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Pedestrian induced vibrations in footbridges: Reappraisal of code provisions

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ABSTRACT: Over the last few years, the trend in footbridge design has been towards greater spans and lightness. Once followed, such trend gives increased flexibility in dynamic behaviour. As a consequence, stiffness and mass sometimes decrease and lead to smaller natural frequencies. In practice, such footbridge has particularly been found to be more sensitive to dynamically imposed pedestrian loads. The requirements in the codes for design of this class of structure widely vary because of the poor understanding of the complex human-structure interaction phenomena and associated bio-mechanical problems. Most current design codes in the world consider the dynamic force induced by a single pedestrian. But actually it is more complex in nature. Again, internationally accepted different codes and provisions do not fulfill the design data for footbridge vibrations. These codes do not provide sufficient guidelines and information to address such vibration problems and to ensure safety and serviceability due to the lack of knowledge on the dynamic performance of such footbridge structures. This paper discusses those problems and revision of codes.

1 INTRODUCTION

Human-structure dynamic interaction is defined not only as the influence of humans on the dynamic properties of structures they occupy, but also as forces which excite these structures. Both of these issues are becoming increasingly important for all slender civil engineering structures occupied and dynamically excited by humans, such as footbridges, long-span floors, grandstands and staircases. The problems are typically caused by excessive vibrations of such structures due to normal activities of their human occupants, such as walking, running and jumping. The human involvement in the problem is the key source of considerable randomness.

Footbridges are now an important part of city infrastructures. These structures allow safe movement of pedestrians over the urban roads, city waterways or highways. These structures also connect urban installations at different elevations (Amin et al. 2005). Now-a-days structural materials are becoming stronger and these have higher strength to weight ratio. However, live load of footbridge is quite low compared to vehicular traffic loads. For this reason, the design based on static analysis may offer slender bridge structures for pedestrian and cycle track use. As a consequence, stiffness and masses decrease and the structure becomes more flexible and easy to be excited under dynamic forces having smaller natural frequencies.

In the current trend, the architects, in the design process carefully consider the aesthetic appeal of these bridges to maintain a harmony with the surrounding infrastructure of the neighborhood while the structural engineers follow the current design codes to ensure the stability, safety and durability of the structure. But current design codes and regulations do not fulfill all the requirements for dynamic design of footbridges. In this situation, this paper discusses the revision of different widely used codes and standards.

2 HUMAN-STRUCTURE DYNAMIC INTERACTION IN FOOTBRIDGES

Every step of the pedestrian movement can be treated as one impulse, series of steps as impulses along the way and shifted in time. Therefore, load induced by walking can be assumed as sum of loads caused by continual steps, which further can be simulated with moving pulsating point load. With accurate assumptions that the load applied by every step is approximately of the same value, and that the time needed for transmission of pressure is constant for given walking pace, one can assume that this load is periodic in nature. In this way, a pedestrian creates a repeating pattern of forces as his mass rises and falls against the ground. The force has vertical, lateral and a torsional component. Figure 1 illustrates the methodology of human-structure dynamic interaction in footbridge structures.

