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The effect of laminate stacking sequence and fiber orientation on the dynamic response of FRP composite slabs

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ABSTRACT

In this paper, different stacking sequences (0 / ± 45/90°) of laminated FRP slab under human-induced loads using finite element techniques are investigated to assess the dynamic characteristics of a composite floor and corresponding human comfort problems.

Four layers of FRP, with different angles comprising 256 cases, are modeled using ANSYS software. Load models with variable parameters are applied as pattern loads. Material properties and damping ratio are calculated separately for each case with the aid of MATLAB software and considered as input to ANSYS for obtaining the maximum responses in terms of deflection and acceleration from the walking load of people. Then the results are compared with the limiting values proposed by the design standards. A comparison of the two results reveals that 54 cases of investigated FRP laminate seem to be ideal for practical use in satisfying both the acceleration and displacement requirements. This study was carried out to provide a more realistic evaluation of this type of structure when subjected to vibration due to human walking.

1. Introduction

Laminated FRP composite panels, due to their high structural stiffness, low weight, and low maintenance costs have been recognized as a cost-effective material for use as a floor in structures. One of the features of these anisotropic materials is their ability to be tailored for specific applications by optimizing the design parameters such as stacking sequences, ply orientation and performance targets [1]. However, a direct consequence of using FRP laminate for floors, is a considerable increase in the undesired vibration, which leads to discomfort of the occupant's [2]. This phenomenon mostly happens in composite structures subjected to human rhythmic activities. In several instances, these vibrations have contributed to structural failure. Some examples are the Cardiff Millennium Stadium [3], Liverpool's Anfield Stadium, and Old Trafford Stadium [4]. These structures are all slender with natural frequencies that approach the frequency of the human-induced loads, and, consequently, lead to the production of intense vibration. As a result, they cause human discomfort, crowd panic, or, in extreme cases, the collapse of the structures [5]. Since composite slabs, due to their substantial benefits and great promise for future applications, are widely used in a variety of structures, the dynamic behavior of the laminated composite slabs has received widespread attention and has been investigated by many researchers [6–21].

Murray [22] classified the human perception of vibration into four categories, i.e.: The vibration is not noticed by the occupants, the vibration is noticed but does not disturb the occupants, the vibration is noticed and disturbs the occupants, and the vibration can compromise the security of the occupants. Hence, the design of floors for vibration is very important as it is mentioned in the AISC and SCI_P354 standards [23,24]. The work of 250 references, in which different experiments and analytical characterization of walking loads and their application in vibration serviceability design of structures, such as floors, footbridges and staircases, when subjected to pedestrian movement, was comprehensively reviewed by Racic et al. [25].

One of the critical points in designing a structure, is knowing the natural frequency. If a natural frequency of the structure is close to the excitation frequency, then resonance, which is the severe vibration of the structure, could occur. In order to avoid resonance, the natural frequency of the structure must be changed by making suitable adjustments in the design. Allen et al. [26] examined the minimum values for the natural frequencies of structures in common with the kind of occupation. These values were based on the dynamic load produced by human rhythmic activities, such as dancing and aerobics, as well as limiting the acceleration values related to these activities. The obtained

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Table 1
Minimum natural frequency (Hz) according to the construction type and application [26].

Floor characteristics	Floors used in ballrooms[a] and gyms[b]	Areas and stadiums[b]
Concrete constructions	7	5
Composite constructions	9	6
Timber constructions	12	8

[a] Limit peak acceleration: 0.02 g.
[b] Limit peak acceleration: 0.05 g.

minimum natural frequencies can be referred to in Table 1.

In terms of the load description for human activity, Alves [27] and Faisca [28] studied experimentally two kinds of concrete platforms - rigid and flexible - when a group of people acts on them. Walking motion forces, which are defined as a function of the heel impact over the floor, were simulated by a load model. This load type, regarded as the main excitation source caused by human walking motion, produces a transient response. The control of walking exerted vibration on large span composite floors had been offered by Varela and Battista [29] in the form of tuned mass dampers where it was experimentally found that such devices cause a significant drop in the vibration amplitudes, thereby improving user comfort and enhancing the structural dynamic performance. The influence of rhythmic events, such as jumping and stamping, dancing as well as aerobics, on various floor systems had been explored by Littler [30], Ellis and Ji [31], and Allen [32], respectively. De Silva and Thambiratnam [33] investigated numerous load patterns contributed by humans on continuous floor panels employing the finite element method, in which the vibration characteristics are due to different configurations of panels. Battista and Varela [29] indicated experimentally that the problem of dynamic vibrations induced by human rhythmic activities is more severe in continuous slab panels, such as composite slabs, waffled and grilled slab systems or precast concrete slabs, which present coupled vibration mode. Hence, the vibration caused by people walking on the floor is a major problem in the lightweight composite floors, and this issue will be discussed in detail in this study.

