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PERFORMANCE OF RC BRIDGE COLUMNS SUBJECTED TO LATERAL LOADING

S. Sotoud[1] and R.S. Aboutaha[2]

ABSTRACT

Old existing reinforced concrete bridge columns that had been designed before the development of new seismic codes are at risk of damage due to lateral loading. For an ideally designed concrete column subjected to lateral load, mode of failure is flexural. However, even if most of the inelastic action is flexural, lack of transverse reinforcement would limit the flexural ductility of columns under lateral loads. Shear failure has been a common mode of failure in RC bridge columns during recent earthquakes. This paper presents investigation of effect of different parameters on load carrying capacity of RC columns subjected to axial and lateral forces. A finite element model was developed using ANSYS and the lateral load-deflection curves of RC columns were calibrated against existing experimental tests data, conducted by others. Based on shear span to depth ratio, amount of transverse reinforcement and compressive strength of concrete, failure mode of RC column could be flexural, flexural-shear, or shear failure. Impact of other factors such as axial load ratio and reinforcement ratio on performance of RC columns were also studied. The results of this study indicate how load carrying capacity of RC bridge columns influenced by different factors. Knowing the existing strength and ductility of columns, a cost-effective retrofit system could be developed to prevent brittle failure of bridge columns.

[1]Graduate Assistant, Dept. of Civil & Environmental Engineering, Syracuse University Syracuse, NY 13244
[2]Associate Professor and Program Director, Dept. of Civil & Environmental Engineering, Syracuse University Syracuse, NY 13244

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Old existing reinforced concrete bridge columns that had been designed before the development of new seismic codes are at risk of damage due to lateral loading. For an ideally designed concrete column subjected to lateral load, mode of failure is flexural. However, even if most of the inelastic action is flexural, lack of transverse reinforcement would limit the flexural ductility of columns under lateral loads. Shear failure has been a common mode of failure in RC bridge columns during recent earthquakes. This paper presents investigation of effect of different parameters on load carrying capacity of RC columns subjected to axial and lateral forces. A finite element model was developed using ANSYS and the lateral load-deflection curves of RC columns were calibrated against existing experimental tests data, conducted by others. Based on shear span to depth ratio, amount of transverse reinforcement and compressive strength of concrete, failure mode of RC column could be flexural, flexural-shear or shear failure. Impact of other factors such as axial load ratio and reinforcement ratio on performance of RC columns were also studied. The results of this study indicate how load carrying capacity of RC bridge columns influenced by different factors. Knowing the existing strength and ductility of columns, a cost-effective retrofit system could be developed to prevent brittle failure of bridge columns.

Introduction

Old existing reinforced concrete bridge columns that had been designed before the development of new seismic codes are at risk of damage under lateral loading. Generally, it is more economical to retrofit vulnerable structures than replacing them. In order to propose an effective rehabilitation method, good estimation of load carrying capacity of RC columns is very important. According to Performance-based earthquake engineering (PBEE), in order to present various performance acceptance criteria for different failure modes, it is essential to define specific failure modes primarily [1].

The two main reasons for column failure are insufficient deformation capacity which results in flexure-shear and flexure failure; and lack of shear resistance which results in shear failure [2]. In this study, response of RC columns subjected to axial and lateral loads is investigated. Various parameters were investigated; shear span to depth ratio, amount of transverse reinforcement, and compressive strength of concrete. Impact of other factors such as axial load ratio and reinforcing ratio on performance of RC columns are also presented.

[1]Graduate Assistant, Dept. of Civil & Environmental Engineering, Syracuse University Syracuse, NY 13244
[2]Associate Professor & Program Director, Dept. of Civil & Environmental Engineering, Syracuse University Syracuse, NY 13244

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Failure Modes of RC Columns

ASCE/SEI 41-06 and FEMA 356 categorized three different failure modes for reinforced concrete columns as flexural failure, shear failure and flexural-shear failure [3]. For an ideal designed concrete column subjected to lateral load, mode of failure is flexural. However, even if most of the inelastic action is flexural, lack of transverse reinforcement would limit the flexural ductility of columns under lateral loads. Shear failure has been a common mode of failure in RC bridge columns during recent earthquakes. Inadequate transverse reinforcement, especially those with large spacing, causes this type of failure. Shear failure happens at relatively low structural displacements; it may occur even before yielding of longitudinal reinforcement. In general, inelastic loading decrease shear capacity of columns alternatively which results in shear failure after flexural yielding.