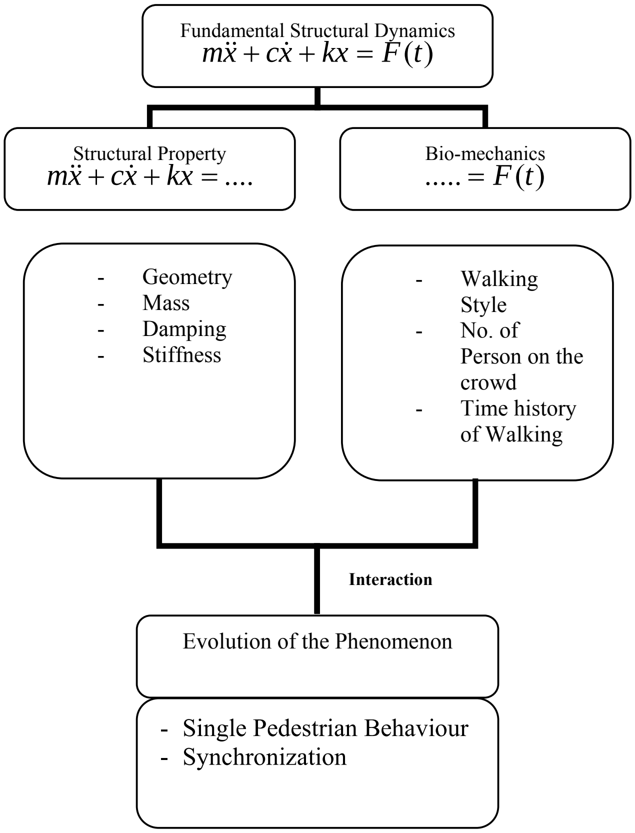

Figure 1: Human-structure dynamic interaction in footbridges.

Two types of footbridge structures are being studied in this paper. These are: Footbridge-I: Arch supported suspended footbridge (Figure 2) Footbridge-II: Girder footbridge (Figure 3)

Table 1: Brief Description of Footbridges

Bridge Type	Location of the Bridge	Geographic Co-ordinates	Span Length (m)	Width (mm)	Structural System	Foundation System
Footbridge-I	Over Crescent Lake, Dhaka	$23^{0}45^{'}54.43^{''}$ N $90^{0}22^{'}42.01^{''}$ E	57.30	4572	Arch supported suspended footbridge	Pile Foundation
Footbridge-II	Near Radisson Water Garden Hotel, Dhaka	$23^{0}48^{'}59.65^{''}$ N $90^{0}24^{'}21.24^{''}$ E	Two span. Each span is 20.38	3000	Steel girder footbridge	Pile Foundation

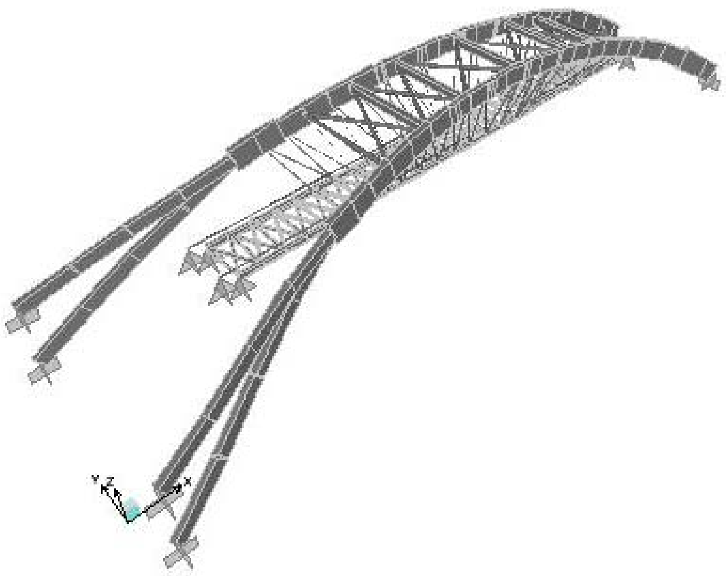

Figure 2: Footbridge over the Crescent Lake.

