Effect of reinforced concrete beam confinement under cyclic loading on ultimate drift ratio

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Abstract. The purpose of this paper is to evaluate the effect confinement on ultimate drift ratio of reinforced concrete beam specimens using normal concrete. All beam specimens were tested under cyclic loading. The measured compressive strength of the concrete is in the range of 25 – 41.8 MPa, longitudinal reinforcement yield strength is in the range 350 – 570 MPa and transverse reinforcement yield strength is in the range 275 – 570 MPa. Test parameters include s/d_b ratio, \( \rho_t \), and \( V_s/a/M_n \) ratio. The results showed that \( V_s/a/M_n \) ratio have a significant effect on the ultimate drift ratio. Increase the nominal shear strength by confinement leads to an increase of ultimate drift ratio. In other hands, spacing of transverse reinforcement not exceeding 8d_b can achieve minimum 3.00% ultimate drift ratio.

1. Introduction

In the previous research, the amount of transverse reinforcement has an influence on the performance of reinforced concrete beams under cyclic loading and has an effect on shear strength and ultimate drift ratio. One of ACI318-14 [1] requirement for spacing of hoops is eight times the diameter of the smallest longitudinal bar enclosed. Based on ASCE 41-13 [2], drift limit for reinforced concrete beams to achieve life safety condition are between 2.0% to 2.5%. Test results by Panagiotou et al. [3] shows beam with reduced transverse reinforcement spacing was capable of more displacement cycles and larger displacement amplitude than beam with wider transverse reinforcement spacing. Ultimate drift ratio is defined as the ratio of maximum lateral displacement to the total of shear span. The analysis presented seeks to establish a direct relationship between, s/d_b ratio, transverse reinforcement ratio, and \( V_s \times a/M_n \) ratio on ultimate drift ratio. This study focused on reinforced concrete beams under cyclic loading.

2. Experimental Database

The beams were subjected to cyclic loading and single curvature. 15 specimens were tested in a vertical position and 11 specimens were tested in a horizontal position. The test setup is presented in Fig. 1. The shear span, measured from the center of load application to the top of the concrete base block. Data of 26 beam specimens were collected from various sources (Kinugasa and Nomura [4], Fang et al. [5], Ou et al. [6], Vu [7], Cheng and Giduquio [8], Panagiotou et al. [3], Marefaat et al. [9], Walker and Dhakal [10], Ou and Chen [11], Tanarslan [12], and Jin et al. [13]). Details of the beam data including dimensions, material properties, and ultimate drift ratios. The ultimate drift capacity ratio of the beams is defined as the displacement corresponding to the maximum shear strength \( (V_{max}) \) or 20% drop of the maximum shear strength \( (V_{max}) \).
The parameters considered in the study included concrete compressive strength ($f'_c$), yield strength of the longitudinal reinforcement ($f_y$), longitudinal and transverse reinforcement ratio, and aspect ratio. The following criteria were considered in establishing database are 1) Only cantilever beams subjected to standard cyclic testing procedure as in figure 1 and figure 2) Only beams which has the ratio of top reinforcement is the same as the ratio of bottom reinforcement ($\rho = \rho'$), 3) Only beams for which the complete data are known were used. Table 1 presents the range of properties of the beams included in the database. A summary of beam specimen and material properties is provided in table 2.

![Test setup](image)

**Figure 1.** Test setup

| Variable | Units | Minimum | Maximum |
|----------|-------|---------|---------|
| $f'_c$ | MPa | 25 | 41.8 |
| $f_y$ | MPa | 350 | 570 |
| $\rho = \rho'$ | % | 0.42 | 2.16 |
| $f_{yt}$ | MPa | 275 | 570.2 |
| $\rho_t$ | % | 0.19 | 1.43 |
| a/d | - | 2.6 | 5.0 |
| s/db | - | 2.62 | 25 |
Table 2. Summary of beam specimen and material properties.

