Recommendations for Design of RC Beam-Column Connections with Headed Bars Subjected to Cyclic Loading

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ABSTRACT :

New ACI 318-08 provisions for headed deformed bars (§12.6) detail the development of headed deformed bars and mechanical anchorage of reinforcement, such as development length, maximum allowable concrete strength, bar and head size, as well as side cover and clear bar spacing. However, the restriction of §12.6.1(f) hinders use of headed bars for the case where bar clear spacing is less than $4d_b$, which is in fact common for beam or column reinforcement of moment frames. Given this conflict, the need exists to provide guidelines to supplement ACI 318-08, particularly for headed bars terminating in beam-column joints of frames. For these, all the existing data concerning headed bars (a total of 91 beam-column joint specimens) have been complied and re-assessed. As well, all available ACI standards have been reviewed and discussed. Finally, this study documents all these test results in a uniform format and provides a detailed review of the data needed to update ACI 352R-02 recommendations on the design of beam-column joints with headed bars.

KEYWORDS: Headed bars; beam-column joints; cyclic loading; development length; earthquakes.

1. INTRODUCTION

The use of headed reinforcing bars is increasingly popular for longitudinal and transverse reinforcement for high-rise buildings and earthquake-resistant structures, as well as for perimeter ties which are provided to resist progressive collapse. Its use as longitudinal reinforcement often provides an adequate solution to steel congestion in a reinforced concrete beam-column joint, one of the most congested components. New code provisions for headed bars have been added to the 2008 edition of ACI 318. The new provisions of §12.6.1 and §12.6.2 detail the development of headed and mechanically anchored deformed bars in tension, such as development length, maximum allowable f'_c, bar and head size, as well as side cover and clear bar spacing .

According to ACI 318B (2006), the development length (l_{dt}) in tension for headed bars was determined based solely on the tests conducted at UT Austin concerning splices (Thompson et al., 2006), CCT nodes (Thompson et al., 2005), side blowout (DeVries et al., 1999), and shallow pullout (DeVries et al., 1999). The data used to develop the l_{dt} equation (§12.6.2 of ACI 318-08) and to set forth certain conditions (§12.6.1 of ACI 318-08) consist of those for headed bars in lap splices with (A_{brg}/A_b) = 5.7 & 5.04 (Thompson et al., 2006), single headed longitudinal bar embedded in beams with strain gauges located $7d_b$ from the head face (Thompson et al., 2005), and pullout of headed bars with high & low side covers (DeVries et al., 1999). The certain conditions include the limitation of f_y, bar size, concrete, as well as head size, clear cover, and bar clear spacing (c_{bs}). These restrictions were imposed mainly based on the lower limits used for the establishment of the development length of a headed bar (l_{dt}). However, some other available tests (e.g., Wallace et al., 1998; Chun et al., 2007) which conformed to ACI 318-08 were not used for the analysis (**Table 1**). These data could have been included, given that R12.6 and Fig. R12.6(b) are essentially provided as guides for the design of beam-column joints. As a consequence of excluding these data, ACI 318-08 (§12.6.1) discourages using headed bars with c_{bs} less than $4d_b$, which is indeed common for U.S. reinforced concrete construction.

For a design that does not conform to §12.6.1 of ACI 318-08, experimental verification should be submitted to and approved by the building official as required by §12.6.4. This approval process may be exempt if the use of headed reinforcement is part of the design of the beam-column joint, and complies with the ACI 352R-02 recommendations. Design guidelines for headed bars in beam-column joints were first incorporated into the

2002 edition of ACI 352 report on the basis of both monotonic tests (e.g., DeVries et al., 1999) and cyclic tests (e.g., Wallace et al., 1998). As a result, an equation for the development length was recommended in ACI 352R-02, along with some other recommendations such as the location of head ends and the amount of restraining reinforcement for preventing the loss of cover. As the concrete bearing capacity is substantially higher in the diagonal compressive strut, a head is required to be located within 51 mm away from the back of the joint core. As for the details of the bar head, the report refers to ASTM Specification A970.

