Engineering Structures 37 (2012) 167–178

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Full-scale dynamic testing and modal identification of a coupled floor slab system

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ARTICLE INFO

Article history:
Received 7 March 2011
Revised 9 December 2011
Accepted 12 December 2011
Available online 2 February 2012

Keywords:
Ambient vibration test
Bayesian FFT
Forced vibration test
Modal identification

ABSTRACT

This paper presents work on full-scale vibration testing of the 2nd and 3rd floor slabs of the Tin Shui Wai Indoor Recreation Center. The slabs are supported by one-way long span steel trusses, which are connected by diagonal members and vertical columns to form a mega-truss. On the 2nd floor are a large multi-function room and children play area, while the 3rd floor hosts two basketball courts. Based on their expected usage, significant cultural vibrations with possible rhythmic activities can be expected. To determine the dynamic characteristics of the constructed slab system, ambient and forced vibration tests were performed. Thirty-five setups were carried out in the ambient test to determine the mode shapes using six triaxial accelerometers. A recently developed Fast Bayesian FFT Method is used to identify the modal properties using the ambient data in individual setups. The mode shapes from the individual setups are assembled by a least square fitting procedure. Forced vibration tests were performed by loading the slabs at resonance with a long-stroke electromagnetic shaker, resulting in vibration amplitudes in the order of a few milli-g. A steady-state frequency sweep was carried out and the modal properties were identified by least square fitting of the measured steady-state amplitude spectra with a linear dynamic model. The dynamic properties identified from the ambient and forced vibration tests, as well as their posterior uncertainty and setup-to-setup variability, will be compared and discussed. The field tests provide an opportunity to apply the Fast Bayesian FFT Method in a practical context.

1. Introduction

The Tin Shui Wai (TSW) public library cum Indoor Recreation Center is an ex-Provisional Regional Council project to meet the demand for library and recreational facilities of the Tin Shui Wai district in the New Territories of Hong Kong. It is a three-storied concrete building with a height of approximately 40 m. Fig. 1 shows the exterior view of the building at the time of instrumentation. The slabs on the 2nd floor (2/F) and 3rd floor (3/F) span over a 35×35 m area and are supported by one-way long span steel trusses. The two floor slabs are connected by six vertical columns and diagonal members at about quarter spans, forming a combined system where the slab dynamics are likely to be coupled. On the 2/F are a large multi-function room and a children playground. The 3/F hosts two basketball courts. Based on their expected usage, significant cultural vibrations with possible rhythmic activities are expected. At the design stage, a finite element model was created to estimate the dynamic properties of the slab system, revealing natural frequencies of 5.4 and 6.6 Hz for the first two vertical modes. Realizing the limitations in the model and the absence of the damping ratios [1], it was of interest to both the building owner and design engineer to experimentally determine the modal properties in order to assess the likely vibration level under service loading to a higher confidence than was possible from the information available at the design stage. A series of field vibration tests were performed with these objectives in mind. They include ambient vibration test, forced vibration (shaker) test and service load (jumping) test.

Full-scale testing provides an important means for acquiring in-situ knowledge of a constructed facility [2–5]. Ambient vibration tests can be performed without artificial loading and hence require less equipment [6–9]. They were performed first to obtain a first-hand estimate of the natural frequencies, damping ratios and mode shapes. A number of setups were performed to determine the mode shapes using six triaxial accelerometers. Due to the nature of ambient loading, the modal properties are applicable only for low vibration levels (e.g., up to 100 μg). This qualification is especially relevant for the damping ratios, which are well-known to be amplitude dependent [10–13]. In order to determine the damping ratios at vibration levels comparable to the target serviceability limits (of milli-g level, e.g., ISO 2631-2 [14]), forced vibration (shaker) tests were performed with a long-stroke electrodynamic shaker, where the mode shapes along a critical line of the slab were also identified. Service load tests with a large number of participants jumping to cause resonance were finally performed to obtain the likely vibration in some design scenario. This paper presents the field instrumentation and modal identification of the coupled

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0141-0296/$ - see front matter
doi:10.1016/j.engstruct.2011.12.024

Fig. 1. The TSW Indoor Recreation Center.

slab system, focusing on the ambient tests and shaker tests. The field tests are described in detail with particular reference to their implications on the identified modal properties. The paper also contributes to the application of established Bayesian modal identification theory and discussion of practical issues encountered. The posterior uncertainty and setup-to-setup variability of modal properties shall also be discussed from a Bayesian and frequentist point of view, respectively.

