Measurement and prediction of the pedestrian-induced vibrations of a footbridge

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Vibration serviceability has become an important issue in the design of modern slender footbridges with large spans. This paper presents the measurements and the numerical predictions of the footfall-induced vibrations of a pedestrian bridge. A series of experiments were carried out with different-sized groups crossing the bridge, varying in number from 10 up to 50 participants and recording the vertical and lateral accelerations at different locations on the bridge. Two types of tests were performed: free walking and synchronized walking by means of a metronome signal, recorded on a tape recorder carried by the group of students. The effect of the test type is analyzed and shows a magnitude in difference between the vertical accelerations caused by the free and the synchronized walking. The increasing trend of the acceleration levels with increasing group size is also clearly observed. A numerical prediction method is used to simulate the synchronized walking experiments based on an updated finite element model of the bridge and a single pedestrian load model. It is shown that the predicted acceleration level is sensitive to the assumptions made regarding the level of synchronization between the pedestrians and the magnitude of the dynamic load generated by each pedestrian. Taking into account these specific measurement conditions, a fair agreement is obtained between the predicted and the observed vertical acceleration levels at seven positions along the length of the footbridge.

1. INTRODUCTION

Vibration serviceability has become an important issue in the design of modern slender footbridges with large spans. Moreover, recent examples are reported where the vibrations of footbridges due to the footfall excitation of large groups of pedestrians have reached unexpected levels, as was the case with the opening of the Millennium Bridge in London. For an extensive literature review on this topic, reference is made to the work of Živanović *et al*. [1], which states that the modelling of the crowd-induced dynamic force is not clearly defined yet. Furthermore, the phenomenon of synchronisation between the pedestrians and between the pedestrians and the structure requires more research. This paper presents the results of the experimental and numerical analysis of the pedestrian-induced vibrations of a footbridge in Wetteren, Belgium. Two types of tests were performed with different-sized groups crossing the bridge, varying in number from 10 up to 50 participants and recording the vertical and lateral accelerations at different locations on the bridge: free walking and synchronized walking. The first part of the paper analyzes the measurement

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data and studies the effect of the group size and the type of walking (free or synchronized) on the vertical acceleration level of the bridge deck. The second part starts with a brief outline of a numerical prediction method for the pedestrian-induced vibrations. Then the vertical vibrations due to the synchronized walking of groups of 10 and 50 people are predicted and compared with the measurements at seven locations along the bridge length. For these numerical predictions an updated finite element model of the footbridge is used as derived by Degrauwe et al. [2].

2. DESCRIPTION OF THE FOOTBRIDGE

The footbridge, over the E40 highway (Brussels-Ghent, Belgium), provides a connection for cyclists and pedestrians between Wetteren and Zottegem (Figure 1).

Figure 1. Footbridge over the E40 highway.

The steel bridge has two spans: a large span of 75.23m, which is designed as a bowstring bridge with outward inclined bows (13.78° and a maximum height of 12.82m with respect to the bridge deck), and a short span of 30.33m. The two main beams along the bridge length, at each side of the bridge deck, have a distance of 3.55m between the axes.

3. MEASUREMENTS

3.1 INTRODUCTION

This section explains the measurement and the analysis of the pedestrian-induced vibrations of the footbridge. Two types of tests were performed with groups of students crossing the bridge, varying in number from 10, 20, 30, 40 up to 50 participants (Figure 2):

- Free walking: 4 passages for each group size.
- Synchronized walking by means of a metronome signal at 1.9Hz, recorded on a tape recorder carried by the group of students: 2 passages for each group size.

All students were weighed and identified by numbers.

(a)

(b)

Figure 2. Groups (10-20-30-40-50) of students crossing the footbridge: (a) free walking and (b) synchronized walking by means of a metronome signal at 1.9Hz, recorded on a tape recorder carried by the students.

3.2 SETUP

The measurement locations along the bridge length are shown in Figure 3. At each location the vertical accelerations

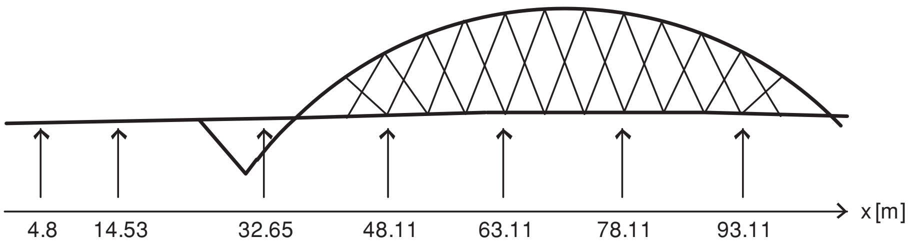

Figure 3. Measurement locations along the bridge length.

were recorded at both sides of the bridge deck (perpendicular to the x-axis at a distance of 1.6m from the central axis of the bridge). The horizontal acceleration was measured at one side of the bridge deck, except at the location x=93.11m.

