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A CASE STUDY OF PERFORMANCE-BASED SEISMIC EVALUATION AND RETROFIT OF AN EXISTING HOSPITAL BUILDING IN CALIFORNIA, U.S.

W. Huang[1], L.A. Toranzo-Dianderas[1], A.D. Reynolds[1], J.R. Gavan[1], and J.W. Wallace[2]

[1] *KPFF Consulting Engineers, Los Angeles, CA, USA*
[2] *Professor, Dept. of Civil and Environmental Engineering, University of California, Los Angeles, USA*
Email: whuang@kpff-la.com

ABSTRACT :

Performance based design for structures subject to strong ground motion has been gaining major attention in the last few years. A conceptual framework for performance based design of structures has been developed in the NEHRP Prestandard for the Seismic Rehabilitation of Buildings (FEMA 356), and has recently been adopted, with some modifications, as a design standard for Seismic Rehabilitation of Existing Buildings (ASCE 41). Performance based design has been used to provide a reasonable and transparent relationship between an earthquake event and the corresponding seismic structural performance of a building.

This paper presents a case study of performance based evaluation and retrofit of an existing hospital building in California, U.S. Built in 1955, the subject hospital building is a four-story, plus basement and mechanical penthouse, “T”-shaped perforated concrete shear wall structure. A nonlinear static pushover analysis using the displacement coefficient method, as described in FEMA 356, was used to evaluate the seismic performance of the existing building. A seismic retrofit based on the pushover analysis was proposed and the results showed that the life-safety target performance of the upgraded building was achieved. In addition, this performance based retrofit scheme was compared to a different seismic retrofit scheme based on a traditional force-based procedure.

This case study provides a unique and intriguing investigation of seismic retrofit and evaluation of an existing concrete shear wall hospital building using performance based procedure.

KEYWORDS: Performance based design, pushover, hospital, concrete, shear wall building

1. INTRODUCTION

The Alfred E. Alquist Hospital Seismic Safety Act ("Hospital Act") was enacted in 1973 in response to the 1971 San Fernando earthquake when four major hospital campuses were severely damaged and evacuated. Senate Bill 1953 ("SB 1953"), enacted in 1994 after the Northridge Earthquake, expanded the scope of the 1973 Hospital Act. The earthquake caused more than twenty of California's hospitals to suspend some or all of their services, and resulted in more than $3 billion in hospital- related damages. SB 1953 served to establish the Hospital Seismic Retrofit Program, which aims to prevent hospital collapse and ensuing loss of life, as well as continuing operation of acute care facilities during and following earthquakes. It applies to all urgent care facilities (including those built prior to the 1973 Hospital Act) and affects approximately 2,500 buildings on 475 campuses. It required that all hospital evaluate their general acute hospital buildings for structural and non-structural seismic vulnerability by 2001. Structural Performance Categories (SPC-1 thru 5) were introduced for building seismic classification purpose. Under SB 1953, all hospitals are required, as of January 1, 2008, to survive earthquakes without collapsing or posing the threat of significant loss of life.

Followings are definitions of first two Structural Performance Categories that are related to the case study building.

- SPC1: Buildings posing a significant risk of collapse and a danger to the public. These buildings must be brought up to the SPC2 level by January 1, 2008 or be removed from acute care service;

- SPC2: Buildings in compliance with the pre-1973 California Building Standards Code or other applicable standards, but not in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act. These buildings do not significantly jeopardize life, but may not be as repairable or functional following strong ground motion. These buildings must be brought into compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act, its regulations, or its retrofit provisions by January 1, 2030 or be removed from acute care service.

Recent evaluations of hospital buildings reported to the Office of Statewide Health Planning and Development (OSHPD) show that a large percentage (40%) of California's operating hospitals is in the category of highest collapse risk (SPC-1).

2. BUILDING DESCRIPTION

The hospital building in this report was originally constructed in 1955. The non-conforming building is a four-story, plus basement and mechanical penthouse, "T"-Shaped concrete shear wall structure, as shown in figure 1.