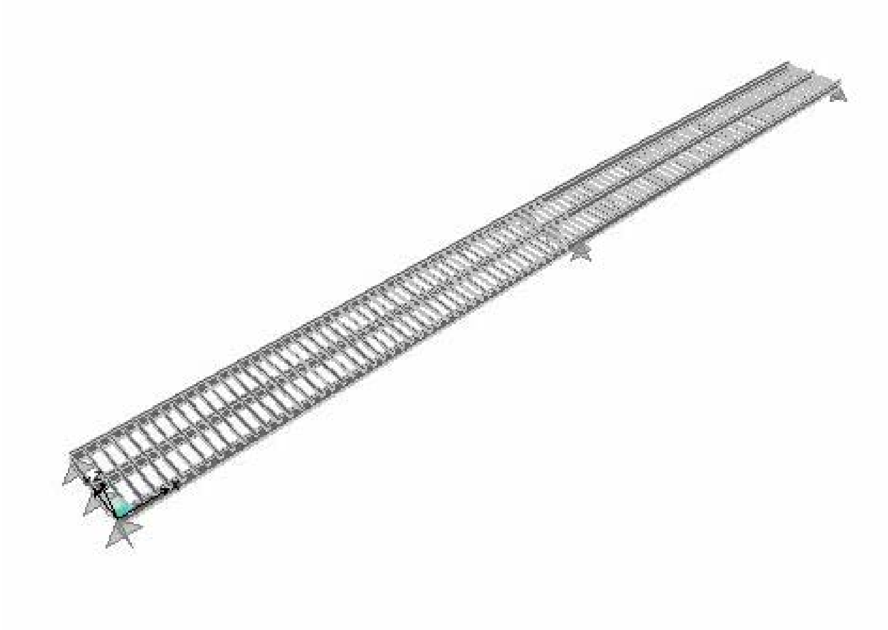

Figure 3: Footbridge near Radisson Water Garden Hotel (simplified model).

3 VIBRATION CONSIDERATIONS IN DIFFERENT CODES

Different widely used standards have been used in this paper. These codes and standards are BS 5400, Eurocode, ISO 10137 and Bro 2004.

3.1 *Risk Frequencies noted in the literature and in current regulations*

Compilation of the frequency range values given in various articles and regulations has given rise to the Table 2, drawn up for vertical vibrations.

Table 2: Risk frequencies in different standards

Standards	Frequency Range
Eurocode 2	1.6 Hz and 2.4 Hz and, where specified, between 2.5 Hz and 5 Hz.
Eurocode 5	Between 0 and 5 Hz
Appendix 2 of Eurocode 0	<5 Hz
BS 5400	<5 Hz
Regulations in Japan	1.5 Hz – 2.3 Hz
ISO/DIS standard 10137	1.7 Hz – 2.3 Hz
CEB 209 Bulletin	1.65 – 2.35 Hz
Bachmann	1.6 – 2.4 Hz

As concerns lateral vibrations, the ranges described in the Table 2 are to be divided by two owing to the particular nature of walking: right and left foot are equivalent in their vertical action, but are opposed in their horizontal action and this means transverse efforts apply at a frequency that is half that of the footsteps.

However, on the Millennium footbridge it was noticed that the lock-in phenomenon appeared even for a horizontal mode with a frequency considerably beneath that of the lower limit generally accepted so far for normal walking frequency (Dallard et al. 2001a,b). Thus, for horizontal vibration modes, it seems advisable to further lower the lower boundary of the risk frequency range.

3.2 *Different Code Comparisons*

In addition to the frequency comparison presented in Table 2, Table 3 compares the serviceability criteria in terms of acceleration set forth in the four standards discussed in this paper. A comparison of the vertical and the horizontal vibration criteria are presented in Figure 4 and Figure 5 respectively. The ISO 10137 and Bro 2004 curves are obtained by converting the RMS acceleration to the maximum value by multiplying by the factor $\sqrt{2}$.

A comparison of the vertical vibration criteria show that Euro code and Bro 2004 present a frequency independent maximum acceleration limit of 0.7 m/s^2. For a footbridge with a natural vertical frequency of 2 Hz, which is the mean pacing rate of walking, the BS 5400 criteria also gives $a_{\max} \le 0.5\sqrt{2Hz} = 0.7$ m/s^2. ISO 10137 gives, on the other hand, a slightly lower value, $a_{\max} \cong 0.6$ m/s^2.

Table 3: Acceleration Criteria

Standard	Vertical Acceleration	Horizontal Acceleration
BS 5400	$a_{\max} \le 0.5\sqrt{f}$ m/s^2	No requirements
EN 1990	$a_{\max} \le 0.7\sqrt{f}$ m/s^2	$a_{\max} \le 0.2$ m/s^2
ISO 10137	60 times base curve, Figure 4	60 times base curve, Figure 5
Bro 2004	$a_{RMS} \le 0.5$ m/s^2	No requirements

A comparison of the horizontal vibration criteria show that Euro code presents a frequency independent maximum acceleration limit of 0.2 m/s^2. ISO 10137 gives a frequency independent maximum acceleration of $a_{\max} \cong 0.31$ m/s^2 up to a frequency of 2 Hz. Neither BS 5400 nor Bro 2004 presents numerical acceleration criteria for horizontal vibration. However, BS 5400 states that if the fundamental frequency of horizontal vibration is less than 1.5 Hz, the designer should consider the risk of lateral movements of unacceptable magnitude.

