RECENT ADVANCES IN CONCRETE MATERIAL MODELING AND APPLICATION TO THE SEISMIC EVALUATION AND RETROFIT OF CALIFORNIA BRIDGES

Joseph Y R RASHID[1], Robert A DAMERON[2] And Robert K DOWELL[3]

SUMMARY

This paper describes recent developments in concrete material modeling and the utility of continuum based methods in the dynamic analysis of important concrete structures. Experimental data generated in quasi-static cyclic tests and dynamic shake-table tests, conducted in the United States and Japan, provided the data base used for both improvement of behavior models and validation of the analysis method. The behavior models affected are shear resistance, reinforcement bond and damping. High quality agreement is achieved for analytical results compared with measured data, both in blind predictions as well as post-test analyses, for a variety of dynamically and quasi-statically tested structures. This provided the confidence needed to integrate the methodology with traditional structural analysis methods for application to the seismic retrofit program in California following the 1989 Loma Prieta and the 1994 Northridge earthquakes.

INTRODUCTION

Structural failures in recent California earthquakes identified serious deficiencies in seismic design methods. As case studies, the failures became the object of extensive experimental and analytical research at University of California (UC) laboratories and private engineering firms. This research formed a critical component of a major earthquake-engineering effort by the California Department of Transportation (Caltrans) for the development of new design methods for the bridge retrofit program following the Loma Prieta earthquake of 1989, Housner [1]. The Caltrans program produced fundamental changes in design philosophy, including the adoption of ductility-based design methods that take advantage of the non-linear-deformation and energy-absorption capabilities of structures. This redirection in design philosophy introduced two new elements into the design process, namely, the use of deformation-based acceptance criteria and the reliance on non-linear analysis methods for the design verification of important transportation structures. The information generated in the Caltrans research and retrofit program provided the engineering basis for the new design criteria, as well as the data required for the validation of analytical methods used for design verification.

Coincidentally with Caltrans' activities in California, and partially motivated by the Kobe earthquake of 1995, an experimental/analytical collaborative research program was conducted by the Nuclear Power Engineering Corporation (NUPEC), a research arm of the nuclear power industry in Japan, and the United States Nuclear Regulatory Commission (USNRC). NUPEC's program consisted of shake-table tests of two large-scale models of pre-stressed and reinforced concrete reactor containment structures. The data generated in these tests was then used in the USNRC program to evaluate the predictive capabilities of state-of-the-art analysis methods for concrete structures, USNRC [2].

Since no structural damage was ever observed in reactor containment structures as a result of an earthquake, the NUPEC-USNRC program was aimed at evaluating safety margins and analytical capabilities, in contrast with Caltrans' program, which dealt with actual failures and structural redesign. The two research programs dealt with two different classes of concrete structures, employing very different approaches for the experimental simulations of earthquake loading. In the UC-Caltrans program, this simulation typically took the form of quasi-

[1] *ANATECH Corp., 5435 Oberlin Dr., San Diego, California, U.S.A.*
[2] *ANATECH Corp., 5435 Oberlin Dr., San Diego, California, U.S.A.*
[3] *ANATECH Corp., 5435 Oberlin Dr., San Diego, California, U.S.A.*

statically applied load cycles with progressively increasing displacement amplitudes until failure of the specimen or a pre-determined ductility capacity was reached. In contrast, NUPEC used time-history simulations of strong-motion earthquakes in which the shaking-table energy input was progressively increased until failure occurred. The same analytical tools were used in both programs, and this provided a rare opportunity to assess the effectiveness and the general applicability of analytical methods for the modeling of concrete structures.

As already mentioned, the analytical capability used to analyze the UC quasi-static tests, was used in the analysis of the NUPEC dynamic tests, with differences only in the geometry of the finite element grids and the loading definition. This analytical capability, given the acronym ANACAP [3], has its origin in the smeared-crack model developed in the sixties, Rashid [4]. Since then, the methodology has undergone extensive development and structural application. Following the Three-Mile Island (TMI) reactor accident in 1979, the ANACAP methodology was used to predict reactor containment failure progression in a loss of coolant reactor accident. ANACAP predictions were confirmed experimentally through a 1/6-scale containment model test conducted by Sandia National Laboratory for the USNRC, Clauss [5]. The Sandia test was the first known example of a blind-prediction, round-robin exercise with wide international participation. Several such large scale tests and pretest analysis exercises have been conducted since that time, and the CAMUS shake-table test of a five-story building in France is the latest example, Mazars [6].