3.3 DATA ANALYSIS

The vertical acceleration of the bridge deck is calculated as the mean of the two measured vertical accelerations at each side of the bridge deck for all seven measurement locations. This acceleration is filtered with an eighth order Chebyshev Type I low pass filter with a cut-off frequency of 100Hz, before resampling of the data. A running root-mean-square (RMS) acceleration is calculated, with an averaging period of 1s, of which the maximum in time is identified (MAX-RMS). This procedure is illustrated in Figure 4, for the case of 30 students crossing the bridge (free walking) at the position x=78.11m (Figure 3).

3.4 EXPERIMENTAL RESULTS

Table 1 presents an overview of the analyzed data of the free and the synchronized walking experiments: the variation of the maximum RMS-value of the vertical acceleration (characterized by the minimum, the maximum and the mean value) for the different passages of each group size (a number of 4 passages in the case of free walking and 2 in the case of synchronized walking). No statistical analysis is possible due to the limited number of passages for each group size, but based on the acceptable difference between the minimum and the maximum value in most cases, it may be concluded that fairly representative values are obtained. The maximum RMS-values of the vertical acceleration (mean value for the passages) are shown in Figure 5 as a function of the position x along the bridge length for the free and the synchronized walking experiments. Also shown in Figure 5 are

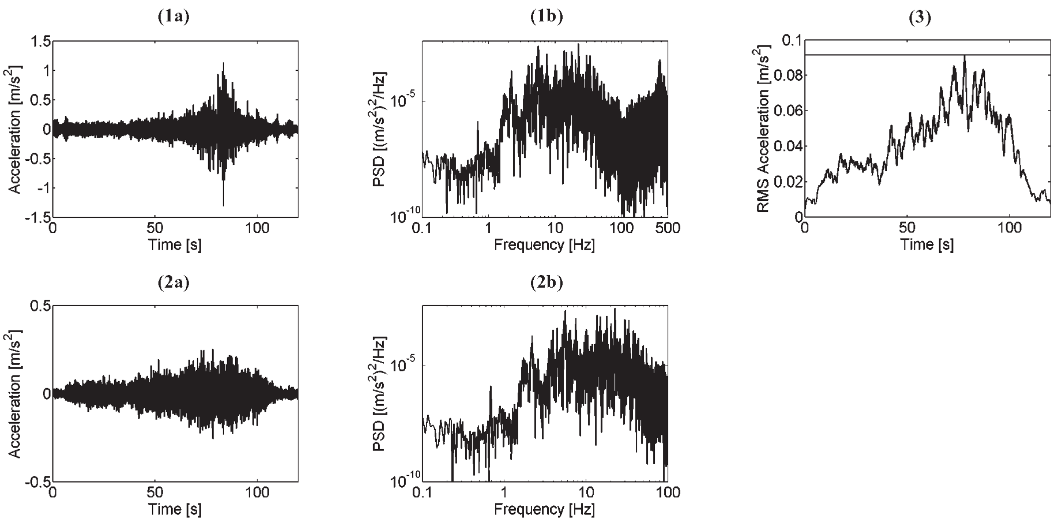

Figure 4. Measured vertical acceleration of the bridge deck at the position x=78.11m during the passage of 30 students (free walking): (a) Time history and (b) power spectral density of (1) the original signal and (2) the filtered and resampled signal; (3) Running RMS-value of the acceleration.

Table 1. Variation of the maximum RMS- value of the vertical acceleration (minimum, maximum and mean value) for the different passages of each group size. Free walking: 4 passages and synchronized walking: 2 passages.

