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Static loading experiment of RC beams focusing on buckling of longitudinal bars
Part 4 Comparison among safety limits

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1. Introduction

The evaluation of drift at buckling of beam longitudinal reinforcing bar was explained in **Part 3**. This part describes an analytical study to evaluate each safety limit of RC beam member based on the seismic performance evaluation of RC buildings [1]. Moreover, this part analytically verifies that the buckling of the beam longitudinal reinforcing bars should be considered as the safety limit of RC beam member.

2. Analytical Evaluations

A flexural analysis was performed to evaluate each safety limit of RC beam member according to the seismic performance evaluation [1]. The analytical results were also used to evaluate one of the safety limits by the buckling of beam longitudinal bar. In the present study, the evaluations were performed only focusing on **Specimen 1** of **Part 1** [2], as it was the standard beam specimen representing the weak beam-strong column RC frame in the previous study [2]. Details of the flexural analysis are explained in the following sections.

2.1 Flexural analysis

In this study, a pushover analysis was performed to investigate the moment-curvature relationship of the RC beam specimen based on fiber approach to evaluate the safety limits. The cross section of the specimen was replaced by finite elements representing the concrete and longitudinal bars. The concrete was divided into finite numbers of small fibers with the depth of 5 mm, as shown in **Fig. 1** and the longitudinal bars were defined as per their positions in the cross section. During the analysis, a constant axial load of 673 kN was applied because the specimen was subjected to the same amount of axial load during the experiment, as explained in **Part 1** [2].

The modified Kent and Park model [3] was used for the compressive stress-strain relationship of the concrete as it offers a good balance between simplicity and accuracy. Whereas, the bilinear steel model was used for reinforcing bars, where the post-yield stiffness was assumed to be 0.1% of the elastic stiffness. The tensile strength of the concrete was neglected within this analysis. The concrete and reinforcement properties were as explained in **Table 2** and **Table 3** of **Part 1** [2].

2.2 Flexural analysis results

The flexural analysis provides the relation between the moment (M) and the curvature ($\emptyset$). On the other hand, the experimental results were represented by the relation between shear force (Q) and drift ratio (R), as shown in **Part 2** [4]. Hence, to verify the reliability of the analysis for the experiment, the analytical relation was converted in the form of shear force (Q) and drift ratio (R) by using the **Eqs. (1)** and **(2)**. In **Eq. (1)**, H_s is the shear span of the specimen (=2,650 mm) shown in **Part 1** [2].

$$Q = M/H_s \quad (1)$$

$$R = l_p.\emptyset \quad (2)$$

Fig. 2 shows the curvature profile along the beam length during the experiment, which was evaluated using the strain data from the strain gauges. The range exceeding the yield curvature of the beam specimen was limited about half of the beam depth, as shown in **Fig. 2**. Hence, the plastic hinge length (l_p) was assumed to be half the beam depth (= 350mm) in **Eq. (2)**.

Fig. 3 shows the shear force vs. drift ratio relationships from the analysis and from the experiment. In **Fig. 3,** the symbols (▲), (△) represent drifts at the formation of a yield mechanism with flexural hinging at the beam critical section from the analysis and from the experiment, respectively, whereas (●) and (X) represent the maximum strength and the ultimate state at buckling of longitudinal reinforcing bar from the analysis in the same figure.

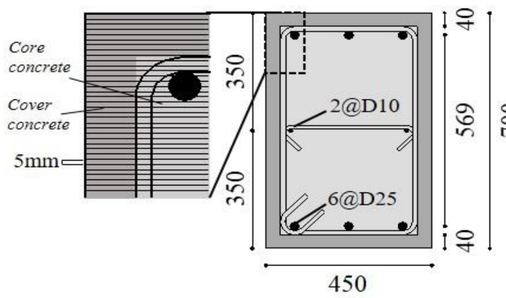

Fig. 1 Fiber modeling for flexural analysis

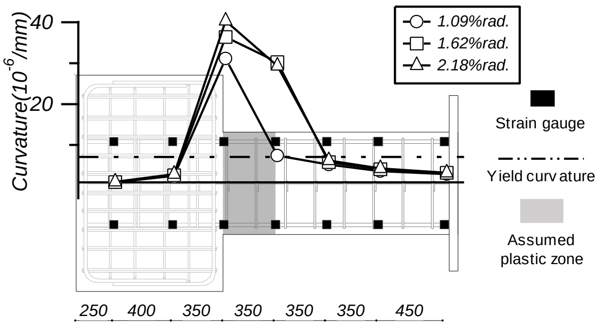

Fig. 2 Curvature profiles along the specimen

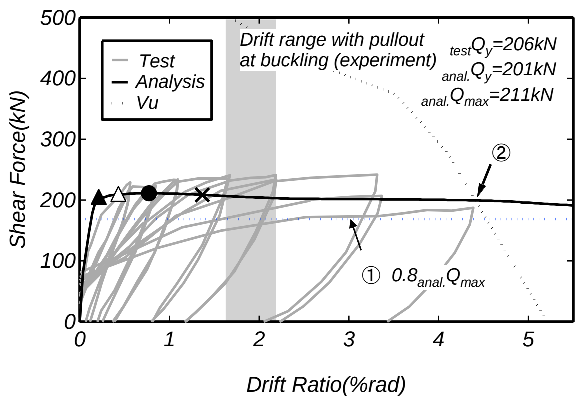

Fig. 3 Safety limits related to ① and ② based on the Japanese guideline [2]

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The analytical drift at buckling was evaluated by considering the equivalent analytical drift at which the tensile strain of the longitudinal bar was the same as the buckling limit strain (ε_B) as evaluated in **Part 3**. Moreover, **Fig. 3** also shows the drift range where the longitudinal bar buckling was observed in the experiment.

