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Application of pre-stressed SMA-based tuned mass damper to a timber floor system

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ABSTRACT

Shape memory alloy (SMA) is becoming a popularly studied smart material in the field of structural control. The feasibility of utilising an SMA in a tuneable mass damper to reduce the excessive vibration of a timber floor system was revealed in a pilot study. However, the in-service excitations on a floor can be complex and involve more frequencies and randomness; therefore, this paper aims to assess the effectiveness of the SMA-based semi-active TMD in a real-scale timber floor, where the free vibration and human footfall-induced vibration are considered as inputs. This study is conducted using numerical simulations on OPENSEES. By reducing the floor vibration at a range of frequencies, both cooling and heating the SMA are effective in retuning the off-tuned TMD and reducing the structural response. Footfall excitation involves more than one excitation frequencies, and the higher dominant frequencies can resonate with the off-tuning frequencies, increasing the structural response. Simulation results demonstrate that retuning using SMAs can effectively lower the structural response at a wide range of frequencies, thus attenuating the footfall-induced vibration.

1. Introduction

Timber floor is a common structural system utilised around the world, as such flooring materials can add benefits to construction; for example, they are light-weight, pre-fabricated and environmentally friendly because of their carbon storage capacities. However, human activities and machine operations can cause excessive vibrations in timber floors. Such excessive vibration can lead to building occupants experiencing uncomfortable sensations or even feeling anxious, which is a problem that designers should address [14,25,27]. In order to investigate how to reduce timber floor vibration, several studies have examined the design criteria for this type of floor [25,16,12,2]. The traditional passive approach requires the floor natural frequency to be higher than 8 Hz, which avoids resonance with human-induced vibration and requires less root mean square (RMS) acceleration response. With the development of vibration control techniques, studies on tuned mass damper (TMD) systems have been conducted in order to assess their application in floor systems as a more effective vibration reduction approach, with various levels of success [8,24,6].

However, the mass on a floor system always changes, the stiffness of the floor system is usually modified owing to ageing or moisture variance, and the damping changes as a result of furniture or excitation changes. In such cases, the traditional passive TMD is unable to function effectively because of off-tuning [24]. Moreover, in civil structures, excitations can involve a broad range of frequencies and, once resonance occurs, the serviceability of the floor system could be significantly reduced. Installing an active TMD is an approach that attenuates the vibration by exerting forces; however, it is considered to be expensive and power-consuming, as demonstrated by Connor [10] and Setareh et al. [24]. Semi-active TMDs are becoming increasingly studied devices, as they provide adjustable dynamic parameters and are mechanically simple [17,28,26]. The variable properties of the semi-active TMD enable it to retune the natural frequency of the main structure, so as to reduce the structural response. Compared with active TMDs, semi-active TMDs do not introduce energy to the entire system; however, semi-active TMDs can provide comparable vibration control capacities and can even behave in a more effective manner. More importantly, semi-active TMDs are more cost effective, easier to install and possess energy-saving capabilities.

To achieve the purpose of retuning, shape memory alloy (SMA) can be of significant benefit in respect to its self-centring capacity, temperature controllability and adequate fatigue life compared to traditional construction materials. SMAs have two particular phases: austenite and martensite, which are highly dependent on the in-service temperature. As illustrated in the literature, as well as in Fig. 1(a), M_s, M_f, A_s and A_f indicate the start and finish temperatures of the

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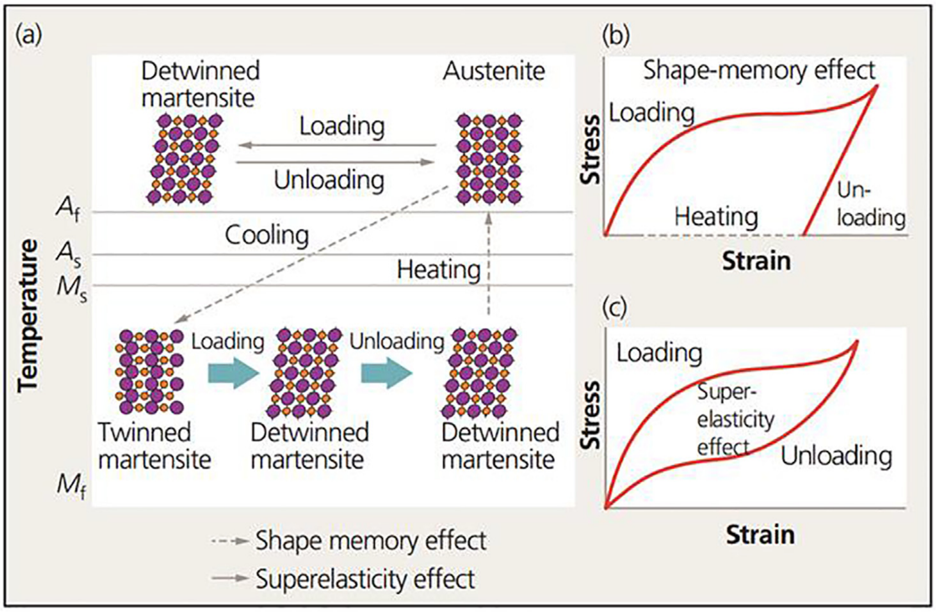

