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Development of passive viscoelastic damper to attenuate excessive floor vibrations

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ABSTRACT

Recent changes in the construction of building floors have included the use of light material composite systems and long span floor systems. Although these changes have many advantages, such floor systems can suffer from excessive vibration due to human activities. This problem is exacerbated in office buildings due to the reduction in inherent damping associated with modern fit outs. Excessive floor vibrations are often realised after the completion of construction or following structural modifications and normally arise due to inadequate knowledge of the damping values in the design process. Thus rectification measures are normally required to reduce floor accelerations. This paper proposes a new innovative passive viscoelastic damper to reduce floor vibrations. This damper can be easily tuned to the fundamental frequency of the floor and can be designed to achieve various damping values. The paper discusses the analytical development of the damper with experimental results presented on a prototype to demonstrate its effectiveness.

1. Introduction

Building floors are subjected to dynamic loads from people when they walk, run, dance or engage in aerobics activities. Such excitation forces cannot be easily isolated from the structure and they occur frequently [1]. Typical pacing rates for walking are between 1.6 and 2.4 Hz (slow to fast walk) whilst for jogging the rate is about 2.5 Hz and running occurs at rates up to about 3 Hz.

Although the excitation from pedestrians is dominated by the pacing rate, it also includes higher harmonic components with frequencies corresponding to an integer multiple of the pacing rate. Since annoying vibration amplitudes are caused by a coincidence of the natural frequency of the floor (f_1) with one of the harmonics of the walking excitation, the problem may be avoided by keeping these frequencies away from each other. For this reason, engineers may aim to design floor systems to have a fundamental frequency greater than three times the walking frequency (i.e. above about 6 Hz) [2]. This is a simple and effective approach for design but it does not necessarily guarantee acceptable floor performance since it does not take account of damping. Indeed composite floors with very low damping ($\leq 2\%$), can experience high levels of vibration even if their fundamental natural frequency is above 7.5 Hz [3].

The reaction of people who experience floor vibration depends on the activity they are engaged in, as reflected in the commonly used acceptance criteria as illustrated in Fig. 1. For example, offices and residences are normally designed to have a maximum peak acceleration of about 0.5% gravity (g) whereas pedestrian bridges can be designed for acceleration levels 10 times greater (5% g) [4]. In addition to acceleration amplitude, people's perception is also affected by the characteristics of the vibration response including frequency and duration [1]. Comfort studies for automobiles and aircraft have found that humans are especially sensitive to vibration in the frequency range of 4–8 Hz. This is explained by the fact that many organs in the human body resonate at these frequencies [5] whilst outside this frequency range, people accept higher vibration acceleration levels [4] as shown in Fig. 1.

There are several design models for predicting the maximum response of a floor due to walking excitation. One of the most commonly used method is that documented in the American Institute of Steel Construction Design Guide 11 (AISC DG11) [5,4]. This is the most popular method used by Australian designers. This method is based on reducing the floor structure to a Single Degree of Freedom (SDOF) system. The peak acceleration response is calculated using Eq. (1) (the full derivation of this expression can be found in [4]).

$$\frac{a_p}{g} = \frac{P_0 \mathrm{Exp}(-0.35 f_1)}{\zeta_1 W} \tag{1}$$

where a_p/g is estimated peak acceleration in units of gravity acceleration (g), f_1 is the fundamental frequency of the floor

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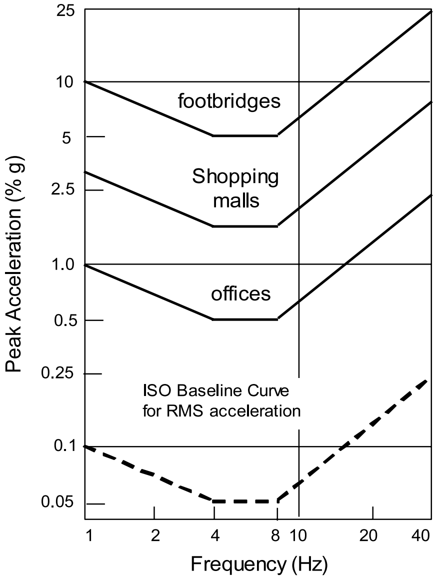

Fig. 1. Acceptance criteria for floor vibrations.

structure, P_0 is a constant force based on a person's weight and taken as 0.29 kN, ζ_1 is the damping ratio of the floor and W is the effective weight of the floor which oscillates because of the walking. The a_p/g value has to satisfy the values in Fig. 1 for satisfactory performance.

