Deformation Capacity and Performance-Based Seismic Design for Reinforced Concrete Coupling Beams

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Abstract
Reinforced concrete (RC) coupling beams are essential structural elements for their ability to reduce the bending moment of coupled walls as well as their capacity to dissipate energy. Deformation capacity of RC coupling beams is influenced by the relative depth coefficient of compression zone, the span-depth ratio, and the concrete confinement. In this paper, the relationship of the relative depth coefficient of compression zone $\xi$, the span-depth ratio $\chi$, the confining reinforcement characteristic value $\lambda_{\nu b}$, and the ultimate plastic hinge rotation $\theta_{pib}$ is established firstly. Then, the $\lambda_{\nu b} - \xi - \chi - \theta_{pib}$ relationship is verified by the 48 RC coupling beam experiments conducted by 8 research institutions. Based on the relationship, the performance-based seismic design (PBSD) method for RC coupling beams is proposed. According to the method, the transverse reinforcement can be assessed if the plastic hinge rotation $\theta$ and the damage index $D_{b}$ are predetermined, which forms an important part of the PBSD method for RC coupling beams.

Keywords: reinforced concrete; coupling beam; deformation capacity; performance-based seismic design

1. Introduction
Reinforced concrete (RC) shear walls are frequently used in high-rise buildings as a main lateral resistant system and considerable results have been derived in this field (Zhang et al., 2010). Under the architectural and structural requirements, it is common practice to cut openings in shear walls, so that coupled walls and coupling beams are therefore formed. Coupled walls are not only primary lateral resistant components but also vertical load-bearing elements. If coupling beams are too rigid to rotate at their ends, coupled walls will fail before coupling beams in an earthquake and the buildings’ stability will be at stake, leading to increased difficulties in retrofitting. However, if coupling beams are appropriately designed, they will yield before the failure of coupled walls in earthquakes, and damage or severe damage can be avoided on account of energy dissipation. On the other hand, the performance-based seismic design (PBSD) method has been widely adopted in practice and the global demand indexes have been studied by many researchers (Zhou et al., 2012). Although playing an important role in high-rise building design, the PBSD method regarding members and its demand indexes such as the deformation capacity of the coupling beams has not been received enough attention and needs further investigation. For this reason, the PBSD method for RC coupling beams is proposed in this paper.

There are a variety of factors that influence the deformation capacity of coupling beams, including the relative depth coefficient of compression zone, the span-depth ratio and the ultimate compressive strain of concrete in the plastic hinge region. When the relative depth of the compression zone $\xi$ is between 0.25 and 0.35, the ductile displacements of coupling beams can be 3 to 4. The span-depth ratio $\chi$ of the coupling beam indicates the ratio of its net span to its cross section height which directly influences its seismic behavior; experiments show that coupling beams with a span-depth ratio of $\chi$ less than 2 are more vulnerable to shear failures. The confining reinforcement (usually quantized as transverse reinforcement characteristic value $\lambda_{\nu b}$) is also critical to the ductility of coupling beams owing to its confinement to concrete and against the development of cracks.

The deformation capacity design of coupling beams is aimed at establishing the relationship between the deformation of coupling beams and its influences. In this paper, the relationship of the relative depth...
coefficient of compression zone $\xi$, the span-depth ratio $\chi$, the transverse reinforcement characteristic value $\lambda_{\text{tr}}$, and the ultimate plastic hinge rotation $\theta_{\text{plb}}$ is established, so that the transverse reinforcements at beam ends could be determined according to the proposed deformation demands. As a result, the PBSD method of RC coupling beams could be realized.