Flexural failure happens because of damage due to flexural deformation such as buckling of longitudinal bars, crushing or spalling of concrete. Flexural failure occurs after yielding of longitudinal reinforcing bars. Shear distress and diagonal cracking reduces lateral load capacity of columns even before yielding of longitudinal bars. This kind of column failure is known as shear failure. Flexure-shear failure is another common failure mode of RC columns which starts with flexural deformation (while longitudinal bars have yielded) and ends in shear deformation [3].

Priestley et al. [4] defined column failure modes according to lateral load- lateral displacement curve. Based on intersecting point of the degrading shear capacity envelope and lateral load-displacement curve, mode of failure may change. If this point is located before yielding point of lateral load-displacement curve, as in Figure 1(A), shear failure occurs. If the intersecting point is set after yielding point of lateral load-displacement curve, as in Figure 1(B), flexural-shear failure happens. If there is no intersecting point, mode of failure is flexural; as in Figure 1(C).

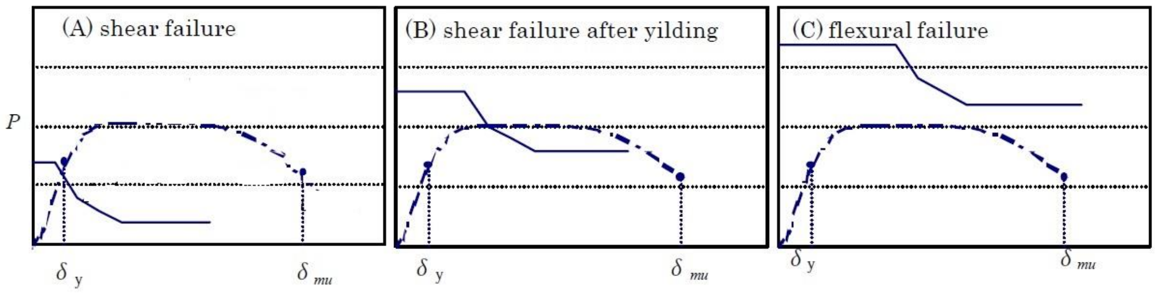


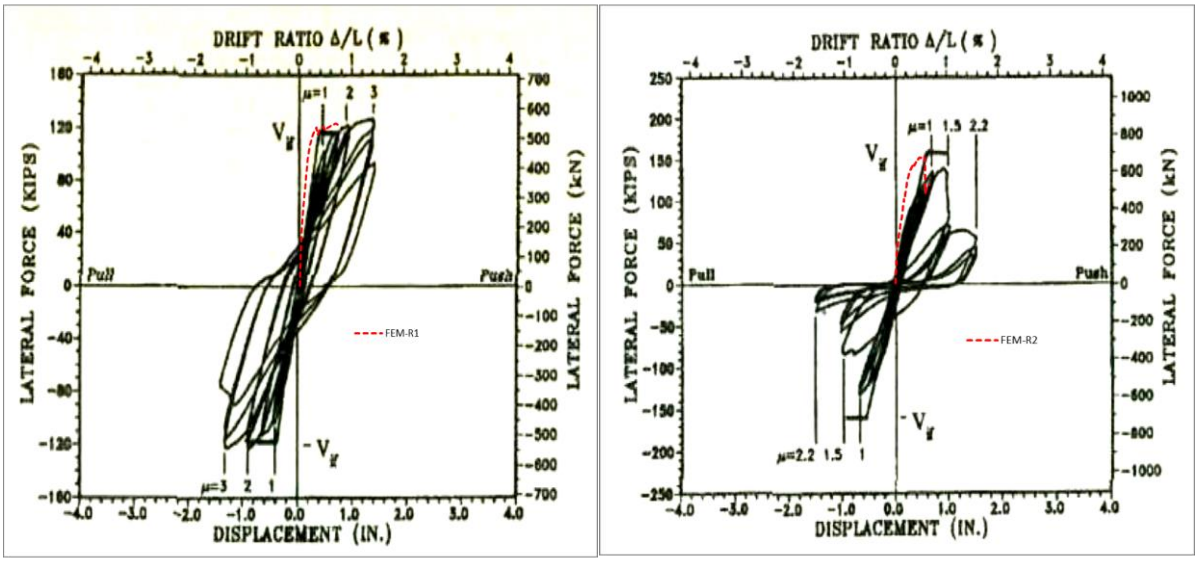
Figure 1. Failure mode classification [5]

