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SEISMIC PERFORMANCE OF REINFORCED CONCRETE COLUMNS WITH 90 DEGREE END HOOKS FOR SHEAR REINFORCEMENT UNDER HIGH SPEED LOADING

Shigeru HAKUTO[1]

SUMMARY

In order to investigate the seismic assessment procedures of existing reinforced concrete frames with poorly detailed reinforcement, five 5/9 scale reinforced concrete columns with reinforcement details typical of concrete buildings designed before 1971 were constructed and tested under high speed loading. Three columns have the shear reinforcement with 90 degree end hooks and their seismic performance were compared with those with 135 degree end hooks. The seismic behaviour of the columns with plain round bars for the reinforcement were also compared with those with deformed bars. As the results, the test units with deformed bars for the longitudinal reinforcement failed in shear after the flexural strengths were reached while those with plain round bars did not show shear faiure up to the end of testing. It was found that the 90 degree end hooks were pulled out of the longitudinal bars under the large inelastic displacement while shear reinforcement without hooks fractured. It was also demonstrated that when using the plain round bars for shear reinforcement, the 135 degree end hooks with the extension of 6 times the bar diameter were also ineffective when compared with the same anchorage configuration using deformed bars.

1. INTRODUCTION

The Hyogo-ken Nanbu Earthquake of 17 January 1995 damaged a large number of reinforced concrete buildings. According to the observation and assessments by the Reconnaissance Team of Architecural Institute of Japan, most of the buildings damaged were designed to old seismic codes, especially prior to 1971. This is mainly due to the lack of the capacity design concepts and good detailing procedures. The collapse of buildings by the Hyogo-ken Nanbu Earthquake was mainly caused by column shear failure due to the inadequate amount of shear reinforcement. It was also pointed out that another reason was the use of the poorly detailed reiforcement, that is 90 degree end hooks for shear reinforcement[Park 1995], which is commonly used for the concrete buildings designed before 1971.

The experimental study focused on the 90 degree end hooks for shear reinforcement was carried out under static seismic loading by Kameda and Ogura[Kameda 1986], and Ohno and Miyamoto[Ohno 1998]. Ohno et al. concluded that the effects of the configuration of the end hooks for shear reinforcement on the seismic behaviour of concrete columns were shown under the large inelastic displecement. However, the effects of the end hook configuration have not yet been fully clarified under the seismic loading. The seismic assessment procedures regarding the end hook configuration should be established.

In this study, the effects of the configuration of the end hooks for shear reinforcement were investigated on the five 5/9 scale reinforced concrete columns under high speed loading. The seismic behaviour of the columns with plain round bars for the reinforcement, which was commonly used for the reinforcement of the old concrete buildings, were also compared with those with deformed bars.

[1] Institute of Technology, Tokyu Construction Company, Sagamihara-City, Kanagawa, JAPAN
Email:hakuto@hd.tokyu-cnst.co.jp

2. TEST UNITS

Table 1 lists the summary of the test units. Fiv 5/9 scale reinforced concrete columns with reinforcement details typical of concrete buildings designed before 1971 were constructed. All test units had the column cross section of 500mm square and 1600mm height. For Units 1 and 2, the plain round longitudinal reinforcement(12-R22) was used, while the deformed longitudinal reinforcement(12-D22) was used for Units 3, 4 and 5. Plain round bars of 8mm diameter were used for the column hoops except that deformed bars of 6mm diameter were used for Unit 5. All test units contained the same quantities of both longitudinal reinforcement and hoops.

Figure 1 shows the column sections and reinforcing details of Unit 1. The 90 degree hooks at the ends of hoops for Units 1, 2 and 3 had a straight extension at the tail of the hooks of length $4d_b$, where d_b is the bar diameter. The 135 degree hooks at the ends of hoops for Units 4 and 5 had a straight extension at the tail of the hooks of length $6d_b$, as illustrated in Figure 1.

Units 1 and 2 were identical test units. Unit 1 was tested under static loading while Unit2 was under high speed loading(dynamic loading) , as shown inTable 1.

