Soil Dynamics and Earthquake Engineering 88 (2016) 92–108

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

A linearized approach for the seismic response analysis of flexible cable net structures

Yang Xiang, Yongfeng Luo, Xiaonong Guo*, Zhe Xiong, Zuyan Shen

Department of Building Engineering, Tongji University, Shanghai 200092, PR China

ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form
15 May 2016
Accepted 2 June 2016

Keywords:
Cable net structure
Nonlinear seismic response
Equivalent single-degree-of-freedom system
Equivalent linearization
Non-iterative approach
Seismic response spectrum
Flexible curtain wall

ABSTRACT

Cable net structures are characterized by significant geometrical nonlinear properties. The linear modal superposition method (LMSM), which ignores the effect of nonlinearity, is believed not suitable for the seismic response analysis of this kind of structures. To conquer the drawback of LMSM, a non-iterative linearization method (NILM) is proposed in this paper. An energy parameter named the "stiffness parameter" is utilized in generating the nonlinear equivalent single degree of freedom (ESDF) systems for the dominant vibration modes of cable nets. The nonlinear stiffness of an ESDF system is simulated by a quadratic function about the equivalent displacement. Based on a stochastic linearization process, the relationship between the equivalent linear stiffness and the displacement response of a modal ESDF system is established. Then the structural responses are computed according to the design response spectra through a non-iterative procedure. Finally, the effectiveness of the proposed NILM is illustrated by a numerical example that carried out on a trapezoid-shaped cable net supported curtain wall structure. It is demonstrated that the proposed NILM, which takes the stiffness hardening effect into consideration, could not only yield better results than the LMSM does, but also exhibit satisfying timesaving property over the nonlinear RHA.

1. Introduction

The monolayer cable net facades have been widely used in building structures over the last several decades. These flexible cable net structures mainly consist of pre-tensioned cables and glass panels, as shown in Fig. 1. Because the structural stiffness and the bearing capacity are mainly provided by the cable members, the monolayer cable net systems are characterized by significant geometrical nonlinear behaviors. And this nonlinearity makes it pretty complicated to analyze the structural responses under dynamic excitations, such as seismic actions (Memari et al. [1]) and fluctuating wind pressures. To accurately compute these dynamic responses, a response history integration process is necessarily needed. Consequently, a series of response history analyses (RHA) is involved in either design or evaluation of a flexible cable net structure.

In order to simplify the analysis procedure and, possibly, avoid the time consuming RHA process, notable works have been done on investigating the dynamic properties of the pre-tensioned cable net systems. Kwan [2] provided a simple technique for calculating the initial natural frequencies of cable nets, yet it was also pointed out that the period of a cable net is amplitude dependent. Vassilopoulou and Gantes [3,4] studied the natural frequencies and the corresponding vibration modes of saddle-formed cable networks with either rigid or flexible supports, and reported in details the nonlinear resonance phenomenon of this kind of structure. In investigating the behavior of cable net facades subjected to blast loads, the influence of negative phase loading were particularly discussed by Teich et al. [5]. During the last decade, Feng et al. [6–9] did a series of work on analyzing the dynamic responses of cable net structures. Firstly, Feng et al. [6] carried out static experiments and numerical simulations to study the working mechanism of monolayer cable net supported glass curtain walls. Besides, based on the continuous membrane theory, Feng et al. [7] established an equivalent single degree of freedom (ESDF) system and the corresponding nonlinear vibration governing equation of a cable net, and calculated its wind induced linear response by using a harmonic balance method. Meanwhile, Feng et al. [8] did dynamic model tests, as well as finite element analyses to learn the dynamic performance of cable net facades which considers the effects of the glass panels. Furthermore, according to the nonlinear ESDF system, Feng et al. [9] proposed the nonlinear response spectra for flexible cable net structures under four groups of site conditions.

The research done by Wang et al. [10], Shi et al. [11], Wang and Zhao [12], together with the aforementioned Feng et al.'s work [6–

---

* Corresponding author.
E-mail address: guo-xiao-nong@tongji.edu.cn (X. Guo).

