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A case study of reinforced concrete short column under earthquake using experimental and theoretical investigations

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Abstract. The purpose of this paper is to carry out both experimental and theoretical investigations of R.C. short column subjected to horizontal forces under constant compressive loading. Eight specimens with section of 40 cm × 40 cm, height 40 cm and 50 cm and different type hoop were used of the steel cage to detect the seismic behavior of reinforced concrete short columns. Hoop spacing of column, strength of concrete, and the axial load of experiments were the three main parameters in this test. A series of equations were derived to reveal the theory could be used on analysis short column, too. Through test failure model of R.C short column being established, the type of hoop affects the behavior R.C short column in ductility rather than in strength. And the effect of analysis by Truss Model is evident and reliable in shear failure model of short column.

Keywords: short column; reinforced concrete; truss model.

1. Introduction

Short column is an element of a construction of a building. Because of it is a partial structure of a building that it has to contain seismic resistant capacity under earthquake. Some of the damage will reveal even pre-reveal before main damage coming (Morshed and Kazemi 2005). From the inspection of hazard of buildings in earthquake area of Ray-Lie and Chi-Chi in Taiwan (Koike *et al.* 2007, Lei and Chien 2009, Kung *et al.* 2009, Chang and Taboada 2009), with the failure performance of short columns of the building inclined even collapsed. From Fig. 1 and Fig. 2 reveal the serious damage and typical failure mode of short columns of the buildings. To reinforce R.C short column is a good way to retrofit and strengthen original building to promote its bearing

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capacity under earthquake (Morshed and Kazemi 2005, Kazemi and Morshed 2005).

To strengthen short column in some research had discussed concerning about the effect of confining steel in tie column, Tegos and Penelis (1988) had found to set inclined arrangement of main reinforcement is one of the most effective ways to improve the seismic resistance of reinforced concrete (R/C) short column. A proposal of strengthening the R/C short column by setting steel square tube around short column besides the inclined bars in column were suggested by Kenji and Yoshimura (1992). In the mean time, Masataka and Nakazawa (1992) developed a new multi-type hoop instead of conventional hoop to reinforce the concrete column and a good performance of column ductility was found with its economic efficiency. Actually, the feasible performance in working of a structure is important the same as the structural mechanism that Sheikh (1989) had indicated that in a series research. The use of 90 deg hooks may provided sufficient restrain to the middle bars up to a certain stage of loading, but at large deformation the 90 deg hoop tend to open, and the restrain provided to the bars becomes ineffective resulting in a loss of confinement. And the ductile of confined concrete columns depends significantly on the level of axial load and lateral support provided to the longitudinal bars (Shamim and Shafik 1997). The purpose of this paper is to carry out both experimental and theoretical investigations of R.C. short column subjected to horizontal forces under constant compressive loading with different type of hoops. Eight specimens with column section of 40 cm × 40 cm, height 40 cm and 50 cm were used to detect the seismic behavior of reinforced concrete short columns. Hoop spacing of column, strength of concrete, and the axial load of experiments were the three main parameters in this test. A series of equations were derived to reveal the theory could be used on analysis short column, too.

In this paper experimental research not only investigated the relation between loading and drift, but also resolved test results to accommodate with the predict results from the theory. The theoretical researches, besides applying constitutive laws of concrete and rebar, inclined crack model and softening model approaches to solve shear failure of short column was proposed. By the way the strength of concrete, the hoop spacing of column and height of a specimen to affect the short column was confirmed. After the failure model of R.C short column being established, school buildings and residential buildings near Chi-Chi earthquake area may take as a sample to check the effect on aseismatic buildings in retrofitting.

