SECTION 5

CONCLUDING REMARKS

5.1 Remarks on Testing of Retrofitted Model

5.1.1 Retrofit Design

For typical low-rise and for upper stories of higher-rise GLD R/C frame structures, the seismic response of the structure is governed by weak column - strong beam behavior, which can lead to an undesirable column-sidesway/soft-story collapse mechanism under severe earthquake loadings. A retrofit design should seek to strengthen the vulnerable columns for strong column - weak beam behavior. Global seismic retrofits are required for improved overall structural performance. Seismic retrofit can be used to upgrade existing structures or to repair previously damaged structures for improved behavior during earthquakes.

Since the GLD R/C model was categorized as in a *moderate* - *"repairable"* damage state from the previous earthquakes (Bracci et al., 1992b), retrofit was required to reinstate a *"serviceable"* condition. The retrofit considered not only to repair the previous seismic damage but also to upgrade the structural strength to resist any future earthquakes or large lateral loads. Several retrofit methods were presented and analyzed in various global arrangements for a future strong ground motion. Based on response behavior and several factors concerning modeling, the improved concrete jacketing alternative of the critical interior columns with discontinuous added rebars at the foundation was selected to retrofit the model structure. Prestressing of the added reinforcement was applied to enhance the shear strength of the columns and beam-column joints, to supply a compressive pressure on the discontinuous beam reinforcement in the joints to deter pull-out, and provide an initial strain in the new composite section. A reinforced fillet was also used in the beam-column joints to ensure elastic joint behavior and to provide additional embedment length for the discontinuous beam reinforcement.

5.1.2 Experimental Studies

The characteristics of the retrofitted model in comparison with the original damaged model can be summarized:

1. Large story stiffness and corresponding natural frequency increases after retrofit from column strengthening and stiffening.

2. Decreased "equivalent viscous damping" factors from smaller contributions from hysteretic damping. Post-tensioning reduces the degree of cracking in the structure and thus lowers the equivalent damping.

The seismic behavior of the retrofitted model during the moderate (Taft N21E, PGA 0.20 g) and severe (Taft N21E, PGA 0.30 g) earthquakes can be summarized:

1. Large first story drifts of 1.37% and 2.13% of the story height, respectively. However the second and third story drifts were considerably smaller.

2. The retrofit beam-column joints (R/C fillet) remained primarily elastic throughout the shaking.

3. Cracking and yielding was observed in the interior beams at the ends of the fillet. The moment demands in the exterior beams remained primarily below yielding. The interior beam moment demands exceeded moment capacities that considered slab steel contributions from the full slab width. Strength increases in excess of 30% were observed due to strain hardening of the rebars and dynamic strain rate effects.

4. The columns remained primarily undamaged with exceptions to the lower first story columns. A desirable beam-sidesway mechanism was apparently in development, however beam hinging was not observed in the upper stories. Thus the complete beam-sideway collapse mechanism had not formed.

5. For a typical beam-column-slab component, the nominal moment capacity of the retrofitted columns were about 59% stronger than the nominal strength capacity of the beams that considered slab steel contributions from the full slab width.

6. The response was governed by the first mode of vibration.

7. Large reduction in first story stiffness (60%) and corresponding first natural frequencies (about 35%) occurred after the moderate and severe shaking.

8. The equivalent viscous damping factors were determined to have doubled after the moderate and severe earthquakes due to contributions from hysteretic damping.

9. The measured base shear force demands were 25.0% and 26.4% of the total structural weight for the moderate and severe shaking, respectively. Note that base shear demands were increased about 70% after retrofit as compared to before retrofit from the same earthquakes.

5.1.3 Analytical Studies

Analytical modeling, with structural parameters determined from: (i) engineering approximations; and (ii) component tests, was used to simulate the seismic response of the model.

It can be concluded that:

1. The inelastic analytical modeling based on stiffnesses obtained from engineering approximations grossly underpredicted the first story drift for the moderate and severe earthquakes by about 50%.

2. The inelastic analytical modeling based on stiffnesses obtained from component tests had different initial member values that better fit the experimental response. For the moderate and severe shaking (consecutive runs), the initial stiffness of the retrofitted columns were 0.71 $(EI_{col})_g$ with prestressing and 0.50 $(EI_{col})_g$ at the base columns (no prestressing and discontinuous added reinforcement). The initial stiffness of the interior and exterior beams were 0.32 $(EI_{bm})_g$ and 0.23 $(EI_{bm})_g$, respectively. The analytically predicted damage state was similar to the experimentally measured and observed.

3. The damage evaluation indicated *moderate - "repairable"* damage to the first story beams. The retrofitted interior and unretrofitted exterior columns of the first floor remained within a *minor - "serviceable"* damage state. The overall damage indices were 0.14 and 0.32, respectively after the moderate and severe earthquakes, which imply *minor/moderate* damage states. These are considerably less than the original building under the same earthquakes.

4. The strength reduction factors from inelastic response were comparable to the inelastic design values from UBC (1991) for the severe shaking only (near ultimate strength capacity). However for the moderate earthquake, the code based design reduction factors from UBC (1991) do not relate well with the experimentally observed.

5.2 Conclusions on Retrofit of GLD R/C Structures

Based on the proposed concrete jacketing retrofit of the critical interior columns, the following conclusions can be made about the behavior of this particular type of retrofit for GLD R/C frame structures during earthquakes:

1. Structural retrofits can be designed to successfully enforce strong column - weak beam behavior.

2. Damage can be significantly reduced in the columns by transferring the inelastic behavior to beam hinging.

3. To minimize additional foundation loads, the strengthening should seek to toughen rather than stiffen the base columns. Thus the added rebars in the columns can be discontinued at the foundation leading to only a slight increase moment demand at the foundation.

4. Inaccurate identifications of member properties in non-linear time history analyses can lead to large deviations in response predictions. Since experimental data are not available in actual structures, in extreme uses, component testing can be used to identify the initial member properties for analytical models. In other cases rational proportions of virgin properties may produce satisfactory results.

5. Stiffening and strengthening only selected critical columns can provide adequate control of the response behavior. However the integration of locally retrofitted members must be such to control the overall global response.

6. Repair and seismic retrofit of a moderately damage structure is a viable economic and structural alternative as compared to demolition and reconstruction of another. However, economical aspects must be carefully checked.