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Serviceability Assessment of Composite Footbridge Under Human Walking and Running Loads

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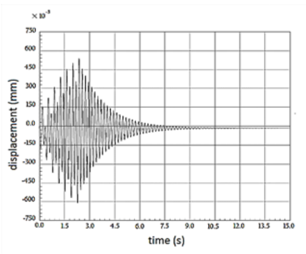
Graphical abstract



Abstract

Footbridge responses under loads induced by human remain amongst the least explored matters, due to various uncertainties in determining the description of the imposed loadings. To address this gap, serviceability of an existing composite footbridge under human walking and running loadings is analyzed dynamically in this paper employing a finite element approach. The composite footbridge is made-up of a reinforced concrete slab simply supported at two ends on top of two T-section steel beams. To model the walking and running loads, a harmonic force function is applied as the vibration source at the center of the bridge. In the model verification, the computed natural frequency of footbridge exhibits a good agreement with that reported in literature. The vibration responses in terms of peak acceleration and displacement are computed, from which they are then compared with the current design standards for assessment. It is found that the maximum accelerations and displacements of composite footbridge in presence of excitations from one person walking and running satisfy the serviceability limitation recommended by the existing codes of practice. In conclusion, the studied footbridge offers sufficient human safety and comfort against vibration under investigated load prescription.

Keywords: Composite footbridge; finite element; serviceability; walking load; running load

■1.0 INTRODUCTION

Lightweight and slender footbridges have attracted considerable attention as modern structures in recent years, due to their aesthetic values and reduced usage of materials. Although, from the structural point of view, the prevalent design and construction proficiencies are well-established for footbridges, in the recent years more accurate analyses are demandingly required for some specifically sophisticated structures [1]. The vast majority of existing studies indicate that for slender and light structures, such as the footbridges, the natural frequencies domain frequently coincide with frequencies of dynamic load like human walking, running, dancing and jumping [2, 3].

Since availability of the responses of footbridges due to the human induced loads is scarce from the experimental work because of various undetermined interlinked effects [1], the aim of this study is to generate a fundamental research knowledge on the vibration characteristics of slender composite footbridge structures under human running and walking loads in order to evaluate serviceability requirement of these structures against the current design standards. The evaluation not only important in assessing the performance of existing structure, it feeds information whether the existing structure is overdesigned. If it is, certain material saving can be made to save the construction cost for sustainability of structures and materials. For the latter, several recent researches are of interest [4, 5]. Also, studies on composite structures have elevated due to various advantages exhibited [6].

The footbridge vibration response is typically assessed through the analyses of its natural frequency, acceleration, displacement and velocity. The natural frequency is a significant parameter in the vibration serviceability design. It represents the frequency coming from a free vibration state when a structure is displaced and quickly released [7]. The lowest or first natural frequency, which is usually defined as the fundamental natural frequency, is the most considerable parameter since it may match the load excitation frequency, and thus providing possible cause for resonant [7]. Therefore, a calculation of the first natural frequency constitutes one of the principal steps in preventing the footbridge disastrous vibration. In addition, vibration responses such as acceleration and displacement are essential complementing its natural frequency in the serviceability assessment. In the current work, a modal analysis is employed using the finite element software to determine the aforementioned parameters, to be checked against allowable limitations given by the existing codes.

■2.0 HUMAN WALKING AND RUNNING AS VIBRATION SOURCE

Figure 1 shows the description of human load on the footbridge via a point load. Dynamic induced load such as machinery or human activities are reasons for floor vibration problems. Evaluating human discomfort criteria for appraisal of the vibration of floor structures has been a new exercise in the process of design. The loads induced by human activities such as walking, running, dancing, jumping and aerobics are complex and the dynamic response may be based on various modes of vibration. These load types can be presented as sinusoidal or similar functional forces.

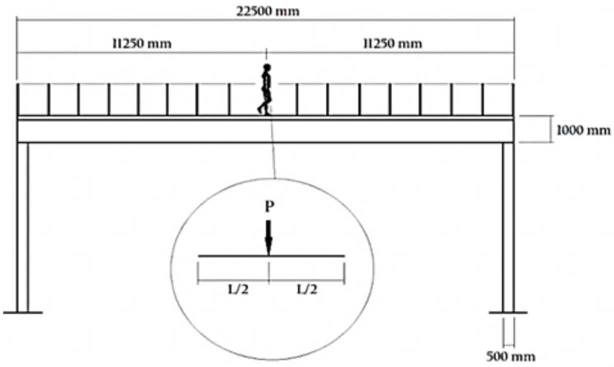


Figure 1 Applied load model on the footbridge

A combination of various harmonic forces can be used to represent the human activities induced dynamic excitation. In any case, it is assumed that the induced forces by human feet are similar to walking and running model in the time domain [8, 9]. These harmonic forces can be expressed by the Fourier series:

$$F(t) = P\left(1 + \sum_{i=1}^{n} \alpha_i \cos(2\pi i f_s t + \varphi_i)\right) \qquad (1)$$

where P is the weight of one person, α_i is the dynamic coefficient of the harmonic force, which is decreased by increasing harmonic. i, f_s, t and φ_i are the harmonic multiple, step frequency, time and harmonic phase angle, respectively.