2. Relationship of Coupling Beams

It was proposed by Mander et al. (1988) that the ultimate strain of confined concrete $\varepsilon_{\text{cm}}$ could be obtained as follows:

$$\varepsilon_{\text{cm}} = 0.004 + \frac{1.4\rho_v \sigma_y}{f_c} \varepsilon_{\text{sm}}$$

where $\rho_v$ is the confining transverse reinforcement rate; $f_{\text{cm}}$ means the yielding stress of transverse reinforcement; $\varepsilon_{\text{sm}}$ represents the ultimate tensile strain of transverse reinforcement. Meanwhile, the peak stress of the confined concrete is $f_c = f_{\text{cm}}$ where the strength enhancement coefficient $k$ is related to the transverse reinforcement characteristic value and $f_c$ represents the design value of the concrete axial compression strength. According to the reference (Lu et al., 1996), when the transverse reinforcement characteristic value $\lambda_{\text{tr}}$ is 0.05 to 0.30 (which covers the common practices in constructions), $k$ varies from 1.12 to 1.62, meaning that $k$ does not change much in this range.

The transverse reinforcement characteristic value in the boundaries of coupling beams:

$$\lambda_{\text{ab}} = \rho_v \frac{f_{\text{cm}}}{f_c}$$

Substitute Eq. (2) into Eq. (1), therefore,

$$\lambda_{ab} = \frac{k}{1.4} \varepsilon_{sm} - 0.004$$

The ultimate compressive strain is

$$\varepsilon_{\text{cm}} = (x_n - d) \frac{\phi_{\text{ab}}}{f_{\text{cm}}} \approx x_n \frac{\phi_{\text{ab}}}{f_{\text{cm}}} = \xi h_{\text{ho}} \phi_{\text{ab}}$$

Substitute Eq. (4) into Eq. (3), there is,

$$\lambda_{ab} = \frac{k}{1.4} \frac{\xi h_{\text{ho}} \phi_{\text{ab}} - 0.004}{\varepsilon_{sm}}$$

where $\phi_{\text{ab}}$ is the ultimate curvature of the beam cross section; $x_n$ means the depth of the actual compression zone and $x_n = \xi h_{\text{ho}}$ where $\xi$ stands for the relative length of the actual compression zone; $h_{\text{ho}}$ is the effective depth of the beam cross section. In the following derivations, the minor difference between $h_b$ (which stands for the depth of the beam cross section) and $h_{\text{ho}}$ is ignored and $h_b$ is uniformly replaced by $h_{\text{ho}}$ in this paper; $d$ is the distance between the inner edge of transverse reinforcement and the edge of the compression zone.

Calculate the relative depth of the actual compression zone $\xi_h$, as,

$$\xi_h = \frac{\xi}{\beta}$$

where $\xi$ is the relative depth of the compression zone specified by the "Code for design of concrete structures" (GB50010-2002) (MOC, 2002). If $\beta = 0.8$ then the relative depth of the compression zone could be,

$$\xi_h = 0.25 \xi$$

The ultimate curvature of the beam cross section at boundaries $\phi_{\text{ab}}$ could be calculated as below,

$$\phi_{\text{ab}} = \frac{\theta_{\text{plb}}}{l_{\text{ph}}}$$

where $\theta_{\text{plb}}$ stands for the ultimate plastic hinge rotation of the boundaries and $l_{\text{ph}}$ stands for the equivalent plastic hinge length at boundaries.

Substituting Eq. (7) and (8) into Eq. (5), gives,

$$\lambda_{ab} = \frac{k}{1.4} \frac{1.25 \xi h_{\text{ho}} \phi_{\text{ab}}}{l_{\text{ph}}} \frac{l_{\text{ph}}}{l_{\text{ph}}} - 0.004$$

Shen (1981) proposed that the equivalent plastic hinge length $l_{\text{ph}}$ is related to the span-depth ratio $\chi$,

$$\frac{l_{\text{ph}}}{h_b} = 0.25 + 0.05 \frac{\chi}{h_b} = 0.25 + 0.05 \chi$$

where $l_b$ stands for the length of the beam. Substitue Eq. (10) into Eq. (9), therefore,

$$\lambda_{ab} = \frac{k}{1.4} \frac{1.25 \xi h_{\text{ho}} \phi_{\text{ab}}}{\left(0.25 + 0.05 \chi\right)} - 0.004$$

