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Ductility Enhancement of Moderately Confined Concrete Tied Columns with Hook-Clips

by Panitan Lukkunaprasit and Chadchart Sittipunt

An experimental investigation of the effectiveness of hook-clips in improving the performance of conventional 90-degree hook-ties and crossties in moderately confined reinforced concrete (RC) tied columns is described. The tie configurations provided in the five large-scale specimens tested included 90-degree hook-ties and crossties, with and without hook-clips, and 135-degree hook-ties. The columns were subjected to moderate levels of compression and cyclic lateral loads. The hook-clips were found to be effective in improving the performance of concrete columns confined with 90-degree hook-ties and crossties, resulting in the displacement ductility factor and energy dissipation capacity to be increased by approximately 85 and 400%, respectively.

Keywords: ductility; hook; reinforced concrete.

INTRODUCTION

Although extensive studies of reinforced concrete (RC) columns confined with 135-degree hook-ties have been carried out,[1-6] little work has focused on the performance of 90-degree hook-ties, in spite of the fact that crossties with a 135-degree hook at one end and a 90-degree hook at the other are permitted by the ACI Code,[7] even in areas of high seismic risk. Razvi and Saatcioglu[8] tested two specimens with 90-degree hook-ties, and the results indicated that they were inferior to columns confined by 135-degree hooks at axial strains in excess of approximately 0.015. Sheikh and Yeh[9] investigated the behavior of tied columns with different reinforcement and tie configurations under medium to high axial load levels and flexure. Crossties with 90-degree hooks were reported to result in brittle failure and to be harmful rather than beneficial, especially at high axial loads. Lynn et al.[10] tested eight full-scale reinforced concrete columns having details widely used before the mid-1970s in the U.S. and including 90-degree hook-tie details among others. Cyclic load-displacement curves were obtained for light and moderate level axial loads. The poor performance of 90-degree hook-ties was evident, leading to rapid loss of gravity load resistance. Wehbe, Saiidi, and Sanders[11] tested four RC tied columns bound by 135-degree hook peripheral ties and crossties with moderate confinement. In all specimens, it was observed that opening of the 90-degree crosstie hooks initiated failure, leading to buckling of the outer longitudinal bars. Subsequently, the 135-degree hooks also started to open up.

The deficiency of 90-degree hook-ties in columns was witnessed in past earthquakes in bridges, RC buildings, and steel-reinforced concrete structures.[12-14] Despite their poor performance, 90-degree hook-ties are still used extensively worldwide in low to moderate seismic risk regions because of the ease of their placement compared with the 135-degree hooks. Ninety-degree hook-ties are even more appealing in developing countries where laying of reinforcing bars is commonly not practiced to a high level of precision, making it extremely difficult to put 135-degree hook-ties in place when the vertical bars are misaligned. Recently, Lukkunaprasit[15] introduced a simple device called a hook-clip to be clipped onto the conventional 90-degree hook-ties or crossties at the sites. Experimental tests on axially loaded short columns revealed that the performance of RC tied columns with 90-degree hooks and hook-clips was comparable to that of columns with 135-degree hook-ties.

RESEARCH SIGNIFICANCE

In view of the importance of vertical load resistance members, it is essential to have ductility in columns to ensure vertical load resistance, even in zones with low to moderate seismic risk. Enhancement of the performance of 90-degree hook-tied columns would contribute to reduced damage due to earthquakes in such seismic risk regions. Furthermore, while numerous test data exist on RC tied columns with ductile detailing for areas of high seismicity, there is a paucity of test results for lower ductility demand suitable for moderate seismic risk regions. The experimental results from this study would form a valuable addition to the database of RC tied columns under cyclic loading. The effectiveness of hook-clips in improving the performance of conventional 90-degree hook-ties and crossties in columns for a moderate level of ductility was investigated. Enhancement in displacement ductility and energy dissipation capacity was also examined.

HOOK-CLIP

To prevent premature opening of 90-degree hooks, a supplementary tie or hook-clip has been devised that is to be embedded in the concrete core with its hooks holding the legs of the ties. The clip resists opening of the 90-degree hook after loss of the concrete cover. Figure 1(a) shows the details of the clip proposed for binding 9 mm-diameter ties or smaller. The hook-clip may be employed to clip the legs of any peripheral tie or crosstie with 90-degree hooks (refer to Fig. 1(b)). With the clips prefabricated, they can be applied easily at the site without any welding.

EXPERIMENTAL PROGRAM

Test specimens

Five column specimens, 400 x 400 mm in cross section and 1500 mm in height, served as test specimens. Each test unit was reinforced with 16 longitudinal deformed bars of 20 mm (DB20) nominal diameter. Transverse reinforcement consisted of 9 mm-diameter peripheral ties and crossties,