2.1 Acceptance Criteria

In the case of floor system, to obtain the vibration serviceability limit state caused by human running, the design standard for indoor footbridges, outdoor footbridges and residences [7] is considered using two following criteria: peak acceleration limit values and the harmonic force component.

- *Peak acceleration limit values:* International Standard Organization (ISO) 2631-2 [10] guideline has recommended the acceleration limit values, which are related to frequencies. When the range of vibration frequency is between 4Hz and 8Hz, it is 50 for outdoor footbridges, and the duration of vibration can be considered in the range of 0.8-1.5 times the recommended value [10] for design proposes.
- *The harmonic force component*: A time dependent harmonic force component, which occurs at the same time with the structural fundamental frequency, can be written as:

$$F(t) = P\alpha_i \cos(2\pi i f_s t) \qquad (2)$$

In our cases, the static load (P) is 700–800N corresponding to the individual weight [9, 11, 12]. Here, by considering that the resonant state occurs in the first harmonic (based on the criteria of design), only one harmonic force is used since the contribution of remaining harmonics is small. Table 1 presents the dynamic coefficient of walking and running in different forcing frequency averages [7].

Table 1 Dynamic coefficient of running and walking In different forcing frequency averages [7]

Harmonic *i*	**Running**		**Walking**	
	f_s(Hz)	**α_i**	**f_s(Hz)**	**α_i**
1	2.2-2.7	1.6	1.7-2.2	0.4
2	4.4-5.4	0.7	3.4-4.4	0.1
3	6.6-8.1	0.2	5.1-6.6	0.1

A resonance response function is defined as [7]:

$$\frac{a}{g} = \frac{RF(t)}{\beta W} \qquad (3)$$

Therefore, the maximum system acceleration can be expressed by substituting $F(t)$ from Equation 2 as:

$$\frac{a}{g} = \frac{RP\alpha_i \cos(2\pi i f_s t)}{\beta W} \qquad (4)$$

where a is the floor accelerations, $g = 9.81$ m/s^2 is the gravity acceleration. W and β are the floor effective weight and the modal damping ratio, respectively.

In this model, the reduction factor (R) considered as human activities, such as walking and running, is equivalent to 0.5 and 0.7 for floor structures and footbridges, respectively [7]. The design criteria imply that the lowest harmonic where the excitation frequency matches the structural natural frequency should be selected to calculate the peak acceleration due to human walking and running in Equation 4.

■3.0 FINITE ELEMENT MODEL

In detail, the investigated structural model (Figure 1) is a composite pedestrian footbridge [13] simply supported at two ends of span on columns with a reinforced concrete slab and T-section steel beams, geometrical characteristics of which are as shown in Figure 2 and Table 2. The constructed model for the bridge slab is characterized as 22.5m and 2.30m in length and width, respectively, with a thickness of 100 mm.

Table 2 Geometrical characteristic of steel sections [13]

Beams	VS 900 x159	I 200 x27.3
Height (mm)	900	203.2
Flange width (mm)	350	101.6
Top flange thickness (mm)	19	10
Bottom flange thickness (mm)	19	10
Web thickness (mm)	8	6.86

The steel sections, which are utilized as girders, are welded along the flange with a Young’s modulus of 2.05x10^5

MPa and a yield stress of 300 MPa. In addition, the Young's modulus of concrete slab is 3.84×10^4 MPa and its compression strength is 30 MPa. Furthermore, a damping ratio β = 3% is prescribed [1].

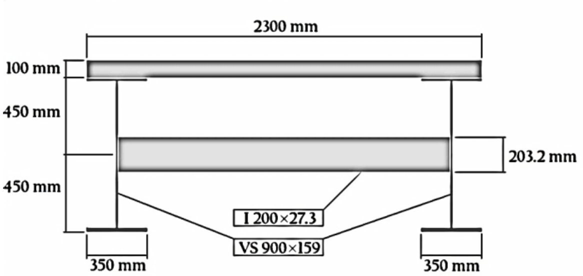


Figure 2 Geometrical characteristics of the footbridge's cross section

In the finite element model, both the composite slab and steel girders are meshed by three-dimensional solid elements using the SAP2000 software [14]. Verification of the numerical simulation is based on a comparison of its fundamental frequency to that of Da Silva *et al.* [13]. It is found that a similar first natural frequency to that computed by Da Silva *et al.* [13] is predicted by the current model as shown in Table 3. Also shown are the remaining natural frequencies calculated by the present model. Associated modes are shown in Figure 3.

