EFFECT OF LATERAL REINFORCEMENT RATIO ON STRENGTH AND DUCTILITY OF RC COLUMNS

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ABSTRACT

In this paper, effect of lateral reinforcement spacing or ratio on the cyclic behavior of reinforced concrete columns is analytically investigated. The finite element analysis (FEA) is performed using computer software VECTOR. Two types of RC columns, i.e., short and long columns were modeled with varying lateral reinforcement rations such as 6 mm bars placed at 200 mm spacing (Type-1) and 6 mm bars placed at 75 mm spacing (Type-2). The RC Columns with Type-1 reinforcement details represent the non-ductile columns that are mostly found in the buildings of Thailand. In FEA plane stress rectangular elements were used for the modeling of reinforced concrete. Smeared cracking approach was considered in concrete and steel over the element. Finite element analysis (FEA) results indicate that performance of RC short columns with Type-1 reinforcing details is very poor against lateral loading with the development of significant cracks at very low drift levels. Whereas the behavior of RC short columns with Type-2 reinforcement were observed highly improved in terms of crack pattern, fracture mode, ultimate load capacities and ductility ratio as compared with non-ductile columns. However; the increase of lateral reinforcement ratio in long columns is found not effective to enhance ductility against lateral displacement.

KEYWORDS: Finite element analysis (FEA), reinforced concrete (RC), reinforcement ratio and ductility

1. Introduction

Postearthquake reconnaissance and experimental research around the world indicate that existing building columns with poor and inadequately detailed transverse reinforcement are vulnerable to brittle failure mode during earthquake activity. Such sudden and brittle failures of column members can lead to reduction in building lateral strength, change in inelastic deformation mechanism, loss of axial load-carrying capacity, and ultimately, building collapse. Recognizing the risk posed by column failures, engineers evaluating existing buildings or designing new buildings for seismic effects [1]. Numerous experimental studies have examined the seismic shear strength and deformability of reinforced columns having inadequate and poorly detailed transverse reinforcement [2]. Hudson experimentally investigated the effect of lateral tie spacing on the ultimate strength of RC columns. In his study, sixty-four concrete columns were loaded to destruction to investigate the effects of tie spacing on ultimate strength. Variables included in the tests were column size, spacing of ties, strength of concrete, size of tie, percentage of longitudinal reinforcement, and position of load. Principal data obtained were failure loads, modes of failure, and strains [3]. Lynn reported a study of older existing building columns from the western United States. Lynn found a wide range of column proportions and details, with typical details including both 90 and 135° hooks at the end of column ties; hook extensions usually shorter than the lengths specified in current codes; 10--mm- or smaller-diameter column ties spaced at 250 mm or wider over the mid height of the column, with smaller spacing sometimes used near column ends; longitudinal reinforcement ratios ranging from 0.5 to 4.5%; longitudinal reinforcement lap splices just above the floor level with lengths ranging from 20 to 30 times the longitudinal bar diameter, d_b; specified concrete compressive strength of about 20 MPa; and specified yield strength of steel reinforcement varying between 200 and 500 MPa [4].

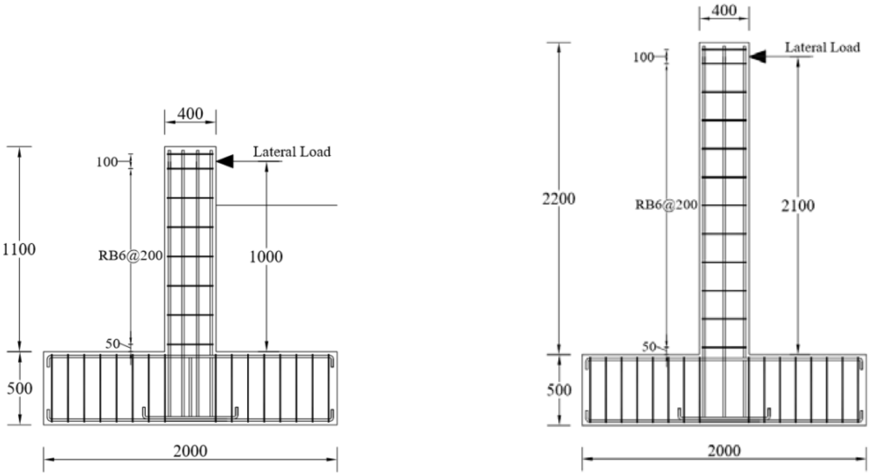
In addition to the laboratory research, several analytical studies have investigated the behavior of RC columns under different conditions such as strength of concrete, longitudinal and lateral reinforcement ratio of steel bars [5-7]. Yalcin and Saatcioglu developed a computer software for inelastic analysis of reinforced concrete columns under combined axial compression and monotonically increasing lateral loads. The software incorporates effects of concrete confinement, steel strain hardening, reinforcement buckling, and secondary deformations due to P-Delta effect. The program was verified extensively against available experimental data [8].