Fig. 1 The failure of a short column earthquake

Fig. 2 The typical failure mode of under Chi-Chi short column

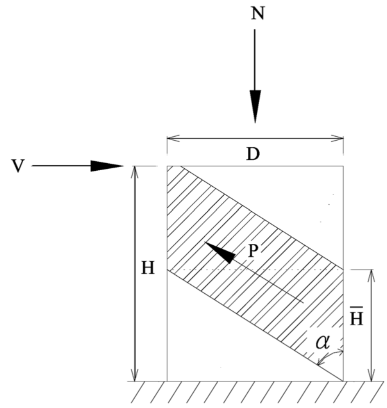

Fig. 3 Truss model philosophy of short column

2. Analytical formula for short columns

By truss model to analyze shear failure element was used early in 1929 (Mo and Rothert 1929). The fundamental theory is assumed cracking happened at the edge of a short column with the inclined angle α. The cracking made a strut element and maintained equilibrium with the subjected axial force N, shear force V and longitudinal bar forces. In Fig. 3 reveals the geometrical relation of a short column. The concrete strut stress σ_d which following Kent and Park Modified model (1971) (Eq. (1)~) and strut inclined angle α will be found with the equilibrium equation. Owing to the cracking of concrete that it should be modified by a coefficient $1/\lambda$. In the mean time, the strain of longitudinal reinforcement will be transformed into the strain of concrete. Then the force (f_l) of reinforcement will be calculated. In another, from the strain compatibility in deformation of the element the strain of reinforcement and principle compressive strain (ε_d) of concrete will be established. From above the force equilibrium, constitutive law of material and compatibility of deformation made the truss model established. Finally, lateral shear force and shear deformation can be found from relative equations (Eqs. (19)-(22)). The main equations are derived as followed.

For equilibrium condition

$$P = N \cdot \cos\alpha + V \cdot \sin\alpha + f_l \cdot \rho_l \cdot B \cdot D \cdot \cos\alpha \tag{1}$$

$$\alpha = \tan^{-1}\frac{D}{\overline{H}} \tag{2}$$

$$\sigma_d = \frac{P}{B \cdot \overline{H} \cdot \sin\alpha} \tag{3}$$

if $\varepsilon_d \leq \varepsilon_0 \Rightarrow$

$$\sigma_d = K \cdot f_c' \cdot \frac{1}{\lambda} \cdot \left[2 \cdot \frac{\varepsilon_d}{K \cdot \varepsilon_0} - \left(\frac{\varepsilon_d}{\varepsilon_0}\right)^2\right] \tag{4}$$

$$\overline{H} = A_1 \cdot H \tag{5}$$

$$\text{if} \quad \varepsilon_d > \varepsilon_0 \Rightarrow \quad \sigma_d = K \cdot f_c' \cdot \frac{1}{\lambda} - (\varepsilon_d - \varepsilon_0 \cdot K) \cdot Z_c \cdot \frac{1}{\lambda} \tag{6}$$

$$\overline{H} = A_2 \cdot H \tag{7}$$

$$K = 1 + \rho_t \cdot \frac{f_{ty}}{f_c'} \tag{8}$$

$$\varepsilon_{50u} = \frac{0.211 + 0.002 \cdot f_c'}{f_c' - 70.37} \tag{9}$$

$$\varepsilon_{50h} = 0.75 \cdot \rho_t \cdot \sqrt{\frac{b}{S}} \tag{10}$$

$$Z_c = \frac{0.5 \cdot f_c'}{\varepsilon_{50u} + \varepsilon_{50h} - \varepsilon_0 \cdot K} \tag{11}$$

$$\lambda = \frac{1}{\cos\alpha} \tag{12}$$

$$\text{if} \quad \varepsilon_l \le \varepsilon_0 \Rightarrow \quad f_l = E_s \cdot \varepsilon_l \tag{13}$$

$$\text{if} \quad \varepsilon_l > \varepsilon_0 \Rightarrow f_l = f_{ly} \tag{14}$$

