Dynamic response of girder footbridges with tuned mass dampers under pedestrian loading through stochastic analyses

Respuesta dinámica de puentes peatonales viga con amortiguadores de masa sintonizada bajo carga peatonal a través de análisis estocásticos

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RESUMEN

Este artículo muestra un estudio paramétrico de los efectos de la implementación de amortiguadores de masa sintonizada para controlar las vibraciones inducidas por peatones en un rango de puentes peatonales tipo viga, considerando que cada paso no produce la misma fuerza (intra-variabilidad para cada sujeto), las diferentes características antropométricas (inter-variabilidad entre distintos sujetos), la interacción entre los peatones que cruzan el puente al mismo tiempo (originando cambios de trayectoria) y la influencia de las barandillas. Se mostrará la eficiencia de los amortiguadores en la reducción de la respuesta dinámica y las diferentes propiedades de éste, como la relación de masa, y dimensiones del mismo.

ABSTRACT

This paper shows a parametric study showing the effects of the implementation of one or two tuned mass dampers to control human-induced vibrations in a range of girder footbridges considering that each step does not produce the same force (intra-subject variability), the different anthropometric characteristic (inter-subject variability), the interaction between pedestrians crossing the bridge at the same time (leading to change of trajectories), and the influence of the parapets. The TMD's efficiency on the reduction of the dynamic response will be shown, as well as the different TMD's properties such as mass ratio, and geometrical dimensions.

PALABRAS CLAVE: Amortiguadores de masa sintonizada, puentes viga, vibraciones inducidas por peatones

KEYWORDS: Tuned mass dampers, girder footbridges, human-induced vibration

1. Introduction

The footbridge construction has experienced a noticeable change over the last century leading to the design of slenderer and lighter structures. As a result of this change, some of the footbridges have shown serviceability problems under pedestrian loads. In these cases, supplemental damping devices were employed to satisfy the serviceability criteria. Some girder footbridges which have experienced unexpected vibrations are the Langelinie footbridge in Denmark, the Passerelle Léopold-Sédar-Senghor in Paris, France, and the footbridge in the Rotterdam central station in The Netherlands. These footbridges required the use of supplemental damping devices to control the human-induced vibrations. Supplemental damping devices for the reduction of the dynamic response under pedestrian loads have witnessed a variety of applications in footbridges, including tuned mass dampers, fluid viscous damper, and tuned liquid column dampers [1-5]. Among them, tuned mass damper has played a prevailing role in the mitigation of human-induced vibrations. Tuned mass damper has positive characteristics such as reliability, efficiency and low cost [6].

This paper shows the dynamic response in vertical and lateral direction under a probabilistic pedestrian load model with and without damping devices of footbridges with one span. The main aim of this paper is to provide a design guidance for girder footbridges employing tuned mass dampers in cases where the serviceability criteria is not fulfilled. The probabilistic pedestrian model considers the pedestrian's anthropometric characteristics, the force that each step transmits to the structure, the intra- and inter-subject variability, and the interaction between pedestrians and boundaries while they are crossing the bridge [7,8]. The TMDs characteristics (optimal damping frequency α-ratio between the TMD and the structural frequency linked to the vibration to be damped- and the TMD damping ratio [ξ]) were obtained according to the Asami criteria (equations (1) and (2)) as a function of the TMD mass ratio [μ] [9].

$$\alpha_{opt} = \sqrt{\frac{1}{1+\mu}} \qquad (1)$$

$$\xi_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}}\sqrt{1+\frac{27\mu}{32}} \qquad (2)$$

2. Characteristics of the girder footbridges

The girder footbridges considered in this research have geometric and material properties that have been extracted from a dataset of girder footbridges found in the literature. Figure 1 represents the number of spans of the dataset of girder's footbridges. It can be seen that most common girder footbridges have one and two spans. Their average span lengths are approximately 43 and 57 m for one and two spans, respectively (Figure 2). These footbridges, without tuned mass dampers, were studied by Ramos-Moreno [7], and it was highlighted that the serviceability limit state of vibration is not fulfilled for certain spans ranges.