Response of RC Test Columns Based on Finite Element Modeling

In order to investigate the lateral load-deflection curves of RC columns and calibrating them against existing experimental test data, finite element models have been developed using ANSY.

Several researchers carried on tests on rectangular RC columns to study lateral respond of columns and their failure modes. Priestley et al. [6] tested columns with rectangular sections having 22#6 longitudinal bars and #2@5in transverse reinforcement, subjected to cyclic reversals of lateral displacement. Low ductility or brittle shear failure was mode of failure of columns with shear span ratio of 2. While column R1 with Grade 40 main bars showed flexural-shear failure mode; column R2 with Grade 60 main bars failed in shear.

A finite element model developed to model the as-built specimens. All the properties including material and geometry properties applied to the model. Cyclic lateral loading is replaced by monotonic lateral loading. Figure 2 shows comparison between experimental and FE modeling results, which has reasonable adaption.



Column R1 Column R2

Figure 2. Lateral force – lateral displacement curves of Priestley's specimen; experimental vs. FEM model. (a) Column R1 (b) Column R2

Ohno and Nishioka [7] carried on lateral cyclic loading on column specimen with 8Φ19 longitudinal bars and Φ9@100mm transverse reinforcement. Flexural failure happened at the ultimate limit state, where the shear span ratio for the column is 4. Flexural cracks were mostly concentrated in plastic hinge region.

The finite element model based on Ohno and Nishioka's specimen and subjected to monotonic lateral loading has developed. Figure 3 shows comparison between experimental and FE modeling results, which has reasonable agreement.

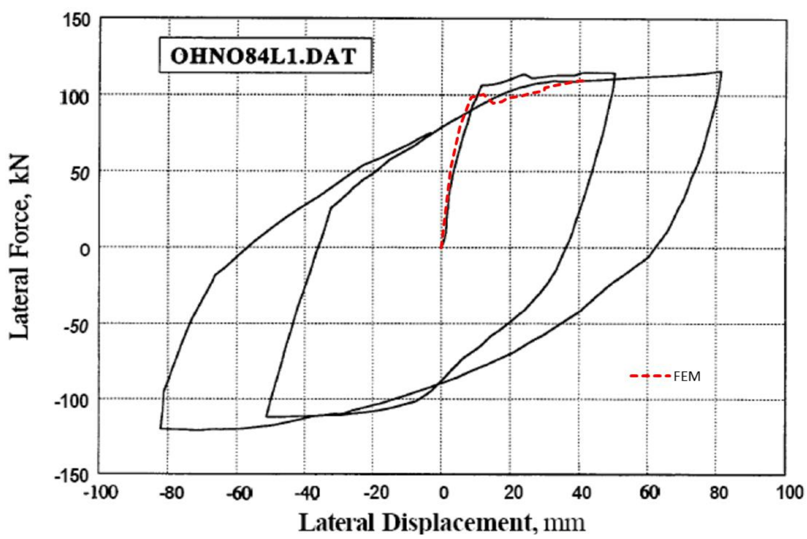


Figure 3. Lateral force – lateral displacement curves of Ohno&Nishioka's specimen; experimental vs. FEM model

Li et al. [8] conducted combined lateral cyclic and constant axial loading test on RC columns with 4D14 longitudinal bars and D8@100mm transverse reinforcement. They found that by increasing the lateral load, flexural cracks was developing. After yielding of longitudinal bars, diagonal shear cracks appeared and finally the column failed in shear. Shear span ratio for this column was 2.73. Result of finite element modeling of Li's specimen shows a reasonable estimation of lateral force capacity, as shown in Figure 4.

