Engineering Structures 174 (2018) 646–662

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Probabilistic inelastic seismic demand spectra for large-span planar steel structures subjected to vertical ground motions

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ARTICLE INFO

Keywords:
Large-span planar steel structure
Vertical ground motion
Vertical seismic demand
Inelastic response spectra
Probabilistic seismic demand

ABSTRACT

Severe vertical ground motions (VGMs) may lead to detrimental seismic damages of large-span planar steel structures (LSPSSs), thus the inelastic seismic demand of LSPSSs under VGMs needs to be quantified so as to ensure the structural seismic reliabilities. In view that the uncertainties of VGMs greatly influence the seismic responses of LSPSSs, the VGMs-induced seismic demands of LSPSSs are investigated in a probabilistic way in this paper. Based on 680 strong VGM records, the vertical ductility demands (μ) of 2,100 equivalent single-degree-of-freedom (ESDF) models representing a series of LSPSSs are computed. It is revealed that the influences of VGM properties, including peak ground acceleration, epicentral distance, hypocenter depth, moment magnitude and local site condition, are tiny and irregular on the values of μ. Accordingly, the probabilistic seismic demand model for LSPSSs under VGMs is established regardless of the VGM properties in this paper. From the 1,428,000 computed values of μ, the VGMs-induced seismic demand of LSPSSs follows a positively skewed probabilistic distribution, and the distribution could be well fitted by the lognormal distribution model. The parameters of the lognormal distribution model for μ are simulated by two elementary functions subsequently, in which the effects of vertical strength reduction factor R, post-yield stiffness ratio α and elastic vibrating period T are accounted for. Using the lognormal model and the proposed functions, a group of probabilistic inelastic seismic demand spectra for LSPSSs under VGMs are generated. The established probabilistic spectra could provide the statistic properties of both the peak and the residual seismic demand of LSPSSs in association with pre-set values of T, R and α. Combining the proposed model with certain seismic hazard models that define the probabilistic characteristics of VGMs, the seismic reliability of LSPSSs could be quantified, and a proper structural seismic performance could be guaranteed.

1. Introduction

Large-span planar steel structures (LSPSSs) are widely used as mega building roofs, large-scale floors or components that cover large areas. Typical usage of LSPSSs, just to name a few, includes truss floor systems [1–4], spatial latticed roofs [5], and long-cantilever steel structures [6]. For a LSPSS, the effect of the vertical component of earthquake ground motions is believed to be potentially detrimental [7,8]. On one hand, the pre-dominant period of a vertical ground motion (VGM) record is commonly shorter than its horizontal counterparts, leading to a larger VGM spectral acceleration demand in the short-period region [9,10]. On the other hand, the dominant vibrating frequencies of LSPSSs are usually high [11–13] and un-favorably, are somehow close to the pre-dominant frequencies of VGMs. Therefore, the VGM action could become the controlling factor in the design of a LSPSS, especially in seismic regions that are prone to endure strong VGMs, for example, the near-fault areas [14,15]. Thus, it is necessary to quantify the effects of VGMs on LSPSSs in both design and evaluation to guarantee the seismic safety of LSPSSs.

Nowadays, the structural seismic safety are mostly measured in probabilistic manners, in which the seismic responses are quantified based on statistic computations, revealing the probabilities of structural responses exceeding a series of performance levels under appropriate seismic hazard situations [16,17]. Some recent advances about this topic include a number of probabilistic seismic demand models (PSDMs) developed for various types of structures such as reinforced concrete buildings [18–20], buckling-restrained braced frames [21], rocking symmetric blocks [22], concrete dams [23] and nonstructural components [24]. While these achievements deal with the PSDMs under horizontal earthquake excitations, much fewer research findings are focused on the VGM-induced probabilistic structural demands. Gülerce and Abrahamson [25] used a probabilistic seismic hazard framework to

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https://doi.org/10.1016/j.engstruct.2018.07.087
Received 26 March 2018; Received in revised form 26 July 2018; Accepted 29 July 2018

Nomenclature

ESDF	equivalent single-degree-of-freedom
LSPSS	large-span planar steel structure
VGM	vertical ground motion
PSDM	probabilistic seismic demand model
EDP	engineering demand parameter
IM	intensity measure
RHA	response history analysis
PSDS	probabilistic seismic demand spectra
PGA	peak ground acceleration
ED	epicentral distance
HD	hypocenter depth
MM	moment magnitude
IDR	vertical inelastic displacement ratio
μ	vertical ductility (demand) ratio
η	vertical residual displacement ratio
d_y	yield displacement
f_y	yield force
R	vertical strength reduction factor
d_e	peak displacement of a linear elastic oscillator
d_p	peak displacement a nonlinear oscillator
$d_{e,rc}$	recoverable elastic displacement
k_{py}	post-yield stiffness
α	vertical post-yield stiffness ratio
k_e	elastic stiffness
d_r	residual displacement of a nonlinear oscillator
f_p	peak restoring force of a nonlinear oscillator
f_e	peak restoring force of a linear elastic oscillator
T	elastic vibrating period
S_a	(pseudo) spectral acceleration
g	gravity with value 9.8 m/s^2
μ_{ave}	mean of μ
$\mu_{s.dev}$	standard deviation of μ
PDF	probabilistic density function
P(μ)	probability of μ
$(\ln\mu)_{ave}$	mean of $\ln\mu$
$(\ln\mu)_{s.dev}$	standard deviation of $\ln\mu$
A, B	coefficients of the T-$(\ln\mu)_{ave}$ formula
C, D, E	coefficients of the T-$(\ln\mu)_{s.dev}$ formula
CDF	cumulative distribution function

