SEISMIC RETROFIT OF THE LAX THEME BUILDING WITH MASS DAMPER: ANALYSIS AND EXPERIMENTATION

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SUMMARY
The Theme Building at the Los Angeles International Airport (LAX) is a landmark structure. The main load-bearing component of the structure is a core structure consisting of an annular wall and interior reinforced concrete walls. Analysis showed that the concrete core was subject to large seismic forces and had insufficient flexural and shear capacity to resist the loading. Non-ductile shear failure and reinforcement pull out were identified. A mass damper was selected as the main retrofit option to reduce the seismic demand. Such retrofit allowed preserving the unique architectural features of the building. Parametric studies were conducted to optimize the properties of the damper. At the conclusion of the retrofit, field tests of the structure were conducted. Force vibration and snap back tests showed that the dynamic properties of the structures correlating closely with the values obtained from analysis and that the mass damper was effective in reducing seismic demand.

Keywords: Mass damper, seismic retrofit, concrete core, iconic building, non-ductile concrete

1 INTRODUCTION

The LAX Theme Building is a landmark structure at the Los Angeles International Airport; see Figure 1. The building was constructed in 1959. The structure is comprised of a concrete core and a system of steel arches. Figure 2 presents the elevation view of the building showing the concrete core and the steel arches. The overall height of the structure is 44 m extending from ground, at elevation 27.5 m, to the apex of the arches at elevation 71.5 m.

The concrete core is approximately 33 m tall and is connected to the four arches at the observation level. Figure 3 presents the section cut of the concrete core. The concrete core consists of a 5.2-m diameter annular wall and a system of internal rectangular walls; see Figure 4. At the base, the core thickness is 400 mm. and reduced to 300 mm at the first floor. The core is supported by a mat foundation and a system of 128 steel H piles. The annular wall is the main component resisting the seismic forces. Structural drawings specify 28 MPa normal weight concrete (NWC) up to elevation of 42.7 m and 21 MPa lightweight concrete (LWC) above. These openings are not symmetric with respect to the principal orthogonal axis of the core and as such could affect the flexural and shear capacity of the core.

Figure 1. Photograph of the building.

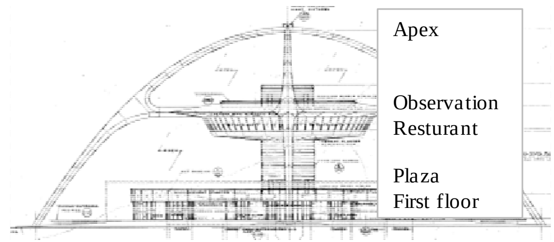

Figure 2. Building elevation.

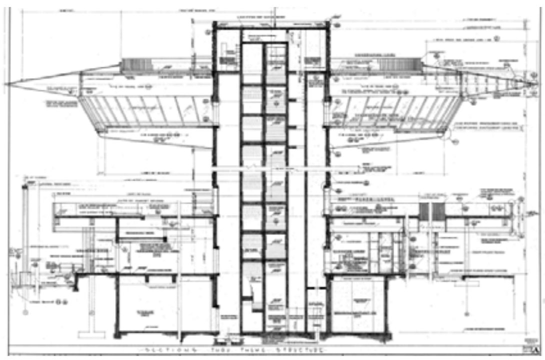

Figure 3. Concrete core elevation

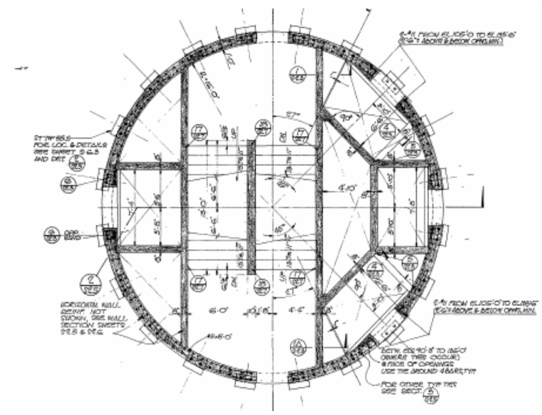

Figure 4. Cross section of core

1.1 Condition Assessment

Site-specific response spectra were. The (Design Earthquake or 475-year event) DE spectrum is anchored at 0.40 g and has a peak spectral acceleration of 0.92 g. The spectral peaks are similar to the values computed using the ASCE-SEI 7-05 (ASCE, 2005) procedure based on the mapped acceleration of the USGS web site (USGS, 2007). Three pairs of spectrum-compatible motions were developed based on the seeds from past earthquakes of similar magnitude and site condition.