Fig. 3 shows that the analysis results are almost consistent with the experimental results. However, the maximum strength from the analysis underestimated the experimental value. The assumed post-yield stiffness of the reinforcing bars neglecting strain hardening as well as the neglected tensile strength of the concrete for the simplicity of the analysis might be the reasons behind such underestimated value. In addition, the stiffness to the yield point from the analysis a little overestimated the experimental result because the deformation with the pullout behavior of the longitudinal reinforcing bars from the stub was not taken into account in the flexural analysis.

3. Assessment of the Safety Limits

This section evaluates the safety limits of the RC beam specimen according to the seismic performance evaluation guidelines for RC buildings [1] based on the flexural analysis results explained in **Section 2**. The definition of each safety limit is as explained below:

① The flexural resistance decreases to 80% of its maximum strength. As shown in **Fig. 3**, the shear resistance of the beam specimen in the flexural analysis did not fall below the 80% of the maximum strength (even up to R = 6% rad).

② Shear failure occurs after flexural yielding. The ultimate shear strength after flexural yielding of the RC beam specimen was evaluated by using **Eq. (3)** according to the design guidelines for earthquake resistant reinforced concrete buildings based on inelastic displacement concept [5].

$$V_u = \mu p_{we}\sigma_{wy}b_e j_e + \left(\nu\sigma_B - \frac{5p_{we}\sigma_{wy}}{\lambda}\right)\frac{bD}{2}\tan\theta$$

$$V_u = \frac{\lambda\nu\sigma_B + p_{we}\sigma_{wy}}{3}b_e j_e \qquad (3)$$

$$V_u = \frac{\lambda\nu\sigma_B}{2}b_e j_e$$

where,

$$\mu = 2 - 20R_p$$

$$\nu = \left(1 - 20R_p\right)\cdot\left(0.7 - \frac{\sigma_B}{200}\right)$$

$$\lambda = 1 - \frac{s}{2j_e} - \frac{b_s}{4j_e}$$

$$\tan\theta = 0.9\frac{D}{2L}$$

Symbols in the equations are referred to the reference [5].

As shown in **Fig. 3**, the evaluated ultimate shear strength became lower than the shear resistance after R = 4.40% rad. This indicated that the shear failure after flexural yielding was likely to occur in R = 4.40% rad.

③ Tensile rupture of beam longitudinal reinforcing bars. In general, the tensile breaking strain is approximately 100 times the yield strain. As shown in **Fig. 4**, the tensile strain of the longitudinal reinforcing bars obtained from the flexural analysis was much lower than the estimated tensile breaking strain (200,000μ); thus. the tensile breaking of the longitudinal reinforcing bars was not likely to take place. In addition, the averaged experimental tensile strain of the longitudinal reinforcing bar was also much lower than the tensile breaking strain, as shown in the same figure.

The analytical drift had a good agreement with the experimental drift range at buckling of beam longitudinal reinforcing bars (evaluated as R = 1.62% to 2.18% rad), as explained in **Part 3**, which was a smaller drift than the safety limits of the RC beam specimen evaluated by the above mentioned seismic performance evaluation guidelines [1]. Hence, this study confirmed that the buckling of beam longitudinal reinforcing bars should be considered as the safety limit of RC beam member.

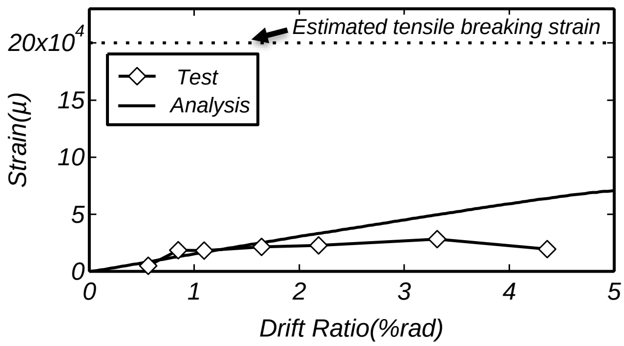

Fig. 4 Strain vs. drift ratio relationships

4. Concluding Remarks

The flexural analysis showed the consistent results with the experimental results representing that the buckling of beam longitudinal reinforcing bars occurred before the safety limits of common RC beam member as stated in the seismic performance evaluation of RC buildings [1]. Hence, this study concludes that the buckling of the beam longitudinal reinforcing bars should be considered as the safety limit of weak beam-strong column type RC moment-resisting buildings.

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