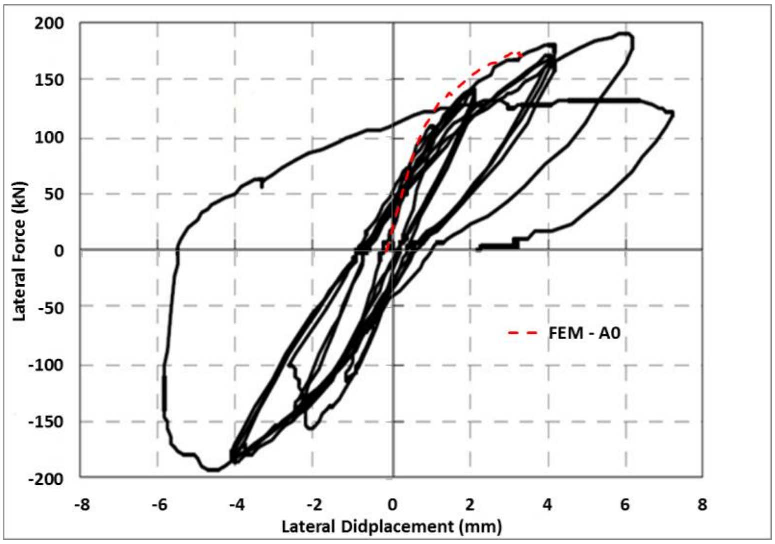


Figure 4. Lateral force – lateral displacement curves of Li et al. specimen; experimental vs. FEM model

Finite element model of RC columns subjected to axial and lateral loading has good agreement with experimental data to estimate the maximum lateral load capacity of columns; however, FEM cannot predict ultimate lateral displacement of columns. Although FE model doesn't provide any rough estimation of ductility, it can show the load carrying capacity of RC columns very well.

Factors Effect on Respond of RC Columns

As mentioned before, based on shear span to depth ratio, amount of transverse reinforcement and compressive strength of concrete, response of RC columns can be different. Other factors such as axial load ratio and reinforcing ratio have also impact on performance of RC columns. To investigate the effect of all those factors, a finite element model has developed. The model is a 72 in cantilever with square cross-section of 24 in by 24 in. Cross section of column includes 12#9 longitudinal bars with #3@12in transverse reinforcement all over the column length. Compressive strength of concrete is assumed to be 4000 psi. Yield strength of steel for both longitudinal and transverse reinforcement is considered 60000 psi. Monotonic lateral load is applied to free end of the cantilever.

Shear Span to Depth Ratio

Shear span to depth ratio is the main factor to define mode of failure in columns. Generally, mode of failure for a/d<2 is shear; while for a/d>4 flexural mode of failure dominates. For 2<a/d<4, both shear and flexural strength demands are equal and mode of failure is uncertain, which is called as flexural-shear mode of failure [9]. The experimental data show that only

63% of columns with a/d<2 failed in shear; and only 51% of columns with a/d>4 failed in flexure. Therefore, there is no certain boundaries for a/d to specify failure mode and obviously, shear span to depth ratio cannot be enough to define failure mode of columns [1].