At present, in the regions of low to moderate seismicity such as Thailand, there are many buildings that are designed to the old codes considering only the wind and gravity loads. Majority of the RC columns that are found in these buildings have insufficient shear reinforcement and during an earthquake it may lead to the buckling of longitudinal reinforcement or even brittle shear failure in the plastic hinge region. As a result, the lateral strength of existing RC columns could significantly drop soon after the peak load is reached. Rodisn et al. experimentally investigated the behavior of non-ductile RC columns under cyclic loading. Six reinforced concrete columns 250 mm x 350 mm in cross section with a height of 2050 mm, 1570 mm and 1100 mm were tested. The experimental results showed that shear failure associated with rapid lateral strength degradation could be observed in short columns whilst long columns were failed in preferable flexure mode [9]. Shahzad et al. investigated the cyclic response of non-ductile reinforced concrete (RC) columns using a finite element (FE) software i.e. VECTOR. The specimens selected, represent the typical long, medium and short non-ductile RC columns that are mostly found in the buildings of Thailand. These RC columns were tested previously and their experimental results are used here to compare with those of the FE software. Comparisons are made between analytical and experimental results considering the default material constitutive models and behavior mechanisms of FE software to assess its accuracy in predicting the actual response of these specimens. It was found that the FE software can predict the strength, deformation response and failure mode of reinforced concrete columns with good accuracy [10]. Tahir et al. performed experimental and analytical study to investigate the seismic performance of flexure–shear dominated RC walls in moderate seismic regions. The analytical study was performed using FE software VECTOR. A good comparison between FE analysis and experimental results were observed [11]. The current study is mainly planned to investigate the effect of lateral reinforcement spacing or ratio on the cyclic behavior of RC short and long columns. In the first, non-ductile columns representative of existing construction practice in Thailand, are modeled using computer software VECTOR and their behavior is investigated. In the second step the lateral reinforcement ratio was increased in the finite element models and analysis results were compared with non-ductile columns to investigate the effect of lateral reinforcement ratio on the ultimate load carrying capacity and ductility of RC columns.

2. Finite Element Analysis

2.1 Column Specimen Details

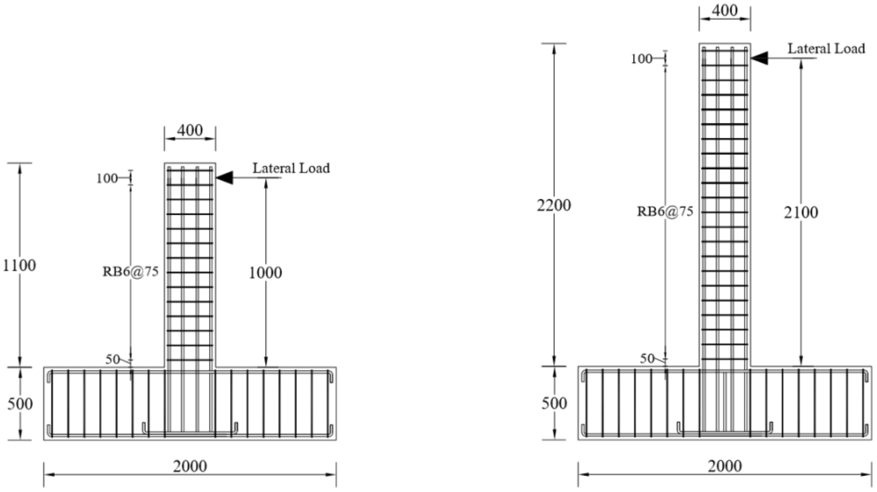
The details of reinforced column specimens are shown in the figures 1-2 and summarized in table 1. Two different aspect ratios (shear span to depth ratio σ) were used to simulate different failure modes i.e., flexure and shear failures that are associated with long column (LC) and short columns (SC), respectively. Two different kinds of lateral reinforcement details were used in this study. Type-1 columns containing lateral reinforcement details following existing practice in Thailand. In Type-2 columns, the lateral reinforcement was increased by reducing space between the lateral ties. Four reinforced concrete columns (SC-Type-1, SC-Type-2, LC-Type-1 and LC-Type-2) 400 mm x 300 mm in cross section with a height of 1100 mm and 2200 mm were modeled using computer software VECTOR. The longitudinal reinforcement ratio of 1.6% was kept constant in all columns. The lateral reinforced was provided in the form of ties of 6 mm round bars spaced at 200 mm (Type-1) and 75 mm (Type-2) as shown in the figure 2. A strong column foundation was also modeled at the base of columns to simulate the real construction practice.