The measured compressive strengths of concrete cylinders and yield strengths of longitudinal reinforcement and hoops were shown in Table 1. Those strengths were obtained from static loading test.

3. METHOD OF LOADING

Figure 1 illustrates the test set-up. The test units were tied down to the reaction floor Horizontal load was applied at the 1000mm height of the column using a servo-controlled actuator which can apply the loading by the maximum velocity of 500mm/sec, which was connected to the reaction wall. Axial load of 441kN(axial load stress was 1.77MPa) was applied to the end of the column and was controlled to be constant during the test by an actuator. All the test units except Unit 1 were tested under high speed horizontal loading, as shown in Table 1. Figure 2 shows the loading sequence. The test units were subjected to half cycle of loading to R=-0.5% and then to that of loading to R=+10%, where R is the drift ratio calculated by /H where is the horizontal displacement

Table 1:Summary of test units and material strengths.

Unit No.	Main Bars f_y (MPa)	Hoops f_{yh} (MPa)	End Hook Configuration of Hoops	Extension at the Tail of Hoops	Loading Method	Concrete Strength f'_c (MPa)
1	12-R22 303	2-R8@100 390	90 degree	$4d_b$	Static	32.8
2	12-R22 303	2-R8@100 390	90 degree	$4d_b$	Dynamic	30.9
3	12-D22 383	2-R8@100 390	90 degree	$4d_b$	Dynamic	27.6
4	12-D22 383	2-R8@100 390	135 degree	$6d_b$	Dynamic	26.4
5	12-D22 379	2-D6@64 355	135 degree	$6d_b$	Dynamic	30.7

Note : f'_c =compressive strength of 100mm dia. concrete cylinder under static loading

f'_y , f_{yh} =yield strength of reinforcement under static loading

d_b=hoop diameter

at the loading point and H(=1000mm) is the the height of the loading point. During the loading to R=10% for the high speed loading tests, the horizontal loading was controlled so that it took about 0.3 second from the -0.5% drift ratio to the +10% drift ratio, as shown in Figure 2, and the maximum loading velocity was up to be 300mm/sec during this loading.