Table 1 Data that showed excellent performance and met ACI 318-08, §12.6.1 except §12.6.1(f)

I.D.	Type	Ref.	d_b [mm]	f_c' [MPa]	f_y [ksi]	l_{p1} / l_{dt}	l_{p2} / l_{dt}	c_{bs} / d_b	A_{brg} / A_b	c_{sb} / d_b
JM-No.11-1a	Ext.	Chun et al. (2007)	36	(32; 33)	(414; 503)	0.80	0.82	3.3	4.0	4.8
JM-No.11-1b	Ext.		36	(32; 33)	(414; 503)	0.80	0.82	3.3	4.0	4.8
BCEJ1	Ext.	Wallace et al. (1998)	25	(28; 36)	(414; 483)	0.86	0.96	2.6	4.0	3.5††
BCEJ2†	Ext.		25	(28; 36)	(414; 483)	0.83	0.92	2.6	4.0	4.0††
KJ16	Knee		16	(28; 37)	(414; 490)	1.38	1.46	2.1	11.4	3.6
KJ17	Knee		16	(28; 37)	(414; 490)	1.38	1.46	2.1	11.4	3.6
KJ18	Knee		16	(28; 38)	(414; 531)	1.40	1.46	2.1	7.0	3.6

†: Subjected to Type 1 loading; ††: Clear cover from the back face of the joint, which is the smallest.
Ext. = Exterior interstory joint; Knee = Knee joint; f_c' & f_y = (design strength; measured strength);
l_{p1} and l_{p2} = development lengths provided from the beam-joint interface, and within the joint core;
l_{dt} = ACI 318-08 defined development length; c_{bs} = clear bar spacing; c_{sb} = clear cover to the head.
Note: Graphs are used in lieu of tables for a complete data set of 91 specimens due to the limited space.

Relatively few details, however, are available in ACI 352R-02, due to a substantial lack of experimental data on beam-column joints utilizing headed bars particularly under inelastic deformation reversals. There are only three available publications in English (Smith, 1972; Wallace et al., 1998; Chun et al., 2007) for the cyclic tests of beam-column joints with headed bars. Additional data of cyclic tests are urgently needed to expand the limited ACI 352 design guidelines and to supplement ACI 318-08 provisions.

Given these needs, Joint ACI-ASCE Committee 352, Joints and Connections in Monolithic Concrete Structures, agreed to update the headed bar recommendations of ACI 352R-02. As part of these efforts, Task Group of Joint ACI-ASCE Committee 352 has compiled all existing international data concerning headed bars terminating in beam-column joints. In this study, a total of 91 beam-column joint subassemblies with headed bars were assembled and assessed. All these specimens were tested under lateral deformation reversals; thus, the review is limited to cases where moderate-to-high seismic risks exist. Each of approximately 19 test programs has different needs and configurations. Therefore, the objectives of this study are to document all these test results in a uniform format and conduct a detailed review of the data needed to update the ACI 352R-02 recommendations and further amends the ACI 318 code provisions.

2. DISCUSSION OF DATA, ACI 318-08 AND ACI 352R-02

2.1. Failure modes

All beam-column joint subassemblies failed in different manners. Based on several performance indicators as detailed in the following paragraphs, failure modes were divided into three different categories as follows; (Category–I) beam/column flexural failure followed by modest joint deterioration; (Category–II) beam/column flexural failure followed by joint failure; and (Category–III) joint failure prior to headed bar yielding. In this paper, the Category–I is considered as "satisfactory seismic performance", while other two categories as "unsatisfactory seismic performance." The parameters used for the classification includes: 1) the ratio of measured peak moment to nominal moment capacity (M_{peak}/M_n); 2) drift ratios of (δ_y, δ_{peak} and δ_{80}); and 3) joint shear distortions during 3.0 to 3.5% story drift cycles, where M_n is the nominal negative moment capacity of the beam estimated based on dimension and reinforcement, and δ_y, δ_{peak} and δ_{80} are the drift ratios at first yielding, at the peak lateral load and at 20% drop from the peak lateral load, respectively.