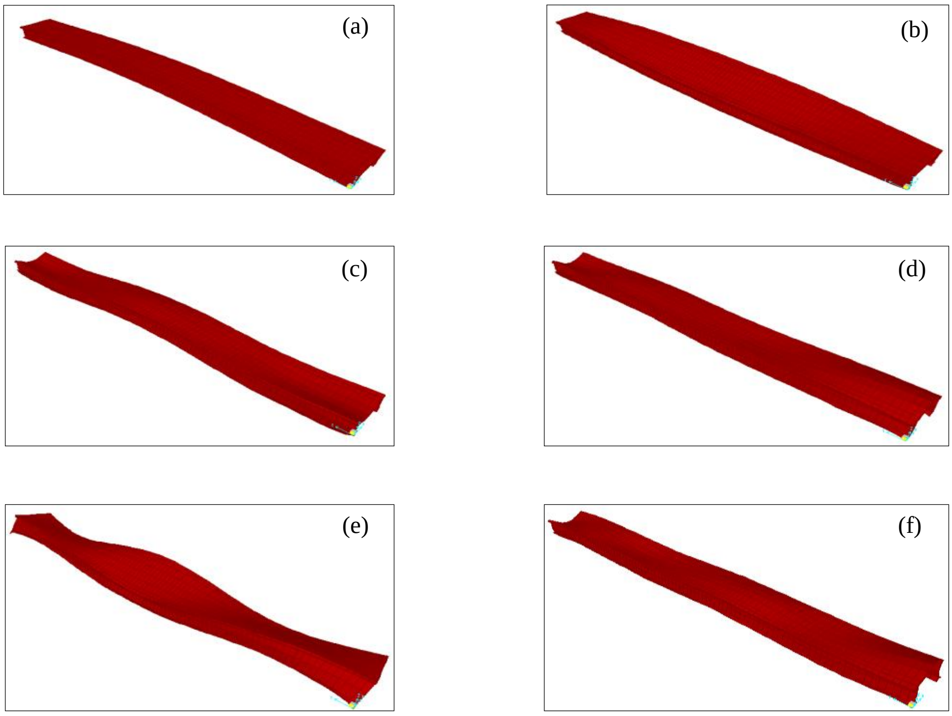


Figure 3 Mode shapes of the (a) first, (b) second, (c) third, (d) fourth, (e) fifth, and (f) sixth natural frequencies

Table 3 Natural frequencies calculated in this paper using SAP2000 and comparison with literature [13]

Number of natural frequencies	f_1	f_2	f_3	f_4	f_5	f_6
Natural frequencies (Hz) calculated in this paper	5.4	13.64	22.51	28.41	30.18	37.01
Natural frequency from [13]	5.5	-	-	-	-	-

When walking or running is exerted by a human, the weight of the body is substantial in each step due to its acceleration and frequency. Ground reaction force induced by acceleration of the pedestrian motion is then applied to the footbridge, which is a three-component force. These force components are expressed in the vertical, lateral and longitudinal directions, estimated using the fundamental frequency [1]. Only the vertical component is taken into account in this study since both lateral and longitudinal loads are only negligibly 4% of the vertical component. Moreover, the longitudinal load is usually not important in the vibration analyses [15].

In the human walking and running model, the load applied to the footbridge consists of the harmonic and body weight components. The loads are assigned at the middle of the bridge span (Figure 1). A synchronization of load, consisting of static and dynamic loads, is performed where the former is due to the human body weight while the latter corresponds to the Fourier series based on the time domain repeated forces (Equation 1). Since it was found that the first natural frequency of the footbridge is 5.4Hz, only the third harmonic with a step frequency of 1.8Hz (3x1.8=5.4) for walking load and the second harmonic with a step frequency of 2.7Hz (2x2.7=5.4) for running load are the resonant harmonics of the structure. To illustrate the human running load, the time is shortened to 2.5 seconds in this paper. Figures 4 and 5 show the dynamic load functions when a person walks at 1.8Hz and runs at 2.7Hz, respectively, in the harmonics where resonance occurs.