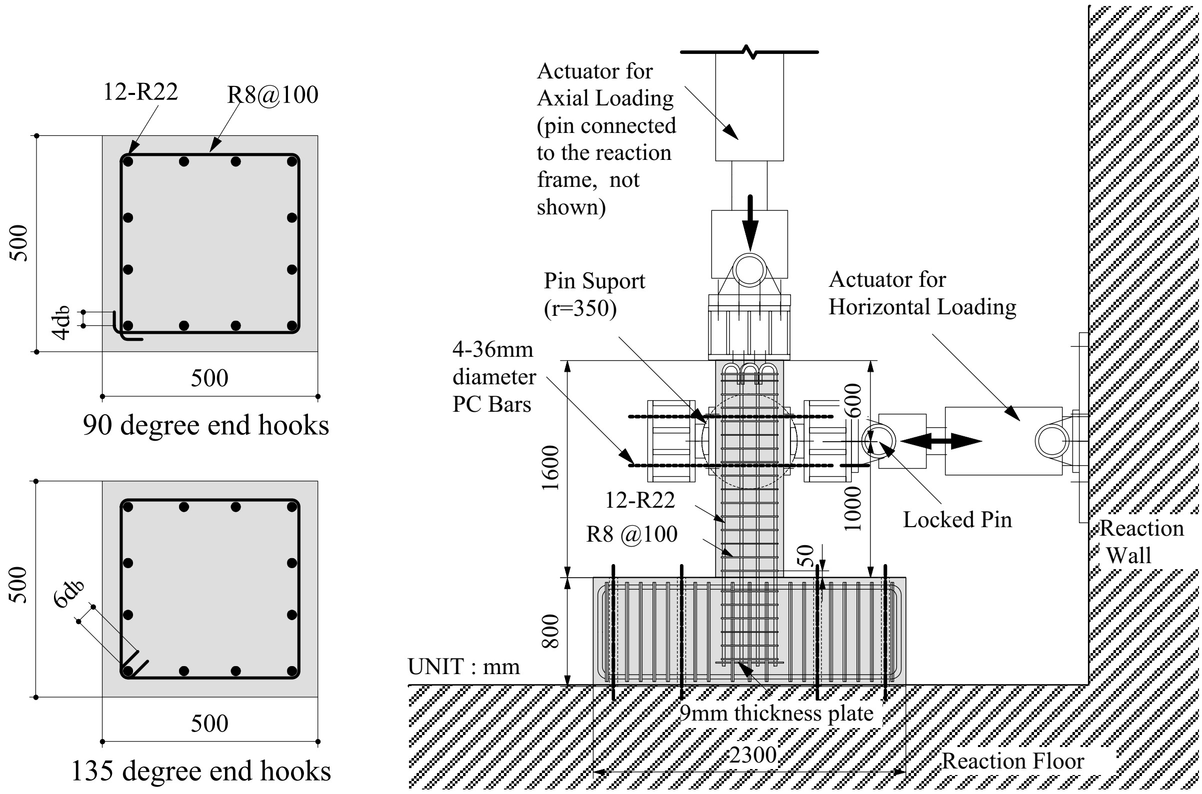


Figure 1:Column sections and Unit 1 as tested

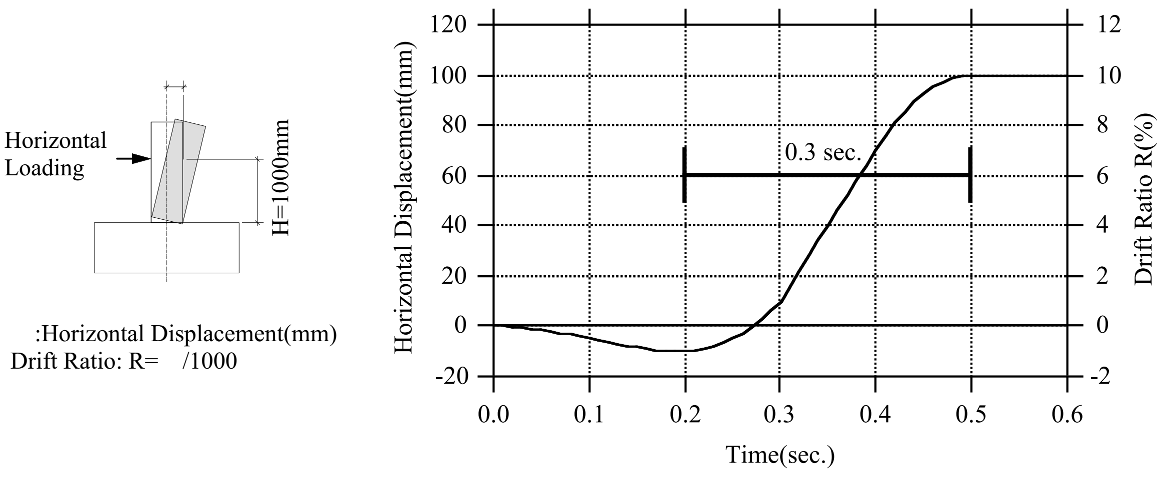


Figure 2:Loading sequence

4. TEST RESULTS

4.1 Shear Force and Horizontal Displacement Relationships and Failure Mode:

Figure 3 shows the test units after testing. The relationships between the shear force applied to the column and the horizontal displacement at the loading point for the test units are also shown in Figure 3. The calculated flexural strengths, V_{mu} obtained by using an equivalent rectangular stress block assuming the maximum compressive strain of concrete to be 0.003 and the shear strengths, V_{su} calculated by AIJ metod[AIJ 1990] are plotted in this figure. The shear force was calculated by including the P- effects due to the column axial load and in the case of high speed loaging tests, inertia force induced by the loading rig on the top of the column was removed from the horizontal forces. Table 2 lists the test results and the calculated strengths as mentioned above.