$$\frac{\gamma}{2} = (\varepsilon_l + \varepsilon_d)\cot\alpha \tag{15}$$

$$\frac{\gamma}{2} = (\varepsilon_t + \varepsilon_d)\tan\alpha$$

ε_t: strain of transverse steel

set $\varepsilon_t = 0$ for rigid foundation (16)

$$\varepsilon_l = (\tan^2\alpha - 1) \cdot \varepsilon_d \tag{17}$$

$$\gamma = 2 \cdot \varepsilon_d \cdot \tan\alpha \tag{18}$$

(a) When $\varepsilon_d \le \varepsilon_0$ ($\varepsilon_0 = 0.002$)

from Eq. (3), Eq. (4), Eq. (5), Eq. (13), Eq. (17) and Eq. (1) the shear force equation was derived as

$$V = K \cdot f_c' \cdot \frac{1}{\lambda} \cdot \left[2 \cdot \frac{\varepsilon_d}{\varepsilon_0} - \left(\frac{\varepsilon_d}{\varepsilon_0}\right)^2\right] \cdot A_1 \cdot B \cdot H - N \cdot \cot\alpha - \rho_l \cdot E_s \cdot (\tan\alpha - \cot\alpha)\varepsilon_d \cdot B \cdot D \tag{19}$$

and the lateral drift equation was derived as

$$\Delta = \eta_1 \cdot \gamma \cdot H - C \tag{20}$$

η_1: coefficient for shear drift before yielding of concrete.

Fig. 4 Test result of STR1

Fig. 5 Test result of SCR2

(b) When $\varepsilon_d > \varepsilon_0$

from Eq. (3), Eq. (6), Eq. (7), Eq. (14) and Eq. (1) shear force equation was derived as

$$V = [K \cdot f_c' - (\varepsilon_d - \varepsilon_0 \cdot K) \cdot Z_c] \cdot \frac{1}{\lambda} \cdot A_2 \cdot B \cdot H - N \cdot \cot\alpha - \rho_l \cdot f_{ly} \cdot B \cdot D \cdot \cot\alpha \tag{21}$$

and lateral drift equation was derived as

$$\Delta = \eta_2 \cdot \gamma \cdot H - C \tag{22}$$

η_2: coefficient for shear drift after yielding of concrete.

3. Specimens and test programs

The specimens represented a portion of a short column. Fig. 6, illustrates the specimen section. A summary of test specimens and properties are presented in Table 1. Longitudinal reinforcement arrangement was identical in all columns. Twelve #5 (ϕ = 15.9 mm) deformed bars were symmetrically placed inside perimeter ties. The test specimens had the same cross-sectional dimensions of 40 cm × 40 cm, with height L = 50 cm and 40 cm for the shear failure type test of short columns. The main variables were the ratio of transverse reinforcement and the level of axial load.

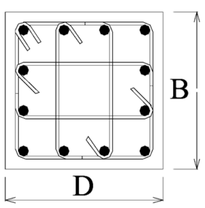

Fig. 6 Section of specimen

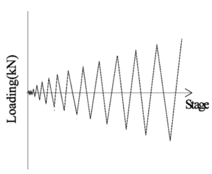

Fig. 7 Reversal cyclic loading history of test

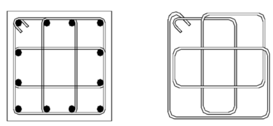

Fig. 8 Conventional, closed-type hoops of specimen

Table 1 Column size, reinforcement arrangement and test results of specimens

Specimen	Column size (cm)	Hoop spacing (cm)	f_c' (mpa)	f_y (mpa)	Axial Load (kN)	ρ_l	ρ_t
STM1	50	10	23.52	383	329.28	0.015	0.021
STM2	50	10	17.64	383	329.28	0.015	0.014
SCM1	50	10	20.48	383	329.28	0.015	0.021
SCM2	50	10	17.64	383	329.28	0.015	0.014
STR1	40	15	23.52	383	588.00	0.015	0.014
STR2	40	15	25.84	383	588.00	0.015	0.008
SCR1	40	15	23.52	383	588.00	0.015	0.014
SCR2	40	15	23.52	383	588.00	0.015	0.008

Note: The 1st word of specimen name S: short column, the 2nd word T: Hoop and tie in conventional type, C: closed type hoop and tie, the 3rd word M (or R): lateral loading in monotonic type (repeat cyclic loading), and the 4th word: number of specimen.