| Reference                        | Beam name | $f_{c'}$ (MPa) | $b$ (mm) | $d$ (mm) | $f_{t'}$ (MPa) | $\rho$ | $f_{ut}$ (MPa) | $\rho$ | sid$\alpha$ | a/d | Type* |
|---------------------------------|-----------|----------------|---------|----------|----------------|--------|----------------|--------|-------------|-----|-------|
| Kinugasa and Nomura (2006)      | A1        | 28.2           | 200     | 170.0    | 352; 361      | 0.95%  | 366           | 0.75%  | 3.93        | 2.94 | V$^a$  |
|                                 | A2        | 26.9           | 200     | 170.0    | 352; 361      | 0.95%  | 366           | 0.75%  | 3.93        | 2.94 | V     |
|                                 | B         | 33.3           | 200     | 170.0    | 402           | 1.75%  | 366           | 0.19%  | 9.43        | 2.94 | V     |
| Fang et al. (1993)              | B1-6      | 33.1           | 200     | 332.0    | 489           | 2.16%  | 310           | 1.43%  | 2.62        | 2.56 | H$^b$  |
| Ou et al. (2011)                | B-0       | 25             | 300     | 426.2    | 448           | 0.78%  | 448           | 0.48%  | 6.29        | 3.52 | H     |
| Vu (2013)                       | A1-0      | 30.36          | 300     | 433.0    | 524           | 1.49%  | 570.16        | 0.84%  | 3.48        | 2.77 | H     |
|                                 | B1-0      | 39             | 300     | 433.0    | 524           | 1.49%  | 431.88        | 0.84%  | 3.48        | 2.77 | H     |
| Cheng and Giduquio (2011)       | SP1       | 37             | 250     | 540.0    | 485; 421      | 0.72%  | 420           | 0.46%  | 7.86        | 3.89 | V     |
| Panagiotou et al. (2013)         | BEAM 1    | 36.8           | 762     | 1115.8   | 503; 455      | 0.65%  | 455           | 0.28%  | 22.00       | 3.42 | H     |
|                                 | BEAM 2    | 36.8           | 762     | 1115.8   | 503; 455      | 0.65%  | 455           | 0.51%  | 12.00       | 3.42 | H     |
| Marefat et al. (2009)           | PN-CS4    | 27.8           | 150     | 265.0    | 356           | 0.51%  | 310.27        | 0.19%  | 25.00       | 3.02 | V     |
| Walker and Dhakal (2009)         | A1 (rev)  | 41.8           | 250     | 349.9    | 350           | 1.71%  | 445           | 0.36%  | 6.94        | 4.00 | H     |
|                                 | A2 (rev)  | 41.8           | 250     | 349.9    | 350           | 1.71%  | 445           | 0.63%  | 3.97        | 4.00 | H     |
|                                 | D1 (rev)  | 25.6           | 410     | 354.5    | 570           | 0.42%  | 560           | 0.22%  | 10.94       | 3.95 | H     |
| Ou and Chen (2014)              | B1-0      | 38             | 300     | 432.5    | 444           | 1.53%  | 432           | 0.88%  | 3.45        | 2.77 | H     |
| Tanarslan (2011)                | Beam 1    | 25.2           | 200     | 320.0    | 414           | 1.47%  | 275           | 0.38%  | 3.75        | 5.00 | H     |
|                                 | CB-1-i    | 35.5           | 80      | 170.0    | 405.97        | 1.66%  | 297.89        | 0.94%  | 8.33        | 4.00 | V     |
|                                 | CB-1-ii   | 35.5           | 80      | 170.0    | 405.97        | 1.66%  | 297.89        | 0.94%  | 8.33        | 4.00 | V     |
|                                 | CB-2-i    | 35.5           | 160     | 345.0    | 392.1         | 1.14%  | 405.97        | 0.66%  | 8.00        | 4.00 | V     |
|                                 | CB-2-ii   | 35.5           | 160     | 345.0    | 392.1         | 1.14%  | 405.97        | 0.66%  | 8.00        | 4.00 | V     |
|                                 | CB-3-i    | 35.5           | 240     | 540.0    | 399.13        | 1.24%  | 392.1         | 0.63%  | 6.25        | 4.00 | V     |
|                                 | CB-3-ii   | 35.5           | 240     | 540.0    | 399.13        | 1.24%  | 392.1         | 0.63%  | 6.25        | 4.00 | V     |
|                                 | CB-4-i    | 35.5           | 320     | 735.0    | 402           | 1.16%  | 392.1         | 0.63%  | 8.33        | 4.00 | V     |
|                                 | CB-4-ii   | 35.5           | 320     | 735.0    | 402           | 1.16%  | 392.1         | 0.63%  | 8.33        | 4.00 | V     |
|                                 | CB-5-i    | 35.5           | 400     | 930.0    | 374.84        | 0.65%  | 392.1         | 0.50%  | 8.33        | 4.00 | V     |
|                                 | CB-5-ii   | 35.5           | 400     | 930.0    | 374.84        | 0.65%  | 392.1         | 0.50%  | 8.33        | 4.00 | V     |