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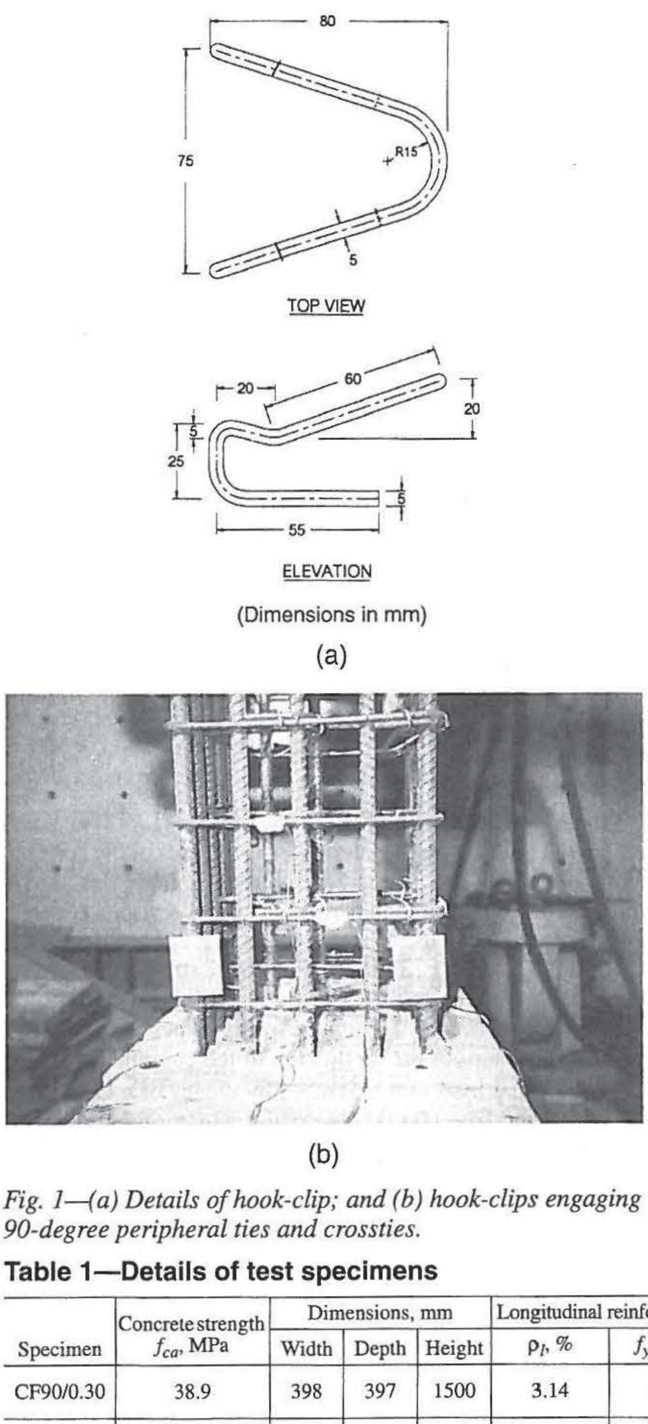

Fig. 1—(a) Details of hook-clip; and (b) hook-clips engaging 90-degree peripheral ties and crossties.

with consecutive crossties alternated end for end along the axis of the column. The ties were supplied with either 90- or 135-degree hooks, depending on specimens. Each hook had an inside radius of twice the tie diameter and an extension of six bar diameters, but not less than 60 mm. The reinforcement detailing was in accordance with the nonseismic detailing provisions in the ACI Code.[7] Figure 2 depicts a typical column cross section, and Table 1 lists the relevant data of the test specimens.

It should be noted that a relatively large bar size (namely, 20 mm diameter) was used for the longitudinal reinforcement so that when the bars buckled, a large outward thrust would be exerted on the ties, which would, in turn, try to pull the hook-clips out of the confined core. The tie spacing provided (120 mm) was smaller than that stipulated by the ACI Code for nonseismic detailing, which allows as much as 300 mm for the specimens tested. The closer spacing was chosen in view of the higher demand on the ties in providing lateral restraint for the longitudinal bars when buckled in shorter unsupported lengths. Consequently, a higher demand was also imposed on the hook-clips to prevent the ties from opening. Nevertheless, as can be seen in Table 2, the lateral reinforcement provided, A_{sh}, was only 39 to 52% of the minimum amount required by ACI in areas of high seismicity.

Special care was taken to achieve the following tolerances in construction: cross-sectional dimensions ±1%; column height ±1%; tie dimensions in the critical region ±1.2%; tie spacing in the critical region ±3%; widths and lengths of hook-clips ±3%; and verticality of specimen ±1/500.

Material properties

All specimens were made of normal-strength materials. Normalweight concrete with a maximum aggregate size of 20 mm was used. The concrete compressive strengths of the

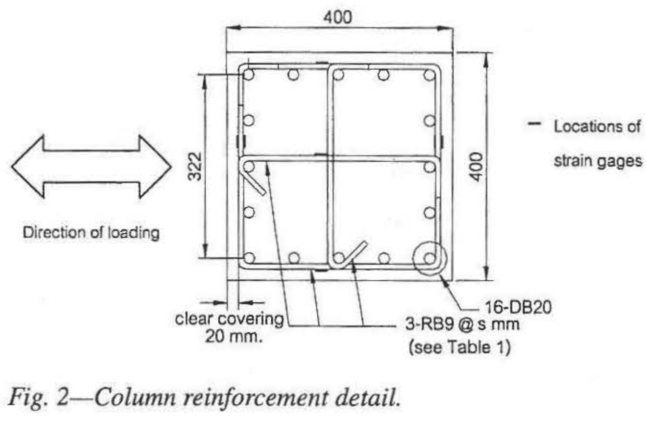

Fig. 2—Column reinforcement detail.

Table 1—Details of test specimens

Specimen	Concrete strength f_{ca}, MPa	Dimensions, mm			Longitudinal reinforcement		Transverse reinforcement				Hook configuration	$P/f_{ca}A_g$
		Width	Depth	Height	ρ_l, %	f_y, MPa	Diameter, mm	s, mm	f_{yh}, MPa	A_{sh}/sh_c, %		
CF90/0.30	38.9	398	397	1500	3.14	471	9	120	305	0.453	90 degrees + ACI crossties; no clips	0.30
CF135/0.30	35.7	398	396	1490	3.14	471	9	120	305	0.453	135 degrees + ACI crossties; no clips	0.30
CFL90/0.30	31.7	398	398	1500	3.14	471	9	120	306	0.453	90 degrees + ACI crossties with clips	0.30
CF135/0.37	30.5	399	397	1500	3.14	475	9	120	318	0.453	135 degrees + ACI crossties; no clips	0.37
CFL90/0.37	32.4	398	397	1500	3.14	471	9	120	297	0.453	90 degrees + ACI crossties with clips	0.37

Note: ρ_l = longitudinal reinforcement ratio; s = center-to-center spacing between sets of ties; h_c = cross-sectional dimension of column core measured center-to-center of confining reinforcement; P = axial load; and A_g = gross area of column section.

