Engineering Structures 148 (2017) 225–238

Contents lists available at ScienceDirect

Engineering Structures

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

Estimating the response of steel structures subjected to vertical seismic excitation: Idealized model and inelastic displacement ratio

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ARTICLE INFO

Article history:
Received 23 February 2017
Revised 8 June 2017
Accepted 17 June 2017

Keywords:
Vertical seismic excitation
Asymmetric vibration
Vertical seismic response
Large-span steel structure
Equivalent single-degree-of-freedom system
Asymmetric hysteresis model
Vertical pushover procedure
Inelastic displacement ratio

ABSTRACT

Vertical seismic excitations (VSEs) could induce severe damage to building structures and infrastructural facilities, especially to those with large-spans or long cantilevers. Thus, there is a need in engineering practice for estimating the seismic response of structures under VSEs. In this paper, a tentative investigation on VSEs-induced inelastic response of steel structures is proposed. The structure is transformed into an equivalent single-degree-of-freedom (ESDF) system in an extended pushover process, in which the vertical component of response is included. Considering the influence of gravity, a novel ESDF model with asymmetric vibrating characteristic is established. In this ESDF model, the inelastic response only occurs at the "lower" side of vibration, whereas at the other side, the system keeps elastic. Based on the idealized ESDF model and 53 recorded strong VSEs, the vertical inelastic displacement ratio (IDR) is computed. The averaged IDRs are plotted against the elastic vibrating period T, and fitted by a piecewise function to generate the IDR spectra, in which the effects of strength reduction factor R and of post-yield stiffness ratio α are accounted for by fitting coefficients. The overall process for estimating the VSE-induced inelastic responses of steel structures, using the extended pushover procedure and the proposed IDR spectra, is summarized. In the numerical example, seismic responses of a large-span space truss subjected to VSEs are computed by means of the nonlinear RHA method and the proposed IDR-based method, respectively, the results demonstrate that the IDR-based method could yield an anticipative estimation of structural responses under severe VSEs. For mid-span displacement, error of the IDR-based method is less than 13.6%; for quantity of yielded member, error is less than 14.2%.

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1. Introduction

Strong vertical ground motions have been observed during earthquake events in the past several decades (Bozorgnia et al. [1], Wang et al. [2], Yang and Lee [3], Wang and Xie [4], Xie et al. [5]). Meanwhile, their detrimental effects were reported (Papazoglou and Elnashai [6]). According to literatures, vertical seismic excitations (VSEs) may lead to severe damages in bridge piers (Tanimura et al. [7], Kim et al. [8,9]), brittle failure of reinforced concrete columns (Verderame et al. [10]), reduction of shear capacity of vertical structural members (Kim and Elnashai [11], Lee and Mosalam [12]), and even collapse of structures (Sarno et al. [13]). Besides of those VSEs-induced structural damages observed onsite, the VSEs-influences were also identified by plenty of numerical calculations and experimental investigations. For frame structures, some recent studies revealed that the VSEs could change the structural collapse mechanisms (Harrington and Liel [14]), as well as amplify the vertical acceleration demands of column lines and deformation demands of beams (Moschen et al. [15], Abdollahiparsa et al. [16]). For bridges, VSEs-induced pounding and vertical separation of girder from bearing, as well as heightened axial forces of piers and larger damages of decks were reported (Yang and Yin [17], Chen et al. [18], Wang et al. [19]). In addition to conventional structures, the complex and un-favored influences of VSEs on base-isolated systems were also investigated, as reported by Faramarz and Montazar [20], Montazar and Faramarz [21], Kwon and Jeong [22], Furukawa et al. [23] and some others.

Seeing the indisputable effects of VSEs, much work has been done so as to get proper approaches for both design and evaluation of constructed facilities that are prone to VSEs (Bozorgnia et al. [24]). Bozorgnia et al. [1], Ambraseys and Douglas [25], Li et al. [26] and Campbell and Bozorgnia [27] investigated the characteristics of vertical spectra based on large number of recorded ground motions, demonstrating that the vertical-to-horizontal response spectral ratio may exceed 2/3 at short periods. In a further study, Bozorgnia and Campbell [28] proposed 5%-damped acceleration response spectra. Tezcan and Cheng [29] developed a nonparametric

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http://dx.doi.org/10.1016/j.engstruct.2017.06.043
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Nomenclature