Figure 1 Case study hospital building

In general, gravity loads are supported by a formed concrete pan joist slab system (with 16 ½” overall depth and a 2 ½” integral slab). Typical joist spacing is approximately 36” on center. The slab system is supported by reinforced concrete bearing walls at the perimeter and reinforced concrete beams and columns at the interior. Walls are supported on continuous spread footings and columns are supported on isolated concrete spread footings. The Lateral Force Resisting System (LFRS) consists of the concrete roof and floor slabs, reinforced concrete shear walls and continuous spread footings. The roof and floor slabs serve as horizontal diaphragms that distribute lateral loads to the perimeter concrete shear walls. The perimeter walls, which are perforated with numerous door and window openings, transfer lateral loads to the continuous spread footings and soil below. The foundation plan of the building as well as typical long walls along both directions is shown in figures 2 thru 4.

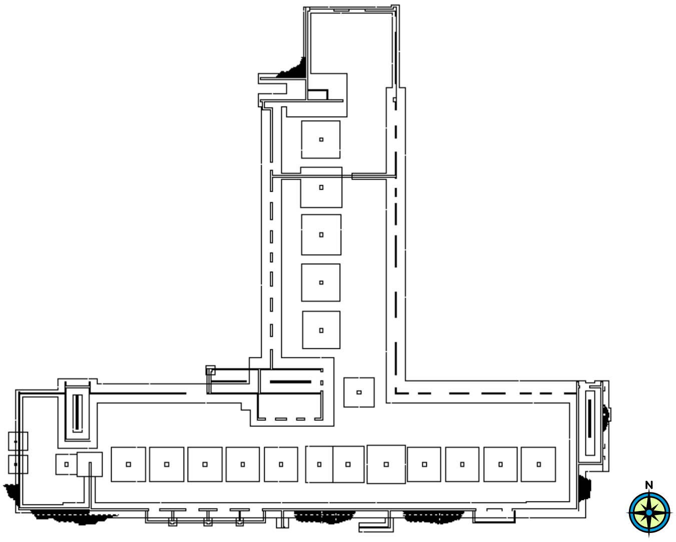

Figure 2 Foundation plan

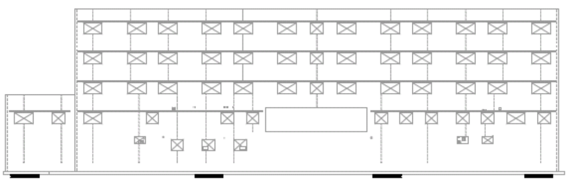

Figure 3 South wall elevation

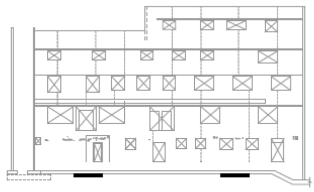

Figure 4 West wall elevation

3. GENERAL EVALUATION AND RETROFIT PROCEDURE

The building was initially evaluated using the Rapid Evaluation Procedure as per the requirements of Senate Bill 1953 (CBSAC 2001). The Rapid Evaluation Procedure identified various potential structural deficiencies and placed the building in Structural Performance Category 1 (SPC1). The retrofit methodologies for the upgrade of this building were per the 2001 California Building Code (CBC 2001), Volume 2, DIV. VI-R. The retrofit objective is to improve the expected performance of the structure from SPC1 to SPC2 by modifying the building such that it will meet the minimum life-safety requirements of Senate Bill 1953. The upgraded hospital building is expected to provide acute care services until the year 2030. First, a prescriptive code design approach (Method A), which is a conventional simplified methodology using a linear elastic analysis procedure, was used for the retrofit design. Then, a performance based design approach (Method B), which is a performance-based methodology using non-linear static analysis procedure described in FEMA 356 Pre-standard for the Seismic Rehabilitation of Buildings (FEMA 2000), was utilized to generate more efficient and cost effective strengthening solution for this building.

3.1 Modeling and Analysis

The original drawings for the Main Building and the adjacent buildings were available. Multiple site visits had been made to observe exposed conditions of the building configuration, building components, site and foundation, and adjacent structures, and to verify that the as-built information was representative of the existing conditions. Since no original material compliance certificates were available for this building, a comprehensive material testing program was performed.