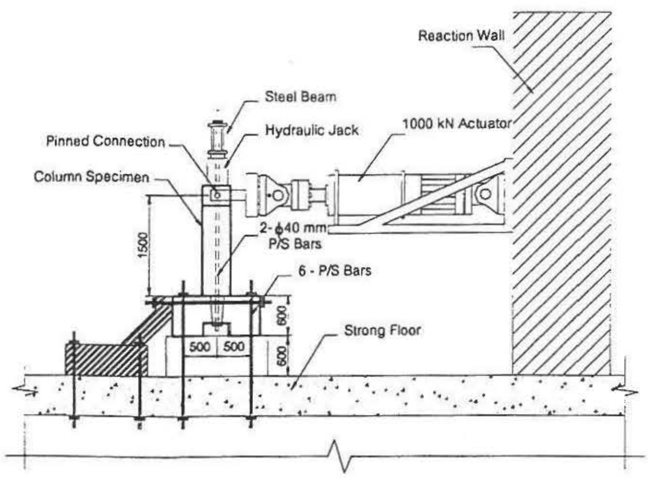

Fig. 3—Test setup.

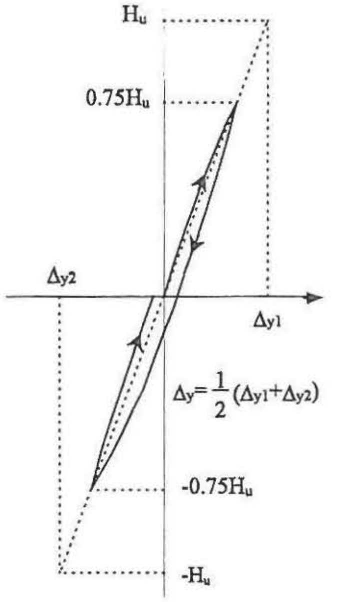

Fig. 4—Definition of first-yield displacement (after Watson and Park[5]).

standard concrete cylinders on the day of testing, f_{ca}, were in the range of 30.5 to 38.9 MPa.

The reinforcing steel used consisted of deformed bars with an average yield strength f_y of 472 MPa for longitudinal reinforcement and smooth round bars with yield strengths, f_{yh}, in the range of 297 to 318 MPa for transverse steel. The average modulus of elasticity of the reinforcing bars was 212,000 MPa. The clips were fabricated from 5 mm-diameter mild steel bars whose yield strength and modulus of elasticity were 450 MPa and 204,500 MPa, respectively.

It should be noted that, except for the slight variation in concrete strengths (approximately 15% from the mean value) and the hook configurations, all specimens were basically the same in physical properties. Specimens CF90/0.30, CF135/0.30, and CFL90/0.30 were designed to investigate the ductility performance of conventional 90-, 135-, and 90-degree hooks with hook-clips, respectively. The label 0.30 designates an axial stress level of $0.30f_{ca}$ (based on gross cross-sectional area). The performance of hook-clips was reconfirmed with another set of specimens, CFL90/0.37 and CF135/0.37, which were compressed to a higher axial stress level of $0.37f_{ca}$.

Table 2—Lateral reinforcement ratio in comparison with ACI Code[7] (seismic design)

Specimen	$P/f_{ca}A_g$	Lateral reinforcement ratio $A_{sh}/(sh_c)$ Provided	ACI Code	$A_{sh}/A_{sh,ACI}$
CF90/0.30	0.30	0.0045	0.0115	0.39
CF135/0.30	0.30	0.0045	0.0105	0.43
CFL90/0.30	0.30	0.0045	0.0093	0.49
CF135/0.37	0.37	0.0045	0.0086	0.52
CFL90/0.37	0.37	0.0045	0.0098	0.46

Note: $A_{sh,ACI}$ = minimum total cross-sectional area of rectangular hoops and crossties as specified by ACI Code.[7]

Test setup

Figure 3 shows the schematic diagram of the test setup. The column footing was tied down to a strong floor by six high-strength steel bars post-tensioned to a total force of 3000 kN. In addition, a strut-and-tie system was employed to further provide lateral restraint to the foundation to minimize its displacement. The axial load on each specimen was applied by means of a hydraulic jack bearing against the column top and a load transfer girder sitting on top of the jack. The reaction from the loading jack was resisted by two Ø40 mm high-strength steel bars that tied the transfer girder to the foundation. A calibrated 1000 kN hydraulic actuator was employed to supply the cyclic lateral force, which was applied through a shaft placed in an embedded sleeve near the top of the column. Although the specimens were set up with extra care to minimize the eccentricity of the lateral force to within 4 mm on average, a lateral bearing system was also used to prevent any out-of-plane movement of the column during testing.

Instrumentation

Linear variable differential transformers (LVDTs) were employed to measure the lateral displacements of the column along its height. The second and third peripheral ties above the base were instrumented with electrical resistance strain gages, placed at the locations shown in Fig. 2. For Specimens CFL90/0.37 and CF135/0.37, additional strain gages were also attached to the crossties at the second, third, and fourth levels in the direction of loading. An angle-measuring device was used to monitor the inclination of the column top.

The vertical load was measured by means of a calibrated pressure gage. The 1000 kN hydraulic actuator for horizontal load application was fitted with a load cell. Signals from the load cell, LVDTs, and strain gages were connected to a computerized data acquisition system.

Testing procedure

The test specimens were first subjected to preliminary loadings under 50% of the specified axial load and a very small lateral load (in the order of 30 kN) to determine accidental eccentricities of the loading, as well as to assure proper functioning of all measurement devices. Any necessary corrective measures would then be applied to ensure that the accidental eccentricity in the vertical load was within a tolerance of 1% of the column width, on average.

Actual testing was carried out following the general procedure proposed by Watson and Park.[5] After the application of the specified axial load, the lateral force was load-controlled to ±75% of the theoretical lateral yield value H_u, computed on the basis of the ACI Code without any strength reduction.