(A) SC-Type-1

(B) LC-Type-1

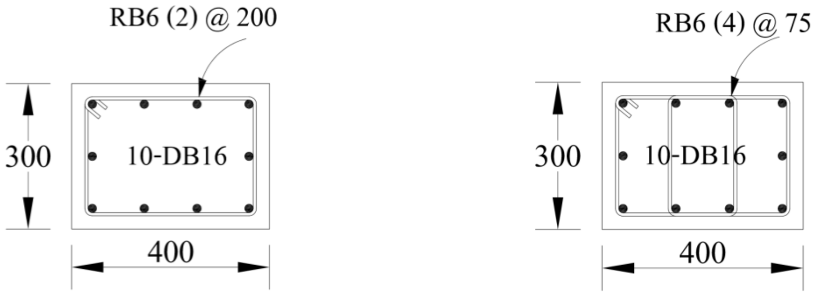
Figure 1 Column specimen details (units – mm)



(C) SC-Type-2

(D) LC-Type-2

Figure 1 **Column specimen details (units – mm) (continued)**



(C) Type-1 Lateral reinforcement

(D) Type-2 Lateral reinforcement

Figure 2 **Lateral reinforcement details (units – mm)**

Table 1 **Specimen Details**

Column	B x H x L (mm)	σ	Main bars	Lateral ties
SC-Type-1	400x300x1100	2.50	10-DB16	RB6@200 (mm)
LC-Type-1	400x300x2200	5.25	10-DB16	RB6@200 (mm)
SC-Type-2	400x300x1100	2.50	10-DB16	RB6@75 (mm)
LC-Type-2	400x300x2200	5.25	10-DB16	RB6@75 (mm)

2.2 Material Properties

In this study, target compressive strength of 30 MPa and 60 MPa was used for finite element models of columns and foundation, respectively. Deformed bars with nominal diameter of 16 mm (DB16) were used for longitudinal reinforcement. Round bars with nominal diameter of 6 mm (RB6) were used for ties. The yield strength and ultimate strength of the 16-mm-diameter deformed steel bars were 450 and 550 MPa, respectively; and the corresponding values for the 6-mm-diameter steel transverse reinforcements were 250 and 350 MPa, respectively.

2.3 Loading setup

The RC columns were subjected to reverse cyclic loading to simulate the seismic demand. The lateral loading was applied in a displacement control mode using a target percent drift of ±0.125, ±0.25, ±0.5, ±0.75, ±1.0, ±1.5, ±2.0, ±2.5, ±3.0 and so on. In lateral loading program, 2 cycles per drift level was applied. The lateral loading history is shown in the figure 3.