Comprehensive material tests of the structural components were conducted. ASCE-SEI 41-06 (ASCE, 2006) requirements for comprehensive testing were followed. The annular wall has compressive strengths of 35 MPa and 32 MPa for normal- and light-weight concrete portions. Reinforcement coupons had an average yield and tensile strengths of 350 and 520 MPa, respectively.

2 STRUCTURAL EVALUATION

ASCE-SEI 41-06 guidelines were used to assess the seismic performance of the structure and to evaluate the effectiveness of the proposed retrofit. Nonlinear response history analysis procedure was used. Three-dimensional mathematical models of the structure were prepared and were subjected to site-specific motions. The flexural and shear demand were extracted from analysis and compared with computed capacity of the complex cross section at critical elevations.

The performance objective for this structure was selected to be Life Safety (LS) for the design earthquake (DE). To ensure acceptable performance, non-ductile modes of failure were checked and mitigated. Typical of this vintage concrete building, this structure has poor reinforcement detailing that does not meet the current ACI 318 (ACI, 2008) requirement. ACI 371 (ACI, 2008) was used to compute the shear capacity of the concrete core. The openings in the core wall—disturb the shear flow path—and the presence of LWC reduces the shear capacity.

2.1 Flexural capacity

The reduced yield strength, as a function of provided splice length and ACI required development length, was computed per ASCE –SEI 41-06; the software program xSection (Mahan, 2007) was used to compute the flexural capacity of the concrete core at various elevations. The cross section was modeled using fiber elements. Figure 5 presents the analysis results for a typical elevation with openings. The compressive area (shown in black) is shown at the top of the core section. The strain corresponding to the compressive strength was set at 0.002. Typical moment-curvature results are presented in Figure 6.

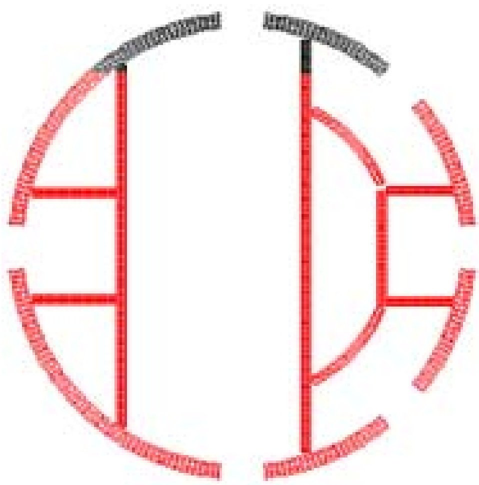

Figure 5. Fiber model

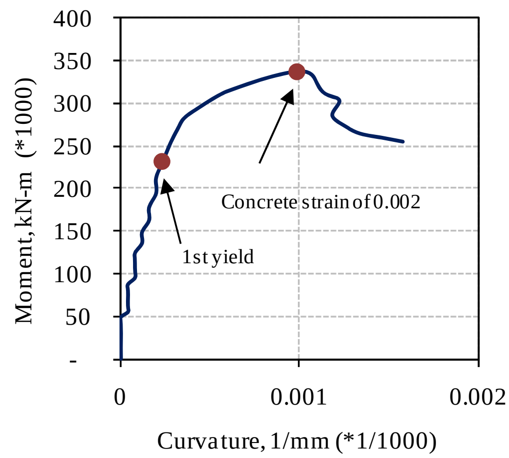

Figure 6. Moment curvature relation

2.2 Dynamic field tests

Field tests were conducted by the University of California at Los Angles (Nigbor and Wallace, 2007) to determine the dynamic properties of the structure. Field tests consisted of ambient vibration surveys and forced vibration (sine sweep and sine hold) tests. For the force-vibration tests, a concrete pad was cast and anchored at the observation level; see Figure 7. The structure was subjected to low amplitude sinusoidal loading and the acceleration data was collected using 51 accelerometers; see Figure 8.