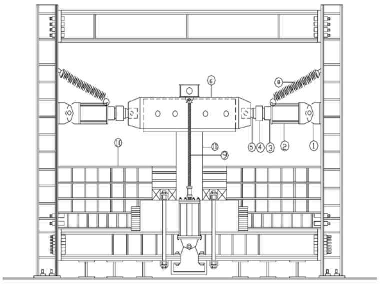

Fig. 9 Instrument of testing setup

With different spacing of hoops being arranged in different specimens, different goal of RC columns were designed and tested. Two kinds hoops of conventional and closed type hoop were arranged in specimens these type as Fig. 8. Table 1 shows these different characteristics of specimens.

Four calibrated load cells, two for lateral loading and two for axial loading, were used to monitor and record applied lateral forces and axial load. Seven potentiometers were mounted on each side of the column parallel to the loading direction to measure vertical, horizontal, and diagonal deformations of the specimen and thus to evaluate the shear and flexural deformation modes. A schematic drawing of the test setup is shown in Fig. 9. The specimen was mounted vertically with the bottom of the RC foundation resting on a steel foundation. The end of column was loaded by a hydraulic jack and controlled to provide a constant axial force varying from 329.28 kN to 588 kN (i.e., about $0.1f_c'A_g$ to $0.2f_c'A_g$). The column was subjected to reversal cyclic loading by an actuator that was horizontally mounted to a steel rigid frame. Each specimen was instrumented with loaded cells, displacement transducers, creep bond gauges, and strain gauges to monitor the behavior of the specimen during testing. And the cracking trails of specimens during test were drawn at each testing step.

The specimens were tested under force control. After the constant axial loading 329.28 kN or

588 kN then horizontally monotonous loading were added increasingly on specimens STM and SCM. In another, the horizontally force after the constant axial loading was increased as repeat cyclic loading test on specimens STR and SCR. The horizontal force subjected to specimens was increased by 50 kN for every cycle after the first 3 cycles with 30 kN. The loading routine, shown in Fig. 9, consists of cycles with column back and forward just as under seismic loading. Fig. 4 and Fig. 5 show the test records and trail of tests.

4. Test results and discussion

The diagonal-tension cracking trail of specimen STR1 is shown in Fig. 4. and Fig. 5 of SCR2 shown the same. Diagonal cracking failure mode is the typical structure seismic behavior under earthquake of short column was revealed. From Fig. 10, Fig. 11, Fig. 12 and Fig. 13 reveal the curve of test results and theoretical analysis results being consistent. Fig. 14 to Fig. 17 show the hysterisis loop of specimen under repeat cyclic loading and the primary curve of those specimens.