The objective of this paper is to present recent developments in concrete modeling and analysis methods and their application to the dynamic analysis of concrete bridges and other safety structures subjected to strong-motion earthquakes. Progress in the concrete structural- analysis state-of-the-art will be illustrated through examples drawn from the Caltrans, NUPEC and other research programs.

MATERIAL MODELING

Tensile Behavior -- Cracking-Consistent Damping

As already noted, the smeared-crack model forms the basis for the analytical treatment of cracking in concrete, Rashid [4]. The emphasis on the modeling of cracking, when the prevailing design practice is to neglect the concrete tensile capacity, stems from the fact that concrete derives significant strength enhancement from confinement. Therefore, a reduction to a lower state of compression due to cracking is in effect a form of strength degradation. Also the extent and progression of cracking plays an important role in the shear behavior of members, as will be discussed later. Consequently, accurate determination of the state of cracking and its time evolution is essential for the dynamic and cyclic loading analysis. Another important factor for the modeling of cracking is the coupling between damping and the cracking-induced damage which, as will be discussed in a later section, has an important effect on the computed dynamic response of the structure.

The smeared-crack concept is rather simple, and is summarized as follows: a crack evolves as a form of damage-induced material anisotropy, smeared over the element integration-point volume. The stress and modulus in the direction of the normal to the crack surface are degraded exponentially until they become vanishingly small at some crack-opening strain. The experimental fracture energy, which is the area under the material's force-displacement curve in a tension test, is used to derive the analytical equivalent stress-strain curve by equating the specific fracture energy represented in the area under the two curves. Figure 2-1 illustrates the material behavior in tension.

Damping in linear dynamic analysis of concrete structures is generally assigned relatively high values to account for cracks and other forms of damage. In modal superposition analysis, Rayleigh damping is generally used either uniformly for all modes or by assigning different damping ratios for each mode. Finite element codes, however, use a single damping ratio, constant in time, for all elements in the finite element model. Such an approach does not recognize the local variation and the time evolution of damage. In the present analysis, damping is treated at the material constitutive level. A cracking-consistent damping model is introduced in which damping is applied locally at the integration point. The material constitutive matrix is modified by adding an anisotropic viscosity matrix in which the crack directions constitute the principal axes of viscosity. The principal viscosities are derived as functions of the damping ratio, which is assigned different values normal and tangential to the crack surface. Nominal damping is assigned in the direction normal to the crack surface (because damage in that direction is explicitly represented in the constitutive matrix) and a higher value is assigned in the plane of the crack.

Compression Behavior

A modified Drucker-Prager yield surface is used to describe material behavior under compression, Drucker and Prager [7]. The model treats concrete as a non-linear material with small elastic range and makes use of the full cyclic stress-strain curve. The yield surface, which is also a loading surface for strain-hardening material, is a function of the first and second invariants of the stress tensor and the effective-stress position on the stress-strain curve. This is represented in Figure 2-2, which shows a cyclic stress-strain curve and the maximum loading surface for biaxial compression, Kupfer et al. [8].

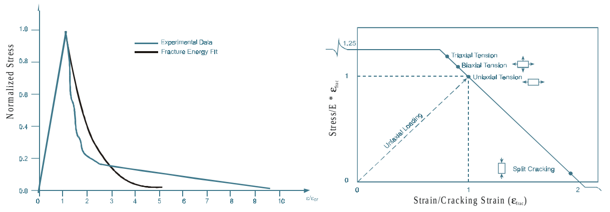

Figure (a). Uniaxial Stress-Strain Curve Figure (b). Cracking Interaction for 3D Tensile Stress