Figure 7. Shaker setup

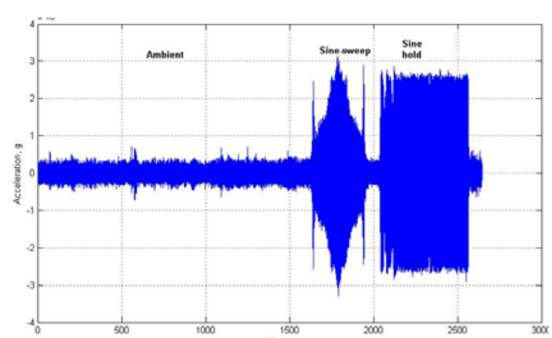

Figure 8. Sample test data (%g)

2.3 Analytical Model

Computer program SAP (version 11) (CSI, 2008) was used to prepare mathematical models of the structure. All pertinent mass and stiffness components were incorporated in the model; see Figure 9. The structure had a seismic mass 2,500Mg and fundamental concrete core frequency 2.5 Hz; similar to the value computed from field tests..

The computed core mode shape from analytical models and the measured mode shape from field tests are presented in Figure 10. Note that the analytical model closely tracks the field measured fundamental mode shape. Due to presence of LWC at the upper levels, the fundamental mode deviates from the typical cantilever mode shape observed in concrete towers constructed of similar material through the height.

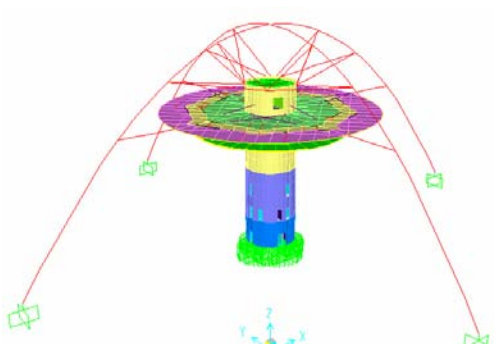

Figure 9. Mathematical model

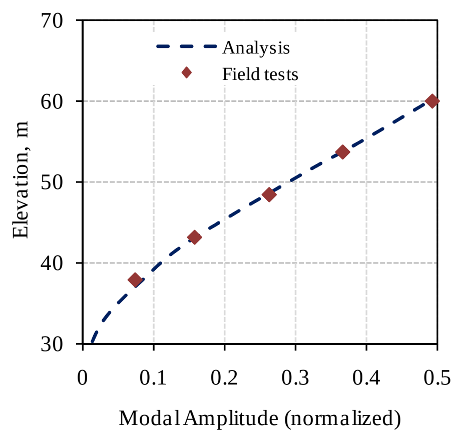

Figure 10. Fundamental mode shape.

2.4 Performance of the existing building

Figure 11 presents the distribution of shear demand and capacity along the height of the concrete core. The shear demands were computed from response history analyses. The shear demands exceeded capacity along most of the height of the core. Figure 12 presents the distribution of bending moment demand and capacity along the height of the core. The flexural demands exceeded capacity in the bottom half of the building. As such, the structure could experience failure during the design earthquake event,