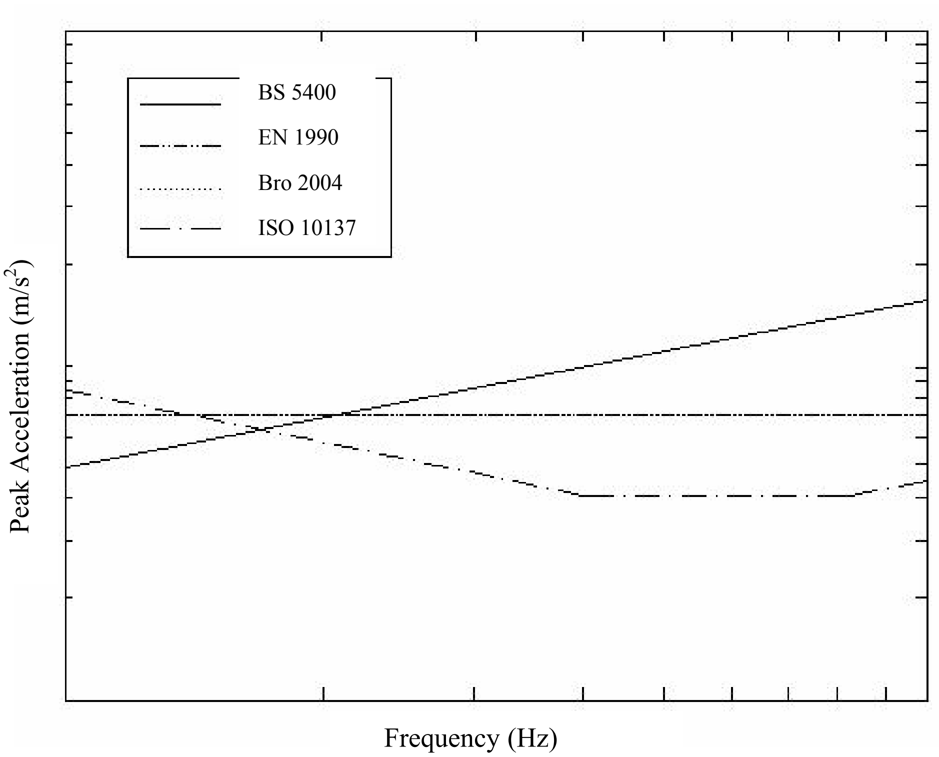

Figure 4: Comparison of acceptability of vertical vibration.