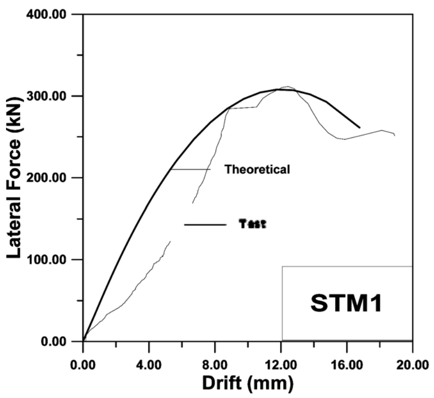

Fig. 10 Curve of test result and analysis result of STM1

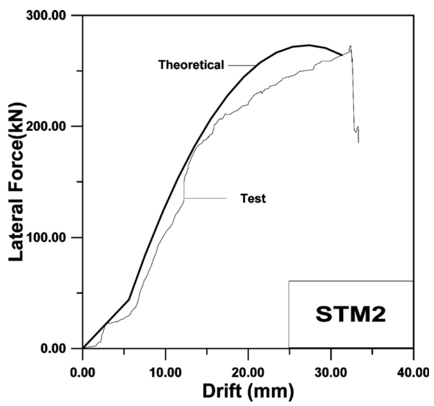

Fig. 11 Curve of test result and analysis result of STM2

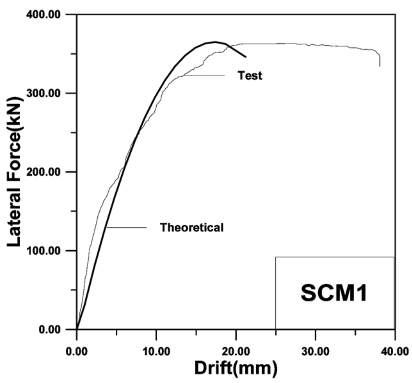

Fig. 12 Curve of test result and analysis result of SCM1

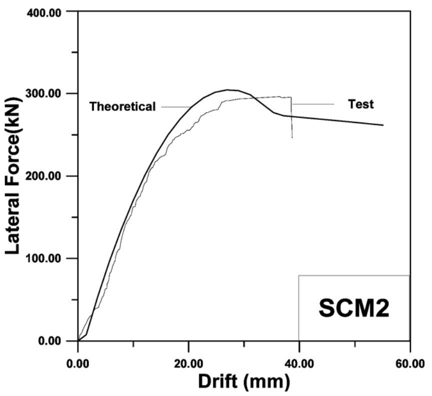

Fig. 13 Curve of test result and analysis result of SCM2

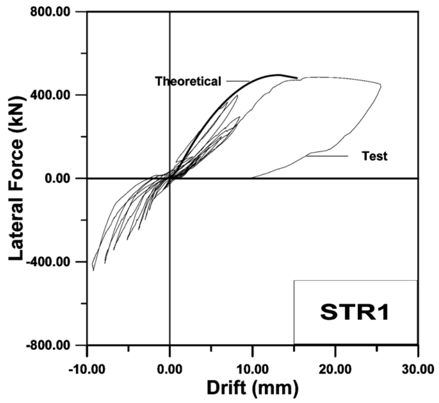

Fig. 14 Curve of test result and analysis result of STR1

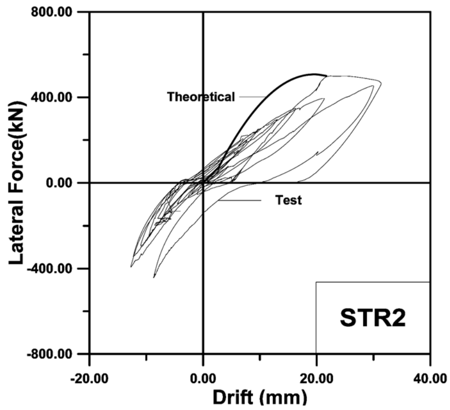

Fig. 15 Curve of test result and analysis result of STR2

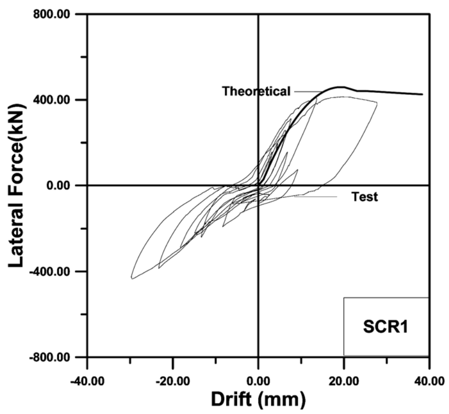

Fig. 16 Curve of test result and analysis result of SCR1

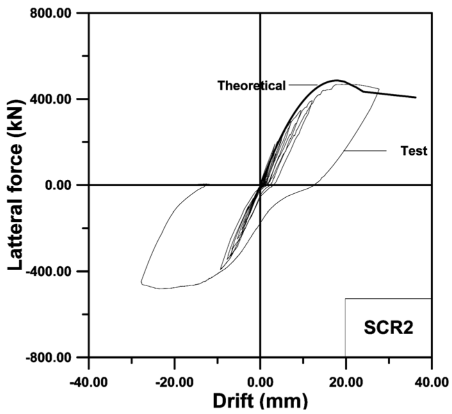

Fig. 17 Curve of test result and analysis result of SCR2

Table 2 Relative coefficient of short column specimens in analysis by truss model

Specimen	A_1	A_2	η_1	η_2	C	H/D	Test		Analysis	
							V_u (kN)	Δu (mm)	V_u (kN)	Δu (mm)
STM1	0.478	$0.65A_1$	6	4	2.5	1.25	300.76	18.90	307.921	16.767
STM2	0.525	$0.79A_1$	13	10	2.5	1.25	273.03	33.33	273.146	35.291
SCM1	0.506	$0.75A_1$	8	6	3	1.25	362.89	56.88	364.9	39.52
SCM2	0.53	$0.81A_1$	14	11	5	1.25	296.45	57.60	304.53	35.314
STR1	0.665	$0.87A_1$	8	7	2.5	1.0	485.59	25.5	495.389	15.350
STR2	0.659	$0.88A_1$	12	10	2.5	1.0	501.47	31.33	506.623	24.593
SCR1	0.659	$0.86A_1$	12	10	4	1.0	453.84	31.41	458.76	38.27
SCR2	0.675	$0.90A_1$	12	10	4	1.0	481.08	15.06	485.72	36.168

From table1 two pairs specimens STM2, SCM2 and STR1, SCR1 are in the same quality but in different type of hoop. Then the results are different. The test results reveal the specimen (ratio of height to width equal 1.25) with closed type hoop are better in resistant force and lateral drift then conventional hoop specimen. But the superiorities only in the lateral drift of specimen ratio of height to width equal 1. From Table 2 the data obtained from analysis revealed that value of A_1 in the range of 0.47~0.67 should be appropriate