Figure 2-1. Representation of the Tension Response

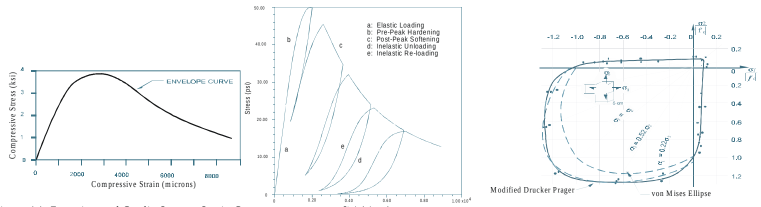

Figure (a). Experimental Cyclic Stress - Strain Curve

Figure (b). Analytical Cyclic Stress - Strain Curve

Figure (c). Biaxial Loading Surface

Figure 2-2. Representation of Compression Response

By itself, a single loading surface is insufficient as a constitutive model for use in dynamic or cyclic analysis. Additional information is needed to develop the incremental constitutive relations that describe stress-strain paths in the five distinct regimes that characterize a full loading cycle, which are: elastic response, pre-peak hardening, post-peak softening, elastic-plastic unloading, and finally elastic-plastic reloading. These states are represented by the analytical stress-strain curve in Figure 2-2b. The three-dimensional constitutive relations are derived in the usual way, making the following postulates: (a) The loading surface evolves as a self-similar surface, namely, it uniformly expands during loading and uniformly contracts during unloading. (b) The effective-stress vs. effective-strain curve is the locus of any stress point on the loading surface. (c) A flow rule exists which states that the plastic strain rate vector remains normal to the loading surface throughout the deformations.

Shear Behavior

The shear behavior of concrete structures is one of the most elusive problems in concrete continuum modeling. Under earthquake loading, shear and cracking are strongly coupled. A simple representation of the shear behavior of cracked concrete is to reduce the shear modulus as a function of the crack-opening strain, shown in plain-concrete tests by Al-Mahaidi [9] and others. While the analytical expressions developed from such tests are convenient to use in finite element computations, they can significantly under-estimate the shear strength of reinforced concrete under combined shear and tension. Under combined shear and compression, these models revert back to the behavior of uncracked concrete, thereby over-estimating the shear response. Both of these deficiencies are corrected by adding to Al-Mahaidi's correlation a sub-model for shear-shedding in the closed-crack regime and a shear-enhancement sub-model for shear retention in the open-crack regime, as shown in Figure 2-3.

Rebar Bond Behavior

ANACAP utilizes rebar sub-elements with a bond-slip model proposed by Dameron [10], coupled with a bond-failure criterion suggested by Priestley [11]. The Priestley Criterion states that the bond strength is nearly nil after the concrete tensile strain normal to the rebar reaches a value of 0.1%. It is interesting to note that, although this criterion was proposed to explain experimental observations and was never intended for finite element applications, it proved to be a useful concept and highly adaptable to implementation in reinforced concrete continuum modeling. This is because, with the use of rebar sub-elements overlain onto a concrete parent element, the concrete strain normal to the rebar is always known at the time of evaluation of the rebar stress-strain state. The bond-slip model is imbedded in the rebar material constitutive model by modifying the failure surface and the shape of the unloading and reloading curves when the local concrete strain criterion is met, as shown in Figure 2-4.

COMPARISON TO EXPERIMENTS

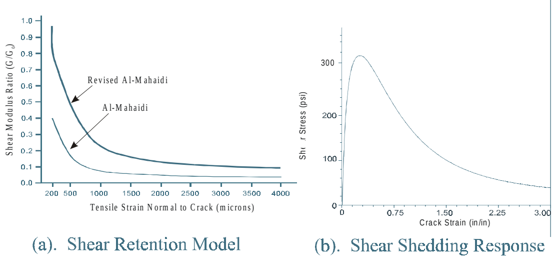

Figure 2-3. Representation of Shear Response

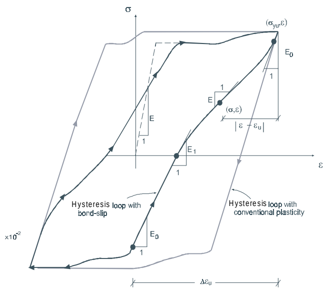

Figure 2-4. Rebar Bond-Slip Model

As previously noted, two types of earthquake simulation tests have been performed to evaluate structural performance under seismic loads: quasi-static cyclic tests and shake-table dynamic tests. Many of the quasi-static tests were performed at UC Berkeley and UC San Diego using large-scale models of bridge components, both in the as-built and the retrofitted conditions. Because of space limitations, only the most recent of the quasi-static tests is presented here - other examples can be found in the cited references. To illustrate dynamic analysis capabilities, two examples having different structural attributes are selected.