2. Ambient vibration test

2.1. Instrumentation

In the ambient tests, six force-balance triaxial accelerometers, Guralp CMG5T, were used to obtain acceleration time histories synchronously in each setup. The analogue signals were transmitted through cable and acquired digitally by a 24 bit data logger. The overall channel noise is about 0.1 $\mu g/\sqrt{Hz}$ in the frequency band above 1 Hz. Acceleration data of $6 \times 3 = 18$ channels from the six triaxial accelerometers were acquired at a sampling rate of 2048 Hz (the lowest allowed by hardware) and later decimated by 8 to an effective sampling rate of 256 Hz for analysis.

2.1.1. Sensor location

For the purpose of identifying mode shapes, the slabs were divided into segments by grid lines, whose intersections defined the sensor locations. Setting out was performed by the building contractor, with precision adequate for field testing. In order to cover all the target degrees of freedom (DOFs) with a limited number of sensors (six only), a number of setups were planned. The measured DOFs in different setups were designed to share a common set of DOFs so that their mode shape information covering different parts of the structure can be assembled (or 'glued') together.

Figs. 2 and 3 show the overall setup plans for 2/F and 3/F, respectively. The instrumented area on each floor measures 30 m long by 20 m wide. A total of $9 \times 7 \times 2 = 126$ locations were planned to be measured triaxially, giving $126 \times 3 = 378$ DOFs. In these figures, the number in the rectangular box shows the location number. Typical locations are filled yellow. Next to the box shows the setup number underlined. The location numbers are assigned with the following convention that facilitates field implementation: the first number indicates the floor; the second number indicates the number of the row; the third and fourth number indicate the column number. For example, '2101' refers to the first row and the first column on 2/F. This nomenclature allows easy recalling of position on site. It also allows additional sensor locations to be added without disturbing the existing location numbers.

2.1.2. Reference sensors

To allow for the assembling of mode shape information on the two floors from different setups, two reference sensors, one on each floor, were placed and remained recording in all setups. Locations 2404 and 3404 have been chosen to be the reference, which are filled light brown in Figs. 2 and 3, respectively. Both theoretical and practical considerations have been taken into account in the choice of these reference locations. On the theoretical side, they should have significant response in the modes of interest. At the planning stage an attempt was made to avoid nodal locations based on intuitive guess of the mode shape. On the practical side, limited cable lengths (max 45 m in this case) required that the reference locations be near the central area of the slab, although this was complicated by the blocking of the partition walls surrounding the multi-function room on 2/F (see column lines 2 and D in Fig. 2). A hole, indicated by 'H' in Fig. 3, was drilled on 3/F to allow the passage of signal cable between 2/F and 3/F. Without this hole, one would have resorted to run the cable through the staircase near C-3 in Fig. 2, which would require much longer cable and create additional safety issues on site. Drilling of this hole could be facilitated as the internal servicing of the building was still in progress.

2.1.3. Roving setups

Using the six triaxial accelerometers, the 126 measurement locations in Figs. 2 and 3 were covered in 35 setups, with 16 setups on 2/F and 19 setups on 3/F. The setups on 2/F and 3/F were performed separately on two consecutive days, from 8am to 6pm. In all setups two sensors were always placed at the reference locations 2404 and 3404. The remaining four sensors were roved in different setups to cover the other locations. In Figs. 2 and 3, the color of the number in rectangular box distinguishes the particular sensor placed, e.g., blue for TM54 and red for TM55. As the setups proceeded, the sensors typically marched from the figure North to South, moved to the right column and then North to South again. The last two setups in Fig. 2 were exceptions in order to cover the right slab boundary.

Ambient test of 3/F, which was done one day after 2/F, followed a similar plan in the early setups until Setup 8, where the channels associated with TM54 failed due to faulty cable. Subsequent setups were revised immediately on site and resorted to proceed with the remaining three roving sensors. As a result, three setups were added to cover all the remaining locations, leading to 19 setups. The plan shown in Fig. 3 is the one actually used.

During the test, one person was responsible for a particular sensor. When transiting between setups, each roving sensor was moved to the next corresponding location. Including taking pictures and leveling, the transition typically could be finished in 5 min. Vibration data in each setup was recorded for 15 min. Exceptions were Setups 17–19 on 3/F, where only 10 min of data were collected due to time limitation and in view of their boundary nature (relatively unimportant). Nevertheless these exceptions have little effect on data quality for the purpose of modal identification. All sensors were oriented with their North aligning with North direction of the figure.

As a note, it rained on the day when the setups on 3/F were performed. As the roof was not completely covered nor sealed, rain water pooled on the 3/F slab. Upon inspection of data on site the rain was found to have insignificant effect on data quality. The pooling of rain water might have increased the dead weight and damping of the slab but the effect was insignificant, as evidenced from the identification results (see later).

2.2. Ambient modal identification

Using the data in each setup, the modal properties of the structure are identified following a Bayesian FFT approach. The original