In recent years, some research has been done on the laminate stacking sequence in applications in different areas [34–38]. Hazimeh et al. [39] investigated the influence of fiber orientation on the impact response of composite double-lap joints. They observed that the lowest shear strength is in joints with fibers oriented perpendicular to the impact loading. The effects of stacking sequence on the impact resistance of the carbon fiber reinforced thermoplastic toughened epoxy laminates have been studied by Strait et al. [40]. Based on the results, the energy to maximum load was dependent on the stacking sequence with quasi-isotropic layups yielding values 26% higher than cross-ply layups and 46% higher than [0/ ± 45] layups. In another study, Hassan et al. [1] investigated the effect of fiber orientation and laminate stacking sequences on the torsional natural frequencies of laminated composite beams. They found that changes in fiber angle, as well as laminate stacking sequences, yield to the different dynamic behavior of the component, that is, different torsional natural frequencies for the same geometry, mass, and boundary conditions.

Although some research has been carried out on the stiffness and strength evaluations of various types of FRP decks, investigations of the stacking sequence of FRP systems against dynamic load and human activities are limited. The orientation of fibers in a lamina (layer), and, consequently, in the laminate (combination of laminas) plays an important role in the dynamic response of composite floors. Hence, changing the angle of the fibers in the laminate may significantly change the results because of alterations to the stiffness and material properties. Hence, selecting a proper angle and fiber orientation is very important in FRP Laminate panels.

In the present work, the main motivation is to examine numerically the vibration characteristics of laminate composite floor structures due to the proportion of fiber orientation and stacking sequence effects when subjected to walking load in order to evaluate their compliance with the serviceability and comfort requirements of the current design standards.

In this study, all possible stacking sequences for a 4-layer laminated FRP plate (0°, ± 45°, 90°) are examined. A total of 256 cases were obtained for different configurations. In each configuration, there were nine parameters (E_1, E_2, E_3, G_{12}, G_{23}, G_{13}, υ_{12}, υ_{23}, υ_{13}), which addressed the laminated FRP plate's specification. For modeling purposes, an equivalent plate, which was formed by a combination of several laminae, was considered. The properties of the fiber/matrix composite material were deemed for FEM analysis. All 256 possible cases were simulated, and the related dynamic responses, including displacements, accelerations, and natural frequencies were obtained. Accelerations and deflections are compared with AISC design guide 11 and ACI 318-05 standards, respectively [24,41]. The results were assessed to determine the applicability of laminated FRP plate as a suitable composite floor against excessive vibration concern.

2. Load model for human walking

Dynamic actions caused by repetitive forces from equipment, machines and human activities such as dancing, jumping, running, and aerobics (gymnastics) or walking produce dynamic actions, which lead to most floor vibration problems. The problem associated with human walking generates special concern because the forces change location and magnitude with each step. In some cases, the applied force is sinusoidal. Also, generally, the structural system's dynamic response involves several vibration modes. Normally, human activities induce dynamic excitations, which could be defined by a combination of harmonic forces, in which the frequencies, f, of the mentioned harmonics are the multiples of the first frequency. For instance, the step frequency, f_s, of human activities. These harmonic forces or time-dependent repeated forces can be represented by the Fourier series, as provided in Eq. (1) [11]. (see Fig. 1 for the force-time distribution).

$$F(t) = P\,[1 + \sum \alpha_i \cos(2\pi i f_s t + \phi_i)] \tag{1}$$

Where

P = ndividual's weight
α_i = dynamic coefficient for the harmonic force
i = harmonic multiple (i = 1, 2, 3, n)
f_s = step frequency of the activity of dancing, jumping, aerobics or walking
t = time in seconds
φ_i = phase angle for the harmonic

As presented in Fig. 1, four harmonics are used in this investigation to generate the dynamic loads. The values for different parameters, which are used in the mathematical model, including phase angle, dynamic load factor, and step frequency, are presented in Table 2.

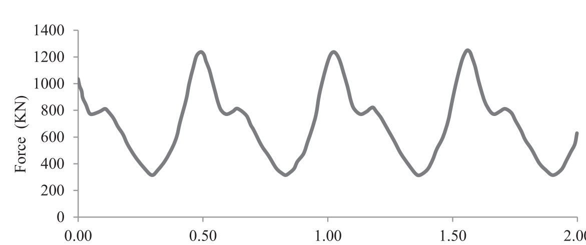

Fig. 1. Dynamic load model of human walking load [11].