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Seismic performance-based design and risk analysis of thermal power plant building with consideration of vertical and mass irregularities

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ABSTRACT

Industrial buildings often have irregularities due to operational and complex industrial process. In this paper, a thermal power plant with mass and vertical irregularities was designed with the 2010 ASCE and AISC design codes. Subsequently, a parametric study was undertaken on simplified braced frames to quantify the impact of mass and vertical irregularities, as well as their combined effect. Detailed numerical models were developed in Open System for Earthquake Engineering Simulation platform. With a high seismicity level in China, ground motions were selected and nonlinear time-history analyses were performed. Subsequently, probabilistic seismic demand models, seismic fragilities, and risks were developed for different performance levels. The results show that the vertical irregularity generated larger detrimental effect than mass irregularity, and need more attention in structural design. Collapse risk increased the most due to the combined effect of mass and vertical irregularities. Furthermore, under small earthquake intensities, the thermal power plant with the combined irregularities had higher risk in functional disruption.

1. Introduction

Electric power is an important lifeline system for any country. Past earthquakes, however, have highlighted the vulnerability of such system with impact on financial losses (e.g. [1,2]) and other cascading effects (e.g. water supply, telecommunications [3]). In developing countries, major electricity generation is using thermal power plants operated with fossil fuels [4]. The thermal power plant buildings carry heavy equipment and machinery needed for operation. Such plants have complex and irregular geometries, and significant mass concentrations on specific floors. The current seismic design procedures for such irregular industrial buildings still follow conventional methods [5,6], however, if the effects of irregularities were not considered properly, would probably result in vulnerable structures [7].

Structural irregularities reported in different codes, e.g. ASCE/SEI 7-10 [8], Eurocode 8 [9] and National Building Code of Canada (NBCC) [10], primarily include mass irregularity (MI) and vertical irregularity (VI) (stiffness and strength irregularities are categorized under VI). Under moderate to high seismic hazards, buildings with one or more of these irregularities sustained severe damage (e.g. [11,12]). Several studies were undertaken to quantify the effect of each irregularity or their combined effects on structural performance (e.g. [13–16]). Letrung et al. [17] designed 20-story steel frame buildings with mass, stiffness and strength irregularities (24 buildings in total) using equivalent static force procedure, and performed nonlinear static and dynamic analyses. Based on the drift values, they discussed that the design criteria in IBC 2000 [18] are conservative for irregular structures. Similarly, Tremblay and Poncet [19] evaluated the effect of MI on a steel braced building and compared two analysis procedures available in NBCC [10] for irregular structural design. They reported that the equivalent static force procedure is inadequate to design a building with 300% MI and the dynamic analysis method is better suited. By using incremental dynamic analysis method, Michalis et al. [20] compared influences of different VIs on the seismic capacities of a 9-story steel frame. They found that the effects of VIs are highly dependent on the selected ground motion records. With consideration of record-to-record variability, Pirizadeh and Shakib [21] adopted the probabilistic design method to evaluate the effect of different VIs on steel moment frames in terms of the exceedance probabilities and confidence levels of various performance objectives.

Reported analytical studies focused on residential/commercial buildings (e.g. [13,20–22]), but limited studies were reported on

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industrial buildings. Thermal power plants, as an important lifeline facility, are designed with stringent performance objectives. Engineers should ensure the thermal power plant meet collapse prevention performance limit under severe intensity earthquakes; and under small and moderate intensity earthquakes, it is allowed to have limited structural damage and normal operational functionality should not be disrupted [23]. Recently, performance-based design framework provided engineers and stakeholders options of quantifying prevalent risk and making an informed decision [24]. Due to operational constraints, MI and VIs are prevalent in thermal power plant building. In this paper, within the framework of performance-based design, seismic risk analysis (SRA) of the thermal power plant was carried out to investigate impacts of MI and VIs. The SRA entails the integration of seismic hazard, structural demand evaluation, and vulnerability [25,26]. The vulnerability assessment, which is generally represented by fragility curves (e.g. [27,28]), can be used to quantify the effect of irregularities (e.g. [13,29,30]).

The paper is outlined as follows. In Section 2, the design of a typical thermal power plant building and corresponding performance levels were introduced. In Section 3, three groups of ground motions based on hazard levels of service-level, design-based, and maximum considered earthquakes were selected. Three simplified irregular structural models and a regular structural model based on the complex thermal power plant building were analyzed in Section 4. In Section 5, seismic risks were computed, presented and discussed, followed by discussion and conclusion sections.