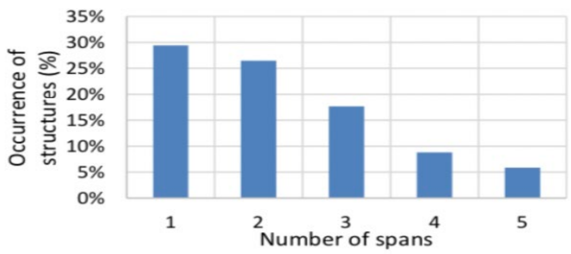


Figure 1. Ocurrence of girder footbridges according to the number of spans based in a dataset of this typology

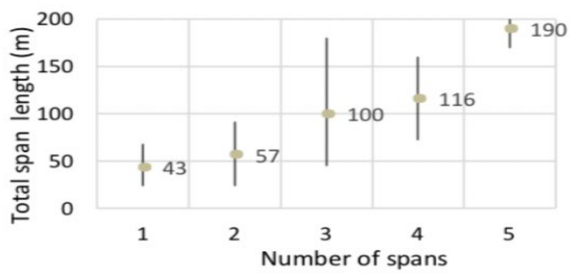


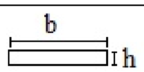
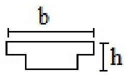
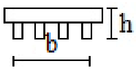
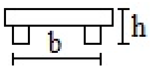
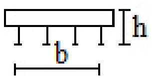
Figure 2. Span length for one, two, three, four and five spans girder footbridges

A set of girder footbridges (Table 1), using structural materials for the deck such as reinforced concrete, prestressed concrete, timber, aluminium and glass-fibre reinforced polymers (GFRP), is analysed herein. The deck width is 4 m. The materials properties were selected according to the standards (Table 2). For the girder footbridges a damping value of 0.4% has been chosen [15].

Table 2. Structural material characteristics of girder footbridges

Structural Material	Standard	Young Modulus (GPa)	Specific weight (kN/m^3)
Reinforced concrete	EC2[10]	31	25
Prestressed concrete	EC2[10]	37	25
Timber	EC5[11,12]	12	7
Aluminium (Alloy EN AW 6082)	EC9 [13]	70	27
GFRP	Eurocomp Handbook [14]	17.2	25.6

Table 1: Girder footbridges considered in the parametric study. These sections types were also used in the Ramos's PhD thesis [7]

Deck cross sections	
	Section Type 1: Reinforced concrete slab
	Section Type 2: Prestressed concrete T-slab
	Section Type 3: Timber beams and concrete slab
	Section Type 4: Aluminium box girders and concrete slab
	Section Type 5: GFRP beams and concrete slab

3. Results

After the evaluation of the dynamic response, the cases where the serviceability criteria is not fulfilled were identified. For these cases, tuned mass dampers were employed to evaluate the effect in the reduction on the dynamic response. The TMD implementation includes an exhaustive analysis of the location and properties of tuned mass dampers [8]. After performing a frequency domain analysis, it is clearly noticed that these footbridges had one critical mode. Therefore, tuned mass dampers have been located at the location where the modes with the larger contribution in the response have a large modal coordinate.

3.1 Dynamic response in vertical direction

For the numerical work performed herein one and two tuned mass dampers were considered locating them at the maximum nodal displacement of the modal shape whose frequency has the largest amplitude in the representation of the excessive acceleration in the frequency domain. When the TMD is located at this point, the efficiency (measured as the percentage of the peak acceleration with and without TMD) is optimal, with values up to 81%.

Figure 3 shows the maximum acceleration for sections types 1, 2, 3, 4 and 5 (Table 1) when the pedestrians are going to work (commuters). When TMDs are not deployed, the serviceability criteria is not fulfilled for some span lengths, as the frequency of the structure matches the average pedestrian frequency, an a resonant effect is induced. For instance, at resonance (Section 2 for commuters) when the span length is 10 m, a single TMD located at mid-span with a mass ratio of 0.04 was enough to mitigate the human-induced vibrations under acceptable limits. It is important to note that there is no point in increasing the mass ratio beyond this value, as the reduction in accelerations from one to two tuned mass dampers is around 9%.

