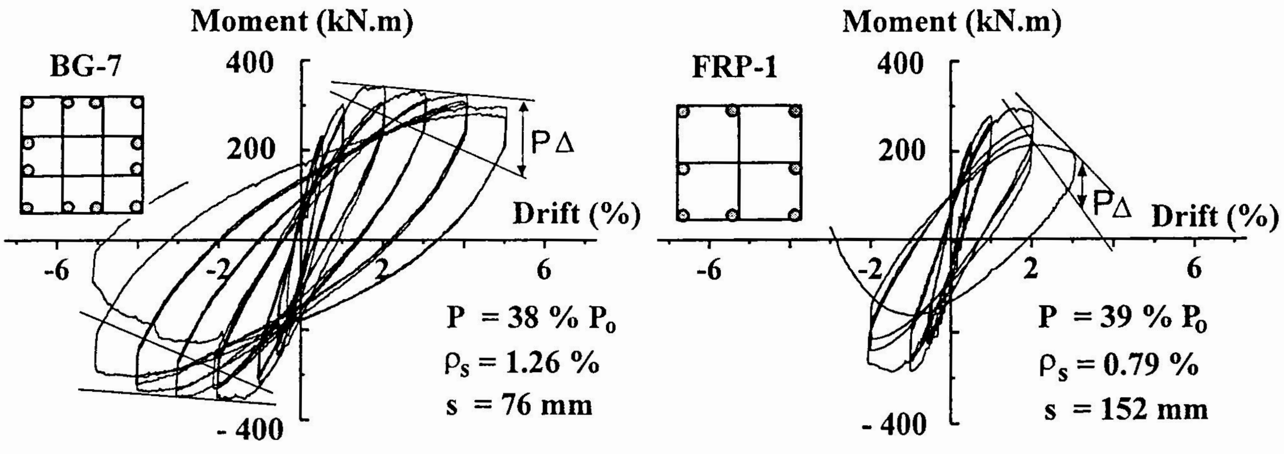
Column FRP-2 was companion to BG-2, with a reduced grid spacing of 76 mm. This resulted in an increase of about 100% in the volumetric ratio. The reduction in grid spacing improved the effectiveness of grids in controlling bar buckling, while also improving concrete confinement. The hysteretic relationship shown in Figure 3(e) indicates that the column behaved much better than the previous column (FRP-1), sustaining lateral deformation reversals at 3% drift without any appreciable strength decay. The column failed during the third cycle at 4% lateral drift when the grids failed prematurely at their joints, and could no longer maintain the stability of longitudinal reinforcement, resulting in bar buckling. The examination of strain gauge data revealed that a maximum tensile strain of 0.22% was developed during the last cycle of 2% drift, before the gauges stopped functioning.

Column FRP- 9 was companion to BG-7, with improved reinforcement arrangement and reduced volumetric ratio. The FRP grids used in this column consisted of 6 x 8 mm crossbars, resulting in 1.69% volumetric ratio. The spacing remained at 76mm, which conformed to the maximum spacing required by ACI 318 (1995). The behavior of column is illustrated by the hysteretic relationship shown in Figure 3(f). The column developed 3% lateral drift without any strength loss, even with reduced volumetric ratio of reinforcement. This was attributed to the improved reinforcement arrangement associated with 9-cell grids. The grids near the based failed at the joints, prematurely, during the second and third cycles at 4% drift, leading to the buckling of longitudinal bars in compression. The maximum transverse strain recorded on the grids was 0.35%, prior to gauge damage.



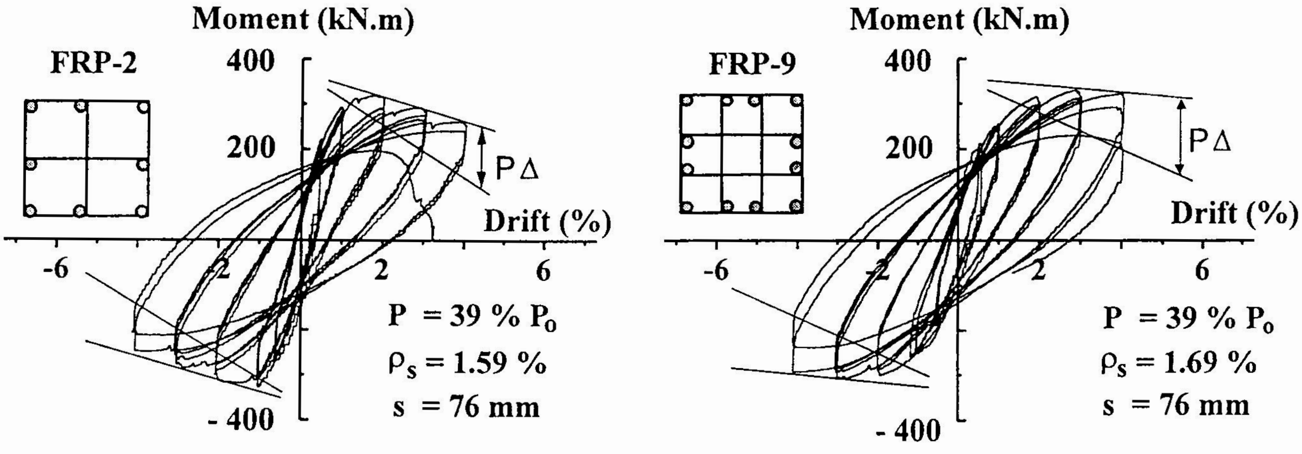
(a) Column BG-1

(b) Column BG-2



(c) Column BG-7

(d) Column FRP-1



(e) Column FRP-2

(f) Column FRP-9

Figure 3 Hysteretic relationships of test columns

CONCLUSIONS

The experimental investigation reported in this paper indicates that welded reinforcement grids, as well FRP grids can be used as column confinement reinforcement for improved seismic performance. The grids offer ease and speed in construction, savings in materials, and improved performance. The grid geometry, with closely spaced crossbars (reduced opening size) results in near-uniform distribution of confinement pressure, without congesting the column cage. The precision attained in prefabricating grids provides perfect support to longitudinal reinforcement, improving the stability of bars. However, the grids must posses sufficient strength and elongation capacity to fulfill these functions. Strength level, comparable to the yield strength of conventional grade 400 MPa tie reinforcement was found to be sufficient to develop the required confinement pressure with the volumetric ratio required for the conventional ties. The elongation of 0.4%, recorded in some columns, appears to be adequate for the columns tested in this investigation, under approximately 40% of concentric compression. The grid reinforcement meeting these conditions resulted in approximately 3% column drift capacity before any appreciable strength decay could take place.

NOTATIONS

d_b : Diameter of transverse reinforcement.
F : Lateral force.
f'_c : Concrete cylinder strength.
ℓ : Column shear span.
M : Total moment at column base.
P : Axial force.
P_o : Column concentric load capacity.
s : Spacing of grid reinforcement.
Δ : Lateral displacement of column.
ρ : Longitudinal reinforcement ratio.
ρ_s : Volumetric ratio of transverse grid reinforcement, computed as the volume of transverse reinforcement divided by the volume of core concrete, measured to the centerline of perimeter hoop.

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