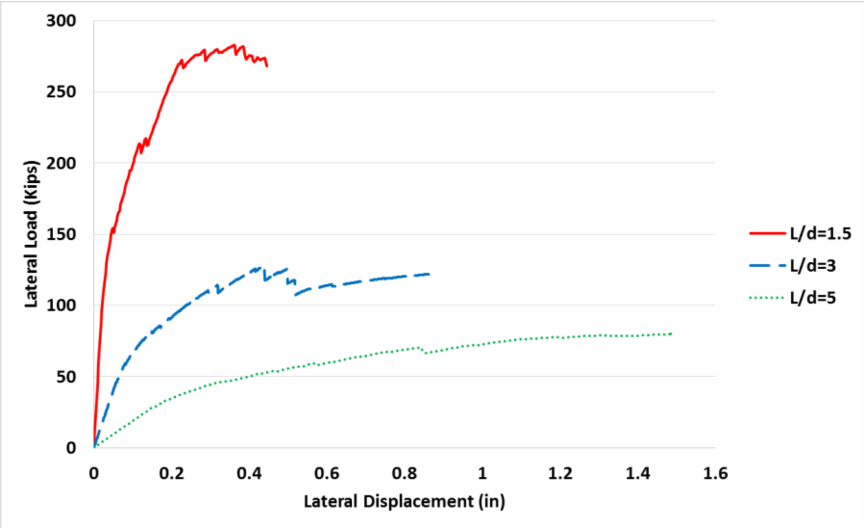


Figure 5. Effect of shear span to depth ratio on column response

The FE model developed for three columns with different lengths. The lateral force-lateral displacement curve of each column is shown in Figure 5. While lateral load-lateral displacement curve for L/d=1.5 shows a low-ductile shear failure; the corresponding curve for L/d=5 indicates the column had a ductile flexural failure. For the column with L/d=3, shear failure happened after yielding of longitudinal reinforcements, implies a flexural-shear failure. Load carrying capacity of columns increases by decreasing shear span to depth ratio; however, there is a significant reduction in ductility for columns with low L/d.

Transverse Reinforcement Ratio

Amount of shear reinforcement ratio has direct impact on shear capacity of columns. By increasing the spacing between transverse reinforcement, shear strength of column drops.

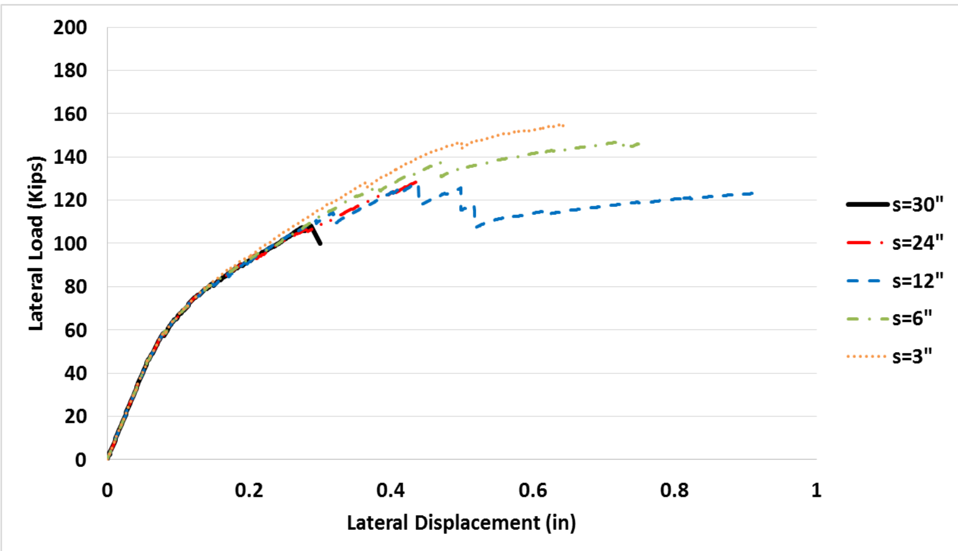


Figure 6. Effect of transverse reinforcement ratio on column response

Concrete Compressive Strength

Although compressive strength of concrete doesn't have significant effect on flexural capacity of RC members, it has substantial impact on shear strength and axial load carrying capacity of reinforced concrete sections.