Quasi-Static Cyclic Tests -- Shear Wall with Confined End Regions

Recent tests were conducted at UC San Diego, Hines et al. [12], to study the behavior of a new composite-column similar to that proposed for two major bridges currently being designed: the East spans of the San Francisco-Oakland Bay Bridge and the new Carquinez Straits suspension bridge. Due to space limitations, only one of the tests is presented here to illustrate the predictive capability of the ANACAP methodology for quasi-static cyclic behavior. The test specimen is not scaled directly from the prototype, but rather was designed to give representative behavior. The test has just been completed, and Professor Frieder Seible at UC San Diego has graciously given his permission to discuss the results in this paper.

The test structure is a composite reinforced concrete column consisting of confined circular elements with connecting shear wall. Of particular concern in this test is the ability of the shear wall to properly link the confined column end regions together so that the entire section can act in a composite manner. Also, as no transverse ties are provided in the wall, there is concern for crushing of the unconfined shear-wall concrete, thus resulting in buckling of the wall's vertical reinforcement.

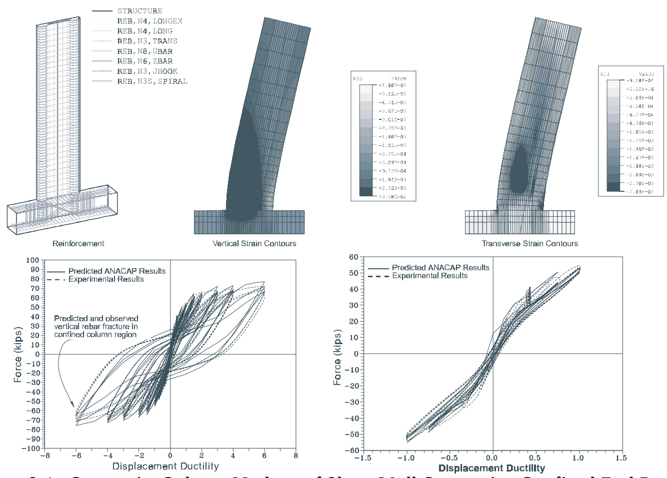

Figure 3-1. Composite Column Madeup of Shear Wall Connecting Confined End Regions

The analysis was performed using a half-symmetry model, as illustrated in Figure 3-1 which includes the structure outline and the reinforcement. Monotonic and cyclic top horizontal displacement was applied in the plane of symmetry. The finite element model consisted of 3-D solid elements for the concrete and bar sub-elements for the reinforcement. The material properties input consisted of the concrete design compressive strength and the measured stress-strain curves of the reinforcement. Analytical predictions are shown in Figure 3-1 for vertical strain distribution at a monotonic-loading ductility 6, indicating the range of concrete spalling in compression (above 0.5%) and reinforcement yielding in tension (above 0.23%). Transverse strain contours show the range of yielding at the transverse wall steel (above 0.23%). The figure also shows hysteresis loops for ductility ratios of one and six.

Note that the analysis and test results are presented in Figure 3-1 up to the fracture of the vertical reinforcement. As can be seen, the prediction matches the test quite well, including the failure mode, force levels and shape of the hysteresis loops. It is relevant to point out, also, that the response regimes exercised in this test encompass the range of quasi-static behavior which includes cracking, cyclic degradation of the compressive strength and shear shedding.

Shake-Table Test of a Five-Story Building -- CAMUS Benchmark

ANATECH participated in the CAMUS International Benchmark, Mazars [6], by conducting blind predictions of the response of a 1/3-scale six-floor reinforced concrete building, designed to the French design code PS 92 and tested on the Saclay shaking table in France. The ANATECH analysis has been discussed in greater detail elsewhere [13]. The structure consists of two cantilever shear walls connected by floors at each level and supported on a heavily reinforced footing. A half-symmetry three-dimensional finite element model of the test structure was developed, which included mass blocks at each floor level, Figure 3-2a. Also modeled was the geometry and mass of the shaking table itself to account for the interaction between the table and the test specimen. The shear-shedding capability of the ANACAP [3] material model was invoked to reduce the artificial buildup of shear stresses at large flexural cracks. All of the specimen reinforcement was modeled in its correct geometry with material properties suggested by benchmark organizers.