Premature joint failure was assumed to occur prior to flexural failure (i.e., Category–III), if the ratio of (M_{peak}/M_n) is less than 1.0 and/or if no flexural yielding was observed before the last cycle of the test. A variety of factors appeared to impact on poor joint behavior, such as a lack of confinement ($\rho_h/\rho_h^{ACI,2}$ = 0.30 versus average of Category–I and II = 0.55) and large joint shear demand (V_u/V_n = 0.95 versus average of Category–I and II = 0.80), or a substantial lack of headed bar embedment length (Watanabe et al., 2004; Matsushima et al., 2000; Takeuchi et al., 2001; Murakami et al., 1998). Here $\rho_h = (A_{sh}/s_h h'')$, A_{sh} is the area of joint hoops and ties within s_h, s_h is the hoop spacing, h'' is the joint core width, $\rho_h^{ACI,2}$ is the minimum ρ_h recommended by ACI 352R-02 for Type 2 joint, V_u is the computed joint shear demand, and V_n is the nominal joint shear capacity.

The drift ratio and joint shear distortion were used to differentiate between the Category–I and II. If the specimen exhibited less than 20% reduction in strength until 3.5% drift, and did not exceed 1.2% joint shear distortions until 3.0 to 3.5% story drift levels, the joint was considered to have satisfactory seismic performance (i.e., Category–I). For the specimens in Category–I, the ductility (μ) was larger than 2 (average = 5.6), where μ is determined as $(\delta_{80} - \delta_y)/(\delta_y)$. For the specimens in Category–II, the joint failure occurred after flexural yielding, with less ductility (average = 2.7). This was a result of significant joint shear deformations.

The bar slip is typical at 3.0 to 3.5% drift levels even for code-compliant exterior beam-column joints. This pinching behavior indicates a slip of the bars, but does "not" indicate complete loss of anchorage. Despite significant bond deterioration, head bearing resistance was not compromised. Drops in bar stress after the peak stress just before the head were only 0 to 30% for all specimens in Category–II.

2.2. Development length for headed bars in beam-column joints under cyclic loads

Development length equations (l_{dt}) for both ACI 318-08 and 352R-02 are functions of ($f_y\, d_b/\sqrt{f_c'}$). The difference is only the constant. Other parameters that may affect the anchorage capacity include head size, restraining transverse reinforcement, and clear cover and bar spacing (ACI 318-08, §12.2.3 and §12.5.3). From the past joint tests (Wallace et al., 1998; Chun et al., 2007), it was observed that a portion of bond contribution to development was large at first. Subsequently, the bond deteriorated due to slip with increasing drifts (1.5 to 2.5%). Finally, head bearing played a significant role in resistance (around 2.5 to 6% drifts). This implies that the head size appeared not to impact the bond stress along the bar at the initial stage.

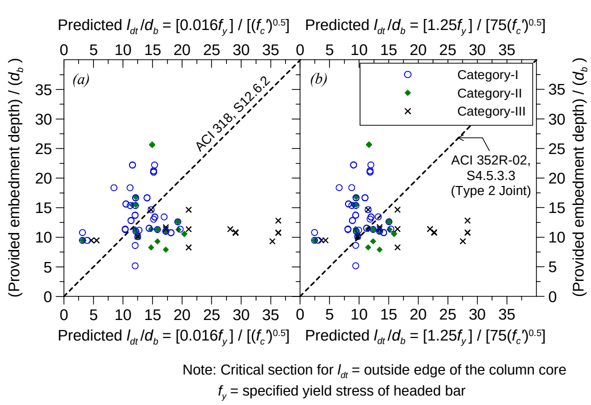

Figure 1 Development length comparisons

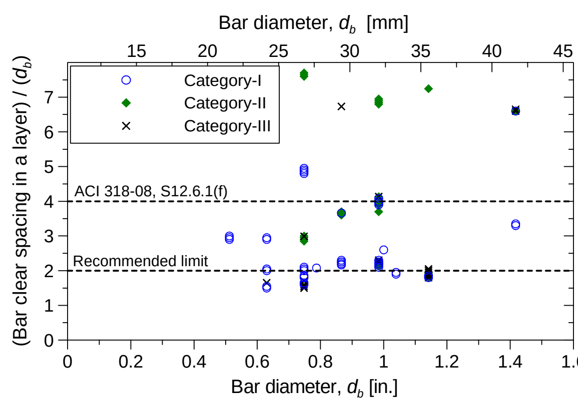

Figure 2 Data of headed bar clear spacing

Figure 1 graphically compares the provided embedment depth and the development length required by ACI 318-08 or recommended by ACI 352R-02. As seen, the ACI 318-08 equation for a headed bar yields conservative estimations for the Category–I data (i.e., 26 of 45 data lie on the right side of the 45-degree line).