According to the ultimate tensile strain of transverse reinforcement $\varepsilon_{\text{sm}}$, and the data range of the strength enhancement coefficient $k$, in order to simplify the equation, let $k/1.4\varepsilon_{\text{cm}}$ in Eq. (11) be 6 so that Eq. (11) can be simplified as,

$$\lambda_{ab} = \frac{7.5 \xi h_{\text{ho}} \phi_{\text{ab}}}{\left(0.25 + 0.05 \chi\right)} - 0.024$$

So far the $\lambda_{ab} = \xi - \chi = \theta_{\text{plb}}$ relationship of coupling beams has been established. Verification of the relationship is executed in the following sections.

3. Verification of the $\lambda_{ab} = \xi - \chi = \theta_{\text{plb}}$ Relationship of Coupling Beams

The regular coupling beam reinforced only with flexural and lateral shear steel bars, is the most extensive pattern adopted at home and abroad due to its simple configuration and convenience for construction. Therefore a substantial number of experiments have been carried out by institutes around the world.

In this paper, experimental data of 48 coupling
beams have been collected from 8 research institutes which are: Tsinghua University (Zhou et al., 2005; Zhao and Kwan, 2006), Tianjin Research Institute of the Building Science and Department of Civil Engineering of Tianjin University (Li et al., 1984), Chongqing University (Yang, 1998; Zhang, 2006; Liu, 2006), South China University of Technology, Harbin Institute of Technology, Hong Kong Polytechnic University (Wu et al., 2002; Liu et al., 2003) and National Technical University of Athens (Tassis et al., 1996). The experimental data of coupling beams from the above institutes are listed in Table 1. with a certain portion of data excluded because of their configuration failure mode. 

The material properties of the above experiments are as follows, which covers the common use in coupling beams: the axial compressive strength of concrete is 22 MPa to 41 MPa; the yield strength of longitudinal rebar is 235 MPa to 484 MPa; the yield strength of stirrup ranges from 235 MPa to 296 MPa. 

$\lambda_{ub}$ in Table 1. stands for the reinforcement characteristic value at the boundaries of the coupling beams, calculated by Eq. (2) with the material data of the experiments.