The experimental yield displacement Δ_y was then extrapolated from the average of the measured displacements at $+0.75H_u$ and $-0.75H_u$ (Fig. 4). Subsequently, each specimen was subjected to displacement-controlled cyclic loading, starting from the displacement ductility level of 1. The displacement ductility level was incremented at an interval of 1, in general, with two cycles of loading performed for each ductility level until the ultimate capacity was reached. Failure was defined as the state when the capacity of the specimen during the loading cycle considered dropped by more than 20% of the maximum capacity of the specimen. The associated displacement is denoted by Δ_u, and the displacement ductility factor is

$$\mu_{\Delta,u} = \Delta_u/\Delta_y \tag{1}$$

Loading was applied at a very slow rate, with one cycle completed in approximately 1 h. The slow rate of loading permitted control of the constant axial force by manual operation of the hydraulic pump.

TEST RESULTS

Test observations

Specimen CF90/0.30 (with 90-degree hooks but without hook-clips) exhibited normal flexural and shear cracks when loaded through two cycles at ductility 1.0, and only a few small spalling cracks developed at the edges in the plastic hinge zone. During the first push cycle at ductility 2.0, however, widespread spalling cracks occurred that were caused by the popping out of the 90-degree hooks of the peripheral tie and crosstie in the second tie set above the footing. At the end of the second cycle at ductility 2.0, those cracks became excessive. During the next push cycle at ductility 3.0, a major part of the concrete cover in the plastic hinge zone on the compression face spalled off, exposing the 90-degree hooks. The member consequently lost its load-carrying capacity. The buckling mode of the vertical bars was not clear at this stage. After being loaded through another half-cycle, however, it could clearly be seen that the longitudinal bars had buckled over approximately twice the tie spacing, indicating the inadequacy of the 90-degree hooks in the critical peripheral tie and crosstie in restraining longitudinal bars at the tie position (Fig. 5).

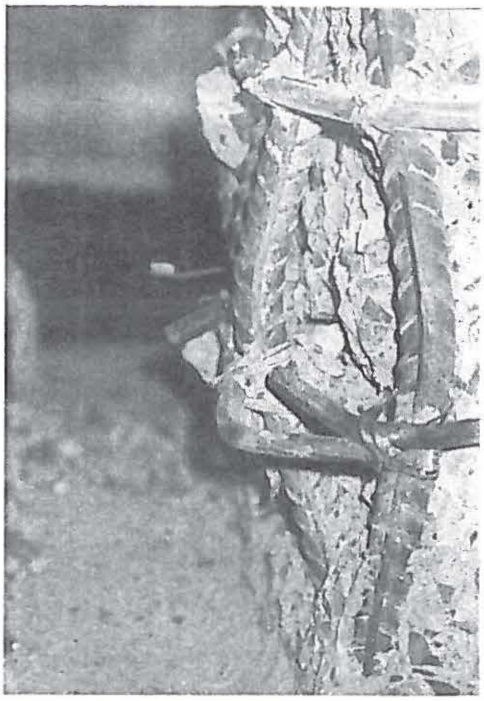

Fig. 5—Failure mode of Specimen CF90/0.30.

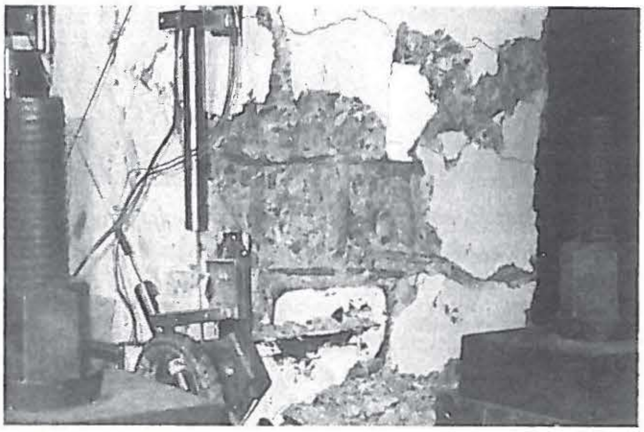

Fig. 6—Failure mode of Specimen CF135/0.30.

Specimens CF135/0.30 (with 135-degree hooks) and CFL90/0.30 (with 90-degree hooks and hook-clips) behaved in a similar manner up to ductility level 2.0 with stable hysteresis loops and little strength degradation. In contrast to Specimen CF90/0.30, which had already developed significant spalling cracks at this ductility level, only a few small ones occurred in CFL90/0.30 and CF135/0.30. When Specimen CF135/0.30 was pushed through the first cycle of ductility level 3.0, the spalling cracks, which had developed earlier at ductility level 2.0 as small cracks along one edge near the base, rapidly propagated with increasing width and length. Spalling cracks and swelling of the concrete cover around the third tie set above the base also developed due to expansion of the peripheral tie. During the last cycle at ductility 3.0, more spalling near the base occurred, and swelling of the concrete in the vicinity of the 90-degree end of the crosstie in the second tie set was evident. The next (incomplete) push cycle to ductility level 4.0 saw excessive spalling and swelling of the concrete covering between the first and third tie sets, with opening of the 90-degree hook in the crossties and eventual buckling of the longitudinal bars (Fig. 6). It was also observed that the 135-degree hook of the most severely stressed peripheral tie was so deformed that it opened up substantially, indicating deficient anchorage of the hook due to the short extension leg provided for nonseismic design.

Specimen CFL90/0.30 exhibited remarkable behavior. Up to the second cycle, at ductility level 3.0, the overall appearance of the column was still in fairly good condition except for minor surface spalling of the cover at the base on the compression faces (that had occurred since ductility level 2.0) and some wide vertical spalling cracks near the edges in the plastic hinge zone. Swelling of the concrete cover on the compression face was observed near the location of one 90-degree end of the crosstie at the second tie set above the base, indicating expansion action of the ties and hooks. Reinforcing bars were not exposed until the specimen was loaded to ductility level 4.0, however, when extensive spalling of the concrete cover took place. Bending of an inner longitudinal bar due to buckling could also be clearly observed at this stage (Fig. 7). Of particular significance is the integrity of the hook-clips in holding the legs of the 90-degree hook-tie, even at a substantial drift of 4% as witnessed in Fig. 8. It was remarkable that the