		Maximum RMS-value vertical acceleration [m/s²]									
Position		**G10**		**G20**		**G30**		**G40**		**G50**	
[m]		Free	Sync	Free	Sync	Free	Sync	Free	Sync	Free	Sync
	MIN	0.078	0.436	0.073	0.438	0.079	0.546	0.080	0.755	0.082	0.508
4.8	MAX	0.113	0.629	0.095	0.739	0.108	1.080	0.112	0.799	0.114	0.840
	MEAN	0.091	0.532	0.085	0.589	0.087	0.813	0.100	0.777	0.098	0.674
	MIN	0.097	0.492	0.090	0.668	0.088	0.411	0.099	0.627	0.094	0.785
14.53	MAX	0.144	0.573	0.118	0.787	0.135	0.771	0.134	1.014	0.147	0.866
	MEAN	0.115	0.533	0.105	0.727	0.103	0.591	0.119	0.820	0.114	0.825
	MIN	0.034	0.429	0.061	0.572	0.082	0.606	0.065	0.613	0.073	0.804
32.65	MAX	0.055	0.742	0.111	0.773	0.090	0.871	0.100	0.710	0.099	0.911
	MEAN	0.047	0.585	0.086	0.673	0.085	0.738	0.084	0.662	0.086	0.857
	MIN	0.029	0.313	0.039	0.415	0.049	0.441	0.050	0.542	0.061	0.550
48.11	MAX	0.052	0.409	0.048	0.492	0.062	0.568	0.068	0.563	0.062	0.602
	MEAN	0.039	0.361	0.045	0.454	0.054	0.505	0.057	0.553	0.061	0.576
	MIN	0.039	0.386	0.063	0.437	0.067	0.445	0.069	0.499	0.086	0.524
63.11	MAX	0.053	0.427	0.072	0.568	0.083	0.669	0.097	0.533	0.092	0.591
	MEAN	0.049	0.407	0.068	0.503	0.076	0.557	0.083	0.516	0.089	0.557
	MIN	0.048	0.346	0.083	0.415	0.078	0.443	0.072	0.464	0.089	0.510
78.11	MAX	0.057	0.356	0.089	0.462	0.087	0.567	0.119	0.563	0.092	0.615
	MEAN	0.053	0.351	0.085	0.439	0.083	0.505	0.088	0.513	0.090	0.563
	MIN	0.034	0.289	0.042	0.398	0.054	0.441	0.057	0.467	0.069	0.453
93.11	MAX	0.047	0.334	0.063	0.439	0.060	0.509	0.067	0.579	0.079	0.590
	MEAN	0.041	0.311	0.053	0.419	0.057	0.475	0.064	0.523	0.074	0.522

the ambient acceleration levels at the measurement locations (characterized by the maximum RMS-value of the vertical acceleration) mainly due to the wind and the passing traffic on the highway. These ambient vibrations were recorded for a period of 13 minutes during the operational modal analysis test [3]. Based on Figure 5, it can be concluded that all performed tests generate acceleration levels which are significantly higher than the ambient vibration levels. The measured acceleration level due to the synchronized walking of a group of students is significantly higher (up to a factor of 10) than the vibration level due to free walking. This was of course to be expected but the magnitude of the difference necessitated the replacement of a number of high sensitivity accelerometers by less sensitive ones with a larger amplitude range. For both types of experiments (free and synchronized walking), the highest acceleration levels are mainly observed in the three measurement locations at the short span of the bridge: x = 4.8, 14.53 and 32.65m.

4. PREDICTION OF THE HUMAN-INDUCED VIBRATIONS

This section presents the results of a numerical prediction method for the pedestrian-induced vibrations of the footbridge. More specifically, the vertical vibrations due to the synchronized walking of the groups of 10 and 50 people are predicted and compared with the measurements at the seven locations along the bridge length. Before the discussion of the results, the prediction method is briefly outlined.

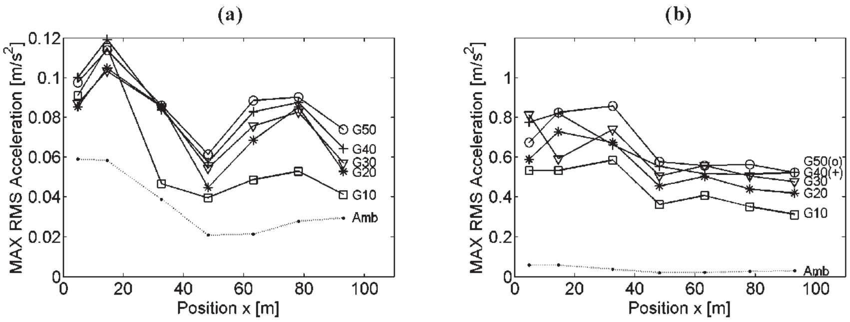

Figure 5. *Maximum RMS-value of the vertical acceleration at the measurement locations during the ing passage of 10 (G10 - □), 20 (G20 - *), 30 (G30 - ▽), 40 (G40 - +) and 50 (G50 - ○) students in the case of (a) free walking and (b) synchronized walking. The ambient vibration levels, derived from a measurement period of 13 minutes, are also indicated (Amb - ●).*

4.1 PREDICTION METHOD

The key elements of the prediction method are explained in the following paragraphs and applied for the case of the footbridge in Wetteren. For the case of the walking of a single person, this method has been experimentally validated for two types of floors [4].