Table 3 shows the TMD properties (mass ratio, length, and width) than can be employed for each of the resonant cases in Figure 3. For cross-sections types such as concrete reinforced slabs, T-shape Prestressed concrete slabs, and timber

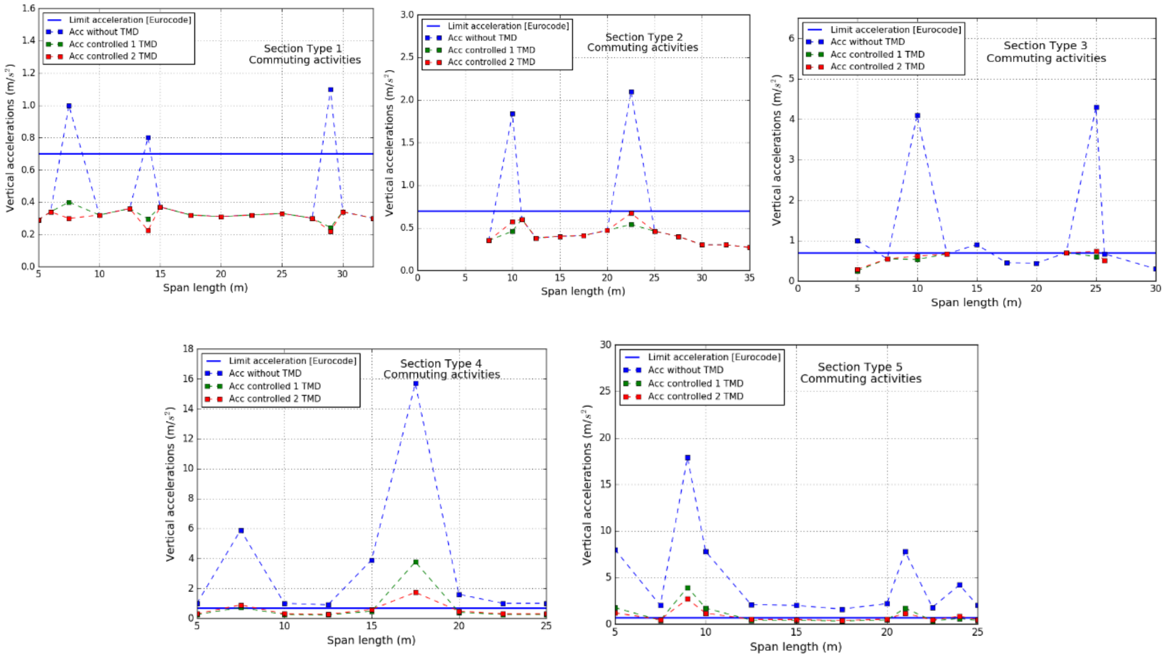


Figure 3. Maximum vertical accelerations for section Types 1, 2, 3 ,4 and 5 (Table 1) when one and two tuned mass dampers are implemented at the maximum nodal coordinate of the modal shape with a larger contribution in the dynamic response, under pedestrian densities of 0.6 ped/m2 for commuting and leisure activities

Table 3: Tuned mass damper properties according the span length under pedestrian densities of 0.6 ped/m^2 for commuting and leisure traffic based on Figure 3

