Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Seismic design of the VA Palo Alto replacement hospital

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ABSTRACT: The Department of Veterans Affairs (VA) Palo Alto Medical Center hospital structure suffered significant damage in the 1989 Loma Prieta earthquake. As a result of this damage, the VA decided to construct a replacement hospital. Because of the proximity of the site to the San Andreas Fault (4 miles, 6.4 km), and the strict seismic design criteria required by the VA, seismic issues were considered at the earliest stages of the design process. The symmetric configuration and lateral force resisting system were developed to ensure proper seismic response. The dual lateral force resisting system consists of eccentrically braced steel frames (EBFs) and a complete moment resisting steel frame. A probabilistic site specific analysis coupled with a soil-structure interaction study to generate the design response spectrum. Two three-dimensional structural models were developed to simulate the dynamic characteristics and design the framing members. Ductile response of the lateral force resisting elements was provided through compliance with the detailing provisions of the 1988 Uniform Building Code (UBC) (ICBO 1988).

1 INTRODUCTION

The October 17, 1989 Loma Prieta earthquake, (M7.1), caused over $7 billion in damage, killed 62 people and injured over 3,700 in the greater San Francisco Bay Area. The VA Palo Alto Medical Center is located approximately 29 miles (46.7 km) from the epicenter of the earthquake. The existing hospital at the Medical Center was designed and constructed in the early 1960s using details typical of that era. By present standards, the building would be classified as a non-ductile concrete structure. At the time of the earthquake, the VA was in the process of developing a program to seismically upgrade the existing hospital. The structural damage to the building caused by the earthquake resulted in the closure of the facility. As a result, the VA decided to commission the design of a complete replacement hospital.

The VA seismic design criteria "Earthquake Resistant Requirements for VA Hospital Facilities", document H-08-8 (Veterans Administration 1986), was developed as a result of the collapse of a VA hospital in the 1971 San Fernando earthquake. This criteria is one of the strictest seismic design criteria in the world, stricter even than that used in the design of typical hospital buildings in California. The performance objective of this criteria is that VA hospitals remain fully functional, as much as practical, after a major earthquake. This performance objective is above that of typical structures, which are intended to resist collapse in a major earthquake, but are expected to have both structural and nonstructural damage which may limit their functionality. As a result of the strict design criteria and the proximity of the site to the San Andreas fault, seismic issues were considered in the earliest stages of conceptual design.

2 SELECTION OF STRUCTURAL SYSTEM

In order to effectively meet the strict VA seismic design criteria, a number of configuration, framing and detailing requirements should be met. These include the following: 1) A continuous, regular lateral force resisting system, without major offsets, 2) Avoiding mass, stiffness and strength irregularities, both in plan and elevation, 3) A ductile, redundant lateral force resisting system, and 4) Connections between all structural elements which provide sufficient strength and ductility. Provision of these features is intended to result in a hospital structure with sufficient strength, stiffness and ductility to limit damage enough to allow continued operation of the facility after a major earthquake.

Selection of the lateral force resisting system for the hospital was complicated by the following conflicting concerns: 1) The planning recommendations of VA

Building Systems recommend the use of tall stories and long span construction, and 2) The system must provide sufficient functional and planning flexibility so that it can properly integrate with the other hospital systems and permit future modifications. These concerns were considered early in the development of the project so that the most desirable structural system would be selected.

A number of lateral force resisting systems were considered for the project. Moment resisting frames, which provide planning flexibility and adequate structural ductility, are inappropriate for VA hospital buildings in regions of high seismicity. The base shear and drift requirements of H-08-8 would require short column bays and large girders, resulting in significantly increased structural costs. Concrete shear walls, while efficiently meeting the structural design requirements, would likely create a severe restriction on the planning and functional flexibility of the facility. The final option considered were braced steel frames. While more efficient than moment resisting frame systems, braced frames are not as restrictive to functional and planning requirements as concrete shear walls.

In the past, the ductility of conventionally braced frames has been questioned because of the limited energy dissipation capacity of the diagonal brace elements. The recently developed eccentrically braced framing system (EBF) eliminates this potential problem by forcing inelastic behavior in ductile beam elements rather than brace members. EBFs can, therefore, provide an efficient, ductile lateral force resisting system without presenting the functional restrictions of concrete shear walls. As a result, EBFs were selected as the primary lateral force resisting system selected for the project. Redundancy was provided through the inclusion of a "back-up" moment resisting frame, creating a dual lateral force resisting system.

3 SELECTION OF BUILDING CONFIGURATION

The earliest stages of the project focused on developing a building configuration which would result in proper seismic response while meeting all of the functional and planning requirements of the hospital. The importance of involving the Structural Engineer at this phase can not be over-emphasized. As stated by Arnold and Reitherman, "...the designer's first ideas on configuration are very important, because at a very conceptual stage, perhaps even before there is any engineering discussion, he is making decisions of great significance to later engineering analysis and detail design". (Arnold 1982). A large number of potential building configurations were developed by the project Architects, and then evaluated for their potential seismic response.