4.1.1 Dynamic behaviour of the footbridge

The numerical predictions presented in this paper, are based on a finite element model which is updated considering as the updating variables the bridge support conditions (modeled by springs in the various directions) and the stiffness of the tension bars connecting the bows and the bridge deck (modeled by a reduction of the Young's modulus). These variables are adjusted to obtain a minimal discrepancy between the modal properties of the model and the experimentally derived modal parameters, which was another objective of the measurement campaign in Wetteren. The results of this updating procedure, for the 5 mode shapes considered in this analysis are presented in Table 2 (from [2]). The results of the updated model agree well with the experimental results. Figure 6 shows the calculated mode shape corresponding to the natural frequency of 3.73Hz. This mode shape exhibits a large deformation at the short span which will prove to be important in the subsequent analysis of the simulations.

Table 2. *Results of the updating procedure: measured natural frequency f_j^m and calculated based on the updated finite element model f_j^c, with the relative error $\varepsilon_j = (f_j^c - f_j^m)/f_j^m$ and the MAC-va value (modal assurance criterion).*

Mode	f_j^m [Hz]	f_j^c [Hz]	ε_j [%]	MAC [-]
1	0.711	0.703	-1.2	0.845
2	1.671	1.653	-1.1	0.891
3	2.191	2.245	2.5	0.979
4	3.743	3.730	-0.3	0.813
5	4.441	4.409	-0.7	0.797

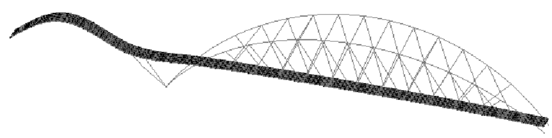

Figure 6. Calculated mode shape at the natural frequency 3.73Hz.

4.1.2 Footfall load

The load model of Willford *et al*. [5,6], developed for the vertical dynamic excitation caused by the walking of a single pedestrian, is used to predict the response generated by the passage of a group of people. The vertical dynamic excitation is characterized as a periodic load due to the repetition of the footfalls and as an impulsive load which develops when the shoe sole touches the floor. These excitations are characterized by load parameters derived from a large set of measurements. The availability of the coefficients of variation for each of the load parameters enables a statistical description by the mean value and the 95% confidence interval. This information will be used in the simulations to assess the influence of the variation of the dynamic walking load on the predicted acceleration level of the footbridge.

4.1.3 Response calculation

The vertical acceleration level of the footbridge during the passage of a group of people is calculated as a summation of the individual contributions of the pedestrians. Each contribution is calculated corresponding to the position of the pedestrian with respect to the output point. For the calculation of a maximum acceleration level in the output point during the passage of the group, the positions of the pedestrians are distributed evenly around the output point. The weight of the walking person, used for the response calculation, corresponds to the average weight of the group of students participating at that specific passage, based on their identification and known weights. The response of the footbridge, due to the walking of each pedestrian, is calculated separately for the periodic load and the impulsive load due to the different nature of the resulting vibrations. A global estimate of the maximum RMS-value of the vertical acceleration is calculated as the square root of the sum of the squared RMS-values due to the periodic and the impulsive load.

4.2 RESULTS

The maximum RMS-value of the vertical acceleration is predicted based on different assumptions made regarding the level of synchronization between the pedestrians and the magnitude of the dynamic walking load generated by each pedestrian. This analysis enables to evaluate the range and the sensitivity of the predicted acceleration level with respect to the assumptions made. The results of these simulations are presented in Figure 7 for two measurement locations x=14.53m, situated at the short span of the bridge, and x=78.11m, situated at the long span of the bridge, and for the groups of 10 and 50 people.