$^a$vertical position
$^b$horizontal position
3. Result and Analysis
The experimental-to-nominal flexural strength ratio \( \frac{M_{\text{exp}}}{M_n} \) is between 0.71 and 1.61 for all test specimens as shown in Table 3, where \( M_{\text{exp}} \) is the average peak flexural strength from the two loading directions and \( M_n \) is determined per ACI318-14[1] with test material properties. Ultimate drift ratio \( (d_u) \) is defined at the point when one of the following two criteria is first met: 1) the load dropped 20% from the peak on the envelope curve; or 2) the load dropped more than 20% in the repeated cycles at the same target drift level. Ultimate drift ratio \( (d_u) \) is the average from the two loadings direction. As shown in Figure 2, most of the specimen can achieve an ultimate drift ratio more than 2.0% and only one specimen has ultimate drift ratio below 2.0%.

| Beam name | \( d_u \) (%) | \( \frac{M_{\text{exp}}}{M_n} \) | \( V_s \times a/M_n \) |
|-----------|---------------|-----------------|-----------------|
| Kinugasa and Nomura (2006) | A1 | 5.42 | 1.15 | 2.573 |
| | A2 | 5.03 | 1.11 | 2.586 |
| | B | 2.39 | 0.90 | 0.325 |
| Fang et al. (1993) | B1-6 | 5.96 | 0.96 | 1.242 |
| Ou et al. (2011) | B-0 | 4.66 | 1.19 | 2.309 |
| Vu (2013) | At-0 | 4.68 | 0.99 | 1.828 |
| | Bt-0 | 4.99 | 1.06 | 1.378 |
| Cheng and Giduqiao (2011) | SP1 | 4.53 | 1.18 | 2.321 |
| Panagiotou et al. (2013) | BEAM 1 | 3.70 | 1.00 | 1.492 |
| | BEAM 2 | 5.46 | 1.08 | 2.735 |
| Marefat et al. (2009) | PN-CS4 | 1.74 | 0.71 | 1.006 |
| Walker and Dhakal (2009) | A1 (rev) | 3.04 | 0.98 | 1.165 |
| | A2 (rev) | 4.29 | 1.01 | 2.038 |
| | D1 (rev) | 3.57 | 0.99 | 2.164 |
| Ou and Chen (2014) | Bt-0 | 4.99 | 1.27 | 1.734 |
| Tanarslan (2011) | Beam 1 | 3.84 | 1.36 | 0.925 |
| | CB-1-i | 5.42 | 1.61 | 1.813 |
| | CB-1-ii | 4.72 | 1.59 | 1.813 |
| | CB-2-i | 5.66 | 1.41 | 2.561 |
| | CB-2-ii | 6.96 | 1.45 | 2.561 |
| | CB-3-i | 7.71 | 1.17 | 2.131 |
| | CB-3-ii | 8.53 | 1.13 | 2.131 |
| | CB-4-i | 5.57 | 1.18 | 2.234 |
| | CB-4-ii | 6.33 | 1.18 | 2.234 |
| | CB-5-i | 4.01 | 1.06 | 1.933 |
| | CB-5-ii | 4.35 | 1.07 | 1.933 |