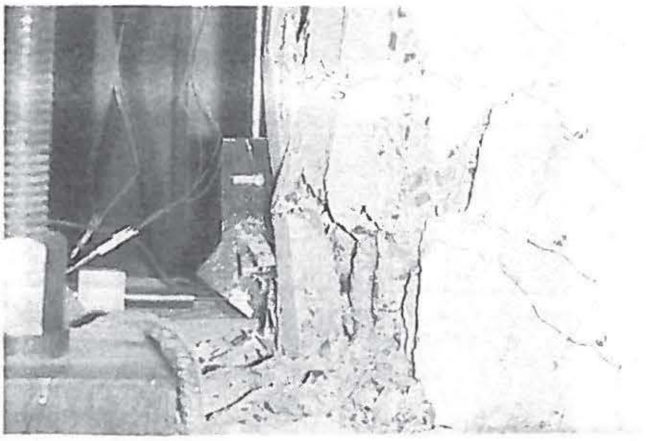

Fig. 7—Specimen CFL90/0.30: Buckling of longitudinal bar in single tie spacing.

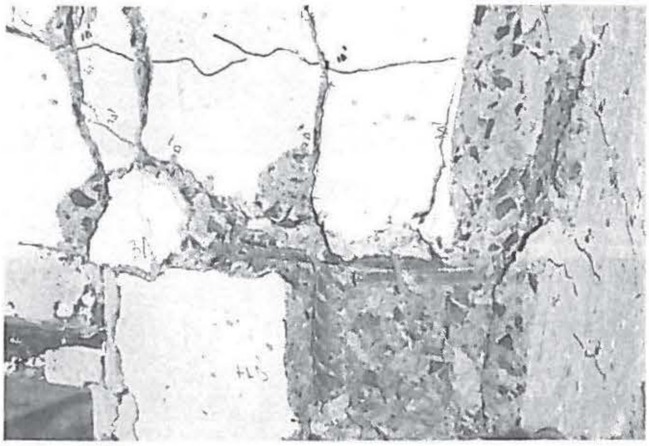

Fig. 8—Specimen CFL90/0.30: Effective restraint of 90-degree hook legs by hook-clips at large drift of 4%.

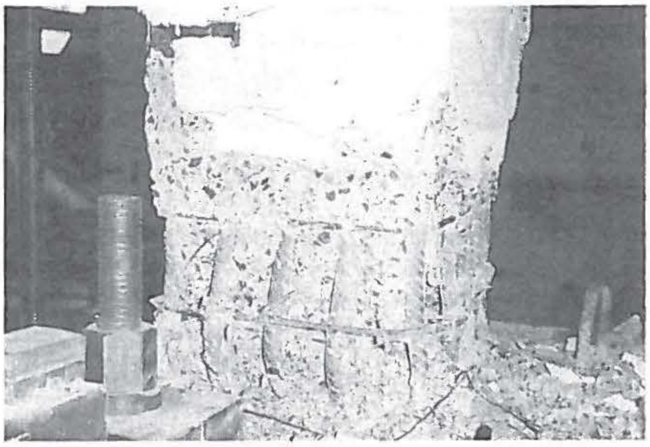

Fig. 9—Specimen CFL90/0.30: Effectiveness of hook-clips in restraining hook opening at failure.

longitudinal bars possessed significant postbuckling strength and the ties and hook-clips were able to confine the core so that a significant amount of the peak load could be sustained, without abrupt failure, through one full cycle before eventual failure by total buckling of the longitudinal bars. The buckling shape of the longitudinal bars in the plastic hinge zone resembled that of Specimen CF135/0.30 (Fig. 9).

Specimen CF135/0.37 displayed extensive spalling cracks near the edges in the plastic hinge zone when loaded to ductility

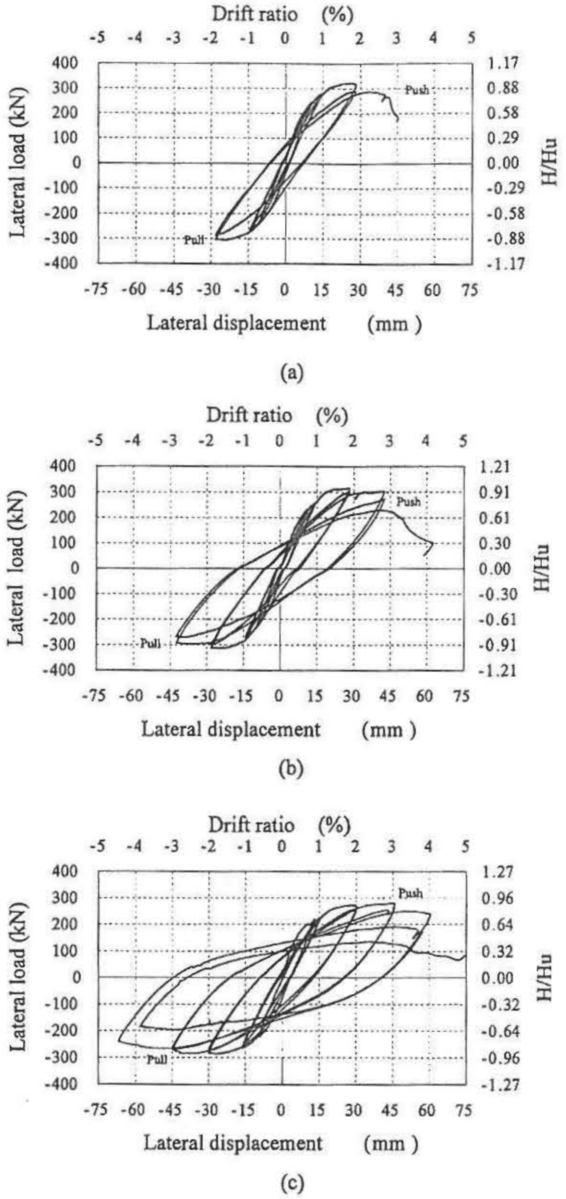

Fig. 10—Lateral load-displacement hysteresis: (a) Specimen CF90/0.30; (b) Specimen CF135/0.30; and (c) Specimen CFL90/0.30.

level μ_Δ 2.0. Swelling of the concrete cover was significant along the third hoop level but less so at the second hoop level. The edges spalled off during the first cycle of $\mu_\Delta = 3.0$, but the longitudinal bars were still not visible. Just before the completion of the second cycle at ductility level 3.0, there was a drastic drop in lateral load resistance, followed by rapid widening of a major shear crack that had previously been minute, leading to eventual failure.