2. Thermal power plant building design

A three-dimensional view of a typical thermal power plant and the corresponding columns layout are shown in Fig. 1a and b, respectively. The main portion of the plant is 66.1 m × 92 m in plan. Based on functionality, the plant can be grouped into three parts: turbine hall (Axis A–B, 31.5 m high), deaerator bay (Axis B–C, 38.4 m high) and bunker bay (Axis C–D, 53.3 m high). The building also includes three extensions, one in the north-east corner of the bunker bay with a 6 m-tall penthouse at the top (Axis 01–1), other two annex in the south-east and south-west corners of the turbine hall (Axis 0A–A). The design loads considered were dead load (due to self-weight of structural members), live load (to account for equipment, pipelines, and cranes), wind load and seismic load. Quantification of the loads and their combinations were performed using ASCE/SEI 7-10 standard [8]. The structural members consist of columns and beams with wide flange W-shape sections, and braces with rectangular hollow structural sections. The beam-column connections were designed to be fully restrained. The sectional strengths (e.g. compression, flexure, buckling) of each structural member were examined with the AISC 360-10 design code [31]. The primary lateral force-resisting systems were concentrically braced frames in both directions. As the building was designed for Chinese high seismic hazard zone, the structural system is expected to have a highly-ductile capacity and therefore, criteria associated with special concentrically braced frame (SCBF) system in AISC 341-10 provision [32] were followed. The structural design examination of the entire thermal power plant was carried out using SAP2000 V18 [33] commercial software.

The three parts of the thermal power plant have different functionalities, and as a result, the corresponding structural configurations and lateral force-resisting systems were altered along the Y-direction. Fig. 1c shows a typical elevation view of the structure in Y-Z plane (i.e. Axis-6 frame). The turbine hall and deaerator bay were designed as moment frames due to high-story clearance requirements while the bunker bay was designed as a concentrically braced frame system. In order to provide enough space for equipment or large-caliber pipelines that extend through the building, the corresponding lateral force-resisting system in bunker bay could not be designed with continuous bracing arrangement and balanced strength hierarchy. Specifically, the bracing in the first story was unsymmetrical. It is a “half” chevron type bracing and there is a lack of brace member that connects the column bottom of Axis-C to the mid-span of the girder on the first story floor. Similarly, for the roof story (i.e. sixth story), lateral loads are resisted by a moment frame. Thus, the discontinuities in lateral force-resisting structural members lead to VIs.

A total of 7 coal scuttles, which are shaped like silos, were installed at the 32.2 m level of the bunker bay (Fig. 1a, d). The coal scuttle, using 12-fixed supports, were rigidly connected to the girders. The mass of each scuttle was assumed to include the self-weight of an empty scuttle combined with the full weight of fossil coals (each coal scuttle weighs 1040 tons) under normal service conditions. Thus, for the 7 coal scuttles, the total weight was 7280 (7 × 1040) tons, which is 5 times to that of the adjacent story. Such large mass concentration on one story introduces significant MI.

Although the structure is featured with complex configurations and irregularities, based on conventional building design codes, practicing engineers have options to examine strength capacities of structural members as well as deformation of the structural system by using elastic analysis methods. However, with performance-based design approach, inelastic structural responses of such special and complex building under earthquake loads should be checked [34]. The performance levels can be defined with consideration of the required operational performance of critical equipment [35]. In this study, three performance limit states of SCBF structural systems as proposed by FEMA 356 [36] were adopted: Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). The structural performance levels can be combined with nonstructural performance levels as shown in Table 1. Unlike residential/commercial buildings with a relatively larger population density, industrial buildings may have limited human loss but higher financial loss due to equipment damage as well as operational interruptions.

3. Ground motion selection

The seismic risk analysis involves consideration of site-specific seismic hazard [37], and for each of three different hazard levels, an ensemble of 15 ground motion records was selected. The three hazard levels are: (i) service-level earthquake (SLE), (ii) design-based earthquake (DBE), and (iii) maximum considered earthquake (MCE). The corresponding exceedance probabilities for these three levels are 63%, 10% and 2% in 50 years, respectively. The ground motion selection criteria are: moment magnitude (M_w) ranges from 5 to 8; source-to-site distance (R_{rup}) is $0 \le R_{rup} \le 120$ km; and as the soil site is classified as stiff soil, average shear velocity in 30 m upper soils, V_{s30}, ranges from 179 to 280 m/s. Each ensemble of ground motion records was scaled to match target uniform hazard spectrum of SLE, DBE, and MCE, respectively. The scaling was done when less than 10% mean squared error (MSE) for each record was achieved. The target spectrum and spectra of scaled records for each hazard level are shown in Fig. 2. The details of the selected ground motions were summarized in Tables 2–4 for SLE, DBE, and MCE, respectively.

4. Simplified structures with consideration of irregularities

4.1. Structural simplification

The X-Z planar frames of the thermal power plant were designed with continuous and paired bracing systems, which provide uniform strength and stiffness distributions. However, as shown in Fig. 1, the MI and VIs exist simultaneously in the bunker bay and make the Y-Z planar frames vulnerable. The lateral force-resisting system in Y-Z planar frames consists of one bay braced frame in bunker bay and moment frames in the rest structural part. To quantify the lateral stiffness provided by the braced frame and moment frames, the frame along Axis-6 without braces (FB1, Fig. 3a) was used for comparison with the original