VSE	vertical seismic excitation
IDR	inelastic displacement ratio
R	strength reduction factor
α	post-yield stiffness ratio
RHA	response history analysis
NSA	nonlinear static analysis
ESDF	equivalent single-degree-of-freedom
l	order of dominant vibrating mode
$\mathbf{s}_l$	pushover load pattern associated with mode l
χ	pushover load factor
$\mathbf{m}$	mass matrix
$\boldsymbol{\varphi}_l$	shape vector of mode l
j	load step during pushover analysis
$k^l_{\mathrm{eq},j}$	equivalent stiffness exhibited in load step j
$\Delta\mathbf{s}_{l,j}$	increment of pushover load vector in load step j
$\Delta\mathbf{d}_{l,j}$	increment of structural displacement in load step j
$\lVert\Delta\mathbf{s}_{l,j}\rVert$	norm of $\Delta\mathbf{s}_{l,j}$
$\Delta\mathbf{s}^T_{l,j}$	transposition of $\Delta\mathbf{s}_{l,j}$
m^l_{eq}	equivalent mass of the ESDF system
$k^l_{\mathrm{eq},1}$	equivalent stiffness exhibited in the 1st load step
T_l	vibrating period of mode l
$\Delta F^l_{\mathrm{eq},j}$	equivalent force increment during load step j
$\Delta d^l_{\mathrm{eq},j}$	equivalent displacement increment during load step j
$\Delta\chi_j$	increment of pushover load factor during load step j
Γ_l	modal participating factor of mode l
σ^*_{y}	yield stress of the idealized beam model
σ^*_{G}	beam stress due to gravity
$\sigma^*_{\mathrm{d,y}}$	nominal yield stress of beam model in lower position
$\sigma^{**}_{\mathrm{d,y}}$	nominal yield stress of beam model in higher position
g	gravity with value 9.8 $\mathrm{m/s^2}$
T	vibrating period
d_{e}	peak displacement of an elastic oscillator with period T
d_{p}	peak displacement of the asymmetric inelastic oscillator
d_{y}	yield displacement of the inelastic oscillator
k_{e}	elastic stiffness of the inelastic oscillator
k_{py}	post-yield stiffness of the inelastic oscillator
t	time
A, B	fitting coefficients of IDR-T formula in short period region
C, D	fitting coefficients of IDR-T formula in medium period region
E, F	fitting coefficients of IDR-T formula in long period region
T_1	vibrating period of the fundamental mode
$d_{\mathrm{eq,\ e}}$	elastic displacement demand of ESDF system
$d_{\mathrm{eq,\ p}}$	inelastic displacement demand of ESDF system
$d_{\mathrm{eq,\ y}}$	yield displacement of ESDF system
$k_{\mathrm{eq,\ e}}$	elastic stiffness of ESDF system
$k_{\mathrm{eq,\ py}}$	post-yield stiffness of ESDF system

approach to characterize the effects of VSEs, by which the vertical seismic effects could be characterized without an assumed functional form. Gulerce et al. [30] derived seismic demand models for typical highway overcrossings, which could be used as risk-based design tools and included in probabilistic seismic risk assessments. Legeron and Sheikh [31] proposed a simplified method to calculate the elastic support reactions of typical bridges with regular span distribution subjected to VSEs.

Generally, the accurate structural responses induced by severe earthquakes can only be obtained via the nonlinear response history analysis (RHA) method. Besides of RHA, the nonlinear static analysis (NSA) approach is also popular in engineering practice, as the NSA can provide reasonable predictions of nonlinear structural responses in a concise, easily-understood manner (Mazza [32], Bosco et al. [33], Martinelli et al. [34], Amini and Poursha [35]). In the NSA approach, one key step is to determine the nonlinear displacement demand of the equivalent single-degree-of-freedom (ESDF) system of the structure. In doing so, the inelastic displacement ratio (IDR) method is considered one of the most effective, as the nonlinear displacement demand of the system can be efficiently computed based on elastic procedures in the IDR method. By now, researchers have reported quite a number of IDR properties and expressions, including IDR on specific site conditions (Miranda [36], Ruiz-García and Miranda [37,38], Iervolino et al. [39]), IDR corresponding to certain types of hysteresis (Chenouda and Ayoub [40], Ozkul et al. [41], Rahgozar et al. [42]), and IDR considering soil-foundation-structure interactions (Eser et al. [43], Khoshnoudian et al. [44], Ghannad and Jafarieh [45]). Moreover, some other researches have computed IDR in accordance with repeated earthquakes and frequency-specific earthquakes, as reported by Hatzigeorgiou and Beskos [46] and Durucan and Dicleli [47].

Given the successful application of IDR method for seismic performance evaluation and aseismic design, it is worthwhile to extend this method from horizontal-ground-motion-resisting situations to vertical ones. On one hand, numerous engineering structures may experience severe vertical seismic actions during their service life-cycle, especially those with large spans or long cantilevers and built in near-fault regions, where the VSEs can be destructive. On the other hand, besides of the nonlinear RHA approach, engineers need more efficient methods for predicting the inelastic seismic responses and evaluating the seismic performances of structures subjected to VSEs. To extend the horizontal IDR method to vertical situations, there is one formidable obstacle, which is, as stated by Elnashai and Papazoglou [48] in 1997, that the structure is pre-loaded by gravity in the vertical direction, making the vertical vibration asymmetric with respect to its steady horizontal plane. Consequently, all the symmetrical hysteresis models and their corresponding IDR regulations are no longer suitable for vertical situations. To the best of the authors' knowledge, that may be one of the key reasons that the NSA approaches (especially the IDR-based method) have not been developed or modified for vertical-seismic-resisting situations by far.

In view of the aforementioned facts, this paper proposes a tentative investigation on estimating the inelastic structural responses due to VSEs. In the proposed process, an asymmetric vibrating model is established by taking the pre-loaded gravity into consideration. Based on the idealized model, the vertical IDR are computed from 53 strong vertical ground motions recorded in Japanese earthquake events, and the obtained results are arranged in IDR-T format. By means of a numerical fitting process, an approximate formula is proposed for vertical IDR. Combining the vertical IDR model and the static pushover curve, the nonlinear seismic response of a steel structure subjected to severe VSEs could be obtained. Finally, the effectiveness of the proposed vertical IDR-based method is demonstrated by a numerical example.

2. Idealized ESDF model for steel structures subjected to VSEs

In computing the vertical IDR for steel structures, an ESDF system is needed to represent the multi-degree-of-freedom structure that vibrates mainly in the vertical direction.

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