Table 1. Experimental Data of Coupling Beams

| No. | Specimen | $\chi$ | $\xi$ | $\theta_{ub}$ (%) | $\theta_{plb}$ (%) | $\phi_{ub}$ ($10^{-4} \text{mm}^{-1}$) | $\phi_{plb}$ (%) | $\lambda_{ub}$ |
|-----|----------|------|------|----------------|----------------|-----------------|---------------|-------------|
| 1   | CB02     | 1.46 | 0.176| 0.66          | 5.00           | 3.96            | 5.32          | 0.082       |
| 2   | CB03     | 1.42 | 0.136| 0.85          | 5.74           | 5.10            | 6.09          | 0.065       |
| 3   | CB04     | 1.45 | 0.169| 0.80          | 3.80           | 4.80            | 3.91          | 0.276       |
| 4   | CB05     | 1.43 | 0.180| 1.00          | 4.26           | 6.00            | 4.35          | 0.211       |
| 5   | CB06     | 1.44 | 0.211| 1.00          | 3.00           | 6.00            | 2.92          | 0.176       |
| 6   | CB07     | 1.44 | 0.278| 0.60          | 3.40           | 3.60            | 3.55          | 0.567       |
| 7   | CB08     | 1.43 | 0.220| 1.00          | 2.34           | 6.00            | 2.18          | 0.262       |
| 8   | CB09     | 1.44 | 0.222| 0.84          | 3.00           | 5.04            | 2.99          | 0.231       |
| 9   | CB10     | 1.42 | 0.273| 0.80          | 3.66           | 4.80            | 3.77          | 0.148       |
| 10  | CB11     | 2.95 | 0.197| 0.64          | 3.61           | 2.56            | 3.45          | 0.058       |
| 11  | CB12     | 3.01 | 0.178| 1.01          | 5.33           | 4.05            | 5.03          | 0.285       |
| 12  | CB13     | 3.06 | 0.201| 0.64          | 4.00           | 2.56            | 3.85          | 0.219       |
| 13  | CB14     | 3.06 | 0.186| 0.99          | 3.11           | 3.95            | 2.66          | 0.131       |
| 14  | CB15     | 2.96 | 0.238| 0.57          | 3.19           | 2.29            | 3.03          | 0.108       |
| 15  | CB16     | 2.94 | 0.371| 0.93          | 2.43           | 3.73            | 1.98          | 0.428       |
| 16  | LL-1     | 1.69 | 0.273| 0.80          | 3.85           | 2.38            | 3.86          | 0.086       |
| 17  | LL-2     | 1.68 | 0.277| 0.61          | 4.10           | 1.82            | 4.23          | 0.097       |
| 18  | LL-6     | 2.50 | 0.284| 1.01          | 7.07           | 3.00            | 7.01          | 0.099       |
| 19  | LL-14    | 2.50 | 0.416| 1.20          | 3.30           | 3.60            | 2.81          | 0.080       |
| 20  | LL-15    | 2.50 | 0.475| 1.30          | 2.30           | 3.88            | 1.67          | 0.067       |
| 21  | L-1      | 5.36 | 0.355| 0.56          | 3.72           | 2.23            | 3.48          | 0.163       |
| 22  | L-2      | 5.36 | 0.396| 0.60          | 3.82           | 2.39            | 3.56          | 0.228       |
| 23  | CB-30    | 1.00 | 0.152| 0.33          | 1.42           | 1.40            | 1.58          | 0.272       |
| 24  | CB-31    | 1.00 | 0.178| 0.34          | 1.55           | 1.46            | 1.73          | 0.198       |
| 25  | CB-1A    | 1.00 | 0.162| 1.56          | 4.84           | 9.36            | 5.26          | 0.117       |
| 26  | CB-1B    | 1.67 | 0.200| 1.28          | 3.71           | 7.68            | 3.47          | 0.132       |
| 27  | L-A      | 5.17 | 0.375| 0.57          | 2.67           | 2.28            | 2.38          | 0.158       |
| 28  | L-C1     | 4.46 | 0.325| 0.56          | 3.19           | 2.68            | 2.95          | 0.113       |
| 29  | L-C2     | 4.46 | 0.300| 0.56          | 3.49           | 2.67            | 3.28          | 0.127       |
| 30  | L-D      | 5.36 | 0.338| 0.67          | 2.62           | 2.68            | 2.24          | 0.089       |
| 31  | L-E      | 5.83 | 0.277| 0.97          | 3.16           | 3.31            | 2.57          | 0.090       |
| 32  | LL-1     | 1.00 | 0.177| 0.78          | 2.29           | 3.33            | 2.47          | 0.046       |
| 33  | LL-2     | 1.00 | 0.194| 0.78          | 2.29           | 3.33            | 4.46          | 0.071       |
| 34  | LL-4     | 1.75 | 0.234| 1.73          | 4.93           | 7.41            | 4.54          | 0.047       |
| 35  | LL-5     | 1.75 | 0.263| 1.49          | 5.46           | 6.37            | 5.25          | 0.088       |
| 36  | LL-6     | 1.75 | 0.375| 1.57          | 5.29           | 6.73            | 5.02          | 0.135       |
The distribution of specimen parameters is visually illustrated in Fig.1., where the span-depth ratio ranges from 1.00 to 5.80; the relative depth of the compression zone $\xi$ covers 0.059 to 0.475; the experimental value of the transverse reinforcement characteristic value $\lambda_{vb}$, $e$ is 0.046 to 0.567. As the uniformly accepted method to decide the yield and the ultimate displacement of a specimen has not been proposed, the Park method (Park, 1989) which is relatively widely used is adopted to decide the yield displacement for the sake of consistency; the ultimate displacement is defined as the displacement when the enveloping curve declines to 85% of the maximum bearing capacity.