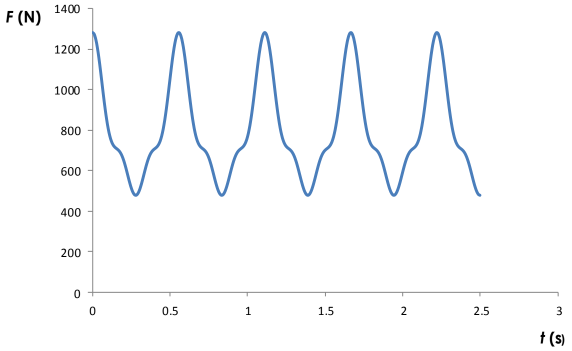


Figure 4 Dynamic load function when a person walks at 1.8Hz in three harmonics

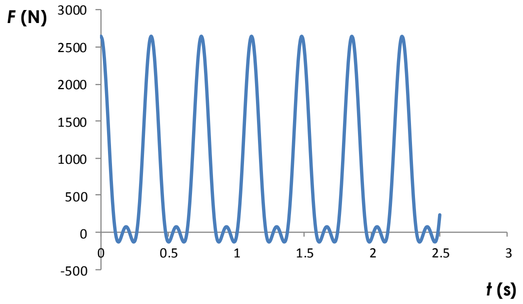


Figure 5 Dynamic load function when a person runs at 2.7Hz in two harmonics

■4.0 DYNAMIC ANALYSIS OF STRUCTURE

Having verified and prescribed an appropriate loading description to the model, its vibration response is then estimated in terms of natural frequencies, accelerations, displacements through a linear time-history modal analysis. The computed maximum acceleration and displacement are subsequently compared to the current design standard [7, 16-17].

The limiting peak accelerations [7, 16, 18] as well as displacements [17, 19] are provided by the existing design criteria. Generally, the limiting acceleration values are remarked as the percentage of the acceleration of gravity. All recommended values by ISO 2631-2 [10], Ontario Bridge Code [16] and BS 5400 (British Standard) [18, 20] are as summarized in Table 4. From the model, the maximum accelerations are 0.07%g and 0.15%g for one person walking and running excitation loads, respectively. Therefore, the exerted outcomes are well below the maximum limits given by the existing codes.

Table 4 Peak accelerations for outdoor footbridge for walking and running

Computed max acceleration		**Limitation of peak acceleration**		
a_{max}(%g)		**ISO 2631-2 [10]**	**ONT [16]**	**BS 5400 [18, 20]**
Walking	0.07%g	5%g	3.46%g	11.95%g
Running	0.15%g			

As illustrated in Figure 6, the vertical accelerations at the mid span of the structure are time-dependent function with the maximum value taken as the vibration serviceability criterion. In general, the vertical acceleration increases with some periodic fluctuations. Its value decreases with a time step size of 0.01 second, which then reduces to zero after 1500 time steps. Walking imposes lower acceleration in the structural response when compared to running, due principally to the frequency of the loading type. Both acceleration evolutions show their tendency to peak before dropping gradually in the time domain. From the results, it is clear that the footbridge structure maximum acceleration can satisfy all the design criteria and practical guide limitations [7, 10].

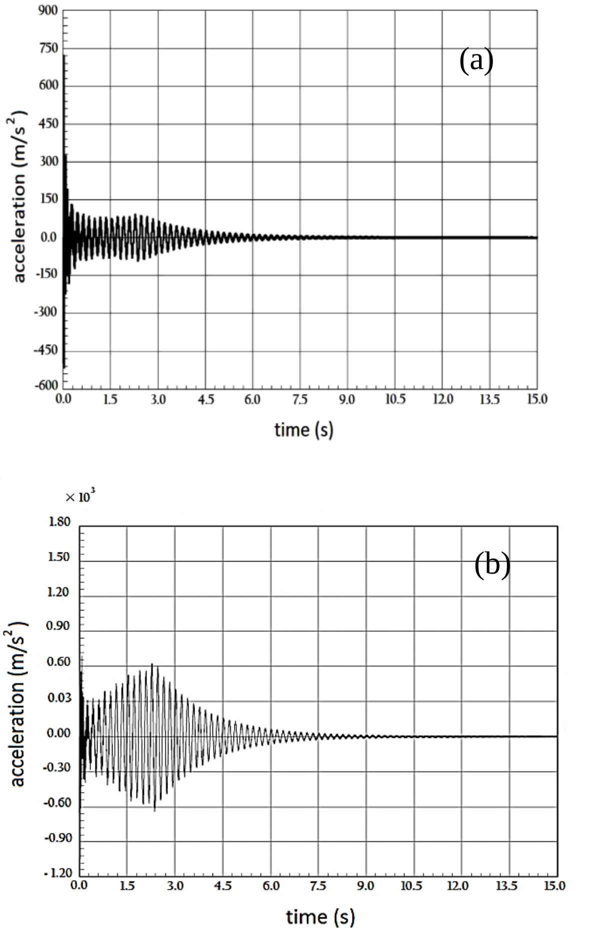


Figure 6 Vertical accelerations at the mid span of the structure due to (a) walking and (b) running