Predicted and measured time-history results are presented in Figure 3-2c, showing that the model quite accurately captured the top floor displacement, base shear and base moment of the building for the entire duration of strong motion loading. Of particular importance is that the analysis correctly predicted the location and time of failure below the third floor in the outside vertical reinforcement bundle at approximately 11 seconds. The observed failure pattern, following vertical bar rupture, is very similar to the predicted failure, as shown in Figure 3-2b.

Earthquake Simulation -- Shake-Table Test of Reactor Containment Model

The NUPEC experimental program referenced earlier consists of two 1/10-scale models of prestressed and reinforced reactor containment structures subjected to a series of design-level-earthquake shake-table simulation tests at the Tadotsu Engineering Laboratory in Japan. The analysis of the prestressed structure will be discussed here, USNRC [2]; the reinforced structure is still in progress. Several seismic simulation tests with varying magnitudes were performed, at the end of which a series of progressively larger amplitude motions were applied until failure occurred. Because of the continually increasing damage with each test, the analysis was carried out in the same sequence as the applied dynamic events.

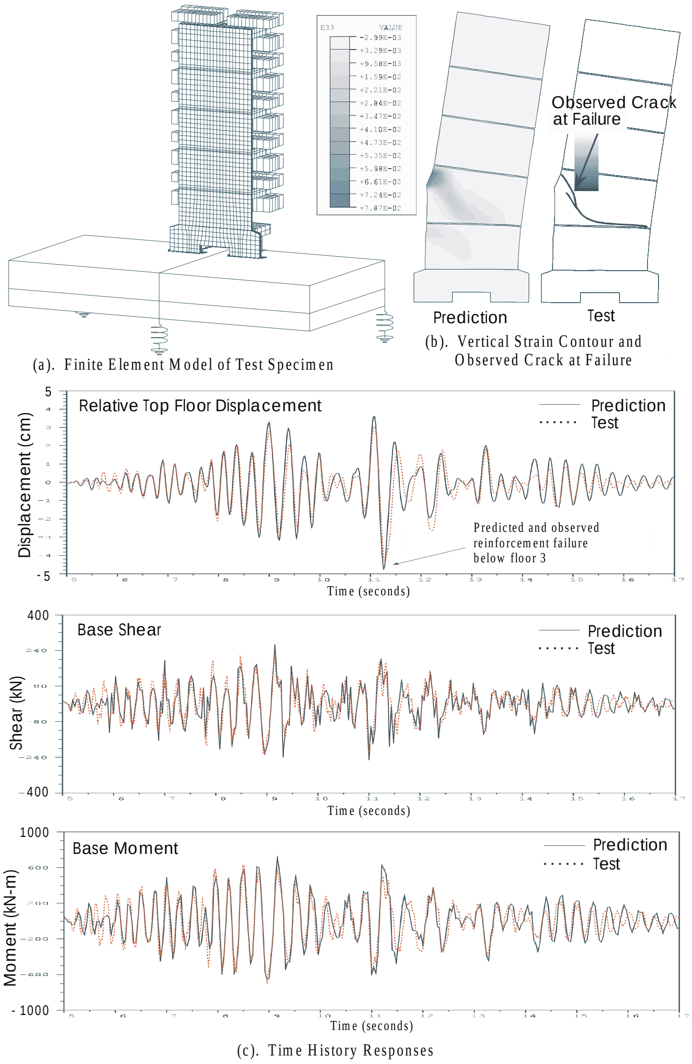

Figure 3-2. Shake Table Test of a Five-Story Building

The finite element model is shown in Figure 3-3, which also shows the prestressing steel; the reinforcing steel and liner are not shown because of space limitations. The top masses were added to the test specimen to bring the dynamic properties of the model into conformance with the full-scale structure with respect to the fundamental frequency.

The entire sequence of time-history analyses was completed prior to testing and then repeated for post-test verification. The improvements in the constitutive model described above, namely, the crack-consistent damping and the shear stiffness of cracked concrete, brought the analysis to much closer agreement with the tests, over the entire range of applied motion, than the pre-test predictions. The analysis produced three significant findings:

- Typical material property tests do not fully capture the structural shear stiffness, because they do not account for such structural properties as the stiffening effects of reinforcement (dowel action), crack roughness and cyclic degradation. Again, this resulted in the modification of the shear modulus vs. crack opening strain curve as previously described in Section 2, Figure 2-3.