Using the structural analysis program, Perform 3D (CSI 2008), a three-dimensional mathematical model of the building, as shown in figure 5, that directly incorporated the nonlinear load-deformation characteristics of individual components and elements of the building was developed. Perform 3D is a program developed for nonlinear analysis of structures with emphasis on the modeling of shear wall structures. The model was subjected to monotonically increasing lateral loads representing inertia forces from an earthquake until the roof (target) displacement as defined by FEMA 356 requirements was exceeded.

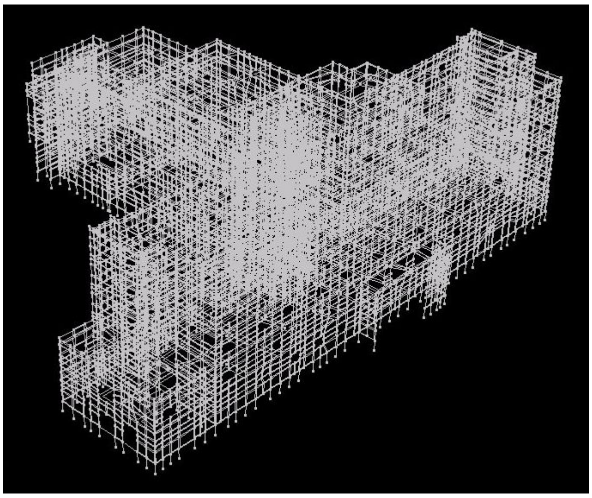

Figure 5 Perform 3D model

The three-dimensional model explicitly accounted for local discontinuities, such as out-of-plane offsets, in the determination of diaphragm demands. All primary lateral-force-resisting elements and designated secondary elements were included in the model. The analysis model was discretized to represent the load-deformation response of each component along its length to identify locations of inelastic action. The force-displacement behavior of all components was explicitly included in the model using full backbone curves that included strength degradation and residual strength, if any.

Extensive component testing was conducted at the structural laboratory of the Department of Civil Engineering at UCLA under the direction of Dr. John Wallace for various shear wall segment conditions. Nonlinear modeling of the primary shear wall elements for the building was based upon the testing results as well as nonlinear shear load-deformation relationships as defined in FEMA 356.

From the existing structural drawings and field verifications, it was determined that most of the existing horizontal wall segments (spandrels) have a vertical groove at the middle of their span. Furthermore, at these “weakened plane joints” 1/2 of the horizontal reinforcing was cut at the time of construction. The impact of the weakened plane joints on the existing wall segment shear capacities was explicitly considered in the component testing in UCLA.

The foundation system was included in the three-dimensional model of the structure. The structure’s footings were modeled nonlinearly utilizing an axial spring element that represents the soil-footing interaction. This element is referred herein as soil spring.

The non-linear static procedure (NSP) described in FEMA 356 was conducted to determine the forces and deformations induced in components of the building by the Code level ground motion (BSE-1) for the rehabilitated building. The NSP was based on applying a predefined lateral load pattern to the building model until the target displacement of a control node was reached. The control node was located at the center of mass at the roof of the building, which coincides with the penthouse floor.

Lateral loads were applied to the mathematical model in proportion to the distribution of inertia forces in the plane of each floor diaphragm. The following two vertical force distributions were considered:

- A vertical distribution proportional to the story shear distribution calculated by combining modal responses from a response spectrum analysis of the building, including sufficient modes to capture at least 90% of the total building mass, and using the appropriate ground motion spectrum.

- A uniform distribution consisting of lateral forces at each level proportional to the total mass at each level.

3.2 Evaluation and Retrofit

The results of NSP analysis of existing building prior to retrofit showed that the structure developed a combined mechanism of a soft story at lower floors and a breaking of the wall spandrels along the height of the building at certain locations. The mechanisms were evident at target displacement under the code based earthquake.

