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# Analysis of human-induced vibrations in a lightweight framework

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ABSTRACT

This article analyzes the vibratory behavior of a Material-Composed Sandwich (MCS) framework for residential buildings. It has been observed qualitatively that the use of this kind of framework leads to poor comfort levels. The goal of this study is to find out the sources of this lack of comfort, in order to suggest guidelines that can enhance the performance of the MCS framework, without jeopardizing its advantages with respect to the traditional frameworks.

To achieve this objective, an Experimental Modal Analysis (EMA) of a sample MCS framework has been carried out in order to determine the dynamic parameters. Then, a numerical Finite Element (FE) model of said sample MCS framework has been developed and adjusted with the results obtained in the experimental test. Based on this, a real-dimension MCS framework FE model has been built and the resultant behavior compared with that of a commonly used framework made of reinforced concrete. This comparison is finally used to assess the uncomfortable dynamic response of the MCS framework and to draw conclusions on the design guidelines in order to enhance the MCS framework vibratory behavior.



## 1. Introduction

The *healthy building* concept is not only related to the health needs of the users and energetic efficiency, but also to comfort features. In a recent study [3], some guidelines are given to develop indicators for healthy and comfortable buildings. Perception of vibration in buildings is an issue linked to discomfort and annoyance of the users [9]. In a paper by Whittle, recommendations are given on how to measure vibration annoyance in residential environments using previously suggested scales [21]. The vibration may be perceptible or not, depending on the kind of building, the activities and the position (standing, sitting, recumbent) of the people inside the building, the intensity and duration of the vibration, sound insulation [11], etc. A building can be considered comfortable, from the point of view of vibrations, when there is no perception of them [7]. The Eurocode [5] classifies the comfort of users related to deflections and vibrations as one of the serviceability limit states.

The use of lightweight frameworks is increasingly important in the building industry because it reduces assembly and transport costs, amongst others. There is a tendency to significantly diminish the mass and thickness of the frameworks and to increase their spans. The structural damping also decreases due to the lack of vibration-absorbing materials. Moreover, these kinds of frameworks usually employ orthotropic materials, whose dynamic behavior varies significantly from isotropic ones [1]. All these factors can produce an inappropriate vibration response to daily activity loads, i.e., human walking forces, machinery, etc. This is the reason why the characteristics of new frameworks tend to shorten the natural frequencies to values close to the human activity range of frequencies. For this reason, human activity usually produces a loss of comfort to the users of these kinds of frameworks, which causes a feeling of lack of safety and affects their normal life. It might even affect the structural integrity of the building. Thus, it is not enough to perform a static analysis, but it is necessary to estimate the vibration response during the design process of new buildings [13] or during refurbishment [2]. Nevertheless, there is not a unique criterion for the vibration design of lightweight frameworks [10]. The reason is that it is a multifaceted problem which depends on framework properties (i.e. mass, stiffness and damping) and other factors related to human activity (use of the building, position and activity of the people, etc.).

In this article, a study is carried out of the vibration response of a new Material-Composed Sandwich (MCS) framework, whose mass is twenty times less than concrete and has been used in the construction of a two-story prototype building. It has been subjectively noticed that this MCS framework has a poor vibrational behavior in terms of comfort in the prototype building. The goal

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**Nomenclature**

| | |
|---|---|
| $E$ | Young's modulus |
| $G_{xy}$ | Shear modulus |
| $I$ | moment of bending inertia |
| $\Delta_{adm}$ | maximum admissible static deflection |
| $\Delta_{dl}$ | static deflection due to dead load |
| $\Delta_{frm}$ | total static deflection |
| $\Delta_{ll}$ | static deflection due to live load |
| $\nu_{xy}$ | Poisson's ratio |
| $\omega_n$ | natural frequency at the $n$ mode |
| $\xi$ | modal damping ratio |
| EMA | Experimental Modal Analysis |
| EPS | Expanded Polystyrene |
| FE | Finite Element |
| FRF | Frequency Response Function |
| MAC | Modal Assurance Criterion |
| MCS | Material-Composed Sandwich |
| MMIF | Multivariate Mode Indicator Function |
| RC | Reinforced Concrete |

of this study is to find out the sources of this lack of comfort, in order to suggest guidelines that can enhance the performance of the MCS framework, without jeopardizing its advantages with respect to the traditional frameworks.