Fig. 1. Different phases of SMA at various temperatures and stress-strain curve demonstrating the (b) shape memory effect; (c) superelasticity [9].

martensitic and austenitic transformations, respectively. When the in-service temperature is above A_f, the SMA exhibits superelastic behaviour, as shown in Fig. 1(c), where the hysteresis is self-centring. When the in-service temperature is below the phase transformation temperature, the SMA exhibits shape memory effect, as one can see in Fig. 1(b), where the recovery strain requires external heating. Superelasticity is the main focus of this study, as it induces faster self-centring and has higher elastic modulus compared with that of the shape memory effect. Overall, the mechanical properties of SMAs, such as the elastic modulus and damping ratio, are highly dependent on the in-service temperature [4,3,15], which augments their potential for use in semi-active TMDs with temperature control in terms of retuning.

Williams et al. [30] devised a NiTi SMA wires-based TMD and applied it to a cantilever beam. Heating the SMA wires through a power supply led to changes in the stiffness of the TMD; thus, excessive vibration in the primary structure could be attenuated for several discrete frequencies. Furthermore, Rustighi et al. [22], Mani and Senthilkumar [18], Savi et al. [23] and Aguiar et al. [1] developed temperature control techniques to change the stiffness of the SMA so as to semi-actively control the vibration of the main structure for a wider frequency range, and the effectiveness of the SMA-based TMD was proved. The aforementioned applications of semi-active TMDs using SMA were predominantly developed to reduce machine-induced vibration in mechanical domains. However, in civil engineering, buildings commonly experience vibrations that have a wider frequency range and are more random, e.g. excitations caused by earthquakes, wind and human activities. Thus, excitations with a wider range of frequencies should be considered in the assessment of SMA-based semi-active TMDs. Unlike the method of using SMA wires in previous studies, temperature control utilising SMAs with the larger size, such as SMA bars, should be considered and studied regarding their feasibility for use in large-scale construction.

As illustrated in the feasibility study conducted by the authors, a temperature controlled semi-active TMD with pre-stressed SMA bar was studied for timber floor applications and was proved to be effective in reducing the response of a timber floor system [15]. This paper continues the study and investigates its application in a real-scale timber floor system under various excitations. The study is based on a structural dynamic analysis program on OPENSEES software, in which the modelling code is developed by the authors. Firstly, the response of the floor system is analysed in the frequency domain in order to control the vibrations over a wide range of frequencies owing to the serviceability of civil structures; moreover, human footfall-induced vibrations is taken into consideration as inputs to assess the effectiveness in the time domain.

2. Assessment of the semi-active TMD in the frequency domain by free vibration

As explained previously, the variable main structural mass could induce off-tuning in a TMD, which means that retuning is required to reduce the vibration. In this section, a timber floor is simulated and designed to be off-tuned; the feasibility of a SMA-based semi-active TMD in retuning the structure by shifting its natural frequencies is then investigated. A timber floor can experience a wide range of excitation frequencies during its service; therefore, the response in the frequency domain is analysed initially.

2.1. Materials and method

The tested timber floor is a joist-free mass timber floor – profideck with plan dimensions of 6 m × 6 m and a thickness of 190 mm, as shown in Fig. 2. The strength class of the profideck is GL 24 h; the self-weight of the floor system is 2394 kg. The timber floor is a one-way

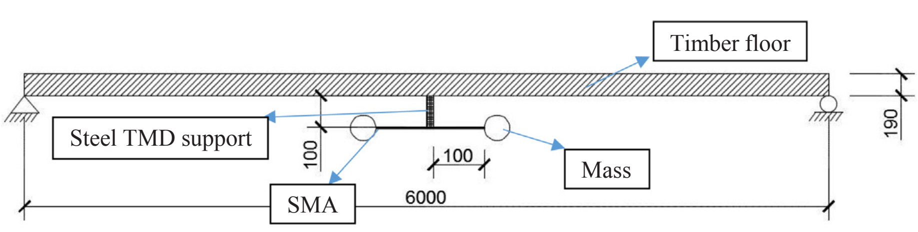

Fig. 2. Timber floor using tuned mass damper by bending SMA (unit: mm).