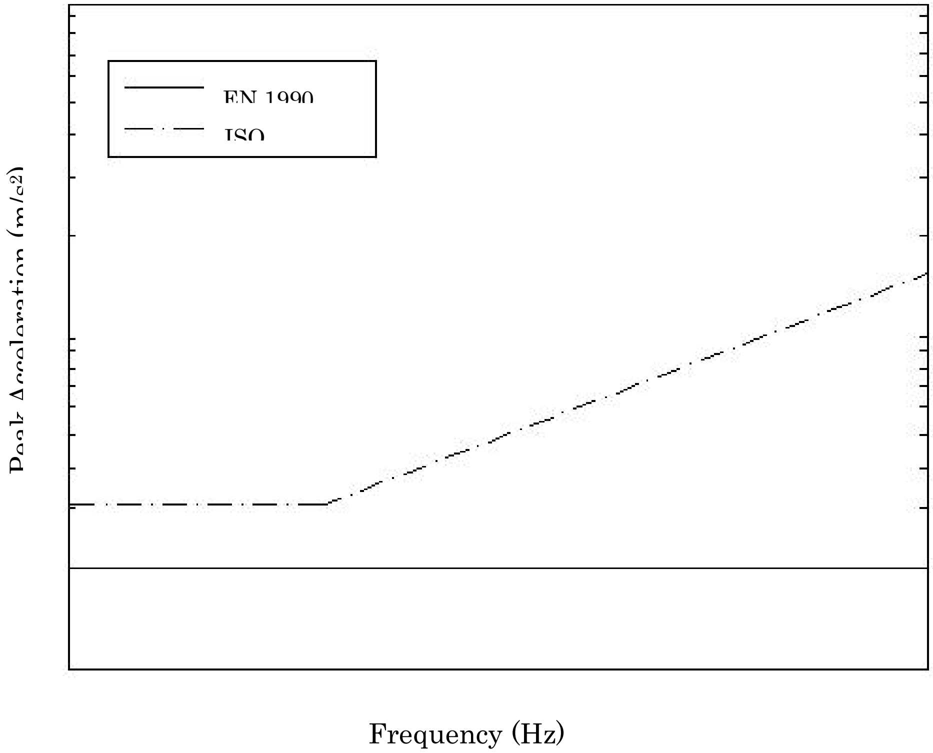

Figure 5: Comparison of acceptability of horizontal vibration.

The British standard BS 5400 proposes a pedestrian load model only in the vertical direction and not in the horizontal. ISO 10137 models both vertical and horizontal loads imposed by one pedestrian. It is noted that the modeling of the horizontal pedestrian load assumes that the static weight of the pedestrian, *Q*, acts in the horizontal direction. Euro code proposes load models for both vertical and horizontal loads only for simplified structures. For more complex structures, the modeling of pedestrian loads is left to the designer. The Swedish standard Bro 2004 proposes a load model for calculations of vertical vibrations. However, it proposes neither a load model nor design criteria for horizontal vibrations.

The load models proposed by these standards are all based on the assumptions that pedestrian loads can be approximated as periodic loads.

4 FINITE ELEMENT MODELING

Dynamic analysis of Footbridge-I and Footbridge-II has been performed using the Finite Element Method using SAP2000, general purpose finite element software. The objective of the analysis is to investigate the response of the bridge structure due to dynamic loads applied by pedestrians. In order to analyze the structures dynamically, 3-dimensional finite element (FE) models of the footbridge structures (Figure 6 & 7) has been established.

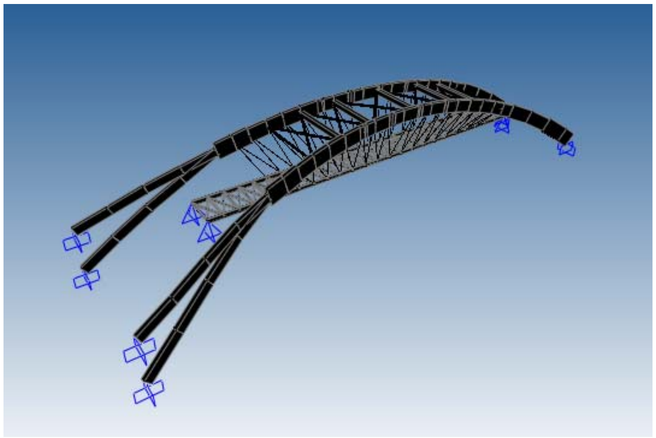

Figure 6: Finite Element model (Solid Element) of Footbridge-I.

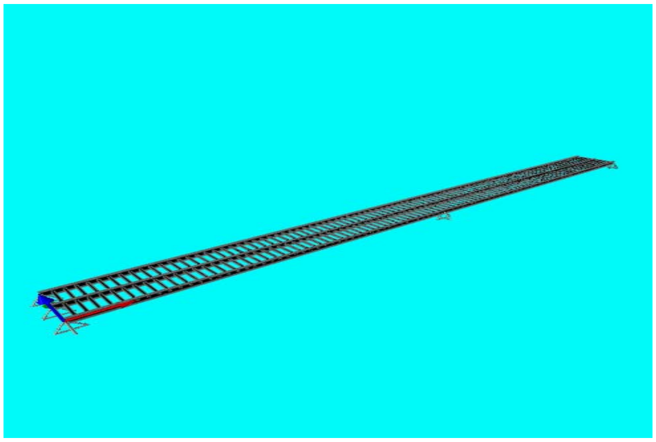

Figure 7: Finite Element model (Solid Element) of Footbridge-II.

