# BACKGROUND OF PROPOSED SEISMIC CODE PROVISIONS FOR REINFORCED CONCRETE BUILDINGS

K. N. Shiu (I)
W. G. Corley (II)
Presenting Author: K. N. Shiu

## SUMMARY

This paper discusses six proposed seismic code provisions for reinforced concrete buildings. The six code provisions have been submitted to model code groups for incorporation into existing building codes. Proposed seismic code provisions are categorized as strength provisions and reinforcement details. Proposed strength provisions include lightweight concrete and shear design of structural walls. Proposed reinforcement details include modifications of supplementary cross-ties, regions for concrete confinement in boundary elements of structural walls, and details of tension lap splices. In addition, special reinforcement for coupling beams with clear span-to-depth ratios of less than 4.0 is proposed.

## INTRODUCTION

In recent years, significant information on seismic behavior of reinforced concrete buildings has been published. With expanding research activities, State-of-the-Art on design of earthquake resistant buildings entered into a new era. However, seismic code provisions have not yet incorporated this large influx of research information. Therefore, an effort was made to incorporate some State-of-the-Art information into seismic codes. This paper discusses the background and reasons for six proposed seismic code provisions for reinforced concrete buildings. The proposed seismic code provisions are categorized as strength provisions and reinforcement details.

## STRENGTH PROVISIONS

Proposed strength provisions include lightweight concrete and shear resistance of structural walls.

### Lightweight Concrete

Many building codes limit lightweight concrete design strength to 4000 psi. This restriction is primarily based on the following two reasons:

1. In the San Fernando earthquake, lightweight concrete structures suffered more damage than normal-weight concrete (Ref. 1).

(I) Structural Engineer, Construction Technology Laboratories, a division of Portland Cement Association, Skokie, Illinois, USA

(II) Divisional Director, Construction Technology Laboratories, a division of Portland Cement Association, Skokie, Illinois, USA

2. "Lack of understanding and experimental data on behavior of lightweight concrete structures under inelastic load reversals (Refs. 2, 3)."

Review of damaged structures after the San Fernando earthquake (Ref. 4) did not indicate that severe damage resulted from use of lightweight concrete. No conclusive evidence was found that lightweight concrete was the cause of collapse. In addition, the limited testing results (Ref. 5) from plain concrete cylinder tests do not reflect behavior of reinforced lightweight concrete under seismic loads. Tests by Kaar, et al, (Ref. 6) have shown that high-strength lightweight concretes exhibit ultimate strains equal to corresponding strains of normal weight concrete of lower compressive strengths. Therefore, there is no basis for limiting use of lightweight concrete to strengths less than 4000 psi.

Recently, Construction Technology Laboratories has tested 16 lightweight concrete column specimens with concrete strengths ranging from 4700 to 6200 psi (Ref 7). Column specimens resisted 15 to 30 inelastic load reversals representing severe earthquakes.

In addition, two lightweight beam-column joint specimens were tested by Bertero at the University of California, Berkeley (Ref. 8). Concrete compressive strength was 5000 psi. Data from the lightweight concrete specimens were compared with data from similar normal-weight concrete specimens. Slippage of the reinforcement in the lightweight concrete specimen occurred under load reversals. Thus, Bertero questioned the performance of lightweight concrete under seismic forces.

Additional development length for reinforcement in lightweight concrete has already been specified in building codes to account for the difference in performance of the two concretes. However, the code required increase of development length for reinforcement was not provided in the two lightweight specimens tested at Berkeley. This failure to provide code-specified development length accounts for the premature slip of reinforcement in Bertero's tests.

Reported experimental data indicate that members with lightweight concrete strength in excess of 4000 psi can be used to resist seismic forces. Consequently, a strength limitation on lightweight concrete is not necessary.

## Shear Design of Structural Walls

Current maximum allowable shear stress for structural walls is limited to $10\sqrt{f'_c}$ psi. Reasons for the restriction are to prevent web-crushing (Ref. 9) and to avoid unsightly inclined cracks at working loads (Refs. 10,11).

While it is legitimate to limit wall shear stresses due to lateral forces such as wind loads in walls for aesthetic and serviceability reasons, control of unsightly cracks caused by a severe earthquake is not justified. Earthquake-imposed deformations are to be accommodated through inelastic behavior of structural walls. Therefore, control of unsightly cracks is not consistent with design philosophy.

It is noted that the maximum permissible shear stress of 10 $\sqrt{f'_c}$ psi is arbitrarily selected for prevention of web-crushing. European researchers suggested that shear stress be limited to 0.3 $f'_c$ for members with transverse stirrups (Ref 12). Maximum shear stresses of 15 to 20 $\sqrt{f'_c}$ psi (Ref. 13) have also been proposed for walls with transverse stirrups. Therefore, current maximum permissible shear provision of 10 $\sqrt{f'_c}$ psi is conservative in comparison with European practice.