to fit the theoretical analysis and obtained good results and which is related with two parameters: concrete stress f_c' and ratio of height to width (H/D) of specimen. Effective height factor A_1 will decrease with f_c', so that the higher strength of concrete, the effective area of shear resistant area smaller. Shear resistant efficiency is higher with the lower ratio of height to width (H/D) of specimen. When in the yielding range the ratio of A_2 to A_1 is increased with the value of A_1 and the value of A_2 is approach the value of A_1 during the ratio of height to width (H/D) being smaller. This reveals that the model will be evident when the ratio of height to width of specimen is small. With the increasing of compressive strength of concrete the drift of specimen is decreasing, so the deformation factor value of η will adopt to be decreasing. Coefficient C is caused by axial load before lateral load subjected on specimen that it should be eliminated in the final of analysis. For calculating, in this study value 2.5 is suggested to fit all specimens.

5. Conclusions

Some conclusions were summary as following from this study:

1. Shear failure model was shown of short column by test and its result curve of lateral shear force to drift of specimen is in agreement with the result from theoretical analysis.
2. The promotion of strength of specimens with closed type is evident only when the concrete compression strength less than 17.64 Mpa, but exceed the stress formal structure behavior isn't evident.
3. Specimens with closed type hoop revealed better resistance in lateral drift than with conventional hoop type.
4. The effect of analysis by Truss Model is evident and reliable in shear failure model of short column.
5. The effective shear resistant coefficient A and drift coefficient η of predict equation had to be found easily and affirmatively that the predict equation could be used widely.

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