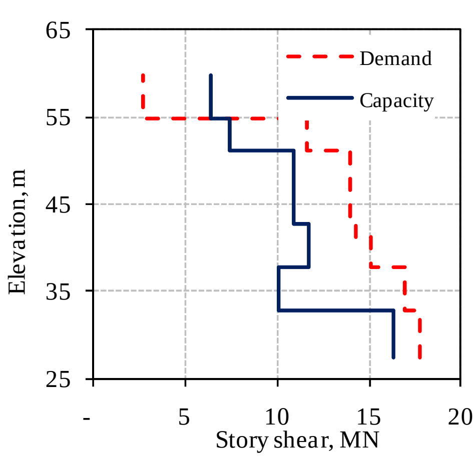

Figure 11. Shear profile

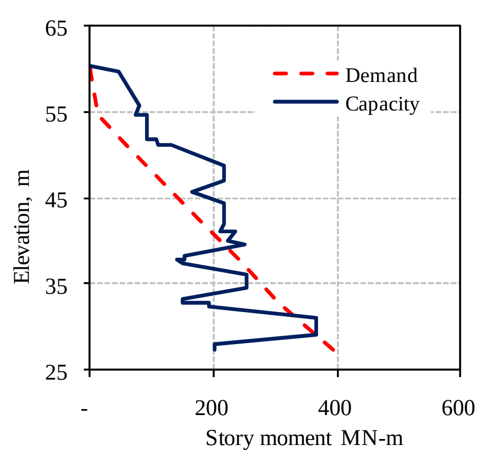

Figure 12. Moment profile

3 SEISMIC RETROFIT

Both conventional and innovative seismic retrofits were investigated. The conventional retrofit of the building would consist of adding a layer of concrete to the outside core of the structure to increase the flexural and shear capacity of the core. The innovative retrofit consists of adding a tuned mass damper (TMD) to the top of the core. The TMD option was selected because it was less expensive, protected the building's architectural features, and minimized building closure.

The addition of TMD will alter the fundamental mode of the concrete core by introducing two modes. In one, the TMD is in-phase with the concrete core, whereas, in another mode, the TMD motion is out-of-phase with the concrete core. As a result, most of seismic motion is taken up by the TMD and reducing drifts and seismic demand of the concrete core. A high-damped TMD with a mass ratio (defined as mass of TMD to the concrete core) of 20% was selected. This large mass corresponds to 25% of the mass in the fundamental mode and was selected to get approximately 30-40% reduction in the responses.

3.1 TMD properties

Consider the concrete core and the TMD mass attached to a SDOF system by elastic and viscous elements. The result is a couple, 2-DOF system. Since the damping matrix is not mass or stiffness proportional. The resulting eigenvalue problem would have two complex mode shapes. The coupled equation of motion can be written as:

$$M\ddot{u} + C\dot{u} + Ku = p(t) - md(\ddot{u} + \ddot{u}_d) \tag{1}$$

Therefore, the TMD mass serves to reduce the applied loading. For MDOF systems, the structure is approximated by a generalized SDOF system whose modal properties are that of the fundamental mode of the structure. For application, the fundamental mode is normalized to have unit participation. For seismic excitation, when many input frequencies are present, the optimal TMD properties are obtained from numerical analysis. One should note that optimizing one response quantity will not necessarily optimize other responses.

Sadek et al (1997) optimized the TMD properties by equating the modal damping ratio in the two complex conjugate modes. Randall et al (1981) all developed optimization equations based on numerical simulations for SDOF systems to select TMD properties. Villaverde (2002) has studied multistory buildings retrofitted with tuned mass dampers. The author has examined both analytical simulations and shake table tests. Most of the emphasis was on the TMD systems with smaller mass ratios. Results similar to the other references were obtained.

3.2 LAX Theme Building TMD

The existing structure produces a complicated system for TMD optimization. Since the structure is lighter and more flexible over its top half, due to the LWC core, wall, and slabs, its fundamental modal mass is only approximately 68% of total mass. Additionally, this structure differs from a typical multi-story structure. Consequently, the TMD properties were initially selected based on the values suggested by the previous researches. However, the properties were further optimized for this specific structure by conducting a comprehensive analysis simulation program.

The TMD will be mounted at the top of the core; see Figure 13. A concrete slab will be placed and the core walls will be extended to accommodate the TMD; see Figure 14.