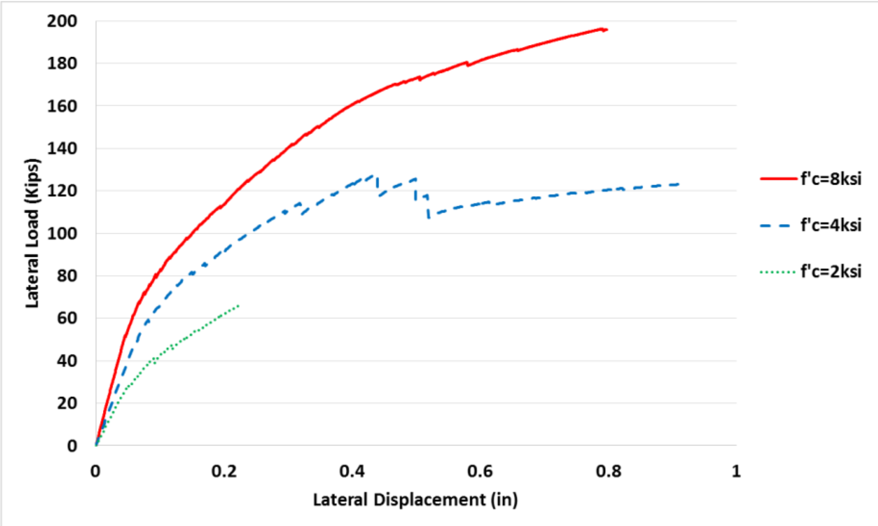


Figure 7. Effect of concrete compressive strength on column response

Figure 7 shows the effect of compressive strength of concrete on load carrying capacity of columns. Mode of failure for column with $f'_c = 8\,ksi$ is flexural, while column with $f'_c = 2\,ksi$ fails in shear. Increasing the compressive strength raises lateral load carrying capacity of columns as well as changing mode of failure from shear to flexural failure.

Axial Load Ratio

According to PM diagram of a column section, increasing axial load reduces flexural capacity of a column section at ultimate limit state, based on yielding of tensile main bars or crushing of compressive concrete. In practice, the columns are usually carry less than 20% of their pure axial load capacity (P<20%Po). Studying the nonlinear behavior of RC columns subjected to axial and lateral loading indicates that increasing axial load increases lateral load carrying capacity in general.

The difference between ductility and load carrying capacity of column with no axial load (as a beam) and a column with 10%Po is a lot; however, lateral load carrying capacity of columns with 10%Po and 20%Po is almost the same.

Longitudinal Reinforcement Ratio

Practical longitudinal reinforcement ratio for columns is 1% to 4%. Increasing the reinforcement ratio in this range raises the flexural capacity of column; however increase in shear capacity of column is insignificant. Figure 9 shows effect of longitudinal reinforcement ratio on the lateral respond of column. When the reinforcing ratio is high, the bars are more likely not to yield before reaching the shear strength demand, or yielding happens just before shear failure. Therefore, increase in reinforcing ratio increase the probability of shear failure or flexural-shear failure.