\( \rho_t \) is ratio of area of distributed transverse reinforcement to gross concrete area perpendicular to that reinforcement. To calculate transverse reinforcement ratio is presented in eq. (1)

\[
\rho_t = \frac{A_{st}}{b \cdot s}
\]

Eq. (1)

where, \( A_{st} \) is total area of transverse reinforcement, \( b \) is width of beam, \( s \) is spacing of transverse reinforcement.
$V_s$ is nominal shear strength provided by transverse reinforcement. To calculate nominal shear strength is presented in eq. (2)

$$V_s = \frac{A_{st} \times f_{yt} \times d}{s}$$

Eq. (2)

where, $A_{st}$ is total area of transverse reinforcement, $f_{yt}$ is yield strength of transverse reinforcement, $d$ is effective depth of beam, and $s$ is spacing of transverse reinforcement.

![Figure 2. Relationship between $M_{exp}/M_n$ and $d_u$](image)

| Confinement parameter | $s/d_b$ | $\rho_t$ | $V_s \times a/M_n$ |
|-----------------------|---------|---------|-------------------|
| Correlation coefficient, $R$ | 0.437 | 0.535 | 0.584 |

A series of linear regression analyses were performed to identify the most influential parameters, on beam ultimate drift ratio. Correlation coefficients $R$, for the complete database of 26 specimen test for various parameters are presented in table 4. Parameters $V_s \times a/M_n$ produce the highest correlation coefficients with beam ultimate drift ratio, with $R$ being 0.584.

### 3.1 Effect of $s/d_b$ ratio

In the database, there are two specimens that have $s/d_b$ larger than $20d_b$. Ultimate drift ratio ($d_u$) of specimen BEAM 1 (Panagiotou et al., 2013) and PN-CS4 (Marefat et al., 2009) is 3.70% and 1.74%, respectively. Results $s/d_b$ presented in figure 3 show that the ultimate drift ratio between that two specimens are different, even though their $s/d_b$ almost the same. The other specimens that have $s/d_b$ less than $15d_b$ can achieve ultimate drift ratio more than 2.0%. Based on figure 3, the relationship between $s/d_b$ and ultimate drift ratio is not clear. Most of the specimen that have $s/d_b$ less or equal than $8d_b$ can achieve 3.00% ultimate drift ratio or larger.
3.2 Effect of transverse reinforcement ratio ($\rho_t$)

Figure 4 and table 3 indicate that ultimate drift ratio is correlated with $\rho_t$, with ultimate drift ratio varying between 1.74% and 8.53% as $\rho_t$ increase from 0.19% to 1.43%. Specimen B (Kinugasa and Nomura, 2006), specimen PN-CS4 (Marefat et al., 2009), and specimen D1 (Walker and Dhakal, 2009) which have a transverse reinforcement ratio below than 0.25%. As shown in figure 4, only specimen D1 can achieve ultimate drift ratio larger than 3.00% compare to other two specimens.

3.3 Effect of $V_s \times a/M_n$

As noted earlier, $V_s \times a/M_n$ has a significant impact on ultimate drift ratio, where $V_s$ is nominal shear strength, $a$ is shear span and $M_n$ is nominal moment capacity. As shown in figure 5, specimen B (Kinugasa and Nomura, 2006) and specimen PN-CS4 (Marefat et al., 2009) cannot achieve 2.50% drift, even though specimen PN-CS4 (Marefat et al., 2009) has $V_s \times a/M_n$ equal to 1.00. Most of the specimens have $V_s \times a/M_n$ larger than 1.00 can achieve ultimate drift ratio larger than 3.00%.
4. Conclusions
Based on the findings of this study, the following conclusions with regards to ultimate drift ratio of cyclic beams can be drawn:
1. The experimental-to-nominal flexural strength ratio ($M_{exp}/M_n$) larger or equal to 1.00 can achieve 3.00% ultimate drift ratio.
2. A maximum transverse reinforcement spacing not exceeding $8d_b$ can achieve minimum 3.00% ultimate drift ratio.
3. The study showed that $V_s \times a/M_n$ increased followed by the ultimate drift ratio.

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Figure 5. Relationship between $V_s \times a/M_n$ and $d_u$
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