During the both loading directions, all test units reached the calculated flexural strengths. The measured maximum strength of Unit 1 tested under static loading was almost the same as the calculaed flexural strength. On the other hand, the test units tested under high speed loading showed about 20% increase in strength shortly after the calculated flexural strengths were reached. This is mainly due to the strain rate effects.

For Units 1 and 2 using the plain round longitudinal reinforcement, the flexural cracks developed at the column base opened wide and the concrete crushing at the critical section became more evident as the horizontal displacement was increased. Diagonal shear cracks were not observed for Unit 1 during the test, while those cracks were developed for Unit 2 only under the loading to R=-0.5%, as shown in Figures 3(a) and (b). The seismic behaviour for Units 1 and 2 was mainly dominated by the fixed-end rotation due to pre-mature bond detarioration along the longitudinal reinforcement and the strengths decreased more gradually when compared with the test units using the deformed longitudinal reinforcement, as shown in Figure 3. When the maximum drfit ratio, R_u was defined as the maximum drift ratio without 20% decrease in the measured maximum strength, the maximum drift ratios for Units 1 and 2 were larger than 5%, as shown in Table 2. For Units 3, 4 and 5 using the deformed longitudinal reinforcement, diagonal shear cracks developed under both loading directions. After the calculated flexural strengths were developed, those shear cracks opened wide and the strengths decreased

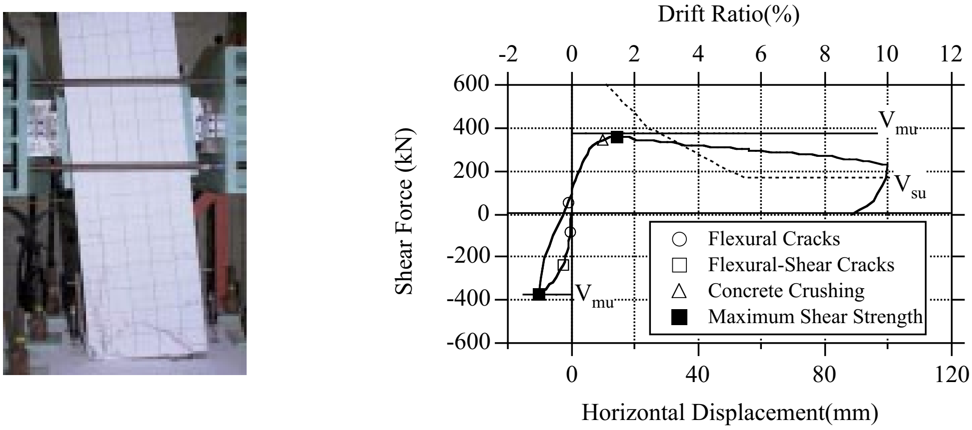
Table 2:Summary of test results.

Unit No.	Calculated Flexural Strength V_{mu} (kN)	Calculated Shear Strength V_{su} (kN) [V_{su}/V_{mu}]	Measured Maximum Strength V_{max} (kN)	V_{max}/V_{mu}	Failure Mode	Measured Maximum Drift Ratio R_u (%)
1	371	696	-369	0.99	Flexure	6.00
		[1.88]	361	0.97		
2	365	649	-377	1.03	Flexure	5.19
		[1.78]	448	1.23		
3	431	624	-424	0.98	Shear after main bar yielding	3.21
		[1.45]	526	1.22		
4	428	609	-440	1.03	Shear after main bar yielding	3.57
		[1.42]	512	1.20		
5	434	643	-466	1.07	Shear after main bar yielding	5.56
		[1.48]	531	1.22		

