Measurement xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Measurement

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

Determination of the natural frequencies of a prestressed cable RC truss floor system

Jiang Li[a,b,c], Ruizhi Zhang[a,b], Jiepeng Liu[a,b,*], Liang Cao[a,b], Y. Frank Chen[d]

[a] School of Civil Engineering, Chongqing University, Chongqing 400045, China
[b] Key Laboratory of New Technology for Construction of Cities in Mountain Area, Chongqing University, Chongqing 400045, China
[c] Postdoctoral Research Station, School of Civil Engineering, Chongqing University, Chongqing 400045, China
[d] Department of Civil Engineering, The Pennsylvania State University, Middletown, PA 17057, USA

ARTICLE INFO

Keywords:
Prestressed cable RC truss (PCT)
Floor
Vertical vibration
Frequency
The energy method

ABSTRACT

The finite element method (FEM) and the analytical formula were used to study the vertical vibration of a prestressed cable RC truss (PCT) floor system. Three element types were compared for estimating the natural frequencies of this floor system. Extensive sensitivity studies using ABAQUS were conducted considering: (a) live load; (b) the number of web members; (c) opening ratio; (d) span; (e) rise-span ratio; (f) span to spacing ratio. Detailed derivation using the energy method for the natural frequencies of an orthotropic floor with four built-in edges is described. The unified formula for the PCT floor system was then developed for the first time based on the orthotropic plate theory to calculate the natural frequencies. The results obtained by the formula were compared with those from the field test and FEM. The comparison shows that the results are generally in a good agreement, indicating that the derived formula for natural frequencies is reasonably accurate and suitable for the vibrational analysis and design of the PCT floor system.

1. Introduction

In recent years, large-span structures have been widely applied in structures like stadiums, exhibition halls, and open-space office buildings. Among them, the large-span prestressed cable RC truss (PCT) floor system is a common one [1], which consists of RC floor, upper chords, web members, and prestressed lower chords (Fig. 1). The ample openings between web members allow utility ducts and pipes to various types of pipelines pass through freely without sacrificing the available space and headroom. Additionally, this system is architecturally appealing and has good fire resistance [2]. It is also found to be economical because of a lighter overall weight [1,2]. However, the light weight and large span raise the concerns on vibration [3]. The vibration amplitude of such floors would be large under a service load condition may increase in normal use and people may feel discomfortable and even panicking. AISC Design Guide 11 [4] and SCI Design of Floors for Vibration: A New Approach [5] provide engineers with the evaluation criteria for vibration serviceability.

Related studies on the human perception of vibrations are available in the literature [6]. According to the widely used vibration evaluation criteria, frequency and acceleration response are deemed as two important indicators for evaluating the vibration serviceability of the floor [4]. Since the acceleration response of the PCT floor has been extensively discussed previously [1,7], this paper mainly focuses on the frequency. Over the past decades, research has emphasized on the determination of natural frequencies for structures like footbridges [8], staircases [9], long-span deck floors [10], and open-space floors [11] under human loading. Davis et al. [12] made a comparison on the natural frequencies of composite slab floors, obtained experimentally and analytically. Kerr et al. [13] proposed an approximate formula for determining the fundamental frequency of a staircase under vertical excitation. Zhou et al. [1,2,7,14] investigated the PCT floor under various human excitations and proposed simplified formulas for calculating the frequencies and accelerations.

Predicting the natural frequencies of a floor is not an easy task and the prediction accuracy is a concern as the floor becomes more complicated involving ribbed slabs, orthotropic properties, and multiple bays [15]. An accurate estimation of frequencies can be done by using the detailed finite element method (FEM) or a reliable formula [16]. The SCI's original P076 document states that using dynamic analysis software to calculate the structural dynamic characteristics could improve the accuracy [5]. However, the FEM may face the following issues: selection of a proper walking load model, integration of walking excitation into the FEM, and the high computational cost of a time-

* Corresponding author at: School of Civil Engineering, Chongqing University, Chongqing 400045, China.
E-mail address: liujp@cqu.edu.cn (J. Liu).

http://dx.doi.org/10.1016/j.measurement.2017.08.048
Received 12 May 2017; Received in revised form 31 July 2017; Accepted 30 August 2017

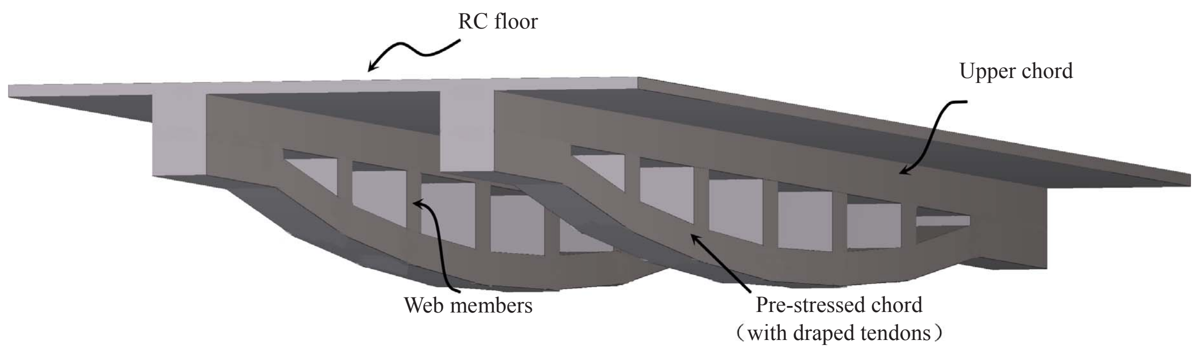

Fig. 1. Prestressed cable RC truss floor system [2].

domain analysis [17]. Hand calculations are useful for a quick estimation of the fundamental frequency of a floor. But the majority of calculation methods for floor responses due to walking are treating the floor as an equivalent beam rather than a plate. As such, these methods are often inaccurate, especially for a more complicated floor having the orthotropic properties [15,4].