The design process ultimately focused on two possible solutions. The first was a "horizontal" scheme, with the nursing units located in separate wings on the same levels as major hospital functions. This configuration is shown in Figure 1. To meet the seismic design objectives, this scheme would have required seismic separations resulting in three structures. The second was a "vertical scheme", which located nursing units on upper stories above the other hospital services. This scheme, shown in Figure 2 resulted in a single structure, without any seismic separations. It includes four stories above grade with a complete basement story. This scheme was ultimately selected by the VA.

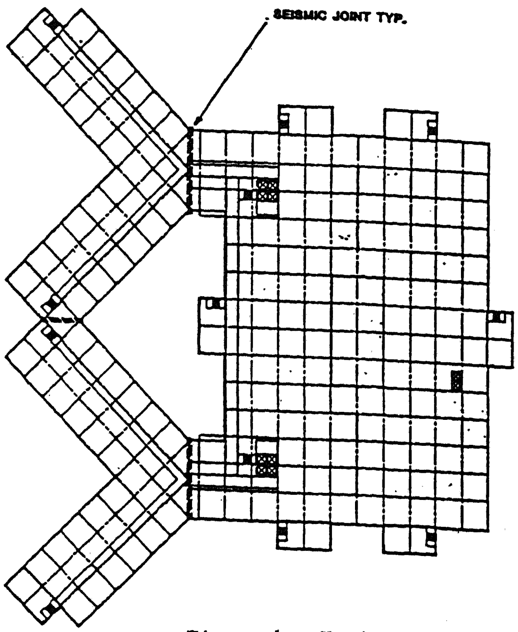

Figure 1 - Horizontal Building Configuration

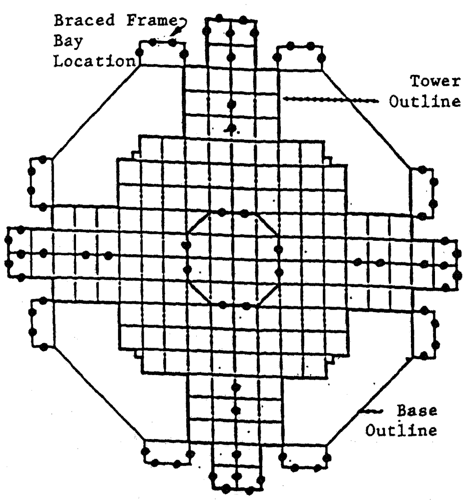

Figure 2 - Vertical Building Configuration

The plan shape of the selected configuration is basically square at the base with the corners removed to result in an octagonal shape. The maximum plan dimension across the building is 560 feet (171 meters). At the upper two levels, the building is set back to basically a cruciform shape. The size of these setbacks was limited so that the building will respond to seismic motions as a unit rather than as four separate tower structures. All setback locations occur on column grid lines, providing direct load transfer paths for diaphragm chords and collectors.

A square column grid of 28 feet (8.5 meters) was selected for planning reasons, and because this size is appropriate for both the EBF and moment resisting frame systems. This square grid was used consistently throughout the structure, resulting in desirable direct, continuous load paths. The resulting structural grid has obvious simplicity and rationality.

The EBF locations were selected to provide a regular, symmetric pattern which would minimize, to the greatest extent possible, the constraints placed on architectural planning and design. As shown in Figure 2, these braced bay locations are concentrated around the exterior perimeter, and at the center core structure. The large number of perimeter braced bays were intended to provide the building with adequate torsional resistance. The interior braced bay locations were chosen to minimize interference with major mechanical system components. All braced bays are continuous from the mat foundation to the highest story at that particular location. The number of braced bays was determined in preliminary studies to eliminate any uplift loading conditions which would result in deep foundations such as drilled caissons.

The selected building and structural system configuration meet all of the seismic design objectives and could be expected to provide superior response to a major earthquake.

4 SITE SPECIFIC SEISMIC STUDY AND SOIL-STRUCTURE-INTERACTION ANALYSES

A probabilistic site specific seismic study was performed by Woodward-Clyde Consultants to develop acceleration response spectra to be used in the structural design. The VA H-08-8 requirements call for spectra with a 10 per cent probability of being exceeded in 50 years. Probabilistic analyses incorporating the latest available information related to regional earthquake probabilities were conducted using published attenuation relationships for rock sites and a range of soil conditions representative of those at the site. Site response analyses were also performed, based on shear wave velocity estimates developed from a deep boring, and the response of the site observed during the Loma Prieta earthquake from strong motion instruments in the existing hospital building. These analyses were used to quantify the effects of local soil amplification so that the probabilistic response spectra could be properly adjusted. The resulting recommended design spectra for 2 per cent damping is shown in Figure 3.