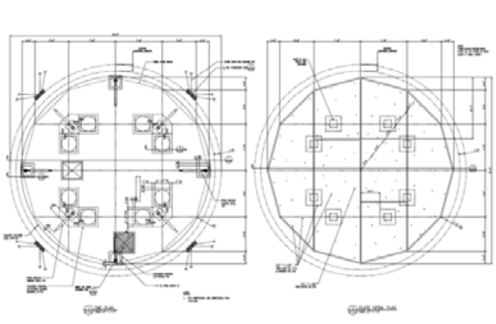

Figure 13. Plan view of the TMD

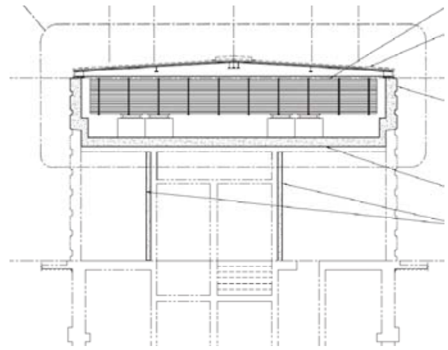

Figure 14. Elevation view of TMD

The TMD mass will be supplied by a system of steel plates; The TMD will weigh approximately 5400 MN. Eight lead rubber bearings (LRB) will be used to supply the TMD stiffness. The TMD damping will be provided by eight fluid viscous dampers (FVD). Production tests of the rubber bearings and viscous were performed; see Figure 15 and Figure 16.

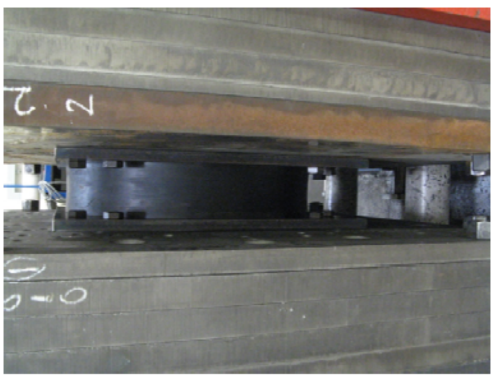

Figure 15. Production test of bearings

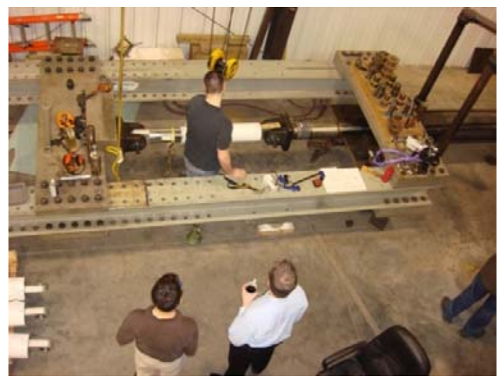

Figure 16. Production test of dampers

3.3 Retrofit of lap splices.

The reinforcement splices at the three lowest elevations were retrofitted by providing additional confinement. ACI 318 development length depends on the confinement. Such confinement can be provided by pre-compression the cross section [Patterson and Mitchell, 2003); see Figure 17and Figure 18 to ensure that the reinforcement could reach its capacity.

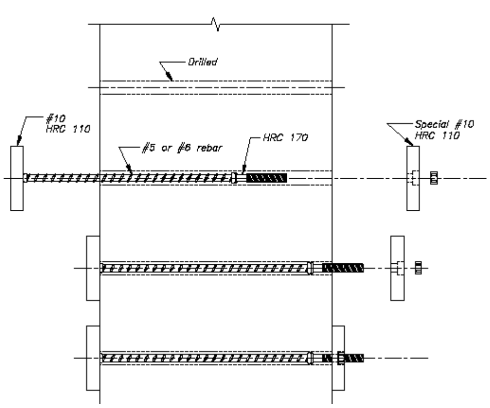

Figure 17. Retrofit schematics

Figure 18. Lap splice retrofit

4 RESPONSE OF RETROFITTED STRUCTURE

Figure 19 presents the shear response of the structure. The capacity values are shown along the orientation with the smallest capacity (most openings). Note that addition of TMD has resulted in significant reduction in shear demand throughout the height of the structure. The demand to capacity ratios (DCRs) are all below 1.0. Figure 20 presents the bending moment distribution along the height of the concrete core for the retrofitted structure. The flexural demands are less than the capacity. In particular, only minor yielding of the reinforcement is expected at one level. At all other locations, the flexural response will result in steel stresses below the yield value.