After the definition of the yield displacement and the ultimate displacement, other deformation-related parameters are subsequently decided and illustrated in Fig.1., where the yield drift $\theta_{yb}$ covers 0.33 to 2.29%; the ultimate drift $\theta_{ub}$ ranges from 1.42% to 10.00%; the ultimate hinge rotation $\theta_{u_{plb}}$ is 1.58% to 10.75%. These

| No. | Specimen | $\chi$ | $\xi$ | $\theta_{yb}$ (%) | $\theta_{ub}$ (%) | $\theta_{u_{plb}}$ (%) | $\lambda_{vb}, e$ |
|-----|----------|-------|------|-----------------|-----------------|-----------------|-----------------|
| 37  | LL-10$^{15}$ | 1.75  | 0.339| 2.17            | 5.61            | 9.31            | 5.07            | 0.099
| 38  | LL-11$^{15}$ | 2.50  | 0.276| 1.71            | 3.93            | 7.35            | 3.17            | 0.119
| 39  | LL-13$^{15}$ | 2.50  | 0.375| 2.14            | 6.00            | 9.18            | 5.13            | 0.224
| 40  | LL-14$^{15}$ | 3.50  | 0.295| 1.57            | 5.00            | 6.73            | 4.22            | 0.110
| 41  | LL-16$^{15}$ | 3.50  | 0.436| 2.29            | 6.64            | 9.80            | 5.47            | 0.257
| 42  | CB-1$^{16}$ | 1.00  | 0.216| 1.00            | 2.53            | 4.29            | 2.70            | 0.179
| 43  | CB-2$^{16}$ | 1.00  | 0.108| 1.21            | 2.57            | 5.20            | 2.69            | 0.242
| 44  | MCB1b$^{18}$ | 1.17  | 0.140| 1.50            | 8.57            | 6.43            | 9.33            | 0.110
| 45  | MCB2a$^{18}$ | 1.40  | 0.190| 1.30            | 3.14            | 5.56            | 2.97            | 0.106
| 46  | MCB2b$^{18}$ | 1.40  | 0.070| 0.85            | 9.86            | 3.66            | 10.75           | 0.113
| 47  | MCB3$^{18}$ | 1.75  | 0.124| 0.57            | 7.00            | 2.45            | 7.45            | 0.119
| 48  | MCB4$^{18}$ | 2.00  | 0.059| 0.59            | 10.00           | 2.55            | 10.62           | 0.123

Fig.1. Experimental Data Distribution of Coupling Beams

Fig.2. Comparison between the Calculation Results $\lambda_{vb}$ and the Experimental Data $\lambda_{vb}$
The calculated transverse reinforcement characteristic values (hereafter called theoretic value) are derived by Eq. (12) and compared with the experimental values, which are demonstrated in Fig. 2. The result shows that: when taking the theoretic value $\lambda_{vb,c}$ and experimental value $\lambda_{vb,e}$ of the boundary transverse reinforcement characteristic value as $x$-axis and $y$-axis separately, the dots uniformly and bilaterally distribute along the $y = x$ line. The ratio of $\lambda_{vb,c}/\lambda_{vb,e}$ ranges from 0.13 to 4.51, averaging as 1.47. And the variation coefficient of the ratio is 0.72, which is slightly weak and may result from the different experimental conditions and the approximate methods to calculate the yield and ultimate displacement.

Now the PBSD method of coupling beams is applicable using Eq. (14), bringing the problem of how to choose the damage indexes of a coupling beam.

In this paper, the damage indexes based on four performance levels are employed and illustrated in Table 2. The damage indexes and their corresponding performance levels are provided in the research results of the Structural Engineers Association of California (SEAOC, 1995) and Applied Technology College (ATC, 1996). And the procedure of the PBSD method concerning the coupling beam is illustrated in Fig. 3.