The results of the site specific study were then incorporated with a soil-structure interaction analysis (SSI), in order to provide the most accurate response spectrum possible for the design of the building. A simple single stick shear beam model of the building was combined with a complete finite element representation of the supporting soils above bedrock. Both two- and three-dimensional models of the soil system were analyzed. Studies of the effects of including the stiffness of the ground floor diaphragm in these analyses were also performed. The final design spectrum, which includes the effects of SSI, is also shown in Figure 3. As this figure shows, including the effects of SSI resulted in up to 20 per cent reductions in the design forces.

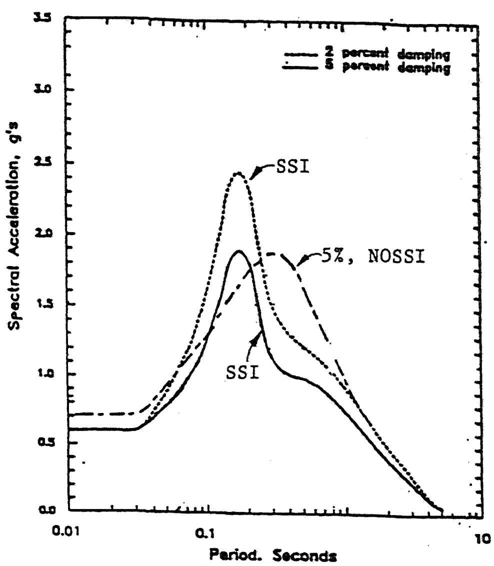

Figure 3- Recommended Design Spectra

5 STRUCTURAL ANALYSES AND MEMBER DESIGN

The design response spectrum generated in the SSI analyses was used as the loading for the three-dimensional dynamic analyses of the building. The model used in the dynamic analyses was simplified in order to allow for multiple design iterations and proper interpretation of results. This was accomplished by reducing the stiffness of the EBFs to equivalent shear beams and the moment resisting frames to single column frames. Equivalent stiffness of the supporting soils was incorporated with rotational springs generated from separate foundation analyses based on the dynamic properties of the soil. The flexibility of the floor diaphragms was included in the model by the use of membrane finite elements. Equivalent lumped masses were distributed at nodal points to model the building masses.

The dynamic analysis model indicated a fundamental building period of approximately 0.8 seconds, which was quite close to the value resulting from typical code equations. Modal combination was performed automatically using the CQC method. The story accelerations and shears were then calculated for inclusion in the frame model used to design the members.

A three-dimensional frame model was developed to design the structural elements. Taking advantage of the symmetry of the building, this model only included one-half of the structure. Appropriate modeling of the boundary conditions along the line of symmetry was required to properly make this reduction in the size of the model. All of the beam, column, brace and basement wall elements in the lateral force resisting system were included in this model. The diaphragm flexibility was again modeled using membrane finite elements. The mat foundation consisted of plate bending finite elements, with a mesh sufficiently fine to properly model the soil support. Gravity forces, from both dead and live loads were combined with seismic lateral forces as required by VA H-08-8. In addition to the complete lateral resisting system analysis, supplementary runs were made to verify that the back-up moment resisting frames had sufficient capacity to resist 25 per cent of the design lateral forces. Additional load combinations were required to check orthogonal effects in columns at the corners of two eccentrically braced bays. The SAP-90 computer program used to do the analysis included a post-processor to check the member stresses with the AISC Specification (AISC 1978).

6 PROVISION OF STRUCTURAL DUCTILITY

In order to provide adequate system ductility, modern codes, such as the UBC, include prescriptive detailing requirements for the various structural elements. For this structure, the detailing provisions of the 1988 UBC were followed (ICBO 1988). For the eccentrically braced frames, these detailing provisions address a number of issues to ensure the proper inelastic response of the system. The link beam sections between braces were designed to ensure shear yielding of the element, and that inelastic member rotations were within the prescribed limits. The link beams were also checked for web stiffener and lateral bracing requirements. Columns, braces and member connections were designed to be strong enough to force inelastic action in the link beam elements. Collector forces were developed in the members which deliver lateral loads to the braced bays.

The back-up moment resisting frames were also detailed to meet the special moment resisting space frame (SMRSF) provisions of the 1988 UBC. The beam-column connections were designed to develop the strength of the beams in flexure. Proper lateral bracing of beam elements was also provided. Panel zone strength was checked, as was the joint restraint requirement. Strong column-weak beam conditions were also analyzed.

7 CONCLUSIONS

The seismic design of the VA Palo Alto Medical Center Replacement Hospital was intended to provide a facility which would remain functional after a major earthquake. To accomplish this goal, seismic issues were considered in the earliest phases of the design. These issues included the selection of the structural system and the development of an appropriate building configuration. Probabilistic and site specific studies were combined with a soil structure interaction analysis to obtain the design response spectrum. Three-dimensional dynamic analyses were performed on a simplified model to obtain design force envelopes. Another three-dimensional model, incorporated the building symmetry to design the structural elements. The 1988 UBC detailing requirements were followed to provide ductility in the lateral force resisting elements. All of these items combined to result in a superior hospital design which would meet the performance objective of remaining functional after a major earthquake.

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