On the other hand, the design criteria for displacement of the pedestrian crossing structure like outdoor footbridges are recommended in bridge design specifications of AASHTO LRFD [17]. According to these criteria, footbridge structures maximum allowable deflection in the mid span is *L*/1000 (*L* is the length of span).

The presently computed displacement evolutions at mid span are displayed in Figure 7, from which the notable maximums are 0.14 mm for walking and 0.55 mm for running. As exhibited in the graphs, the vertical displacements at the mid span are also time-dependent. Since self-weight of the structure generates a minor displacement, these values are not reduced to zero. The peaking and reducing patterns are repeated for both loadings. Running remains as the more severe load compared to walking.

Based on the design criteria and considering 22.5m for the length of span, the limiting displacement for this footbridge is 22.5mm. Therefore, the limit is not exceeded when prescribed with both load descriptions. In other words, the footbridge structure that is analyzed in this paper can satisfy the limiting value for displacement as well.

The results show that the maximum acceleration and displacement due to running load are greater than that of walking. This obviously owes to the intensity of running load’s step frequency, which is 2.7Hz compared to 1.8Hz for walking load. It is worth mentioning that the present model does not consider a precise setting of columns supporting the bridge. For better and wholesomeness of the study, this issue may be treated in a future consideration.

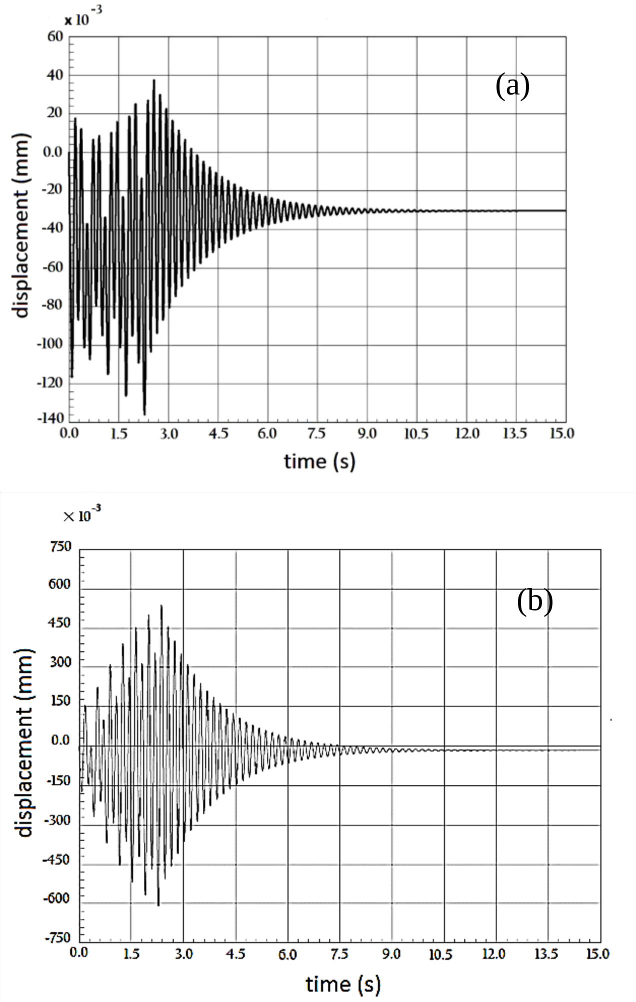


Figure 7 Vertical displacements at the mid span of the structure due to (a) walking and (b) running

■5.0 CONCLUSION

In this paper, assessment of serviceability limit state is carried out through a dynamic analysis of a slender footbridge when subjected to walking and running loads. A structural bridge comprising reinforced concrete and T steel beams is modeled, from which the natural frequency agrees excellently with that from the existing literature. A reasonably accurate mathematical load model has been used to describe the actions of both human walking and running loads on the footbridge by means of the Fourier function. It is generally found that running load imposes greater severity to the bridge compared to walking, in both displacement and acceleration computations. In addition, the footbridge structure maximum accelerations and displacements are compared with existing design criteria from available standards, from which all practical guide limitations are safely satisfied.

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