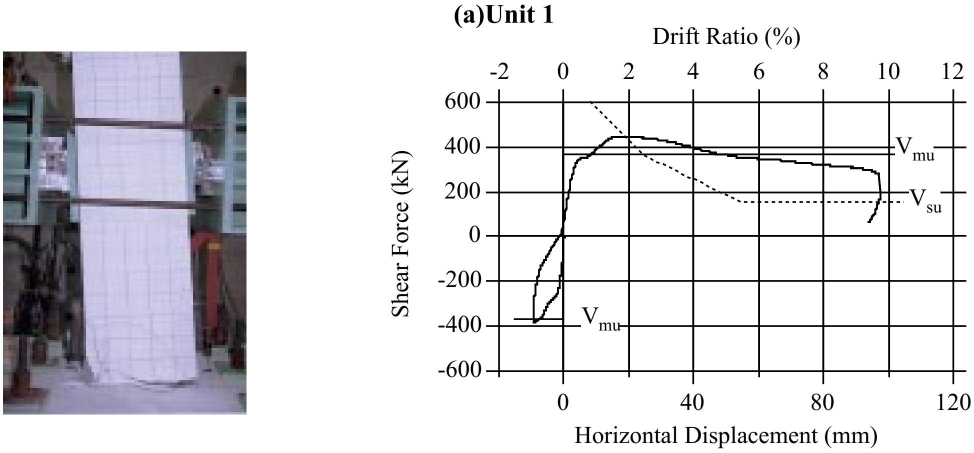
Note : V_{mu} =flexural strength using an equivalent rectangular stress block assuming the maximum compressive strain of concrete to be 0.003

V_{su} =shear strength using AIJ approach

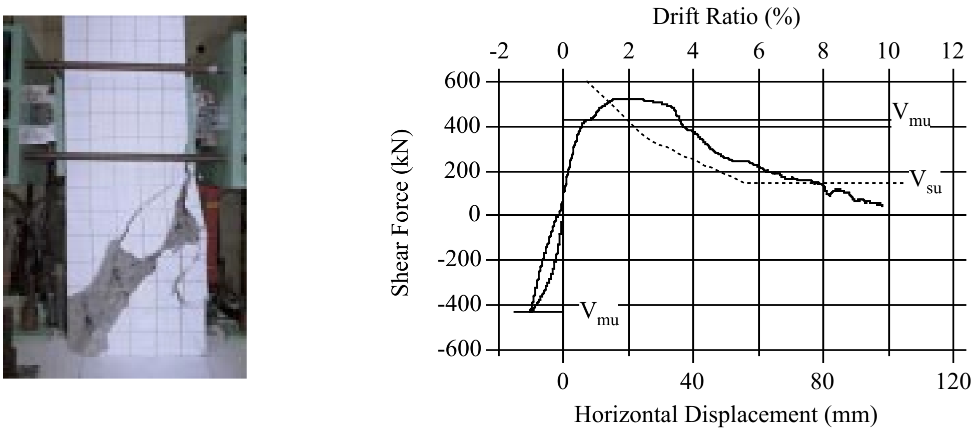
R_u =maximum drift ratio without 20% decrease in the measured maximum strength