http://dx.doi.org/10.1016/j.soildyn.2016.06.001

Nomenclature

RHA	response history analysis
ESDF	equivalent single degree of freedom
LDC	load-displacement curve
SDF	single degree of freedom
k^*	overall structural stiffness index
f_u	unit force
w_u	work done by the unit force
d_u	displacement accordant to f_u
δ_u	flexibility of the system
k_u	system stiffness corresponding to w_u
MDF	multi-degree of freedom
$\Delta\boldsymbol{P_i}$	load increment vector in the *i*th load step
$\Delta\boldsymbol{v_i}$	displacement increment vector caused by $\Delta\boldsymbol{P_i}$
$\Delta\boldsymbol{P_{ui}}$	unitized vector corresponding to $\Delta\boldsymbol{P_i}$
$\Delta\boldsymbol{v_{ui}}$	displacement increment vector caused by $\Delta\boldsymbol{P_{ui}}$
$\lVert\Delta\boldsymbol{P_i}\rVert$	norm of $\Delta\boldsymbol{P_i}$
Δw_{ui}	work done by $\Delta\boldsymbol{P_{ui}}$
k_i^*	equivalent structural stiffness of the *i*th load step
$\boldsymbol{X_n}$	the *n*th modal displacement vector
χ_{ni}	static load factor of the *i*th load step
$\boldsymbol{F_{ni}}$	force vector of the *i*th load step
SLF	static load factor
k_{ni}^*	stiffness of the *n*th mode in the *i*th load step
m_n^*	equivalent mass of the *n*th modal ESDF system
T_n	vibrating period of the *n*th mode
ω_n	circular frequency of the *n*th mode
ξ_n	damping ratio of the *n*th mode
k_{n0}^*	initial equivalent stiffness of the *n*th ESDF system
$F_{ni,j}$	equivalent force on the *j*th node in the *i*th load step
$X_{n,j}$	the *j*th element of $\boldsymbol{X_n}$
α_{ni}	acceleration response of the *n*th mode
m_j	mass of the *j*th node
Γ_n	modal participate factor of the *n*th mode
F_{ni}^*	equivalent seismic action on m_n^*
X_n^*	equivalent modal displacement
ΔF_{ni}^*	force increment during the *i*th load step
Δd_{ni}^*	equivalent displacement increment
d_{ni}^*	equivalent displacement
$\boldsymbol{d_n}$	displacement vector due to the *n*th mode
a_n^*	acceleration of the *n*th modal ESDF system
v_n^*	velocity of the *n*th modal ESDF system
$F_n^*(d)$	restoring force of the *n*th modal ESDF system
c_n	viscous damping coefficient of the *n*th mode
$a_g(t)$	ground acceleration
$\Delta\chi_{ni}$	load factor increment
k	stiffness
d	displacement
a_0	coefficient in the *k*-*d* relationship
b_0	coefficient in the *k*-*d* relationship
$F(d)$	restoring force
$F_e(d)$	linear restoring force
k_e	equivalent stiffness
SGP	stationary Gaussian process
$d(t)$	structural response process
$\Delta F[d]$	deviation process between $F(d)$ and $F_e(d)$
PDF	probability density function
$p(d)$	PDF of the $d(t)$ process
σ_d	standard deviation of $d(t)$
a_{resp}	seismic acceleration response
T	vibrating period
d_{resp}	seismic displacement response
$a_{reap}{}^T(\omega)$	transformed response spectrum
$a_{reap}{}^{TT}$	*m*-*k*-based design response spectrum
NILM	non-iterative linearized method
LMSM	linear modal superposition method
A	cross-section area of cables
E	Young-modulus
ε	initial strain
m	mass on the cable net façade model
ξ_n	damping ratio of the *n*th mode
EMF	effective mass factor
MPF	modal participate factor
PGA	peak ground acceleration
$k_e{}^{\mathrm{N}}$	equivalent stiffness obtained by NILM
$k_e{}^{\mathrm{L}}$	equivalent stiffness obtained by LMSM
$\boldsymbol{d}$	overall structural displacement vector
$\varepsilon_{63}{}^{\mathrm{NILM}}$	error of node 63 displacement of NILM
$\varepsilon_{Fp}{}^{\mathrm{NILM}}$	error of cable force of NILM
$d_{63}{}^{\mathrm{NILM}}$	node 63 displacement computed by NILM
$d_{63}{}^{\mathrm{RHA}}$	node 63 displacement computed by RHA
$F_p{}^{\mathrm{NILM}}$	cable force computed by NILM
$F_p{}^{\mathrm{RHA}}$	cable force computed by RHA
$\varepsilon_{63}{}^{\mathrm{LMSM}}$	error of node 63 displacement of LMSM
$\varepsilon_{Fp}{}^{\mathrm{LMSM}}$	error of cable force of LMSM
$d_{63}{}^{\mathrm{LMSM}}$	node 63 displacement computed by LMSM
$F_p{}^{\mathrm{LMSM}}$	cable force computed by LMSM

9], all demonstrate that the role played by the nonlinear ESDF system is pretty essential in predicting the dynamic responses of the cable net systems. Yet all of the nonlinear ESDF systems in use are established based on a continuous theory, in which the deformed shape of a cable net facade is simulated by a sinusoidal curved surface and the boundary of the cable net model is assumed to be rectangular, moreover, the cable pretensions and nodal mass are considered as uniformly distributed. Taking the typical Feng et al.'s approach [7,9] for example, they assume the fundamental mode dominates the vibration of the cable net structure as shown in Fig. 2, and express the deformation pattern of the overall system as a symmetric function:

$$\varphi_1(x,z) = \boldsymbol{sin}\big(\pi(x/L_x)\big)\boldsymbol{sin}\big(\pi(z/L_z)\big) \tag{1}$$

where $\varphi_1(x,z)$ is the out-of-plane displacement of the cable net at position (x,z), while x and z are the horizontal and vertical location, respectively. Based on this continuous assumption, the vibration equation of the cable net could be derived.

For those cable net structures with irregular boundary shapes, the nonlinear ESDF systems, which represent the mechanical properties of the overall structures, can hardly be established according to the aforementioned approaches, as their two basic assumptions are not applicative anymore. One of them is the sinusoidal curved deformation assumption, and the other is the uniform distribution of pretension and mass assumption. For instance, in designing of the cable net curtain wall of the Beijing New Poly Plaza, (Yang et al. [13]) the structural dynamic properties and responses can only be obtained by a thoroughly executed RHA process, just because the elevation of the curtain wall is "L-shaped".

Besides of the geometrical topology limitation exists in the boundary shapes of cable net structures, another shortcoming of the aforementioned nonlinear approaches is that the amplitude dependent nonlinear stiffness of the ESDF system is not satisfyingly calculated. Feng et al. [14] proposed an applicative approach for nonlinear wind-resistance design of cable net systems, which