The first set of predictions is based on the assumption of perfect synchronization between the pedestrians (implying all pedestrians of the group walking at an identical step frequency), for step frequencies varying from 1.8 to 2Hz, selected around the frequency of the recorded metronome signal used for the experiments. This condition of perfect synchronization is combined with three different assumptions for the magnitude of the dynamic walking load. From the mean values and the coefficients of variation,

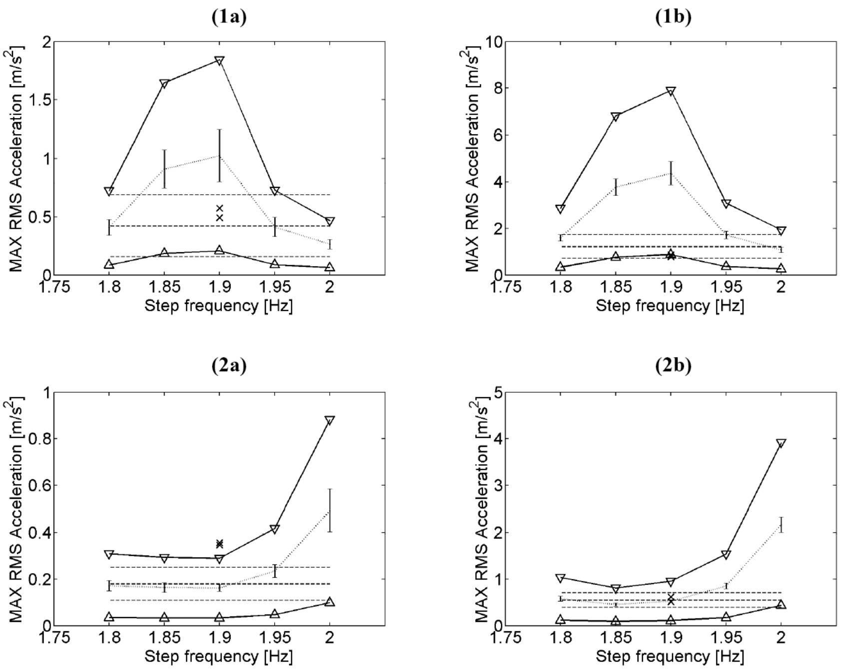

Figure 7. Maximum RMS-value of the vertical acceleration at the measurement locations (1) x=14.53m and (2) x=78.11m for the synchronized walking experiments of groups of (a) 10 studen students and (b) 50 ts students: measured values (×) and predicted results, based on the assumption of perfect synchronization at) the step frequencies 1.8-2Hz in combination with the upper (▽) - lower (△) limit walking load and the random walking load (95 % confidence interval represented by the vertical lines and mean values connected by dotted line) and based on the assumption of a normal distribution of the step frequencies in combination with the random walking load (mean value: ---- and 95% confidence interval: ----).

available for each load parameter [5, 6], it is possible to derive a walking load corresponding to the upper and lower limits of the 95% confidence interval of the load parameters (denoted in the following as the upper and lower limit walking load) or to derive a random walking load in which for each pedestrian the loading parameters correspond to a set of random numbers chosen from the corresponding normal distributions. The predicted results for this case of perfect synchronization are presented in Figure 7: at each step frequency two markers represent the lower and upper limit of the RMS-value of the acceleration calculated with the lower and upper limit walking load respectively and the vertical line represents a 95% confidence interval of the RMS-value derived from the statistical analysis of the results of a large number of simulations with the random walking load. The mean values in the case of the random walking load are connected with the dotted lines.

The second set of predictions is based on the assumption that the step frequencies of the group of walking pedestrians follow a normal distribution, in combination with the random walking load. Therefore, a large number of simulations have been carried out with sets of random numbers characterizing the step frequencies and the load parameters chosen from the corresponding normal distributions. The statistical analysis of these results determines a mean value and a 95% confidence interval of the maximum RMS-value of the acceleration which is presented in Figure 7 by the three horizontal dashed lines over the investigated frequency range. These results are based on a normal distribution of the step frequencies with a mean value equal to 1.95Hz and a small value of the standard deviation equal to 0.075Hz, resulting in a 95% confidence interval of 1.8-2.1Hz. The choice of these parameters will be explained in the section devoted to the comparison of the measured and the predicted results. These results will be referred to in the following of the text as the case with a random step frequency and walking load.