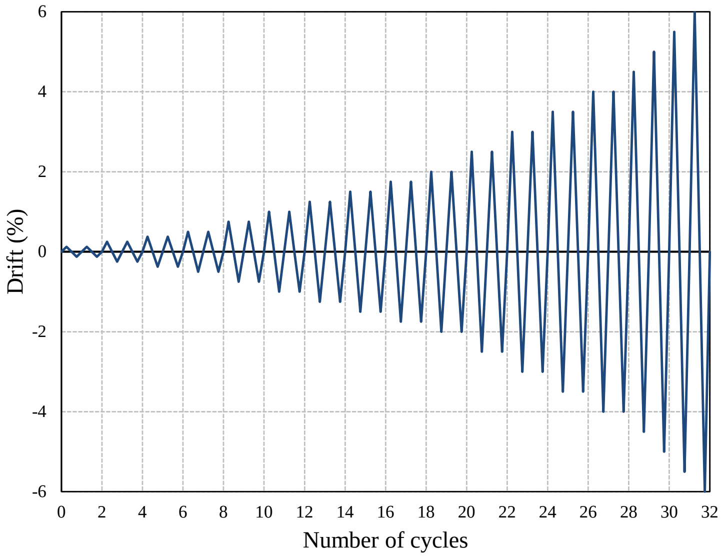


Figure 3 Loading history

2.4 VECTOR

In this study, the cyclic response of RC columns is analytically investigated using a finite element software VECTOR, which is a non-linear finite element analysis program, is based on the smeared rotating crack approach. It also considers the second order effects such as compression softening, tension stiffening, tension softening and tension splitting. It can model concrete expansion and confinement, cyclic loading and hysteresis response, bond slip, crack shear slip deformations, reinforcement buckling and crack allocation processes. It uses a fine mesh of low-powered elements of its models that are computationally efficient and numerically stable. These elements include a three-node triangle, a four-node rectangular and a four-node quadrilateral element for modeling concrete with smeared reinforcement. For discrete reinforcement, a two-node truss-bar element is used and for modeling bond-slip mechanisms a two-node link and a four-node contact element is used [12]. The finite element model is constructed in FormWorks, a pre-processor software that generates input files for VECTOR, and the results are visualized in Augustus program which is a post-processor.

2.4.1 Finite Element Models of RC Columns

The finite element mesh of RC columns was constructed in the FormWorks which is a pre-processor to computer software VECTOR. The size of mesh elements was selected as 50 x 50 mm. The finite element models of RC short and long columns are shown in figures 4 and 5, respectively.

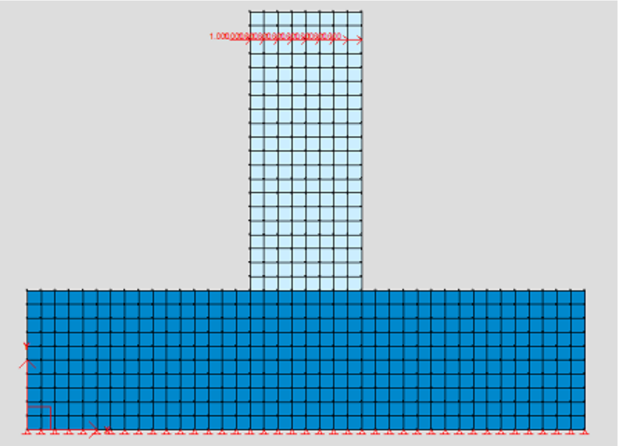


Figure 4 FEM of short Column

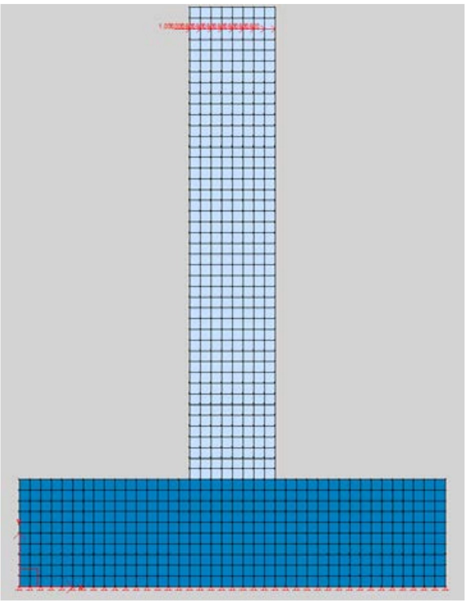


Figure 5 **FEM of long column**

2.4.2 Concrete and Steel Models

Selection of appropriate analytical models for materials and behavior mechanism is very important for the computation of actual responses. It is suggested to choose the default analytical models unless the use of some other models is justified [12]. The constitute models selected for concrete elements, reinforcing elements and concrete bonds are given in Tables 2 and 3.