According to the flow chart in Fig.3., an example of the PBSD method for a coupling beam is conducted as follows, given the span of the coupling beam $l_b$ (2400 mm), the height of the cross section $h_b$ (500 mm), the width (220 mm), and the concrete grade C40 ($f' = 19.1$MPa).

As Fig.4. shows, the reinforcement determined by the first stage design is: $5 \Phi 25 (A_s = 2454 \text{mm}^2, f_y = 300$MPa) at the top of the cross section and $4 \Phi 20 (A'_{s} = 2454 \text{mm}^2, f'_y = 300$MPa) at the bottom of the cross section.

Fig.4. Section and Reinforcement of the Coupling Beam (mm)

The PBSD method of the coupling beam proceeds as below:

1. Suppose the damage index of the coupling beam $D_b = 0.4$;
2. Calculate the plastic hinge rotation demand $\theta_{phb}$ using the method proposed by Huang (2009).
3. Calculate the relative depth of the compression zone $\xi = (A_s f_y - A'_{s} f'_y) / f_b h_b = 0.194$, and the span-depth ratio $\chi = l_b / h_b = 2400 / 500 = 4.8$;
4. Determine the transverse reinforcement characteristic value $\lambda_{vb}$ using Eq. (14);
5. Calculate the confining transverse reinforcement rate $\rho_v = 0.93\%$, and consequently determine the transverse stirrup $\phi 10@100$.

Table 2. Performance Levels and Damage Indices of Coupling Beams

| Condition description | Fully intact | Slightly damaged | Moderately damaged | Nearly collapsed |
|-----------------------|--------------|------------------|--------------------|------------------|
| $D_b$ | 0–0.1 | 0.1–0.4 | 0.4–0.6 | 0.6–0.9 |
| Few slight cracks emerge on the surface of the coupling beams whose width is less than 1 mm. | Some cracks emerge on the surface of the coupling beams whose width is less than 3 mm. | A large amount of shear and flexural cracks emerge on the surface of the coupling beams. | Concrete spalls and flakes away from the coupling beams. |

The PBSD method of the coupling beam proceeds as below:

4. Performance-Based Seismic Design of Coupling Beams

Suppose the plastic rotation demand of coupling beams’ ends is $\theta_{phb}$ and define the damage index of coupling beams as below:

$$ D_b = \frac{\theta_{phb}}{\theta_{phb}} $$

Then, Eq. (12) could be rewritten as

$$ \lambda_{vb} = \frac{7.55 \xi D_b}{D_b (0.25 + 0.05 \chi)} - 0.024 $$
5. Conclusions

Soundly designed RC coupling beams could be regarded as the first seismic fortification line to avoid failure or severe damage in the coupling wall-columns, so the safety of buildings is improved and the difficulty of retrofitting after earthquakes is reduced. Therefore it is critical to apply the PBSD method for RC coupling beams. Deformation capacity design of structural members is required in the PBSD method, which is to build the relationship between member deformation and its influencing factors.

Deformation capacity of the RC coupling beam is dominated by the relative depth of the compression zone $\xi$, the span-depth ratio $\chi$, and the configuration of transverse reinforcement, etc.

In this paper, the relationship between the relative depth of the compression zone $\xi$, the span-depth ratio $\chi$, the transverse reinforcement characteristic value of RC coupling beams $\lambda_{rb}$ and the ultimate plastic hinge rotation at beam ends $\theta_{plb}$ is established, namely the $\lambda_{rb} - \xi - \chi - \theta_{plb}$ relationship.

Then, the equation is verified by 48 RC coupling beams from 8 institutes. On the basis of the equation, a PBSD method of RC coupling beams is proposed. Using this method, designers could calculate the transverse reinforcement at beam ends in light of the proposed deformation requirements, provided that the plastic hinge rotation $\theta_{plb}$ and the damage index $D_b$ are predetermined.

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