Due to lack of ductility and potential loss of vertical load carrying ability, the soft story mechanism was considered undesirable. The breaking mechanism of the spandrels over the height of the building at isolated locations was considered to be a more favorable mechanism because the remaining wall sections form rocking mechanisms without the implications of a soft story. Therefore, the retrofit of the building was designed so that a soft story mechanism was intentionally avoided and a rocking mechanism was forced to develop. Pushover curves for the 4 main orthogonal directions of applied load for the retrofit building are shown in figure 6 with the respective target displacements identified. In figure 7 and 8, the typical south and west wall elevations are shown to illustrate the rocking mechanisms that were developed as intended. The locations where the wall spandrels were breaking is shown in red in the figures.

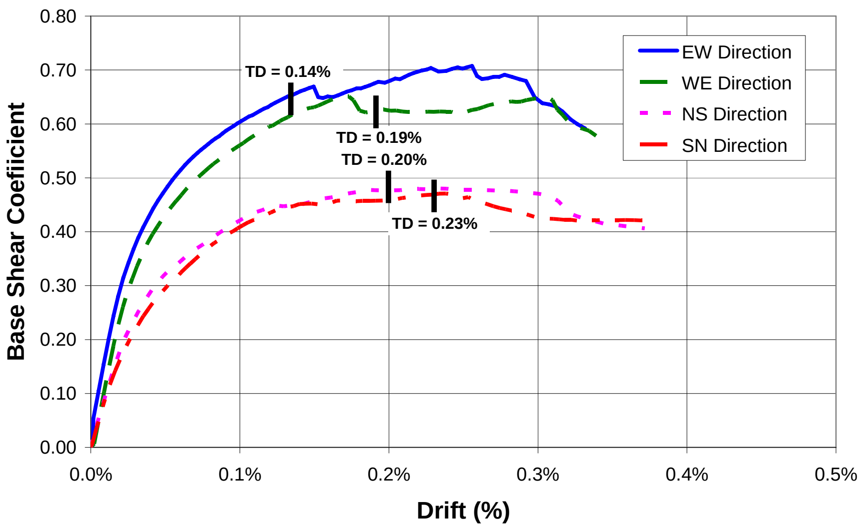

Figure 6 Pushover curves for the four orthogonal push directions for the retrofit building

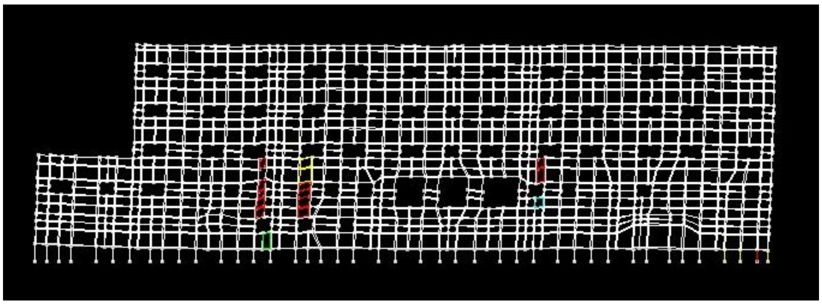

Figure 7 South wall deformation for the WE direction of pushover
at the target displacement of retrofit building

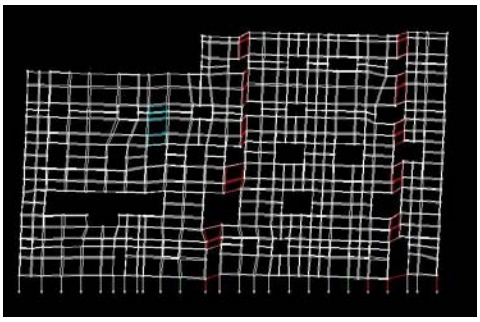

Figure 8 West wall deformation for the NS direction of pushover
at the target displacement of retrofit building

The proposed seismic retrofit work was intended to improve the Structural Performance Category of the building, from SPC1 to SPC2, thus meeting the minimum life-safety requirements of Senate Bill 1953. The proposed retrofit design based on the performance based design methodology significantly reduced the amount of retrofit compared to the prescriptive code methodology. The following are the highlights of proposed retrofit based on the performance based design methodology.