ACI 352 equation fits reasonably well with the Category–I data. For the specimens that met ACI 318 anchorage requirements (i.e., left side of the line) and exhibited premature failures (Category–II and III) (Hattori et al., 2002; Adachi et al., 2006; Tasai et al., 2000; Matsushima et al., 2000; Takeuchi et al., 2001), the primary failure mode was joint shear failure. Limited bond slip was occurred. This was based on the observations and the data assessment as detailed in the preceding and following subsections. An examination of the experimental data indicates that the ACI 318-08 new equation gives a somewhat conservative estimation and that the current ACI 352 recommendations on the development length of l_{dt} are reasonable for both single and multiple layers of headed bars embedded in Type 2 joints.

2.2. Headed bar clear spacing

As mentioned earlier, the new provisions of ACI 318-08 for use of headed bars do not provide practical ranges of clear spacing of headed bars. The minimum clear spacing of $4d_b$ specified in §12.6.1(f) is significantly larger than the value defined as the minimum clear spacing for beam reinforcement (= $1d_b$ per §7.6.1) or column reinforcement (= $1.5d_b$ per §7.6.3), and even larger than that used in practice ($1d_b$ to $3d_b$). According to CB010 (ACI 318B, 2006), the minimum limit of $4d_b$ was developed based on the lower bound value obtained from 10 lap splices tests (Thompson et al., 2006b) and 2 pullout tests (DeVries et al., 1999), indicating that the limit of $4d_b$ could have been different if data were abundant.

ACI 352R-02 recommendations do not provide guidelines for obtaining adequate clear spacing between headed bars in a layer, signaling that the same bar clear spacing for a conventional reinforcing bar ($1d_b$ or 25 mm per ACI 318-08, §7.6.1) is recommended for a headed bar. The database for Category–I indicate that the spacing was less than $4d_b$ for 40 specimens (of 46 specimens), and less than $2d_b$ for 10 specimens, with the average and lowest spacing of $2.7d_b$ and $1.5d_b$, respectively (**Fig. 2**). As discussed earlier, there were no apparent concrete breakout failure (CBF) and no data providing evidence that anchorage (bearing) failures occurred. As well, the small bar clear spacing did not adversely impact the drift ratio. Based on these results, it is suggested that the limit of $4d_b$ be lowered to $2d_b$ for the beam-column joint design. The clear spacing of $2d_b$ would be reduced even further if the database could be updated. This limit, however, may not be applicable for general use or where cone-type failure (i.e., CBF) is likely.

2.3. Material properties

According to §12.6.1 and §12.6.2 of ACI 318-08, the upper limits of the specified yield strength of the headed bar (f_y) and the specified concrete strength (f'_c) are 420 and 41 Mpa, respectively, which are very limiting. On the other hand, ACI 352R-02 headed bar recommendations are valid for f_y up to 540 Mpa per ASTM A970, and for f'_c up to 100 Mpa. The data in Category–I indicate that the measured yield strength of the steel varied from 352 to 710 Mpa (**Fig. 3**). In particular, of these specimens, sixteen specimens had high-strength steel with $f_y \geq 420$ MPa. For concrete, measured compressive strengths ranged from 24 to 130 MPa. These results support ACI 352R-02 recommendations that the use of high-strength steel having f_y up to 420 MPa and high-strength concrete having f'_c up to 100 MPa be permitted.