Table 2 **Concrete Models used in FEA**

Property Description	Model
Compression pre-peak response	Hognested Parabola
Compression post-peak response	Modified Park Kent
Compression softening	Vecchio 1992-A (e1/e2-Form)
Tension stiffening	Modified Bentz 2003
Confined strength	Kupfer/Richard Model
Dilation	Variable-Kupfer
Cracking criterion	Mohr-Coulomb (Stress)
Crack stress calculation	Basic (DSFM/MCFT)

Table 3 Steel Models used in FEA

Property Description	Model
Hysteretic response	Seckin Model (Bauschinger)
Dowel action	Tassios Model (Crack slip)
Buckling	Refined-Dhakal Maekawa
Concrete bond	Eligehausen

The further details of the above mentioned models can be found in the manual of VECTOR [12] and other studies [13, 14].

3. Results and Discussion

The finite element analysis results in the form of lateral load versus drift ratio are graphically shown in figures 6-9. The finite element analysis results in the form of ultimate lateral load carrying capacity and ultimate drift are summarized in table 4. A detail discussion of FEA results is provided in the following sections.

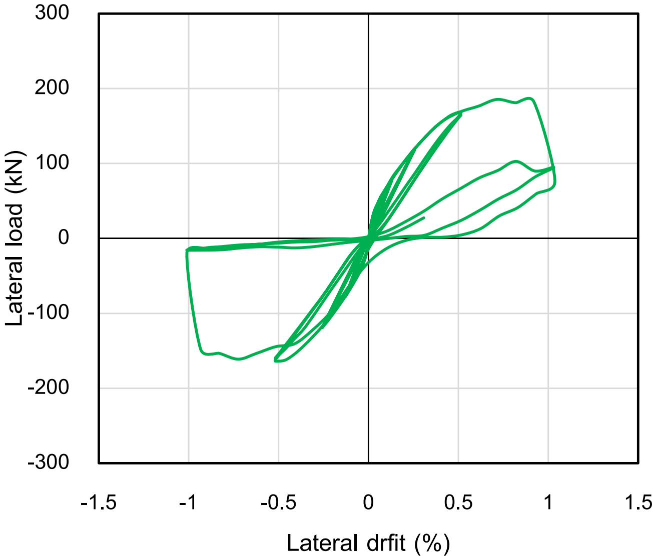


Figure 6 Lateral load vs. drift ratio response of column SC-Type-1

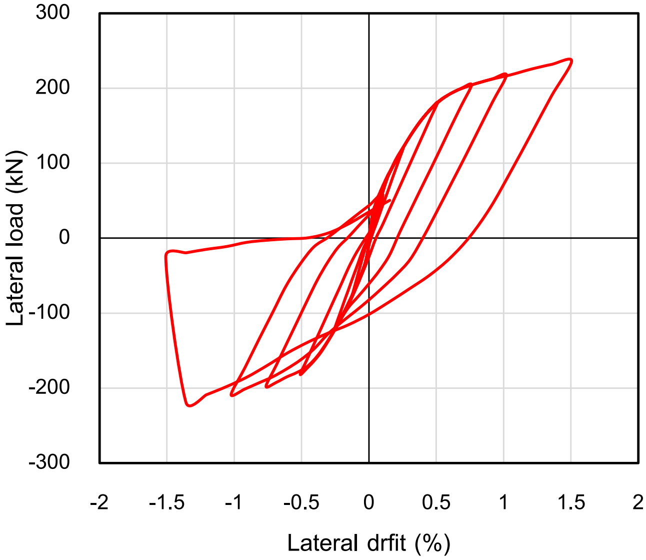