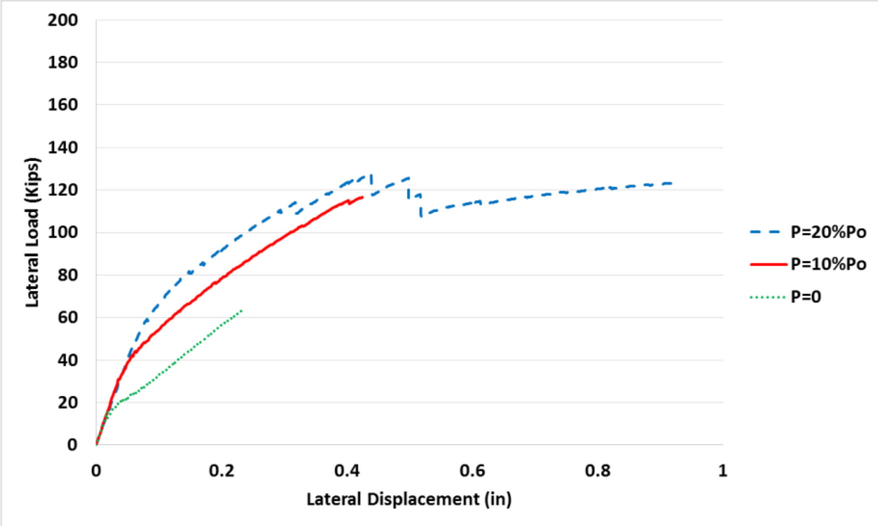


Figure 8. Effect of axial load ratio on column response

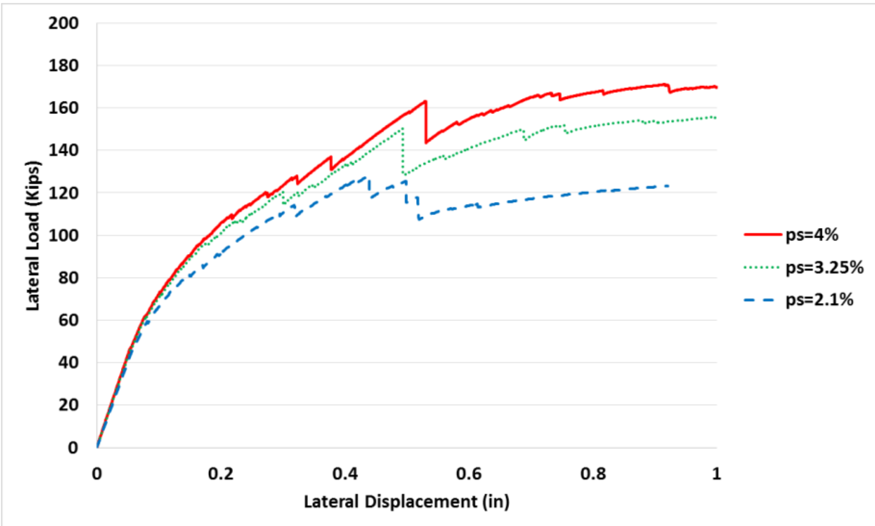


Figure 9. Effect of longitudinal reinforcement ratio on column response

Summary and Conclusion

In order to evaluate existing condition of columns, it is necessary to know mode of failure of column and the factors impact on that. Effect of different factors on response of RC columns has studied in this research. Table 1 shows the summary of FEM results. Maximum lateral load carrying capacity of columns has compared with the one at sound column.

The following conclusions can be drawn based on FE modeling results:

1. The most important factors which change the failure mode of RC columns are shear span to depth ratio, transverse reinforcing ratio and compression strength of concrete. There is no considerable impact on failure mode type due to axial load ratio and longitudinal reinforcing ratio.
2. Although decreasing shear span to depth ratio increases the load carrying capacity of column, it leads the column to fail in brittle shear mode.
3. Spacing of transverse reinforcement doesn’t affect load carrying capacity of columns, but

has a major influence on their mode of failure.
4. Concrete with high compressive strength has low ductility, but its effect on increasing the shear strength of column causes the column fails in flexure.

Table 1. Effect of different factors on maximum load carrying capacity of columns

	variable	Fmax (Kips)	Change in Fmax (%)	Mode of Failure
L/d	5	80.0	-37%	Flexural
	3	128.0	0%	Flexural-Shear
	1.5	282.9	121%	Shear
S (in)	3	155.1	21%	Flexural
	6	147.3	15%	Flexural
	12	128.0	0%	Flexural-Shear
	24	128.9	1%	Shear
	30	108.1	-16%	Shear
f'c (ksi)	2	66.3	-48%	Shear
	4	128.0	0%	Flexural-Shear
	8	196.2	53%	Flexural
P/Po (%)	0	63.1	-51%	Flexural-Shear
	10	129.4	1%	Flexural-Shear
	20	128.0	0%	Flexural-Shear
ps (%)	2.1	128.0	0%	Flexural-Shear
	3.25	155.9	22%	Flexural-Shear
	4	171.2	34%	Flexural-Shear

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