- Reinforced concrete infill of a few openings to prevent soft story mechanisms from developing.
- Fiber Reinforced Polymer (FRP) pier wraps to strength the existing piers where significant shear demands are present.
- FRP "catch" mechanisms for wall spandrel locations where shear deformation life safety limit is exceeded. The purpose of the "catch" mechanisms is to limit the amount of spalled concrete.
- Reinforced concrete thickening for a wall pier at one corner where seismic compressive demand is high.
- FRP chords to strengthen the diaphragm at higher floor levels.

Table 1 further compares the different retrofit schemes using both design methods. Typical south and west wall elevations using the two retrofit approaches are shown in figures 9 thru 12.

Table 1 Retrofit schemes Comparison

	Prescriptive Code Design	Performance Based Design
Foundations	New foundations below 40% of all perimeter walls	No retrofit needed
Shear Walls	18" reinforced concrete wall thickening for 80% of all perimeter walls	Reinforced concrete wall thickening for less than 1% of all perimeter walls Reinforced concrete infill of less than 5% of existing openings FRP catch mechanism for less than 10% of all horizontal wall segments FRP wrap for less than 1% of all vertical wall segments
Diaphragms	New diaphragm chords for higher floor levels Concrete slab thickening for certain areas	FRP chords for higher floor levels
Overall Impact	Significant	Minimal

Figure 9 South wall prescriptive code design

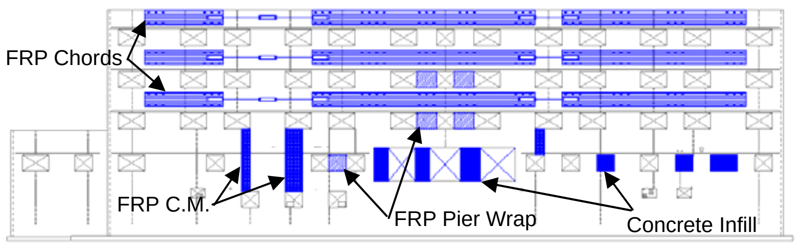

Figure 10 South wall performance based design

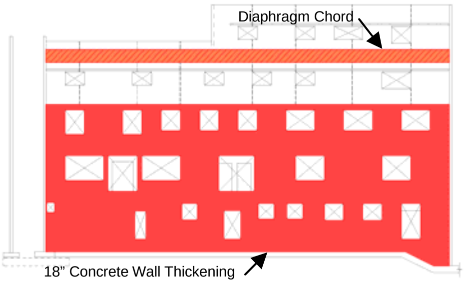

Figure 11 West wall prescriptive code design

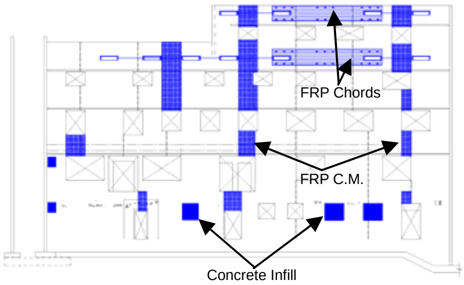

Figure 12 West wall performance based design

CONCLUSIONS

This paper presents a case study of a performance based evaluation and retrofit of an existing hospital building in California, U.S. A nonlinear static pushover analysis using the displacement coefficient method, as described in FEMA 356, was used to evaluate the seismic performance of the existing building. A seismic retrofit based on the pushover analysis was proposed and the results showed that the life-safety target performance of the upgraded building was achieved. In addition, the performance based retrofit scheme was compared to a different seismic retrofit scheme based on a prescriptive code design approach. The comparison showed that the performance based approach lead to a better understanding of the nonlinear behavior of the structure during severe earthquakes and provided a more efficient and cost effective strengthening solution for this building.

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REFERENCES

CBSAC, (2001), 2001 California Building Standards Administrative Code, California, U.S.

CBC, (2001), California Building Code, California, U.S.

FEMA 356, (2000), Pre-standard for the Seismic Rehabilitation of Buildings, U.S.

Computer and Structures, Inc, (2008), Perform 3D User's Guide, U.S.