Figure 7 Lateral load vs. drift ratio response of column SC-Type-2

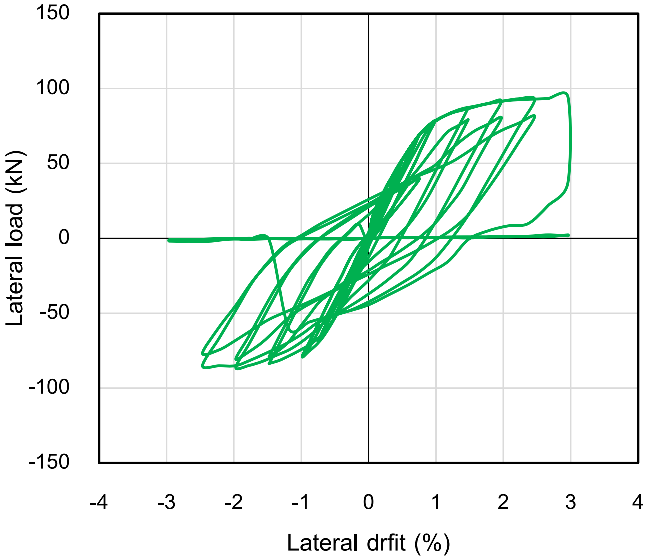


Figure 8 Lateral load vs. drift ratio response of column LC-Type-1

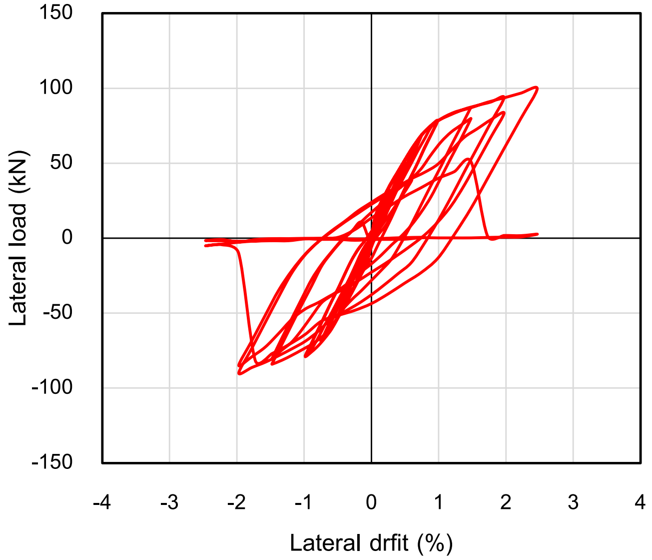


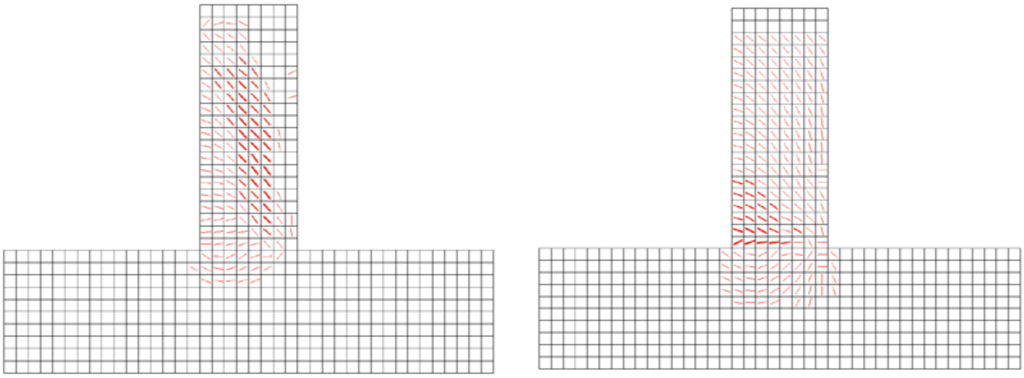
Figure 9 Lateral load vs. drift ratio response of column LC-Type-2

Table 4 Finite element test results

Column specimen	Ultimate lateral load (kN)	Ultimate lateral drift (%)
SC-Type-1	185.4	1.00
SC-Type-2	236.4	1.50
LC-Type-1	94.50	3.00
LC-Type-2	99.80	2.50

3.1 Cracking and Failure Mode

The crack pattern and final failure modes of RC columns are shown in the figures 10 and 11. The short column specimen with Type-1 lateral reinforcement was failing due to the inclined shear cracks as shown in the figures 10a and 10c. The short column specimen, i.e. SC-Type-2 with the increased amount of lateral reinforcement was failed due to flexural cracks as shown in the figures 10b and 10d, indicating yielding of longitudinal reinforcement. The final failure of the column specimen LC-Type-1 was occurring due to the combined shear and flexure cracks as shown in the figures 11a and 11c. Whereas the final failure of column specimen LC-Type-2 was due to the yielding of longitudinal steel bars as shown in figures 11b and 11d.