The results for the case of perfect synchronization clearly illustrate that the predicted acceleration level in this case is very sensitive to the value of the step frequency. For x=14.53m, situated at the short span of the bridge, the peak in the acceleration level at the step frequency 1.9Hz apparent in Figure 7(1a,1b) can be explained by the resonance condition occurring when the loading frequency of the second harmonic of the periodic load coincides with the natural frequency of the footbridge equal to 3.73 Hz (Table 2). The mode shape corresponding to this natural frequency exhibits a large deformation of the short span as shown in Figure 6. A lack of synchronization has an important influence on the predicted maximum RMS-value of the vertical acceleration as can be observed from the level difference between the predicted RMS-value for perfect synchronization at 1.95Hz (mean value) and the RMS-value for the case of a normal distribution of the step frequencies with a mean value equal to 1.95Hz (Figure 7).

4.3 PREDICTED VERSUS EXPERIMENTAL RESULTS

Together with the presentation of the predicted results in Figure 7, the measured maximum RMS-values of the vertical acceleration for the two passages of the group are also presented, as ‘x’ at the metronome frequency equal to 1.9Hz. The comparison between the measurements and the predictions is discussed first for the group of 10 people. For the two measurement locations, presented in Figure 7, the position of the measured value with

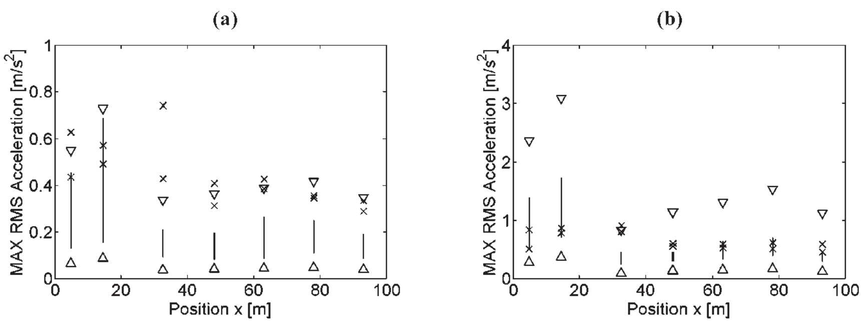

Figure 8. Maximum RMS-value of the vertical acceleration at the measurement locations along the bridge length for the synchronized walking experiments of groups of (a) 10 students and (b) 50 students: measured values (×) and predicted results, based on the assumpt assumption of perfect synchronization at the step ion frequency of 1.95Hz in combination with the upper (▽) and the lower (△) limit walking load and based on the assumption of a normal distribution of the step frequencies in combination with the random walking load (solid vertical lines represent the 95% confidence interval).

respect to the predicted values is different. For x=14.53m, the measured values fall within the confidence interval predicted for the case with a random step frequency and walking load while for x=78.11m, the measured values are well out of this range and correspond more to the level predicted for the case of perfect synchronization at a step frequency of 1.95Hz combined with the upper limit walking load. For a clearer view on the correspondence between the measurements and the predictions, the measured maximum RMS-values of the acceleration for all seven measurement locations are presented in Figure 8, together with the predicted results for the case of perfect synchronization at a step frequency of 1.95 Hz in combination with the lower and upper limit walking load and for the case with a random step frequency and walking load, for which the 95% confidence interval of the response is represented by the vertical line. Figure 8(a) clearly demonstrates that for the group of 10 people, the measured response can be predicted based on the assumption of perfect synchronization at the step frequency of 1.95Hz in combination with the upper limit walking load. The largest deviation occurs at the measurement location x=32.65m, but the large difference between the two measured values may indicate some unexplained irregularities encountered during the measurements. The value of 1.95Hz of the step frequency is slightly higher than the imposed frequency of 1.9Hz by the recorded metronome signal, but seems to be confirmed by inspecting the power spectral density function of the vertical acceleration at x=14.53m presented in Figure 9. The high value of the dynamic walking load can be explained by the military style of walking, adopted by the students as apparent from the recorded images.

A more detailed comparison between the measured and the predicted results is made in the next paragraphs. Figure 10(1) shows the time history (a) and the power spectral density (b) of the measured vertical acceleration at the position x=14.53m (situated at the short span), caused by the synchronized walking of a group of 10 students for one selected passage during the time period when the maximum response was observed (18-22s). This response is clearly dominated by a low frequency peak situated around 3.8Hz. The predicted acceleration, presented in Figure 10(2) shows a good agreement with the measured acceleration both in the time and the frequency domain where a similar low frequency peak can