In addition, limiting shear stress of 10 $\sqrt{f'_c}$ psi was based on beam tests that did not include inelastic load reversals. At the Construction Technology Laboratories, 22 isolated wall specimens with confined boundary elements have been tested under repeated inelastic load cycles and different levels of constant axial forces (Ref. 14). Fourteen wall specimens exhibited web crushing after sustaining maximum top deflections of over four times yield deflection. Similar observations were also made for tests conducted at the University of California, Berkeley (Ref. 15).

Based on reported experimental data and using a theoretical approach, (Refs. 14,16) a relationship between web-crushing shear strength and interstory wall drift was developed (Ref. 17). By limiting interstory wall drift to 0.02 (Ref. 18), the relationship was further simplified into an equation as follows:

$$V_n = 0.14\, f'_c hd + \frac{N_u d}{2\ell_w}$$

$$\text{but} < 0.18\, f'_c hd$$

WHERE:

$f'_c$ = specified compressive strength of concrete, psi

$h$ = overall thickness of wall, inches

$\ell_w$ = horizontal length of wall, inches

$N_u$ = design axial load normal to the cross section occurring simultaneously with $V_n$, to be taken as positive for compression and negative for tension, lbs

$V_n$ = nominal total design shear, lbs

Detailed derivation of the proposed formula is presented elsewhere (Ref. 17).

## REINFORCEMENT DETAILS

Proposed changes of reinforcement details include modifications of supplementary cross-ties, concrete confinement in boundary elements of structural walls, and details of tension lap splices. The new provisions will make construction of earthquake resistant structures more efficient and cost-effective. In addition, proposed special reinforcement for coupling beams with clear span-to-depth ratios of less than 4.0 is presented.

Supplementary Cross-ties

Proposed changes for supplementary cross-ties include revising the 10-bar diameter extension beyond 135° hook to 6-bar diameter extension and the permission to use supplementary cross-ties for concrete confinement.

Over 53 specimens with bar extensions beyond 135° hooks of less than 10-bar diameter have been tested (Refs. 19, 20, 21, and 22) under repeated inelastic load reversals. No sign of distress was reported for the reinforcing detail after testing. In fact, the 6-bar diameter extension beyond 135° hooks is included in the current Japanese Code Requirements of A.I.J. Appendix 18.

Permitting use of supplementary cross-ties alternated end for end along longitudinal bars in place of closed hoops will greatly simplify placement of reinforcement during construction. Tests (Refs. 23, 24) have shown that supplementary cross-ties can effectively replace the currently specified closed hoop reinforcement detail.

Confinement Requirements in Structural Walls

In UBC 82, concrete confinement at the boundary elements of structural walls is required for the full height of the building. However, research over the past decade has found that confinement is not always needed for the full length of the boundary elements. In test specimens, (Refs. 14, 25, 26) and actual structures, hinging regions have been observed to be concentrated at the wall base and other areas such as places with strength discontinuities, and changes in geometry. In some instances, higher mode initial forces can also create hinging along the height of the building. Therefore, it is proposed that special transverse reinforcement be required only at potential hinging regions. Potential hinging regions are identified at base of structural walls, areas with stiffness discontinuities, and other areas as indicated by analyses.

Tension Lap Splices

Current seismic codes specify that lap splices shall be made within the center half of column height. The code-change proposal is to allow longitudinal reinforcement lap splicing outside the center half of column height when special transverse reinforcement is provided along the full splice length.

Tests conducted at Construction Technology Laboratories (Ref. 27) and Cornell University (Ref. 28) have shown that lap splices with proper lateral concrete confinement remain effective and reliable even under inelastic load reversals. It is found that existing recommendations for confinement around splices are conservative. Consequently, imposition of a location limitation on lap splices is unnecessary.

Diagonal Reinforcement in Coupling Beams

Recent research on coupling beams (Refs. 19, 29, 30, 31, and 32) with clear span-to-depth ratios of less than 4.0, indicates that conventional stirrups are less effective than diagonal bars under large repeated inelastic load cycles. Under inelastic load reversals, shear transfer mechanism in short beams changes from conventional truss mechanism to the "sliding shear" type of behavior. Special diagonal reinforcement extending across the full length of beam member (Refs. 19, 30) was found to be able to provide large deformation ductility and energy dissipation capacity for short beams. A simple design equation for the diagonal reinforcement was developed (Ref. 33). The following requirement has been established.

Flexural members with clear span-to-depth ratio of less than four shall have symmetrical diagonal shear reinforcement extended diagonally across full length of member. Required area making up one leg of diagonal reinforcement $A_{vd}$ shall not be less than:

$$A_{vd} = \frac{V_u}{2f_y \sin \alpha}$$

WHERE:

$V_u$ = maximum shear force

$f_y$ = yield stress of diagonal reinforcement

$\alpha$ = angle between diagonal reinforcement and longitudinal axis of member.

Flexural strength contribution by diagonal reinforcement shall be included in the flexural capacity calculation of the member. Diagonal reinforcement shall be located within the confined concrete core.

## CONCLUDING REMARKS

Research work done throughout the world over the last several years has identified several concrete reinforcing details that should be improved. This paper presents recommendations for details of supplementary cross-ties, confinement of boundary elements in structural walls, tension lap splices, and diagonal reinforcement in coupling beams. References showing technical justification for recommendations are cited.

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