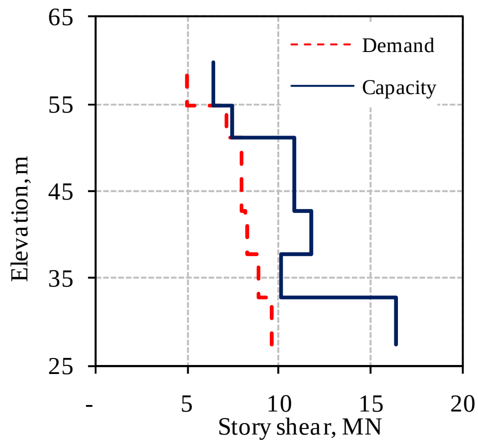

Figure 19. Shear profile

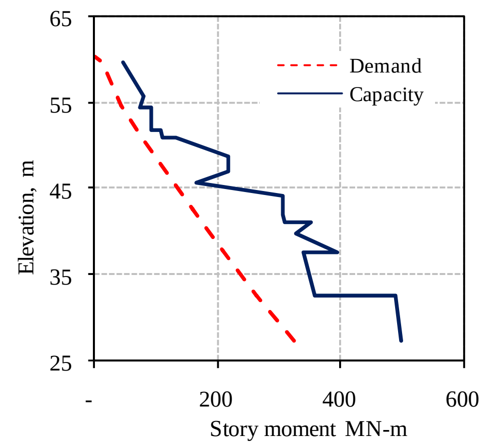

Figure 20. Flexural profile

Figure 21 and Figure 22 present the response at the top of the core (displacement and acceleration, respectively) along of one axis for one of the DE acceleration records. The displacement response is normalized with respect to the height of the core. Drift and force demands were reduced by approximately 30 %.

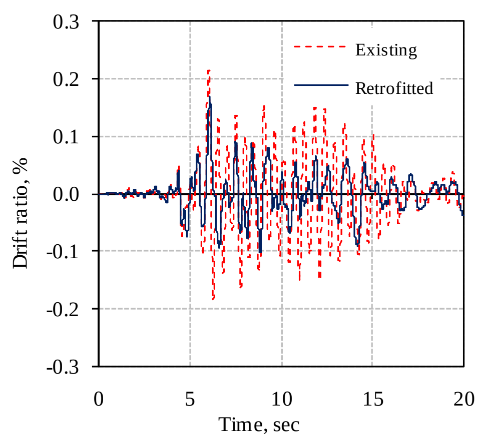

Figure 21. Roof displacement

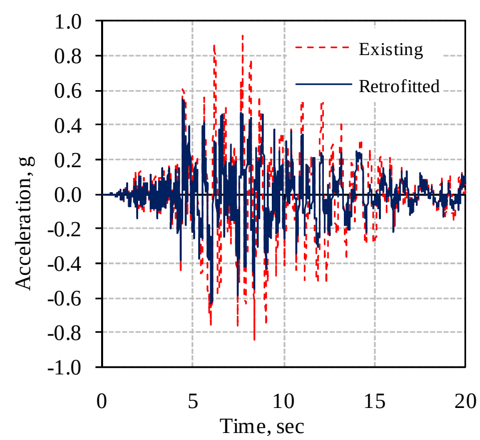

Figure 22. Roof acceleration

4.1 Verification studies

The analysis used to size the TMD used idealized properties for the spring and damping elements. Following the completion of the production tests, expected properties of these components were available. Shown in Figure 23 is the force-displacement response of a typical bearing. Figure 24 presents the force-displacement response of a damper.

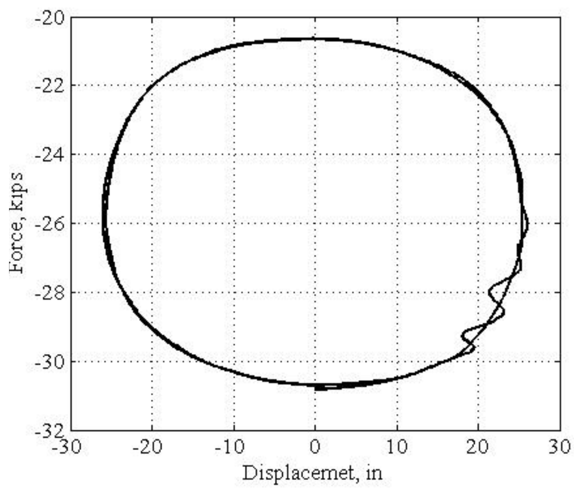

Figure 23. Force displacement response of bearing (DIS, 2009).

