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Experimental measurement of dynamic properties of composite slabs from frequency response

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ABSTRACT

Nowadays, in order to increase the live load bearing capacity and provide large-scale cost savings associated with construction projects, using structures with a lower dead load and higher strength is extremely common throughout the world. This issue causes structures to be highly susceptible to vibration and, as a consequence, meeting vibration serviceability dominates design criteria. Hence, identifying dynamic characteristics is crucial to provide a desirable serviceability. Recently, unfilled steel-concrete composite decks with perfobond rib shear connectors are used in buildings and bridges as a novel structural system. A little amount of research has been reported till date on the dynamic characteristics of this structural system. Thus, this study focuses on the dynamic characteristics of unfilled steel-concrete decks, including normal-weight high-strength concrete (HC) and lightweight high-strength concrete (LHC). Some of the main dynamic characteristics such as damping ratio, natural frequencies, and frequency response functions (FRFs) assessed by means of non-destructive technique (NDT) with hammer excitation. Subsequently, the experimental results in terms of natural frequencies were compared with the finite element model (FEM) predictions. It is concluded that there is good agreement for natural frequencies with difference of less than 13% and consequently the developed FEM model can be used for structural performance prediction and damage detection of composite decks with reliable accuracy. The results show that the damping ratios and natural frequencies of the decks fabricated with LHC (DLHC) and HC (DHC) decreases in comparison to those of decks fabricate with plain concrete (DPC). The most effective mode was the first mode with a damping ratio of almost 0.5% for both DHC and DLHC. DPC and DLHC had approximately similar serviceability, whereas DLHC can be more applicable than DPC due to lower weight.

1. Introduction

Nowadays, using structures with lower dead load and higher strength in order to augment the live load bearing capacity and reduce the impact of the earthquake has been extremely widespread [1–3]. Steel-concrete composite decks are the examples of these structures that have been fostering structural applications as they provide optimization of construction time, cost and performances via profiting from benefits of different materials. In such hybrid structures, the horizontal shear between steel and concrete slab is transferred by welded connections, for instance studs, steel plates, rebars, and others. In order to transfer shear forces, using an alternative type of shear connector, called a perfobond strip, in steel-concrete decks led to introducing this type of deck (Fig. 1). Several researchers studied the static behavior of composite decks composed of perfobond rib shear connectors. References are made to the studies of Leonhardt et al. [4]; Oguejiofort and Hosaint [5]; Higgins and Mitchell [6]; Machacek and Studnicka [7]; Kim and Jeong [8]; Ciutina and Stratan [9]; Ahn et al. [10]; Vianna et al. [11]; Jeong et al. [12]; Kim and Choi [13]; Cho et al. [14].

On the other side, the use of high strength concrete has become more frequent around the world due to the advances in technology, which mainly affects intrinsic properties of concrete including tensile split and flexural strength, stiffness, creep deformation and shrinkage [15,16]. Besides these, due to lower porosity, inhomogeneity and micro cracks in the cement paste, HC is much more qualified compared to PC.

From the seismic point of view, the main dynamic properties of structural materials, such as the mass, stiffness, damping ratio, and resonance frequency, dramatically affect the amplitude of seismic force

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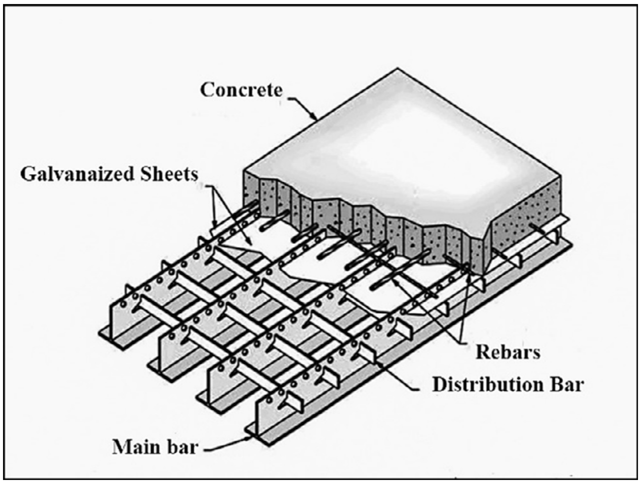

Fig. 1. A composite bridge deck (The D.S Brown Company, (2007)).

of structures [17,18]. Since the seismic force is a response of inertia of mass, a structure with a lower weight would have smaller seismic force in comparison to a heavy structure. Light weight concrete (LWC) is a commonly used material that can effectively replace plain concrete (PC). There are some good examples of bridges and other structures where LWC has been used as the main material. Therefore, using LHC in bridge decks to take the advantages of both HC and LWC is of particular interest.