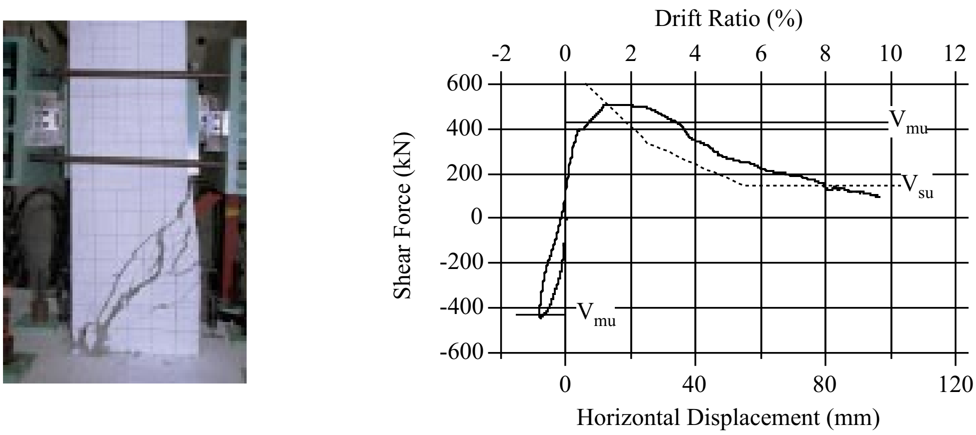
(a)Unit 1



(b)Unit 2

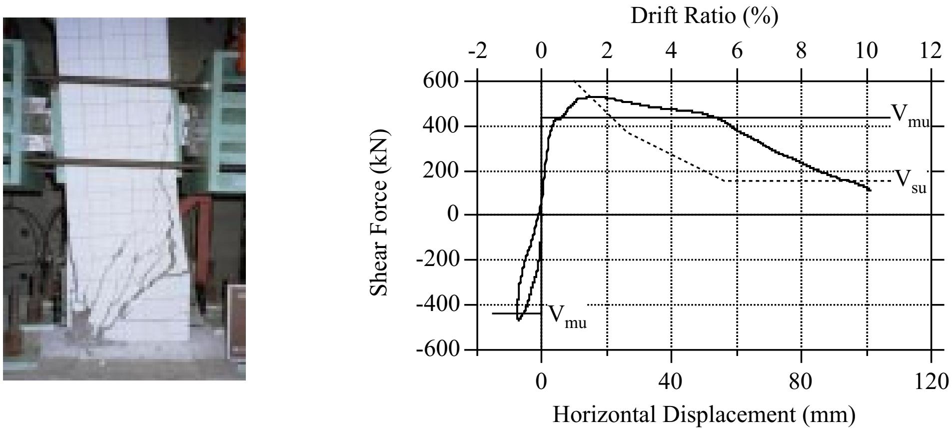


(c)Unit 3



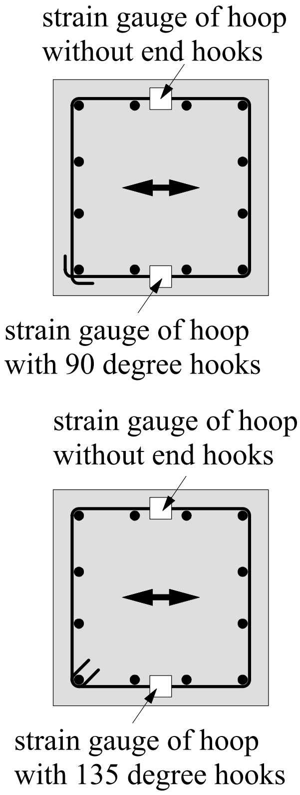
(d)Unit 4

Figure 3 :Units after testing and relationships between shear force and drift ratio.

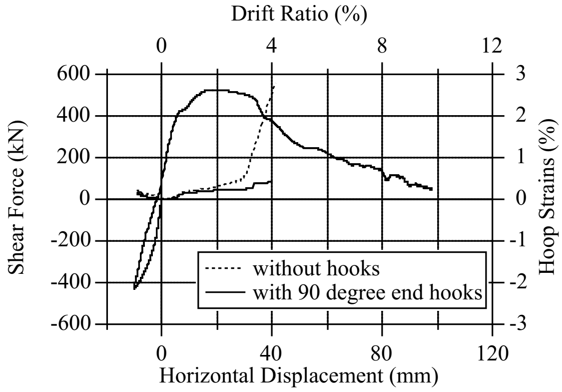


(e)Unit 5

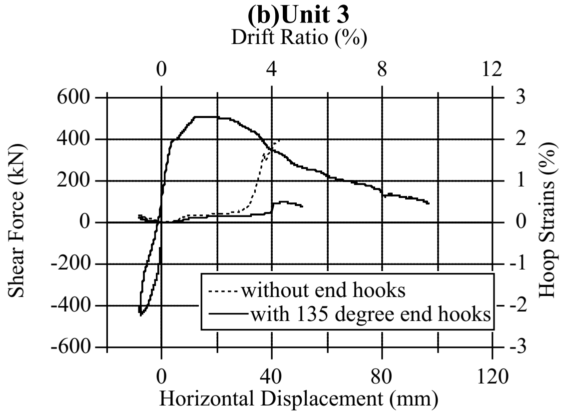
Figure 3 :Units after testing and relationships between shear force and drift ratio(continued).