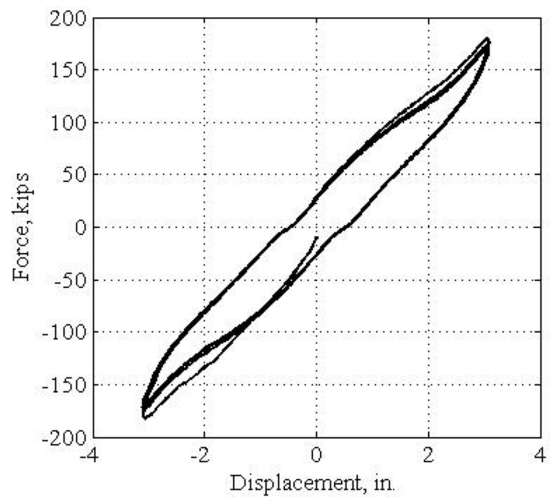

Figure 24. Force-displacement response of damper (Taylor Devices, 2009).

The finite element model of the structure was then modified using the laboratory data and analysis was performed. Figure 25 and Figure 26 presents the responses of the initial and updated models. The variation in response was

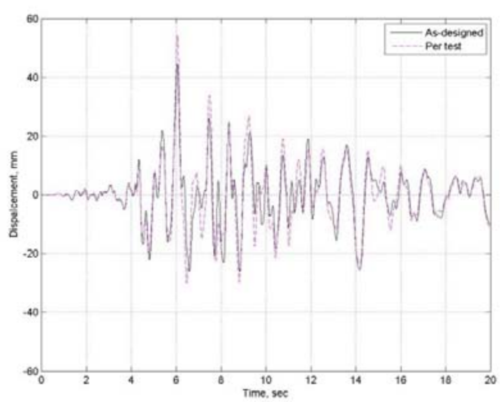

Figure 25. Displacement

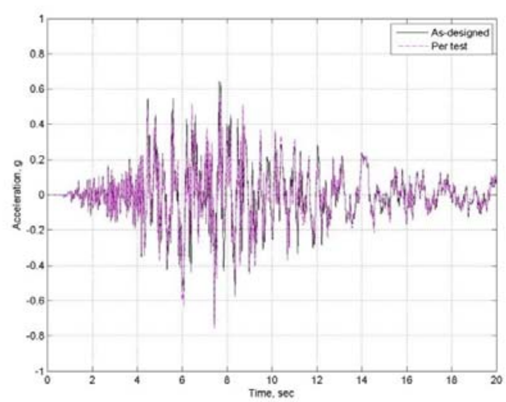

Figure 26. Acceleration

4.2 Dynamic field tests

Field tests were conducted by the University of California at Los Angles (Nigbor and Wallace, 2011) to assess the efficacy of the retrofit. Field tests consisted of ambient vibration surveys, forced vibration (sine sweep and sine hold) tests, and pull-back quick release testing. Sample data from pull back and quick release tests are shown in Figure 27 and Figure 28, respectively.

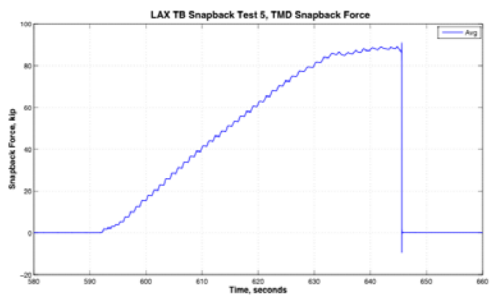

Figure 27. Shaker setup

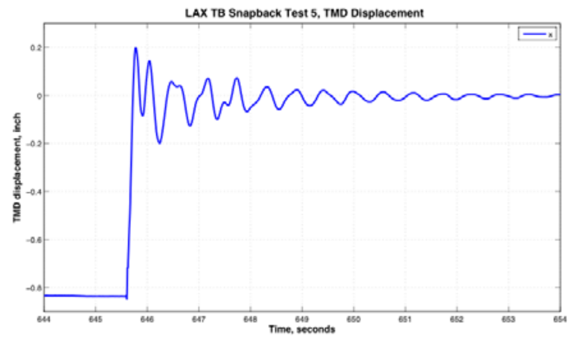

Figure 28. Sample test data (%g)

The data from the field tests were then contrasted with analysis results obtained using the laboratory measured TMD component properties at the level of field tests. (It is noted that the properties of the spring and damper are amplitude dependent and because the field tests were conducted at lower amplitude than that of design earthquake, appropriate properties need to be used.) Good correlation between analysis and field data was obtained.