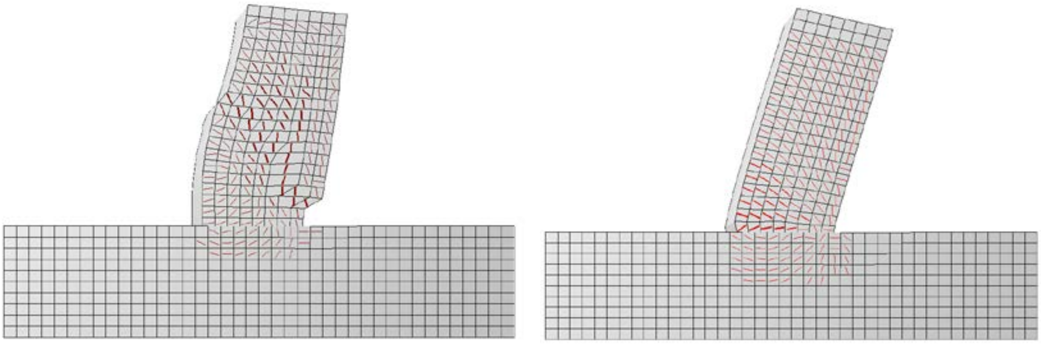


(a) Cracking pattern of SC-Type-1

(Drift = 1.0%)

(b) Cracking pattern of SC-Type-2

(Drift = 1.5%)



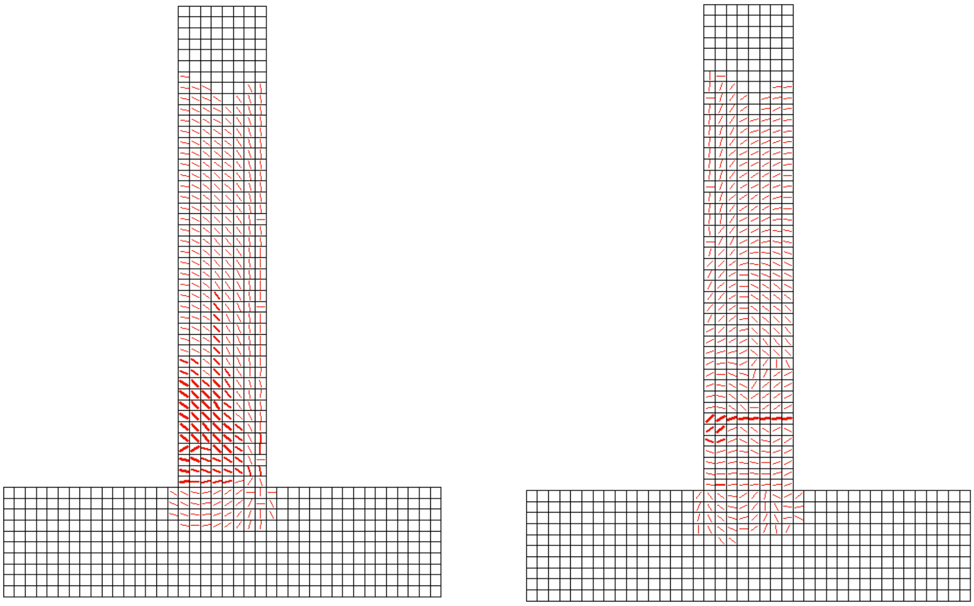
(c) Final failure SC-Type-1

(Drift = 1.0%)