This paper shows the comparison between the measured modal properties of a PCT floor and those predicted by the FEM and proposes a formula for the natural frequencies.

The scope of this research includes:

- Obtain the natural frequencies by the FEM using different element types and compare them with the measured values;
- Investigate the effects of live load, the number of web members, opening ratio, span, rise-span ratio, and span to spacing ratio on the fundamental frequency;
- Derive the formula for determining the natural frequencies of the PCT floor system based on the orthotropic thin plate theory;
- Investigate the accuracy of different modeling techniques and provide a simplified calculation method for this type of floor systems.

2. Experimental tests

2.1. Experimental design

To control the excessive vibration on a large-span floor subjected to human-induced dynamic loading, field testing is necessary to determine the dynamic characteristics [18,19].

In-situ floor is a novel PCT floor system consisting of 160 mm thick concrete slab and 7 PCTs which are transversely spaced at 4 m and spans 28.2 m (Fig. 2(a)). The structure layout and arrangement of accelerometers are shown in Fig. 2(b).

Detailed configuration for the PCT is not available due to space limitation in this paper and it can be referred to the literature [2]. The tested floor portion was free from construction materials, partition walls, or raised flooring. The monitoring system [Fig. 4(d)] consists of accelerometers (DH 610V) with the acceleration range of ± 2 g (g being gravitational acceleration) and a data acquisition system (DH 5927N).

2.2. Experimental results

In performing the dynamic tests, sand-bag drop [20], shaker excitation [21], and heel drop [6] have been considered to capture the dynamic characteristics including natural frequencies, mode shapes, and damping ratios. Among them, the heel-drop test is easier one as it does not require expensive equipment [22]. Hence, heel-drop impact was chosen as the transient excitation to ascertain the modal parameters of the PCT floor system in this study.

The acceleration-time signals were measured at the locations as indicated in Fig. 2(a). The corresponding power spectrums (acceleration against frequency) can then be obtained through the fast Fourier transform [30,31]. The waveform for the frequency range of 0–15 Hz and the frequency spectrum at excitation point 13 are shown in Fig. 3, where the first three natural frequencies are marked with dots (Fig. 3(b)). The fundamental frequency is 4.88 Hz and the peak acceleration is 88 mm/s^2. The frequencies for the second and third modes are 5.47 Hz and 6.45 Hz, respectively.

Floors are usually classified into two groups, depending on the magnitude of their fundamental frequency. The low-frequency floors have the fundamental frequency of < 10 Hz, while the high-frequency floors have the frequency of > 10 Hz [4,5]. Based on the test results, the tested PCT floor belongs to the low-frequency one. For a low-frequency floor system, the walking frequency may match one of the subharmonics of the floor natural frequencies and thus causes the resonance, resulting in a maximum floor response and the possible discomfort to the floor occupants. The frequency for the normal walking on a flat ground ranges from 1.5 Hz to 2.5 Hz [23], while it is between 2.4 Hz and 2.7 Hz for an average running [24]. As indicated above, the PCT floor frequency is nearly three times the walking one or twice the running one. This suggests that the low-frequency floor is likely to be excited at one of its subharmonics and would thus experience a resonance.

3. Finite element (FE) method

3.1. FE model

The mode shapes and natural frequencies were predicted using the available finite element program, ABAQUS [25]. All beam-to-girder and girder-to-column connections were modeled as moment connections. 8-node linear brick elements (C3D8R), 20-node quadratic brick elements with reduced integration and hourglass control (C3D20R), and 20-node quadratic brick elements (C3D20) were taken respectively in modeling of the slab and girder. The columns were fixed to the ground to simulate the boundaries, i.e., the cross-sections at the bottom of all the columns, U1 = U2 = U3 = UR1 = UR2 = UR3 = 0. The approximate global size is controlled at 0.30 m during the mesh using the different element types for comparison. The predicted results of the natural frequencies were then compared to the measured ones.

3.2. FEA results

The first three mode shapes with the natural frequencies as predicted using C3D8R, C3D20R, and C3D20 elements are shown in Figs. 4–6, respectively. The order of the modes computed by the FE model can differ from the order of the corresponding testing data. The modal assurance criterion (MAC) [29] is used to identify matching modes: $MAC_{ij} = |\Phi_i^T\tilde{\Phi}_j|^2/[(\Phi_i^T\Phi_i)(\tilde{\Phi}_j^T\tilde{\Phi}_j)]$, in which, Φ_i is the identified testing mode (mode i) and $\tilde{\Phi}_j$ is the calculated mode (mode j). The MAC values for various modes are listed in Table 1. Clearly, the model using C3D20 element can get the highest accuracy.