address the probability of exceeding the elastic capacity for highway bridges considering VGMs, detecting the negative mid-span moment demand as the most sensitive response parameter, and concluded that the annual probability of exceeding the elastic capacity of the negative mid-span moment is about 0.01 for sites close to active faults in California when VGMs are considered. Later on, Gulerce et al. [26] developed seismic demand models for typical highway overcrossings by incorporating critical engineering demand parameters (EDPs) and intensity measures (IMs) accounting for the combined effects of horizontal and vertical ground motions. Besides of [25,26], many researchers have also studied the VGMs-induced structural seismic demands, including but being not limited to those of bridges [27,29,31], isolation systems [28,30], and frame columns [32]. Despite of all the achievements so far, to the best of the authors' knowledge, the VGMs-induced seismic demands of LSPSSs have not been well investigated, especially in the context of probabilistic structural seismic analyses and evaluations. Therefore, a proper PSDM for LSPSSs under VGMs is needed.

To establish a structural PSDM, several alternative procedures are available, such as the incremental dynamic analysis [33,34], the multiple-strip analysis [35], and the cloud analysis [36,37]. The applications of these approaches involve a number of nonlinear response history analyses (RHAs), and are computationally demanding. To reduce these computation costs, the structural equivalent single-degree-of-freedom (ESDF) models could be used instead of the multi-degree-of-freedom models in performing the nonlinear RHAs [38–40]. However, since a large quantity of earthquake records should be included in the seismic input collection to account for the uncertainties of the seismic excitations in the aforementioned approaches, a number of RHAs are still unavoidable therein.

In order to quantify the probabilistic seismic demands in a more concise and efficient way, the probabilistic seismic demand spectra (PSDSs) are developed [41–43]. The PSDSs are constructed based on statistic calculations of structural seismic demands under some predefined conditions. These pre-set conditions include the seismic hazard of a site and the mechanical properties of a structure, both could be quantified in statistic ways. For example, the structural ductility demand for a given vibrating period and a normalized strength could be assumed to follow the lognormally distribution [43]. Accordingly, an efficient procedure for the probabilistic seismic demand analysis could be reached as long as the probabilistic distribution of ductility and the uncertain properties of ground motions are combined [43].

In establishing the PSDS for a structure, the uncertainties of the structural properties [44,45] and the seismic excitations [46], as well as some other random factors such as inaccuracies of modeling [47] need to be considered. However, it is extremely difficult to accurately model the coupling effects of all these sources of uncertainties [48]. According to Lee and Mosalam [49], the uncertainties in ground motion are more significant for global EDPs than those in structural parameters. Similar conclusions were given by Mehanny and Ayoub [50], that is, the dispersion of inelastic displacement ratios due to randomness in system parameters is much smaller than that caused by earthquake record variability. Thus, in the first step, it is reasonable and relevant to take the uncertainty of seismic excitations as the primary stochastic factor in constructing the VGM-induced PSDMs of LSPSSs, and correspondingly, in establishing the PSDSs for LSPSSs under VGMs.

Given the aforementioned discussions, this paper dedicates to develop a proper PSDM for LSPSSs under VGMs by taking the dispersions of VGMs as the primary uncertainty resource. In doing so, 680 strong VGM records are selected to compute the inelastic seismic demands of 2,100 nonlinear ESDF systems representing a series of LSPSSs. The effects of VGM properties on the structural seismic demands are investigated, including the peak ground acceleration (PGA), epicentral distance (ED), hypocenter depth (HD), moment magnitude (MM) of earthquakes and site type of recording stations. Based on the obtained data, the inelastic seismic demands of LSPSSs under VGMs are studied in a statistic way. It is proved that these seismic demands follow a skewed probabilistic distribution, and could be approximately described by the lognormal distribution model. Accordingly, a lognormal PSDS is established for the VGM-induced probabilistic inelastic seismic demand of LSPSSs. The proposed PSDS model provides a relevant insight of the seismic performance of LSPSSs under strong VGMs, as well as a better estimation of the seismic reliability of LSPSSs.

2. Vertical seismic demand parameters of LSPSSs

As defined in literatures [7,8], the vertical seismic demand of a LSPSS could be measured by its peak and residual seismic displacements. In quantifying the peak seismic displacement, the vertical inelastic displacement ratio (IDR) or the vertical ductility demand μ could be used. While for the vertical residual displacement, the vertical residual displacement ratio η proposed by Xiang et al. [8] is a proper measure. In fact, for a LSPSS, its vertical IDR, μ and η are directly related to each other, as will be illustrated in the following context.