There are three primary reasons to conduct modal tests of bridges. First, accurate information on the actual performance of bridges undergoing serviceability conditions can be provided by vibration-based evaluation. Second, it provides the identification of main dynamic characteristics, particularly, damping ratios, natural frequencies, and mode shapes. Third, updating and validation of finite element models can be possible through the modal parameters. This can be employed successfully as a basis for structural health monitoring and damage detection process [19–21].

Among all modal parameters, damping ratios are of particular interest [22]. Yet, since they cannot determine analytically, measurements from laboratory models are demanded. Nonetheless, they are the most difficult modal parameters to determine accurately. On the other hand, steel-concrete bridge decks are manufactured as lightweight structures with low damping and frequencies. These slender decks are more susceptible to dynamic excitation and, as a consequence, affect the serviceability. Hence, the vibration trouble pertaining to composite bridge decks should be analysed with caution, seeking applicable alternatives to minimize the human activities vibration effects.

A large number of studies have been done in order to explore the dynamic characteristics of the structural system with concentrating on the natural frequencies and damping ratios [23–26]. Some literature and studies are available to represent the significance of natural frequencies to reveal floor systems' serviceability under human activities. Wiss and Parmelee [27] suggested a response rating relation for floor system (FS). Murray [28] suggested a relation in the case of critical damping ratio, Murray et al. [29] presented a design criteria graph regarding the maximum acceleration and natural frequency of a FS. Ellingwood and Talin [30] determined the peak acceleration of a FS.

Fukuwa et al. [31] studied dynamic characteristics of a prefabricated steel structures by obtaining the natural frequency and damping ratio for various construction steps. El-Dardiry et al. [32] detected the natural frequencies of a long span concrete floor using FEM and experimental tests. They modeled a number of FEMs and compared their results with experimental results. Ferreira and Fasshauer [33] carried out a free vibration study on a composite plate through a new numerical method. Ju et al. [34] introduced a new composite FS and measured the natural frequencies and damping ratios by conducting experimental tests. They compared the results with some international codes to assess the serviceability of introduced system. Gandomkar et al. [35] measured natural frequencies of a Profiled Steel Sheet Dry Board (PSSDB), both numerically and experimentally. Neves et al. [36] detected natural frequencies and mode shapes of a composite deck system in a multi-story building. Da Silva et al. [37] investigated acceleration and vibration of a steel-composite floor in order to determine its comfortableness. For timber FS, Jarnero et al. [38] experimentally detected damping ratios, natural frequencies, and mode shapes. Devin et al. [39] indicated the influence of non-structural partition on modal properties of a concrete FS.

Hou and Xia [40] analyzed the dynamic characteristics of a simply supported composite beam, and their results were validated by experimental results. The prominent feature of steel-concrete composite decks is the existence of perfobond connectors contributing to the slip of concrete slab. Thus, perfobond connectors have a potential to reduce the vibrations of structures, and play a crucial role in reducing the amplitude of structural vibrations and in increasing the fatigue life of structures [41].

The damping ratio is of particular interest with a central role for designers, whereas analytical or numerical methods cannot determine that. Hence, experimental measurements are extremely required [7,42–44].

Previous literature has mainly focused on the dynamic properties of the decks and floors manufactured with PC. Inadequate investigations are existed, regarding the natural frequency, the damping ratio, and the mode shapes of the steel-concrete composite deck manufactured with HC and, specially, LHC. This work, therefore, aims at the impacts of using HC and LHC, as the concrete part of steel-concrete composite deck, on the modal parameters of this type of deck using three different methods by means of NDT technique as a rapid, cost effective, and accurate method. Eventually, the experimental frequencies are compared with frequencies derived from FEM. The updated FEM can be used to more reliably predict structural performance of composite deck under unusual situations [45].

2. Theory of methods

Unlike conventional vibration theory associated with the response of a dynamic system, modal analysis is related to intrinsic properties of structures. FRF is one of the most sophisticated methods to examine the modal analysis [46]. In this NDT, the signal at one of the fixed transducers is applied as a reference to obtain the frequency response function and the impulse response function. The vibration anaylizer software is used to analyze the acquired input provided by impact hammer and output amplitude signals derived from the accelerometer. Three supplementary identification methods have been taken into account in the present investigation: two of them based on frequency domain analysis and one on time domain analysis.

2.1. Frequency response function (FRF)

For a harmonic force $f(t) = F(\omega).\, e^{j\omega t}$, the response of a single-degree-of-freedom (SDoF) system is another harmonic function $x(t) = X(\omega).\, e^{j\omega t}$ where $X(\omega)$ is a complex amplitude. Inserting these terms into the equation of motion leads to:

$$\frac{X(\omega)}{F(\omega)} = \frac{1}{k-\omega^2 m + j\omega c} \tag{1}$$

This ratio, often illustrated by $\alpha(\omega)$, is defined as FRF of the system. This FRF known as receptance FRF uses displacement as the response. The response can also be velocity (Mobility FRF) or acceleration (Acceleration FRF).