The overall appearance of CFL90/0.37, on the other hand, was much better than that of its counterpart, CF135/0.37. Similar crack patterns were observed in general, but the extent of cracking and damage was significantly less in the former than in the latter. At $\mu_\Delta = 2.0$, only a few minor spalling cracks occurred over small areas at the base and at the third tie level. The cracks developed into significant ones at the third peripheral tie level at ductility factor 3.0, with a clearly noticeable drop in lateral load resistance. This prompted a reduction of the displacement increment to $0.5\Delta_y$ for the next (and last) loading cycle. Buckling of vertical bars in the plastic hinge

Table 3—Test results

Specimen	Δ_y, mm	Δ_u, mm	$\mu_{\Delta,exp.}$	$\mu_{\Delta,cal.}$	H_{max}, kN	ΣE_i, kN-mm	E_N	Failure mode
CF90/0.30	14.3	28.4	2.0	—	315	16,908	3.8	Flexure
CF135/0.30	14.2	42.6	3.0	—	314	44,806	10.1	Flexure
CFL90/0.30	15.0	55.5	3.7	3.8	284	83,032	19.3	Flexure
CF135/0.37	14.2	42.4	2.5	—	295	27,821	6.6	Flexure
CFL90/0.37	13.2	39.6	3.0	3.5	303	41,448	10.4	Flexure

Note: $\mu_{\Delta,exp.}$ = displacement ductility factor from experiment; and $\mu_{\Delta,cal.}$ = calculated displacement ductility factor in accordance with formula proposed by Wehbe, Saiidi, and Sanders.[11]

zone led to an excessive drop in capacity and termination of the test after 1-1/2 cycles of loading at ductility level 3.5.

Lateral load-displacement hysteretic response

The lateral load-displacement hysteretic responses for the test specimens are shown in Fig. 10 and 11. The curves clearly indicate flexural-dominated characteristics. It is interesting to note that Specimens CF135/0.30 and CFL90/0.30 experienced stable hysteresis loops up to ductility level 3.0, with similar general characteristics. While the specimen with 135-degree hooks and (unclipped) crossties suffered a sharp decrease in lateral load resistance during the next (and last) loading cycle to ductility level 4.0, the specimen with hook-clips exhibited a stable hysteresis loop in the same cycle, with little strength degradation. The latter was able to sustain two complete cycles at this ductility level, although significant degradation in strength and stiffness occurred in the second cycle at $\mu_\Delta = 4.0$. The actual ductility factor that could have been attained by this specimen was estimated to be 3.7, which was based on equivalent energy dissipation and the condition that the loss in strength not exceed 20%.

The sudden drop in lateral load resistance was even more pronounced in Specimen CF90/0.30 when it was being pushed to $3\Delta_y$. The opening of the 90-degree hook of the crosstie in the second tie set above the base caused the rapid decrease in load resistance when the longitudinal bars buckled over approximately two tie spacings.

Specimen CFL90/0.37 exhibited a more stable hysteretic response than CF135/0.37, with much less strength degradation, when loaded from the second cycle at ductility 2.0 to the second loading cycle at $\mu_\Delta = 3.0$. Reduction of the peak load at ductility factor 3.0 was 22% for Specimen CF135/0.37, compared with only 8% for Specimen CFL90/0.37. Prior to unloading from the second cycle at $\mu_\Delta = 3.0$, however, Specimen CF135/0.37 rapidly lost its load capacity (by more than 45%) due to buckling of the vertical bars at a displacement of $+2.54\Delta_y$. The specimen with hook-clips, on the other hand, could still carry 85% of the peak load, and even sustained one complete cycle at $\mu_\Delta = 3.5$ with a remarkable sustained capacity before final failure.

Ductility performance

The displacement ductility factors attained by Specimens CF90/0.30, CF135/0.30, and CFL90/0.30, under an axial stress level of $0.3f_{ca}$, were 2, 3, and 3.7, respectively (refer to Table 3). It may be noted that the displacement ductility of CFL90/0.30 closely agreed with the value of 3.8 predicted by the formula suggested by Wehbe, Saiidi, and Sanders[11] for members with seismic detailing, indicating the effectiveness of the hook-clips in enhancing ductility performance of columns with 90-degree hook-ties. The ductility performance of specimens without clips was expected to be unsatisfactory due to the use of nonseismic detailing, and, hence, it was not compared with that predicted by the Wehbe, Saiidi, and Sanders equation.