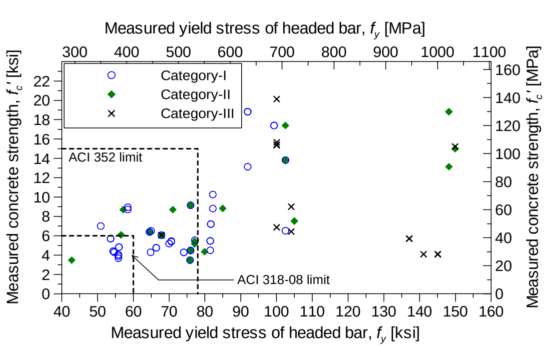

Figure 3 Data of material properties

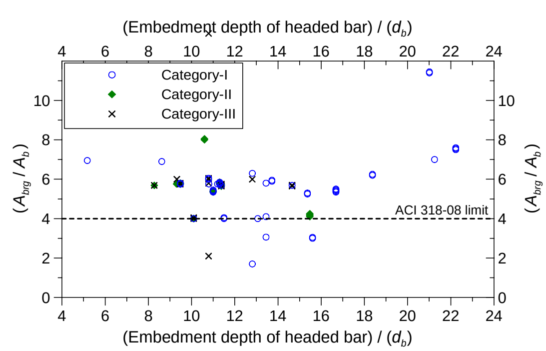

Figure 4 Data of head size

In both ACI 318-08 and 352R-02, the maximum allowable size of the headed bar is a No. 11 (d_b = 36 mm), and only the use of normalweight concrete is permitted when headed bars are provided. On the contrary, ASTM A970, Table 1 allows use of No. 14 and 18 headed bars. The test data indicate that maximum headed bar diameter used for Category–I was 36 mm (**Fig. 3**), which remained consistent with ACI 318-08 and 352R-02. For lightweight concrete (LWC), there were no available data. Given this lack of data, no solid recommendations on the larger bar size and lightweight concrete are provided here.

2.4. Head size

ACI 352R-02 recommends the net bearing area (A_{brg}) at least 9 times the bar area (A_b) by referring to the 1998 version of ASTM A970, whereas ACI 318-08 requires A_{brg} at least 4 times A_b. Two different types of heads were used: 1) head without a sleeve connection; 2) head with a sleeve connection or with an obstruction. In the latter case, A_{brg} is not ($A_{head} - A_b$), but a slightly higher value of ($A_{head} - A_{obs}$); however, in this paper, because A_{obs} is not available and not expected to be considerable, A_{brg} is conservatively taken as ($A_{head} - A_b$).

The joints in Category–I were subjected to more than 3.5% drifts with only modest strength degradation (≤ 20%), revealing no signs of anchorage failures. Eight specimens possessed head size with A_{brg} equal to or smaller than $4A_b$, with the lowest value of $1.7A_b$ (**Fig. 4**). Of these 8 specimens, 4 specimens had a combination of small A_{brg} (not greater than $4A_b$) and small embedment depth (l_{dt} = 0.8 to $0.9l_{dh}$). Particularly, 2 of these specimens (JM-No.11-1a and 1b; Chun et al., 2007) satisfied the requirements of ACI T1.1R-01, with the use of (A_{brg}/A_b) = 4 along with the provided anchorage length of $0.9l_{dh}$. No drop in bearing resistance was clearly reported from the strain gauge measurements for all Categories with the data available (Kiyohara et al., 2005; Chun et al., 2007; Wallace et al., 1998; Hattori et al., 2002; Ishibashi et al., 2003; Ishida et al., 2007; Tasai et al., 2000; Nakazawa et al., 2000; Smith, 1972). No signs of CBF were evident in any of the test specimens. Therefore, A_{brg} of at least $4A_b$ is recommended for headed bars in the beam-column joint, provided that the headed bar embedment length meets ACI 352R-02. This is consistent with ACI 318-08, §12.6.1(d).

2.5. Side clear cover

ACI 318-08, §12.6.1(e) sets a lower limit for the clear cover to the headed "bar" (c_{sb}) as $2d_b$ (equivalent to the clear cover of $1.4d_b$ to the "head" (c_{sh}) for $A_{brg} = 4A_b$, and $0.9d_b$ for $A_{brg} = 9A_b$). At the same time, the clear cover to the outermost part of the head (c_{sh}) should meet ACI 318-08, §7.7 (see R7.7), where c_{sh} is required to be at least 38 mm for beam or column reinforcement. This is for protection of reinforcement against weather or some other effects (R7.7). The provision of §7.7 is slightly more strict than §12.6.1(e) for No. 8 (d_b = 25 mm) or smaller longitudinal reinforcement with a circular head area of (A_{brg}/A_b) = 4, and vice versa for larger reinforcement (**Fig. 5**). Both requirements of §12.6.1(e) and §7.7.1 are not difficult to meet for beam headed bars anchored within an interstory beam-column joint. Also for headed beam or column bars terminating in a roof exterior column joint, these requirements can be simply met if adequate clear cover (38 to 51 mm) is provided over the transverse reinforcement.