- The test/analysis comparisons allowed the development of a structural shear-failure criterion for concrete structures subjected to severe seismic motions. Analytical interpretations of the test results indicate that impending shear failure of the structure would occur at a shear strain value of 0.5% averaged over any cross-section of the structure. In applying the criterion, one has to determine by inspection the controlling cross-section. This criterion was verified for other structures, not included here because of space limitations, and is therefore presented as a generally applicable criterion. Figure 3-4 shows, for the failure earthquake, the shear strain distribution in excess of 0.5% plotted on the deformed configuration. Figure 3-5 shows the hysteresis curve for the safe-shutdown earthquake S2(H+V) compared to the failure earthquake 5S2(H).

- The a-priori selection of a single value for the damping ratio, following current practice, gave poor predictions. This led to the development of the crack-consistent damping model described earlier. The effect of damping on the calculated response compared to the measured response for the Design Earthquake are shown in Figure 3-6 for 1% uniform, 3% uniform and cracking consistent-damping.

THE THREE LEVELS OF R/C BRIDGE ANALYSIS

MODELING REQUIREMENTS →; COMPLEXITY ↓

	GEOMETRY	σ–ε MODELING		WHEN NEEDED
Level 1	LINE ELEMENTS	•LINEAR ELASTIC	GROSS SECTIONS FOR FORCES CRACKED SECTIONS FOR DISPLACEMENTS	FORCE DEMANDS (Vulnerability Studies)
Level 2	LINE AND PLATE ELEMENTS	•NONLINEAR	ASSUMED SECTION BEHAVIOR (M-Φ)	DISPL. DEMANDS (Performance Design)
Level 3	2D & 3D CONTINUUM	•NONLINEAR	σ–ε FOR CRACKING, CRUSHING, SHEAR, CYCLIC DEGRADATION, CREEP, SHRINKAGE, AGING, THERMAL	•DISPL. CAPACITIES (Ductility Evaluation) •FAILURE PREDICTION •LARGE SHEAR OR TORSION •UNUSUAL LOADINGS

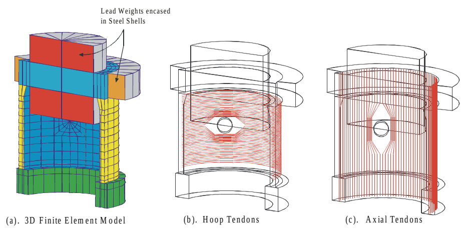

Figure 3-3. Finite Element Model for Prestressed Concrete Containment

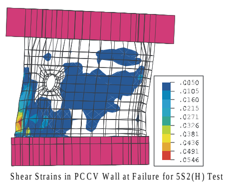

Figure 3-4. Distribution of Shear Strain For the Failure Earthquake

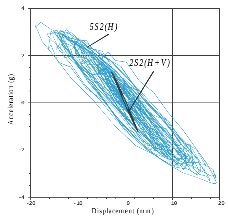

Figure 3-5. Acceleration vs. Relative Displacement of Top Mass

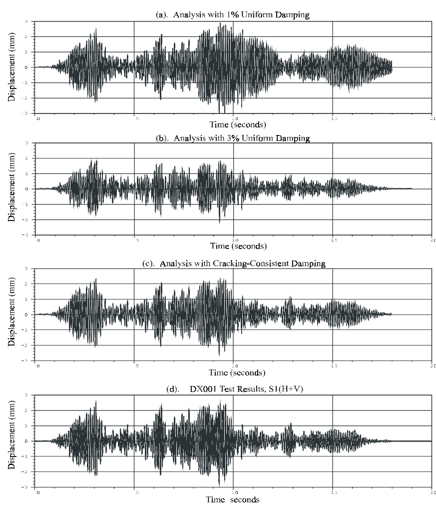

Figure 3-6. Effect of Damping on the Relative Horizontal Displacement for the Design Earthquake S1(H+V)

APPLICATION IN BRIDGE ENGINEERING PRACTICE

General Approach

Seismic analysis procedures for bridges have evolved over the last decade to three types, with increasing levels of complexity as outlined below:

- Linear elastic "stick" models analyzed statically for vertical loads and using linear response spectrum analysis for seismic loads.