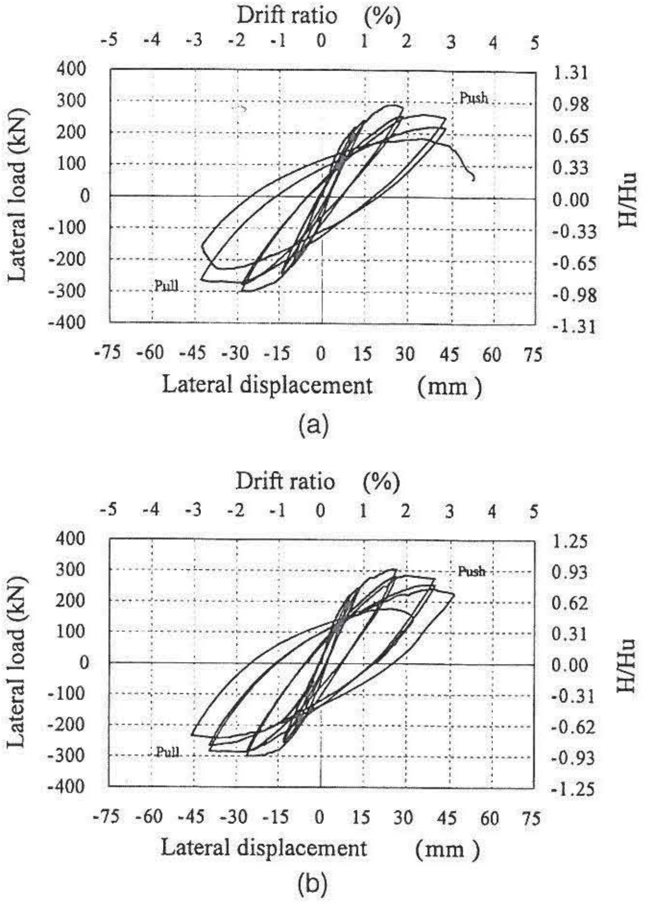

Fig. 11—Lateral load-displacement hysteresis: (a) Specimen CF135/0.37; and (b) Specimen CFL90/0.37.

The effectiveness of the hook-clips was again confirmed by Specimen CFL90/0.37, which was able to sustain the same displacement ductility factor as Specimen CF135/0.30, even though it was subjected to a higher level of axial load.

Strains in transverse steel

Focus was first placed on measurement of the strains in the peripheral ties in the plastic hinge zones of Specimens CF90/0.30, CFL90/0.30, and CF135/0.30. It was unfortunate that some strain gages were damaged during the test (some caused by the spalling concrete), which resulted in incomplete data. Therefore, a comparison of the maximum strains in the peripheral ties could not be made. Furthermore, it was found that the strains in the tie legs perpendicular to the lateral load direction were highly influenced by bending of the ties caused by the lateral pressure exerted by the core and/or buckling of the longitudinal bars. In the last two specimens, therefore, attention was paid to the measurement of the strains in the crossties parallel to the lateral load direction that were predominantly in tension. It was found that the highest strain in crossties in Specimen CFL90/0.37 was 1.5 times that in Specimen CF135/0.37. In fact, the former attained a strain of 0.0015, slightly higher than the yield value of 0.0014. The hook-clips provided better anchorage of the 90-degree hook after spalling of the concrete cover, leading to the ability to develop higher strains in the crossties, and enhanced confinement of the concrete core.

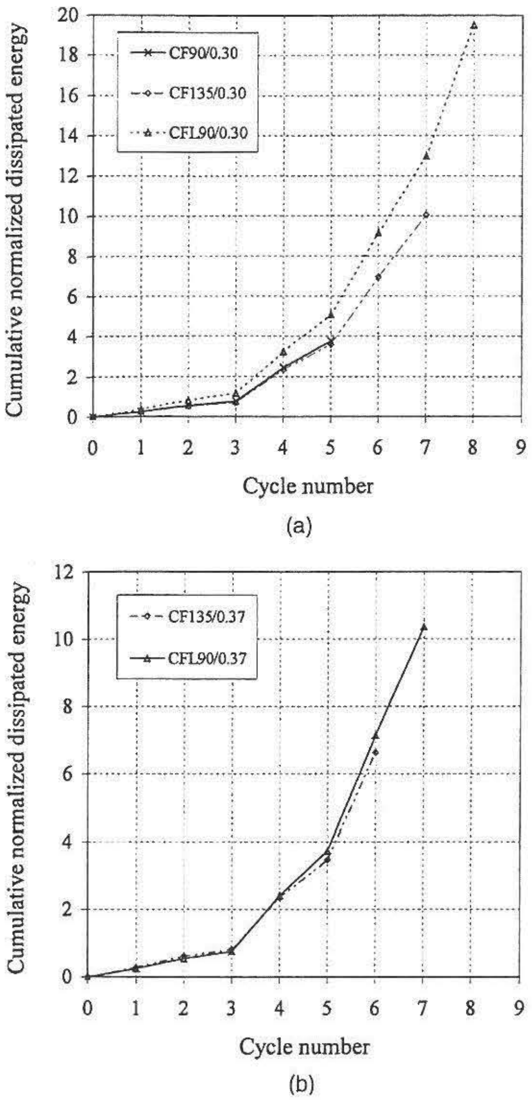

Fig. 12—Cumulative normalized dissipated energy: (a) Specimens CF90/0.30, CF135/0.30, and CFL90/0.30; and (b) Specimens CF135/0.37 and CFL90/0.37.

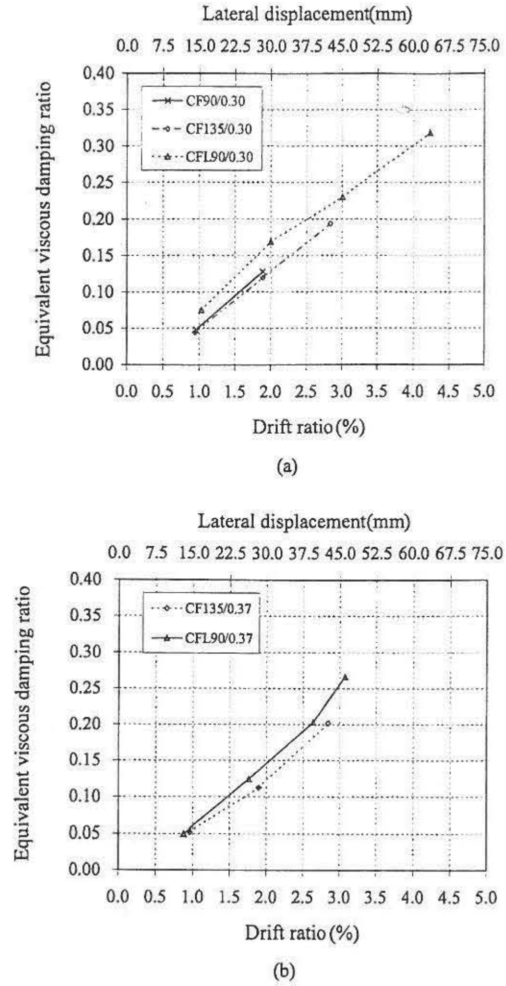

Fig. 13—Equivalent viscous damping ratio: (a) Specimens CF90/0.30, CF135/0.30, and CFL90/0.30; and (b) Specimens CF135/0.37 and CFL90/0.37.