(d) Final failure SC-Type-2

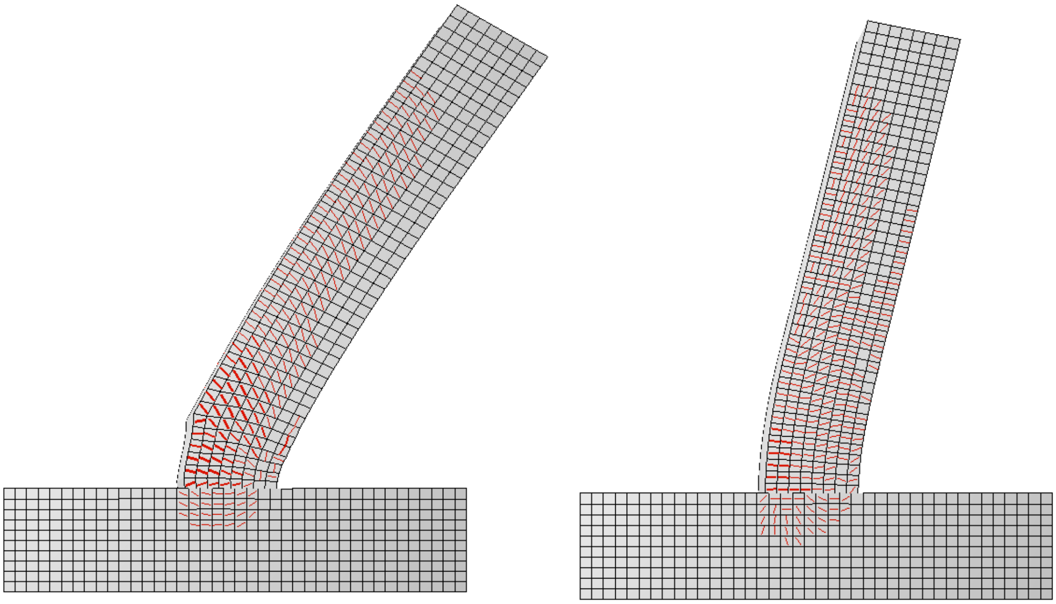
(Drift = 1.5%)

Figure 10 Cracking and final failure modes of short columns



(a) Cracking pattern of LC-Type-1
(Drift = 3.0%)

(b) Cracking pattern of LC-Type-2
(Drift = 2.5%)



(c) Final failure LC-Type-1
(Drift = 3.0%)

(d) Final failure LC-Type-2
(Drift = 2.5%)

Figure 11 Cracking and final failure modes of long columns

2.2 Ultimate load and Drift Ratio

The finite element results in the form of ultimate lateral load carrying capacity and drift ratio are summarized in table 4. By comparing column specimens SC-Type-1 and SC-Type-2, it can be seen that lateral load carrying capacity and lateral drift of column specimen SC-Type-2 increases with an increase in the lateral reinforcement ratio. The lateral load carrying capacity and lateral drift of column specimen SC-Type-2 was observed 28% and 50% higher than column specimen SC-Type-1, respectively. Similar to the short column, the lateral load carrying capacity of long column, i.e., LC-Type-2 was also increased as compared with column LC-Type-1. However the increase in lateral load carrying capacity was not significant. The ultimate lateral drift of long column LC-Type-2 is found lower than the LC-type-1. This is due the reason that higher amount of lateral reinforcement ratio in long columns may cause early yielding of the longitudinal bars prior to the crushing of the concrete. The cracking pattern of column LC-Type-2 is also validating this assumption since there were observed only flexure cracks in this column specimen as shown in the figures 11b and 11d.

4. Conclusions

In this paper, effect of lateral reinforcement spacing or ratio on the cyclic behavior of reinforced concrete columns is analytically investigated. Based on finite element analysis results following conclusions can be drawn;

1. The performance of RC short columns with Type-1 reinforcing details is found very poor against lateral loading with the development of significant cracks at very low drift levels.

2. The behavior of RC short columns with higher amount of lateral reinforcement spacing is highly improved in terms of lateral load carrying capacity, lateral drift and cracking pattern.

3. The increase of lateral reinforcement ratio is found less or not effective to enhance lateral load carrying capacity and lateral drift. This is mainly due to the reason that failure of long columns is associated with the yielding of longitudinal bars. Hence an increase in lateral reinforcement ration is increasing the confinement of the concrete and earlier yielding of the longitudinal steel bars.

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