- Nonlinear "stick" and shell-models with nonlinear time-history and push-over analysis, especially of large global models.

- Two- and three-dimensional nonlinear continuum cyclic and time-history analysis.

Prior to 1990, the only procedure in wide use in California bridge analysis was Level-1. The 1989 Loma Prieta Earthquake changed this for California. Level-1 is clearly limited in evaluating damage, and can greatly under-predict the displacement. Nevertheless, elastic, Level-1 analysis is an important first step in the initial assessment of the seismic vulnerabilities of a structure. Such analysis can provide initial indication of "hot spots" to plan a retrofit strategy, categorize members by their demand/capacity ratio, and envelope peak response quantities to a design spectrum. Level-2 analysis may utilize the same model developed for Level-1 analysis, but it invokes multi-support time history input (usually by direct time integration) and introduces nonlinearities that are essential to accurate response prediction, such as expansion hinge contact, material yielding, and P-Delta effects. The selection of the important nonlinearities requires special skills, but in the hands of experienced analysts both analysis levels can be usefully integrated. The results of Level-1 and Level-2 analyses are used to establish boundary conditions for Level-3 analysis.

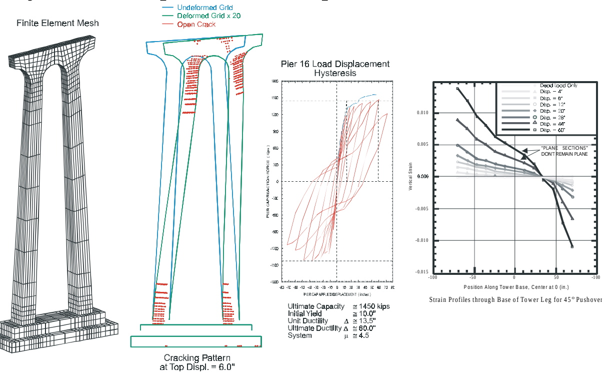

Figure 4-1. Level 3 Analysis of Pier 16 Tower of San Diego - Coronado Bay Bridge

Level-3 analysis is applied to the capacity side of the demand-capacity design equation. The distinguishing feature of Level-3 is the choice of the finite-element modeling strategy and the selection of the appropriate material behavior characteristics in the constitutive model. Stick or beam element models, which constitute the working elements in Level-1 and Level-2 analyses, provide poor representation of shear and torsion, especially in combination with large axial loads and biaxial bending. As previously discussed in Section 2 of this paper, using concrete continuum elements with individually specified rebar sub-elements, and detailed constitutive subroutines for the concrete and steel, Rashid et al. [14], the material stress-strain behavior can be closely simulated.

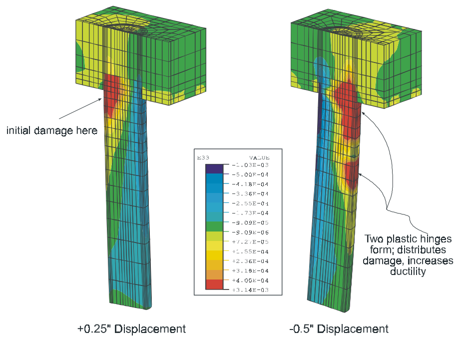

Figure 4-2. Level 3 Cyclic Analysis of Single Pile Beneath Pier 16 Tower of the San Diego - Coronado Bay Bridge

One of the best and most recent examples of the utilization of all three levels of analysis is the seismic vulnerability assessment and performance evaluation of the San Diego-Coronado Bay Bridge, which is described below as an object example.

Application to San Diego-Coronado Bay Bridge

The Coronado Bridge is an 8000-foot long structure linking San Diego with Coronado. It has a steel-girder super structure supported on concrete towers with battered columns varying in height from 40 feet to 200 feet. The columns are supported on pile caps and tall prestressed-concrete piles, 54-inch in diameter.

Linear Level-1 and nonlinear Level-2 modeling of the entire bridge was first performed using three-dimensional stick and beam elements, accounting for soil-structure interaction. These models used a linear response spectrum and nonlinear time-history input, respectively. Level-1 was used in the vulnerability study, which established force demands. Level-2 was used in the performance evaluation of the displacement-based design, which established displacement demands. The results are reported in great detail in Dameron [10].