Other methods for calculating the floor peak response and assessing the performance include the recently published European Commission guide [6–8]. In this method, the total damping of the floor is taken as the sum of contributions from structural damping, furnishing and finishes. Similar to the AISC DG11, this method directly relates the peak response to the total damping which has to be assumed during the design phase. However, damping in practical structures is seldom fully understood as it cannot be determined directly based on the structural properties, as is the case for stiffness and mass. Damping is generally determined based on experimental and historical data. Therefore, in applying assessment methods design engineers have to estimate the damping based on available knowledge during the design phase. However, the designers in many cases may not know the details of the fit out which are specified by the client or architect. Consequently, overestimation of damping or altering the fit out of the floor can lead to excessive vibrations.

2. Control of floor vibrations

There are a few remedial options available to rectify a floor with excessive levels of vibration, including increasing the stiffness and hence the frequency or increasing the damping. The installation of tuned mass dampers can be performed more cheaply than structural stiffening, and often offer the only practical means of vibration control in existing structures [9]. In new constructions viscoelastic materials can be incorporated within the floor system to increase its damping. Both embedded viscoelastic materials and tuned mass dampers represent typical passive damping options whilst more sophisticated and expensive solutions may include the addition of active dampers.

2.1. Viscoelastic materials

Embedded viscoelastic materials (VEM) offer the advantage of reducing vibrations over a broad range of frequencies compared with TMDs. However, viscoelastic damping works optimally only for a specific mode of vibration. Nevertheless use of VEMs is a cheap method of increasing the damping if incorporated during construction [10].

An example of viscoelastic damping is the Resotec system which is illustrated in Fig. 2. This product comprises a thin layer of high-damping viscoelastic material with an overall thickness of about 3 mm. Resotec is sandwiched between the top flange of the floor steel beams and concrete slab for a proportion of the beam near each end where the shear stresses are the greatest. It is reported that the damping of a fitted out floor is typically doubled by the incorporation of Resotec [11]. However, this product needs to be incorporated within the floor during construction and is not suitable as a rectification measure.

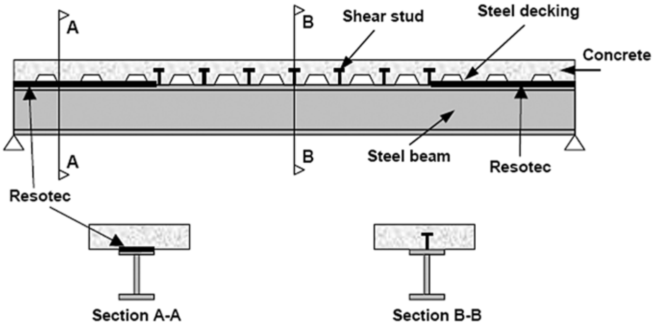

Fig. 2. Illustration for Resotec product in composite floor (after [11]).

2.2. Tuned mass dampers (TMD)

The principle of a TMD was initially utilised when Den Hartog in 1947 reintroduced the dynamic absorber invented by Frahm in 1909 [12–14]. Generally, a TMD consists of a mass, spring, and dashpot and is tuned to the natural frequency of the primary system. When the primary system begins to oscillate it excites the TMD into motion and hence the TMD absorbs energy from the vibrating floor [15]. The TMD inertia forces produced by this motion are anti-phase to the excitation force. The first use of a TMD for floor vibration application was reported by Lenzen [16] who used small TMDs with a total mass of about 2% of the floor mass. The TMDs were made of steel hung by springs and dashpots from the floor beams. Lenzen reported floors with annoying vibration characteristics became satisfactory by tuning the TMDs to a natural frequency of about 1.0 Hz less than that of the floor and using a damping ratio of 7.5% [17]. An example of a more recent TMD is a Pendulum Tuned Mass Damper (PTMD) shown in Fig. 3. Experiments were undertaken to test the performance of the PTMD and it is reported that the damper reduced the floor vibration in the range of 50%–70% [17].

Floor vibrations due to walking excitation typically produce very small floor displacements which are generally less than 0.1 mm. A TMD would typically have a maximum displacement around ten times larger than the floor (i.e. in the order of 1 mm). In reality, it is difficult to produce a practical viscous damper that provides a reasonable level of damping given this very small displacement. Viscous dampers were used in some floor applications such as in the Terrace on the Park building in New York (1992). This problematic floor was cantilevered with a low natural frequency of 2.3 Hz and responded to footfall vibrations with 7% g acceleration and 3.3 mm maximum displacement. In this application the damper used was large and extended from the lower floor to the point of maximum response of the problematic floor. Indeed such access is not always available for office floors. Other applications for viscous TMD can be found in stadia. However such structures tend to have long span cantilevers with larger displacements associated with crowd activities especially from