(a)Strain gauge positions

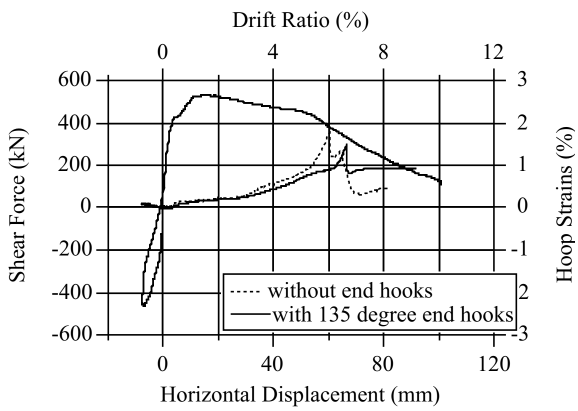


(b)Unit 3



(c)Unit 4

(e) 90 degree end hooks after testing



(d)Unit 5

Figure 4 : 90 degree end hooks after testing and relationships between hoop strains and drift ratio.

significantly as shown in Figures 3(c) and (d), indicating the shear failure. For Units 3 and 4 using the plain round bars for shear reinforcement, the configuration of the end hooks did not affect the seinmic behaviour significantly. When compared Unit 4 with Unit 5 using deformed bars for shear reinforcement, however, the decrease in strength was more evident for Unit 4. This indicates that when using the plain round bars for shear reinforcement, the 135 degree end hooks with the extension of 6 times the bar diameter were also ineffective when compared with the same anchorage configuration using deformed bars.

4.2 Hoop Strains:
Figure 4 shows the relationships between the shear force and hoop strains. The shear force and horizontal displacement relationships were also plotted in this figure.

For Units 3 and 4 using the plain round bars for shear reinforcement, the strains measured at the hoop with and without end hooks showed almost the same tensile strain up to the drift ratio of 2%. As shown in Figures 4(b) and (c), however, shortly after the shear strength began to decrease, only the strains at the hoop wihtout hooks increased significantly and fractured at the end of testing, independent of the end hook configurations. Figure 4(e) shows the 90 degree end hooks of Unit 3, which pulled out of the longitudinal reinforcement after testing. For Unit 5 using deformed bars for shear reinforcement, the tensile strains at the hoop with and without end hooks increased alomost the same manner up to the drift ratio of 5%, as illustrated in Figure 4(d). It should be recommended that the effects of shear reinforcement using the 90 degree end hooks and/or plain round bars with the extension of 6 times bar diameter should be reduced to be half since the reinforcement with end hooks were ineffective for shear reinforcement under the large inelastic displacement, when compared with the effects of the deformed shear reinforcement with the 135 degree standard end hooks.

5. CONCLUSIONS

1. The seimic behaviour of the columns with plain round longitudinal reinforcement was quite different from those with deformed longitudinal reinforcement. The columns with deformed bars for the longitudinal reinforcement failed in shear after the flexural strengths were reached while those with plain round bars did not show shear faiure up to the end of the testing since the seismic behaviour was largely governed by the fixed-end rotation due to premature bond deterioration along the longitudinal reinforcement.
2.The maximum flexural strengths of the columns under high speed loading were increased by about 20% due to the effect of strain rate when compared with those under static loading.
3When assessing the shear strength of the columns using the 90 degree end hooks and/or plain round bars with the extension of 6 times bar diameter for shear reinforcement, the amount of shear reinforcement should be reduced to be half since the reinforcement with end hooks were ineffective for shear reinforcement under the large inelastic displacement.

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