ACI 352R-02 does not provide a minimum standard of clear cover to the "head" (just presumes that the clear cover to the "bar" is provided per §7.7.1 of the 2002 version of ACI 318). Rather, ACI 352R-02 provides the required minimum amount of restraining stirrups or hoop legs crossing just before the head (§4.5.3.3). Such additional restraining reinforcement should be provided for all headed bars adjacent to a free face of the joint (e.g., beam bars in a corner joint, or top beam bars in a joint with a discontinuous column). For side covers to the headed bar (c_{sb}) larger than $3d_b$, ACI 352R-02 allows to reduce the amount of restraining reinforcement. Estimation of the reduced amount is detailed in the report by Kang (2008).

Figure 5 depicts the data for side cover to the head (c_{sh}), along with comparisons with §7.7.1, §12.6.1(e), and Eq. D-17 of ACI 318-08. The SBF-related criteria for c_{sh} can be obtained by setting Eq. (D-17) of ACI 318-08 equal to the maximum bar force of $1.25A_sf_y$ as:

$$N_{sb} = (160c_{a1}\sqrt{A_{brg}})\lambda\sqrt{f'_c} = 1.25A_sf_y \text{ (lbs)}; \quad (13.33c_{a1}\sqrt{A_{brg}})\lambda\sqrt{f'_c} = 1.25A_sf_y \text{ (kN)} \tag{1}$$

where N_{sb} is the side-face blowout strength, c_{a1} is equal to c_{sh} plus the distance from the head end to the center of the bar (e.g., diameter of the round head), f_y = 420 MPa, and λ = 1 for normalweight concrete. The A_{brg} is set equal to a lower bound of $4A_b$ for Eq. (1) as well as for §12.6.1(e) of ACI 318-08. Equation (1) is for the case where the concrete is unconfined; thus, it would be perhaps conservative to apply to well-confined beam-column joints. Also, it is again noted that the cover requirement of §7.7.1 is not for prevention of SBF, but for protection from environmental degradation.

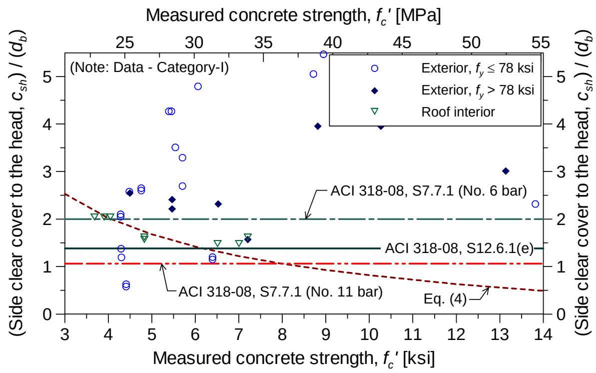

Figure 5 Data of side clear cover to the head

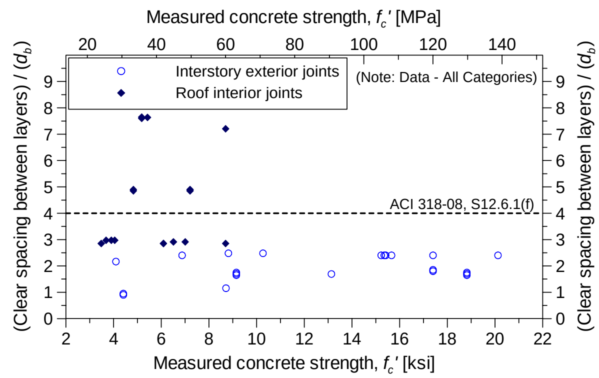

Figure 6 Data for multi layers of headed bars

The side covers to the head (c_{sh}) used for many specimens in Category–I were smaller than the criteria given by Eq. (1) and by §12.6.1(e) (**Fig. 5**); however, the SBF or spalling of the concrete cover was not observed in any of these joints (without restraining reinforcement). No SBF was also supported by the strains measured in joint hoops (Wallace et al., 1998; Hattori et al., 2002). The hoop strains were kept within 2,500 μs until the drift reached 3.0%, indicating that the improved behavior was attributed to lateral confinement of the joint core. The observations showed that even the joints in the Category–II and III did not experience SBF, nor did the joints with two layers of beam bars closely spaced (Chun et al., 2007; Kato et al., 2005; Masuo et al., 2006; Tazaki et al., 2007; Nakazawa et al., 2000; Adachi and Masuo, 2007).