5 COMPARISON OF CODES

5.1 *Dynamic Behaviour of Footbridge-I model*

According to different standards (Figure 4), Footbridge-I has been checked by using different loading conditions.

Table 4: Dynamic acceptability of Footbridge-I model.

Bridge Model	Loading Direction	Loads proposed by Codes	Bridge Frequency (Hz)	Peak Acceleration (m/s2)	Dynamic Acceptability
Footbridge-I	Vertical	BS 5400	2.1	0.62	Acceptable
		ISO 10137	2.1	6.98	Unacceptable
		Bro 2004	2.1	9.42	Unacceptable
	Lateral	ISO 10137	1.6	0.14	Acceptable

A detailed time history analysis has been performed of Footbridge-I. Here typical force patterns from different codes were used. The main focus of this analysis is to evaluate the serviceability requirement of footbridges.

5.2 *Dynamic Behaviour of Footbridge-II model*

Footbridge-II has been checked by using different loading conditions. In Option B model, extra cross tie and cross beam have been installed.

Table 5: Different options for Footbridge-II model.

Bridge Model	Option	Total Deck Width	Deck Bracings		Deck Railing		Extra Cross girder	
		3.00 m	Yes	No	Yes	No	Yes	No
Footbridge-II	A	√		√		√		√
Footbridge-II	B	√	√			√	√	

Table 6: Different options for Footbridge-II model.

Bridge Model	Loading Direction	Loads proposed by Codes	Bridge Frequency (Hz)	Peak Acceleration (m/s^2)	Dynamic Acceptability
Footbridge-II (Option A) Actual Model	Vertical	BS 5400 (British Standard 2001)	3.0	1.38	Acceptable
		ISO 10137 (ISO 2005)	3.0	14.47	Unacceptable
		Bro 2004 (Swedish Standards 2004)	3.0	16.40	Unacceptable
	Lateral	ISO 10137	6.6	0.24	Acceptable
Footbridge-II (Option B)	Vertical	BS 5400	2.1	0.78	Acceptable
		ISO 10137	2.1	3.46	Unacceptable
		Bro 2004	2.1	7.45	Unacceptable
	Lateral	ISO 10137	25.9	0.23	Acceptable

Comparing both footbridges, it is very much clear that Footbridge-I is more serviceable against the vertical and horizontal vibration. Footbridge-II is relatively less serviceable against the horizontal vibration loads. But time history analysis has been done for single person loading condition. Synchronization effect has not been taken.

The British standard BS 5400 requires a check of vibration serviceability in both vertical and horizontal directions. However, it only proposes a load model and a design criterion for vertical vibrations. The load modeling and the evaluation of a design criterion for horizontal vibrations are left to the designer.

The standard ISO 10137 proposes load models for calculation of vertical and horizontal vibrations due to one pedestrian. It also proposes design criteria for vertical and horizontal vibrations. It does not, however, take into account the phenomenon of pedestrian synchronization.

Eurocode proposes load models for both vertical and horizontal loads only for simplified structures. For more complex structures, the modeling of pedestrian loads is left to the designer. Eurocode proposes frequency independent maximum acceleration limits both for vertical and horizontal vibrations.

6 CONCLUSIONS

The load models proposed by the above mentioned standards are all based on the assumptions that pedestrian loads can be approximated as periodic loads. However, it is not perfectly periodic and it is not shown in the standards. They also seem to be incapable of predicting structures sensitivity to excessive horizontal vibrations due to a crowd of pedestrians.

Apart from a single person walking, a group of pedestrians walking at the same speed to maintain the group consistency are a very frequent load type on footbridges (Fujino et al. 1993). But all the standards and codes do not consider this situation.

It can be said that the most advanced design guidelines, such as BD 37/01 and Canadian Highway Bridge Design Code, which served as the basis for most other guidelines, are founded on research data collected in the 1970s (Zivanovic et al. 2005). Also some guidelines require consideration of lateral forces induced by pedestrians, exact procedures as to consider how to consider them are usually not given or are proven to be inadequate. For this reason, current codes and standards should be used carefully.

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