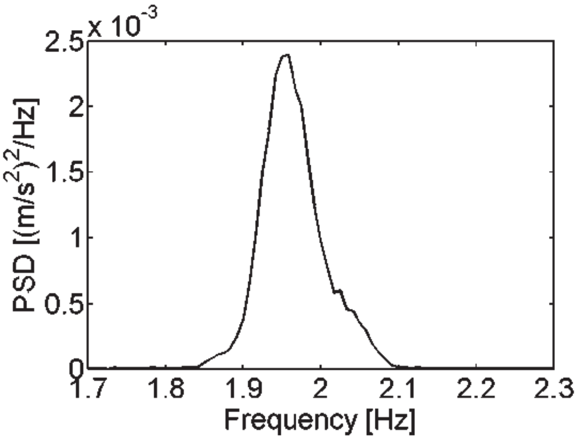

Figure 9. Power spectral density of the vertical acceleration of the bridge deck at the position x=14.53m, during the synchronized walking experiments wi with a group of 10 students: zoom of the frequency range from 1.7 to 2.3Hz.

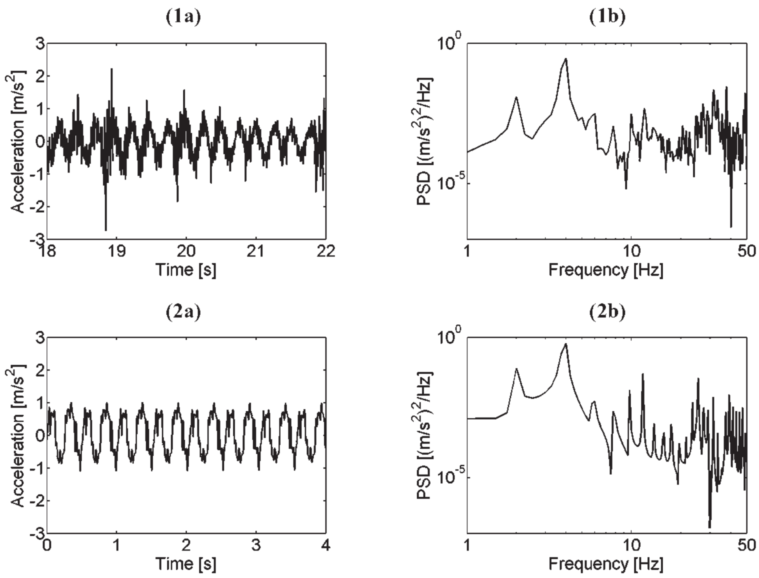

Figure 10. Vertical acceleration of the bridge deck at the position x=14.53m, caused by the synchronized walking of 10 students: (1a) Measured time history a and (1b) power spectral density of a selected time nd period (18-22s); (2a) Predicted time history and (2b) power spectral density at a walking frequency of 1.95Hz.

be detected. Figure 11(1) shows the time history (a) and the power spectral density (b) of the measured vertical acceleration at the position x=78.11m (situated at the long span), caused by the synchronized walking of a group of 10 students for one selected passage during the time period when the maximum response was observed (76-80s). For this position, the power spectrum of the acceleration in the low frequency range (< 11Hz) indicates very low values in contrast with the observations made for the position at the short span. The power spectrum of Figure 11(1b) can be characterized by a series of peaks starting at about 15Hz. Very similar results, both for the time history and the power spectrum, are obtained by the numerical prediction method for this measurement location as apparent from Figure 11(2a) and (2b). The results indicate that this response is caused by the impulsive load, present in the dynamic walking excitation, giving raise to a series of transients. The specific nature of the vibrations, which is clearly different for the two investigated positions, seems to be correctly predicted by the model.

For a group of 50 people, the agreement between the measured and the predicted maximum RMS-values of the vertical acceleration can be observed from the Figures 7(1b,2b) and 8(b). For this case, the majority of the measured values fall within the 95% confidence interval derived from the statistical analysis of the responses predicted with a random distribution of the step frequencies and the random walking load. The difficulty to obtain perfect synchronization with this large group of students with no training in this field can explain the variation of the step frequency within the group. As apparent from the simulations, this condition has a large influence on the acceleration level of the bridge.

Concluding, for both group sizes a fair agreement between the measured and the predicted maximum RMS-values of the vertical acceleration along the bridge length can be obtained, taking into account the specific conditions occurring during the measurements.