5 CONSTRUCTION

The construction of the seismic retrofit has been completed. Figure 29 depicts one of the steel plates lifted in position, and Figure 30 shows one of the dampers and bearings used for the retrofit device.

Figure 29. Steel plate placement

Figure 30. Bearings and dampers

6 CONCLUSIONS

Seismic evaluation of the LAX Theme Building showed that the reinforced concrete core, which is the main lateral load-resisting element of the structure, had deficiencies consistent with its construction vintage. These included non-ductile details such as lack of confinement, low shear capacity and short length of main reinforcement splices. These deficiencies would likely result in severe damage to the structure in the event of major earthquake. A voluntary seismic upgrade was implemented using both increased capacity and reduction in demand.

- The increased flexural capacity was achieved by rehabilitating the splices at vulnerable lower level elevations. It is also proposed to add FRP at two critical locations along the core axis with the lowest shear capacity to provide additional safety. Although not included as part of the current scope, the client is investigating such implementation in the rehabilitation scope.
- The centerpiece of the seismic retrofit is the addition of a TMD at the roof of the core. The TMD was sized to obtain a reduction of approximately 30% for a number of response quantities.
- The proposed retrofit was more cost-effective than a conventional scheme and minimized alternations to the appearance of the building and its closure.
- The retrofitted structure met its performance goal and there was moderate to high confidence of satisfactory performance in a major earthquake

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REFERENCES

American Concrete Institute (2008). "ACI 318-08: Building Code Requirements for Structural Concrete and Commentary", American Concrete Institute, Farmington Hills, MI.

American Concrete Institute (2008). "ACI 371.R-08: Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel- Concrete Water Storage Tanks", American Concrete Institute, Farmington Hills, MI.

American Society of Civil Engineers (2005). "ASCE 7-05 Minimum Design Loads for Buildings and Other Structures", American Society of Civil Engineers, Reston, VA.

American Society of Civil Engineers (2006). "ASCE 41-06: Seismic Rehabilitation of Existing Buildings", American Society of Civil Engineers, Reston, VA.

Computers and Structures, Inc. (2008). SAP v.11. Computers and Structures, Inc, Berkeley, CA.

Dynamic Isolation Systems (DIS) (2009). Personal communications.

Federal Emergency Management Agency (2000). "FEMA 351: Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment-Frame Buildings", Federal Emergency Management Agency, Washington D.C.

Nigbor R and Wallace, J. (2007). Measurement of Dynamic Properties of the LAX Theme Building, Network for Earthquake Engineering Simulation, University of California, Los Angeles, Los Angeles CA.

Nigbor R and Wallace, J. (2011). Measurement of Dynamic Properties of the LAX Theme Building, Network for Earthquake Engineering Simulation, University of California, Los Angeles, Los Angeles CA.

Mahan S. (2007). xSection: Cross Section Analysis Program

Patterson J. and Mitchell D. (2003). "Seismic Retrofit of Shear Walls with Headed Bars and Carbon Fiber Wrap", Journal of Structural Engineering, American Society of Civil Engineers, Reston, VA.

Randall, S.E., Halsted, D.M., and Taylor, D.L. (1981). "Optimum Vibration Absorbers for Linear Damped Systems", Journal of Mechanical Engineering, ASME, 103, 908-913

Sadek, F., Mohraz, B, Taylor, A., and Chung, R. (1997). "A Method of Estimating the Parameters of Tuned Mass Dampers for Seismic Applications", Earthquake Engineering And Structural Dynamics. 26, 617-635

Taylor Devices, (2009). Personal communications.

Villaverde, "A Seismic Roof Isolation System: Feasibility Study with 13-Story Building", Journal of Structural Engineering, American Society of Civil Engineers, Reston, VA. 2002