Cross section Type Table 1	Commuting activities				Leisure activities			
	Span length (m)	Mass ratio	Length (mm)	Height (mm)	Span length (m)	Mass ratio	Length (mm)	Height (mm)
Type 1	7.5 - 14	0.01	600	275	5.0	0.01	600	275
	29.0	0.03	1020	200	-	-	-	-
Type 2	10.0	0.04	1020	200	27.5	0.03	1020	200
	22.5	0.05	1420	240	-	-	-	-
Type 3	5.0	0.03	600	275	7.5	0.05	600	275
	10.0	0.07	1250	325	12.5	0.05	100	325
	25.0	0.07	2000	325	17.5	0.04	800	325
Type 4	5.0	0.04	600	275	6.0	0.05	600	275
	7.5	0.08	1250	325	9.0	0.06	1000	325
	10.0 -12.5	0.03	1000	325	17.5	0.04	1000	325
	15.0	0.07	1000	325	20.0	0.06	2000	325
	17.5	0.09	2780	325	22.5 - 25.0	0.03 - 0.04	1250	325
	20.0 – 22.5 – 25.0	0.04	1250	325	-	-	-	-
Type 5	5.0	0.08	1600	325	5.0	0.06	1000	325
	7.5- 12.5	0.06	1000	325	12.5	0.05	800	325
	9.0	0.07	2780	325	15.0	0.04	2000	325
	10.0 -21.0	0.06	2000	325	17.5	0.04	2000	325
	15.0 – 17.5 – 20.0	0.07	1000	325	20.0	0.05	2000	325
	22.5	0.06	2000	325	23.5 – 25.0	0.06 – 0.05	1250	325
	24.0 – 25.0	0.07 – 0.06	1250	325	-	-	-	-

beams employing one tuned mass damper is enough to satisfy the serviceability criteria. However, for cross-sections types such as the aluminium and the GRFP cross sections (cases 4 and 5 in Table 1) two TMDs are not enough to control the human-induced vibrations. In these light cross-sections it is required to redefine the slenderness and the structural mass otherwise the serviceability limit state is not fulfilled.

3.2 Dynamic response in lateral direction

It was evaluated the lateral peak accelerations in a set of reinforced concrete footbridges with spans ranging from 20 up to 100 m under pedestrian densities of 0.6 ped/m^2 for commuting traffic. Figure 4 shows that when the width is L/20 (where L is the span length in meters) these structures will have lateral vibration problems. It is important to note that if the width is doubled up to L/10 the serviceability criteria are fulfilled from a range of span lengths from 20 to 100 m. Therefore, for a width of L/20 it is required to employ supplemental damping devices in order to mitigate the lateral human-induced vibrations.

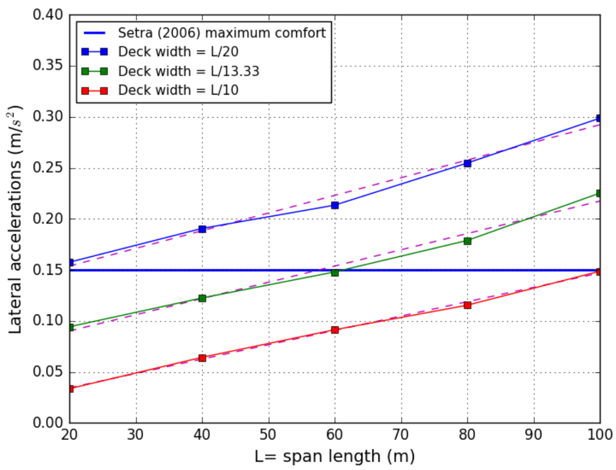


Figure 4. Maximum lateral peak accelerations in footbridges (Setion Type 1) with spans ranging from 20 up to 100 m under pedestrian densities of 0.6 ped/m2 for commuting traffic

4. Discussion and conclusions

This paper focuses on the evaluation of tuned mass dampers in girder footbridges under pedestrian loads. The serviceability criteria can be fulfilled with a single TMD located where the modal shape has the largest nodal displacement as these footbridges have had one critical mode. However, in ultra-light footbridges, with cross sections made of aluminium and glass fibre reinforced polymers (Sections Type 4 and 5 in Table 1) the accelerations do not satisfy the comfort criteria even using two tuned mass dampers. Therefore, the dynamic response must govern the deck slenderness, and structural configuration to make these solutions viable for footbridge applications complying with serviceability requirements.

In general, some research work has been developed employing tuned mass dampers after the construction. However, it can be seen the clear effect of the reduction in the dynamic response can be obtained through the use of tuned mass dampers at the design stage. This work is part of the first author's PhD thesis, being supervised by the co-authors.

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