## 2. Framework description and solution methodology

The framework is composed of a core of Expanded Polystyrene (EPS) and by skins of composite (glass fiber and epoxy), as is shown in Fig. 1. Its dimensions are $5 \times 3 \times 0.2$ m, and the thickness of the skins is 2.5 mm. As the dimensions are so large, a sample of the MCS framework is also used; whose dimensions are $1 \times 2 \times 0.2$ m. This sample is a prototype, which was manufactured especially for this work. The mechanical characteristics of the materials, given by the manufacturer, are shown in Table 1. As can be seen, the material of the skins is orthotropic, and the material of the core is isotropic.

The procedure to obtain a satisfactory solution to the vibration problem is detailed next. First of all, an Experimental Modal Analysis (EMA) of the sample MCS framework is carried out, where its dynamic parameters, namely, natural frequencies and modal damping ratio, are obtained. Then, a numerical Finite Element (FE) model of the sample MCS framework is developed and adjusted with the results obtained in the experimental test. Finally, a real-dimension MCS framework FE model, that will be used in the prototype building, is built. These results are compared with the ones obtained from a commonly used solution: reinforced concrete. This comparison will help in understanding the uncomfortable dynamic response of the MCS framework and lead to formulate conclusions that will enhance the original design.

Combining experimental modal and numerical FE analysis is a procedure widely used in structural engineering. Moreira and Rodrigues [14] present a layerwise finite element, which considers the through-thickness deformation, for the analysis of isotropic and orthotropic laminates and they validate this formulation with experimental data. Matter et al. [12] present an interesting numerical–experimental method, which is based on modal information, for calculating elastic and damping parameters of composite multilayered plates and shells; results are obtained by minimizing discrepancies between numerical and experimental results. Pavić and Reynolds [17] follow this technique to study the differences in the dynamic parameters between the cracked and uncracked states of a high-strength concrete framework. Wu [23] builds a FE model of a scaled crane rig improved by correlation. Dooms et al. [4] present a FE model of a silo correlated with experimental modal analysis in order to improve the design of the silo with respect to ovalling owing to wind. This procedure is also applied for the dynamic behavior of sandwich panels with a non-structural application. For instance, Petrone et al. [18] show a similar procedure for modal characterization of sandwich panels used in interiors of road vehicles. Mucchi [16] shows another study where beach tennis rackets, which are also composed innerly by sandwich panel, are dynamically characterized.

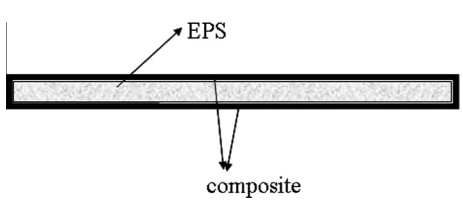


**Fig. 1.** Description of the material-composed sandwich framework.

**Table 1**
Mechanical characteristics of the materials.

| Property | Skins | Core |
|---|---|---|
| $E_x$ | 15 GPa | 15.5 MPa |
| $E_y$ | 15 GPa | 15.5 MPa |
| $E_z$ | 2.5 GPa | 15.5 MPa |
| $\upsilon_{xy}$ | 0.39 | 0.29 |
| $G_{xy}$ | 2.5 GPa | 6 MPa |
| *Density* | 1750 kg/m$^3$ | 70 kg/m$^3$ |

**Fig. 2.** Boundary conditions and grid measurement of the sample MCS framework.