Boundary conditions from these analyses were applied to Level-3 models of a tower and a typical marine pile. Because of space limitations, only some results for the tower and the pile are discussed. Figure 4-1 shows the performance of the tower, indicating an ultimate ductility of 6. It is interesting to mention that Level-3 analysis detected a dual-hinge effect in the marine piles, as shown in Figure 4-2, which was created by arbitrarily terminating the rebar cage at 8 feet below the pile cap. This (accidental engineering) effect, which was confirmed by tests performed at UC San Diego, Silva et al. [15], significantly enhanced the ductility capacity of the piles due to the spreading of the damage caused by the double hinging. These findings allowed many of the pile groups to be left unretrofitted, which resulted in significant cost savings.

CONCLUSIONS

The state-of-the-art in finite element modeling of reinforced concrete has been presented with several example applications in the form of blind predictions of large-scale structural tests. Integration of the method in current structural engineering practice is illustrated through analyses performed in support of the San Diego-Coronado Bay Bridge seismic retrofit project. Pretest analysis serves as the purest basis for validation of the modeling techniques and allows previously unknown or unexplored phenomenon to be investigated and resolved for future applications. Of particular importance in finite element modeling is that the same analysis methodology be applicable to a wide range of structures and loading types, as demonstrated by the quasi-static cyclic analysis of a bridge column, as well as dynamic analyses of a five-story building and nuclear containment structure.

REFERENCES

1. Housner, G. W., et al., "Competing Against Time," Governor's Board of Inquiry Report on the 1989 Loma Prieta Earthquake, State of California, May 31, 1990.
2. U.S. Nuclear Regulatory Commission NUREG/CR-6639, "Analytical Modeling for Seismic Response of Prestressed Concrete Containment Vessels," June 1999.
3. James, R. J., *ANACAP, ANATECH Concrete Analysis Program*, Version 2.1, User's Manual, ANATECH Corp., San Diego, December 1995.
4. Rashid, Y. R., "Ultimate Strength Analysis of Prestressed Concrete Pressure Vessels," *Nuclear Engineering and Design*, 7, 1968, pp. 334-344.
5. Clauss, D. B., "Round-Robin Analysis of the Behavior of a 1:6-Scale Reinforced Concrete Containment Model Pressurized to Failure: Posttest Evaluations," Sandia National Laboratories, NUREG-CR-5341, SAND89-0349, U.S. Nuclear Regulatory Commission.
6. Mazars, J., et al., "Mock-up and Loading Characteristics Specifications for the Participants Report," Report 1, CAMUS International Benchmark, France, 1997.
7. Drucker, D. C., and Prager, W., "Soil Mechanics and Plastic Analysis for Limit Design," Qurt. Appl. Math. 10, 1952, pp. 157-165.
8. Kupfer, et al., "Behavior of Concrete under Biaxial Stresses," J. ACI, 66, No.8, Aug. 1969.
9. Al-Mahaidi, R. S. H., "Nonlinear Finite Element Analysis of Reinforced Concrete Deep Members," Research Report No. 79-1, Cornell University, Department of Structural Engineering, January 1979.
10. Dameron, R. A., et al., "Seismic Analysis of the Existing San Diego-Coronado Bay Bridge," ANATECH Final Report to Caltrans on Contract 59A029, October 1995.
11. Priestley, M. J. N., and Seible, F., "Seismic Assessment and Retrofit of Bridges," University of California, San Diego, Department of AMES, Report No. SSRP91-03, July 1991.
12. Hines, M., Seible, F., Priestley, M. J. N., "Cyclic Tests of Structural Walla with Highly Confined Boundary Elements," University of California San Diego Report No. SSRP-99/15, 1999.
13. Dowell, R. K. and Zhang, Liping, "Reinforced Concrete Building Prediction Analysis," Proceedings of Structures Congress XVII, New Orleans, 1999.
14. Rashid, Y. R., et al., "Constitutive Modeling of Reinforced Concrete and Steel," ANATECH Corp., San Diego, CA, September 1996.
15. Silva, P., Seible, F., and Priestley, M. J. N., "Coronado Pile to Pile Cap Connection Test No.2," University of California San Diego, Report No. TR-97/03, Feb. 1997.