Energy dissipation capacity

The ability of structures to withstand cyclic loading is commonly measured in terms of the energy dissipation capacity, which is defined as the summation of the energy E_i dissipated within each cycle i. The normalized energy dissipation capacity E_N is

$$E_N = \left(\sum_{i=1}^{n} E_i\right) / (H_{max}\Delta_y) \tag{2}$$

in which n is the number of cycles to failure, and H_{max} is the peak lateral load during cyclic loading.

The normalized energy dissipation capacities of the specimens tested are tabulated in Table 3 and the cumulative normalized dissipated energies versus loading cycles are plotted in Fig. 12. Those cycles that resulted in a drop in lateral load resistance of more than 20% of the peak lateral load were excluded in the computation. It is remarkable that the energy dissipation capacity of Specimen CFL90/0.30 was larger than the unclipped Specimens CF90/0.30 and CF135/0.30 by approximately 400 and 90%, respectively. At a higher axial load level of $0.37f_{ca}A_g$, the increase in the dissipated energy was less. At any rate, the energy dissipation capacity of CFL90/0.37 was still 1.5 times that of CF135/0.37.

Equivalent viscous damping

It is interesting to assess the equivalent viscous damping of the columns under increasing lateral drift, which would reflect the ability to reduce the peak response amplitudes due to inelastic deformation caused by earthquake excitations. The equivalent viscous damping ratio ξ_{eq} is obtained from[16]

$$\xi_{eq} = \frac{E_i}{4\pi E_e} \tag{3}$$

where E_e is the elastic strain energy stored in an equivalent linear elastic system when the maximum displacement is reached at cycle i.

Figure 13 shows the variation of the equivalent viscous damping ratio with the lateral drift ratio. Again, the advantage of providing hook-clips is evident. At the axial load level of $0.30f_{ca}A_g$ and prior to failure, the equivalent viscous damping ratio of the specimen with hook-clips was significantly increased by 149 and 64% compared with the unclipped Specimens CF90/0.30 and CF135/0.30, respectively. At the higher axial load level, the damping ratio of CFL90/0.37 was larger than that of CF135/0.37 by a smaller amount of 32%, indicating that the hook-clips are less effective at higher load level.

Effectiveness of hook-clips

From the test results, together with the following observations, it is evident that the hook-clips were effective in improving the performance of the 90-degree hooks in the peripheral ties and crossties:

a) At each ductility level, the number and extent of spalling cracks were significantly lower in the specimens with hook-clips than in those without, indicating less popout action of the 90-degree ends of the crossties and 90-degree hooks in the peripheral ties due to containment by the hook-clips;

b) The hook-clips in the specimen with conventional 90-degree hooks were able to prevent opening of the hook ensuring effective tie restraint of the longitudinal bars. This is in contrast to the specimen with 90-degree hooks and no hook-clips. For the specimen with hook-clips, the buckling length was approximately 1/2 of the longitudinal bars without clips, permitting the bars with clips to sustain a larger load at the same deformation;

c) The ductility performance of the specimen with 90-degree hook-ties and hook-clips far exceeded that of the specimen without hook-clips. In fact, the former even performed better than the specimen confined with 135-degree ties and crossties without hook-clips. The reason is that the crossties in the specimen with 90-degree hook-ties and hook-clips were effectively restrained from opening up by the hook-clips, in contrast to the unclipped crossties in the specimen with 135-degree hooks that popped out at an earlier stage, leading to loss of structural integrity; and

d) The crossties with hook-clips were able to develop larger strains than those without clips as mentioned previously.

CONCLUSIONS

The hook-clips were found to be effective in preventing opening of 90-degree hooks in tied columns under moderate ductility demand, resulting in significant enhancement of the ductility and energy dissipation capacity of columns confined with 90-degree hook peripheral ties and crossties. For the tie configurations studied, the effective restraint of the 90-degree hooks provided by hook-clips resulted in the longitudinal bars buckling by about half the buckling length of those without hook-clips. In fact, for the specimens tested, the overall performance of the specimens with hook-clips was even superior to that of columns confined with 135-degree hook-ties and conventional crossties. The effectiveness of hook-clips also enabled the most severely strained crossties in the plastic hinge region to develop a strain slightly higher than the yield strain value. The effectiveness of the hook-clips should be beneficial, even in regions of high seismicity, pending further investigation.

CONVERSION FACTORS

1 MPa = 145 psi
1 mm = 0.0394 in.
1 kN = 0.2248 kips

NOTATION

A_g = gross area of column section
A_{sh} = total cross-sectional area of transverse reinforcement
$A_{sh,ACI}$ = minimum total cross-sectional area of rectangular hoops and crossties as specified by ACI Code[7]
E_e = elastic strain energy stored in equivalent linear elastic system when maximum displacement is reached at cycle i
E_i = dissipated energy within cycle i
E_N = normalized dissipation energy capacity
f_{ca} = compressive strength on day of testing of standard concrete cylinder
f_y = yield strength of longitudinal reinforcement steel
f_{yh} = yield strength of transverse reinforcement steel
H_{max} = peak lateral load during cyclic loading
H_u = theoretical lateral yield load
h_c = cross-sectional dimension of column core measured center-to-center of confining reinforcement
P = axial load
s = center-to-center spacing between sets of ties measured along axis of column
Δ_u = ultimate tip displacement of column
Δ_y = yield displacement of column
$\mu_{\Delta,u}$ = displacement ductility factor
$\mu_{\Delta,cal}$ = calculated displacement ductility factor in accordance with formula proposed by Wehbe Saiidi, and Sanders[11]
$\mu_{\Delta,exp}$ = displacement ductility factor from experiment
ρ_l = longitudinal reinforcement ratio
ξ_{eq} = equivalent viscous damping ratio

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