Based on the results showing that SBF would not be a concern, the requirements of both §12.6.1(e) and §7.7.1 of ACI 318-08 could also be applied for the design of beam-column joints. For all tests on interstory joints, no additional transverse reinforcement (e.g., lateral U-bars) was needed to retrain the heads. This was essentially due to sufficient lateral confinement provided by closed hoops and by at least one beam member. In fact, use of stirrups or ties crossing the beam longitudinal reinforcement in a corner joint is not a common practice; therefore, a design not requiring the “horizontal” restraining reinforcement for beam bars should be clearly stated, as opposed to the current recommendations of ACI 352R-02 (§4.5.3.3).

2.6. Multiple layers of headed bars

A total of 22 interstory joints had two layers of top beam bars, with clear spacing between the layers ranging from 0.9 to $2.5d_b$ (**Fig. 6**). A total of 17 roof-level interior joint specimens had multiple column headed bars adjacent to free faces of the columns, with clear bar spacing ranging between 2.85 and $7.6d_b$ (**Fig. 6**). As discussed, none of these specimens did undergo concrete breakout (i.e., CBF). The bar clear spacing was smaller than $2d_b$ for 10 of 12 specimens in Category–I, and smaller than $1d_b$ for 3 specimens. For many specimens in Category–I (Watanabe et al., 2004; Nakazawa et al., 2000; Takeuchi et al., 2001), head bearing resistance was maintained without loss until the end of the testing, as evidenced by strain gauge readings.

The maximum bearing stresses ($p_{brg} = A_bnf_y / A_{brg}$) were estimated up to $4.1f'_c$ (Fig. 9) for Category–I, where f_y

is the measured yield stress of the headed bar and n is the ratio of maximum strain measured in the bar just before the head to the yield strain (ε_y) of the headed bar. The level of bearing stresses measured was substantially higher than that ($0.85f'_c$) permitted by ACI 318-08, §10.17.1, but was close to that (2 to $5f'_c$) monitored for CCT node tests with (A_{brg}/A_b) = 3 to 5 (Thompson et al., 2005). The higher concrete bearing stress appeared to be attributed to the confined concrete as well as the diagonal strut action. Based on the results described in this and prior paragraphs, use of multiple layers of headed bars are suggested with a minimum clear spacing of $2d_b$ (or perhaps $1d_b$ or 25 mm as per ACI 318-08, §7.6.2) between the layers.

SUMMARY AND RECOMMENDATIONS

The prior research constitutes all internationally available reversed cyclic tests of reinforced concrete beam-column joints with headed bars (e.g., U.S., Japan, New Zealand, and Korea). The database was carefully compiled and assessed to be used to update the current ACI 352R-02 report. The recommendations that can be drawn based on this review include the following: 1) The current development length (l_{dt}) for headed bars in beam-column joints that ACI 352R-02 recommends corresponds to the experimental data; 2) For the beam-column joint design, a minimum bar clear spacing could be reduced to $2d_b$ from $4d_b$ that is required by ACI 318-08; 3) The test data are consistent with ACI 352R-02 limitations on f'_c (up to 100 MPa) and f_y (up to 540 MPa); 4) The net bearing head size is suggested to be at least 4 times the bar area for the design of beam-column joints, as generally required by ACI 318-08; 5) The ACI 318-08 requirements of minimum side clear covers to the head (c_{sh} = 38 mm) and to the bar ($c_{sb} = 2d_b$) can be applied to headed bars in beam-column joints; 6) The "horizontal" restraining reinforcement is not necessary for a beam bar adjacent to a side free face of the interstory corner joint; and 7) Multiple layers of headed bars are suggested to be allowed with a minimum clear spacing of $2d_b$ (perhaps $1d_b$ or 25 mm) between the layers.

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