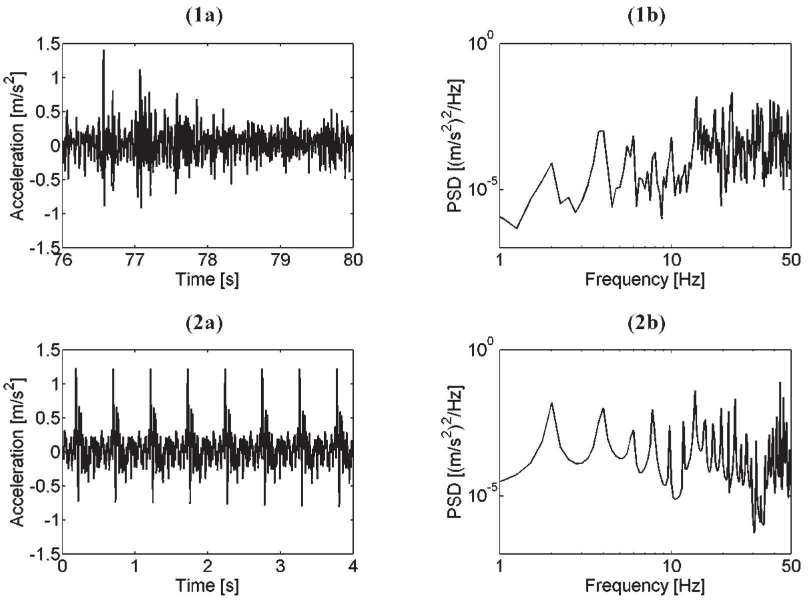

Figure 11. *Vertical acceleration of the bridge deck at the position x=78.11m, caused by the sync synchronized walking of 10 students students: (1a) Measured time history and (1b) power spectral density of a selected time period (18-22s); (2a) Predicted time history and (2b) power spectral density at a walking frequency of 1.95Hz.*

5. CONCLUSIONS

The vertical acceleration levels of a steel footbridge have been measured and analyzed during the synchronized and the free walking of groups of 10, 20, 30, 40 up to 50 people. The predictions of the vertical acceleration level have been made based on an updated finite element model of the bridge. The response at a measurement location is predicted as a superposition of the contributions of each pedestrian corresponding to their position with respect to the output point. The individual contribution is calculated using a load model which takes into account the periodic load and the impulsive load present in the dynamic walking excitation. Based on the results of the simulations, it can be concluded that the response of the footbridge, caused by the group of walking people, is sensitive to the assumptions made regarding the level of synchronization between the pedestrians and the magnitude of the dynamic load generated by each pedestrian, which can be varied corresponding to the statistical parameters available in literature.

For the synchronized walking experiments, a comparison is made between the measurements and the predictions for the two extreme values of the group size: 10 and 50 people. For the group of 10 people, the recorded images demonstrate a high level of synchronization between the pedestrians and a military style of walking giving raise to high values of the dynamic walking excitation. Considering these measurement conditions, a fair agreement is found between the measured and predicted results for all seven measurement locations along the bridge length, assuming all pedestrians walking at an identical step frequency and the magnitude of the walking load corresponding to the upper limit of the 95% confidence interval as derived from the statistical characterization. For the group of 50 people, it was observed during the experiments that it is very difficult to achieve perfect synchronization with a group of students without any training in this field. This measurement condition was taking into account in the simulations by considering a normal distribution of the step frequencies within the group combined with a normal distributions of the load parameters describing the walking load. A mean value and a 95% confidence interval for the RMS-value of the vertical acceleration is then derived from a large number of simulations with sets of random numbers characterizing the step frequencies and the load parameters. From this analysis, it was found that the majority of the measured values fall within the predicted confidence interval.

As a general conclusion, the results demonstrate that the prediction model is capable of predicting the correct order of magnitude of the vertical acceleration levels observed during the experiments when the specific measurement conditions are taken into account. It is important that the relevant codes stipulate which conditions need to be considered in the design of structures subjected to human-induced vibrations. Based on the presented results, it can be assumed that the prediction model used in this study is sufficiently accurate for design purposes.

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NEW YORK HITS NOISY MOTOR BIKES

In an effort to reduce motorcycle noise, New York City Council is considering a law requiring all motorcycles to display tags certifying approval by the Environmental Protection Agency. Without the tag, police can issue a ticket without having to prove the motorcycle exceeded the 80-decibel limit set by the city's noise code. The first conviction carries a maximum fine of $1000 and temporary confiscation of the motorcycle until the penalty is paid. The second conviction increases the fine to a maximum amount of $2500 and imposes permanent forfeiture of the bike. Tickets can be issued not only with bikers being pulled over but also when the motorcycle is parked, with city agents as well as police allowed to issue the proposed citations. The bill is based on a similar law enacted in Denver.