Vibration Control of Pedestrian Footbridges

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ABSTRACT

Single arch bridges with pedestrian walkways spans of 50-200m have very low natural frequencies that are in the range 1-4Hz.

As those natural frequencies can potentially coincide with marching or walking step pacing frequencies, particularly for the case of large crowds, the control of pedestrian bridge vibration response is often essential particularly if there are lateral modes such as that occurred at the Millenium Bridge in London.

For a new pedestrian bridge in Melbourne, the response of a new dramatic design single span bridge was modelled and the expected response to crowds of up to 900 walking persons was predicted.

The modelling technique was validated by field tests on an existing timber pedestrian bridge. The results enabled appropriate vibration control to be specified and selected. Following completion of the bridge construction, dynamic testing was undertaken that included a Tuned Vibration Absorber (TVA) that was designed from the model study. Also, studies of the effect of crowd size on the bridge response, the possible effect of lateral motion synchronization with crowd movement and the criterion for vibration acceptance were related. These studies then enabled the TVA to be tuned and operated to restrict the bridge vibration amplitudes to a criterion value at peak pedestrian loads.

INTRODUCTION

This paper discusses pedestrian footfall excitation of footbridges and how the use of finite element modelling studies examines the effect pedestrian dynamic forces have on the bridge's vibration response. This method was used to determine the dynamic response of a footbridge at Docklands, Melbourne, and this paper gives insight into the selection and specification of a tuned mass vibration absorber to reduce vibration amplitudes.

A pedestrian bridge is susceptible to excessive vibration if its natural frequency is close to or coincides with the fundamental or harmonics of the pedestrian walking frequencies. It is therefore important to conduct a natural frequency analysis on any proposed bridge with low natural frequencies below 6Hz. If the probability of natural frequency coincidence with pedestrian footfall harmonics is high then further dynamic analysis is usually required.

To ensure reliability and accuracy of the modelling technique, a preliminary FEM model was created to predict the natural frequency of an existing bridge at Kew, Victoria. Field measurements were then performed with actual pedestrian pacing excitation to measure the bridge amplitude response and the bridge natural frequencies. These measurements were found to agree well with the FEM modelling technique and hence the accuracy of the finite element method for prediction purposes was confirmed to our satisfaction.

Another finite element model was created for the new Melbourne Convention Centre bridge, across the Yarra river, at the Docklands (MCCD) and from the FEM natural frequencies within the range of typical pedestrian footfall harmonics were identified (see Figure 1 for elevation view of the MCCD bridge). The finite element model was used to perform dynamic analysis to determine whether or not TVA was required.

PROJECT BACKGROUND

The motivation for this study arose from the experiences of other bridges including the Millennium Bridge, London where the reasons for severe vibration behaviour has been extensively studied and documented [1, 3]. The Millennium Bridge (Figure 2) was designed as an icon for London and was opened as a celebration of the new Millennium (2000), therefore its design was highly influenced by aesthetics. These aesthetic attributes created a problem under certain loading, walking, conditions which caused closure of the bridge as a result of excessive lateral vibration within a few days of opening.

Figure 1- View of Completed Bridge

Figure 2 – The Millennium Bridge, London

The major reason for the vibrational motion at the Millennium Bridge was the "synchronization" of footfall with the bridge lateral mode of vibration. This occurs when large numbers of pedestrians walk across a bridge in step (bridge lateral motion causes the pedestrians to fall into step). Excessive vibration occurred at the Millennium Bridge because the bridge's lateral mode frequency was close to that of the pedestrian lateral stepping movement frequency. To avoid such problems at MCCD it was essential that the behaviour of the new bridge across the Yarra River be understood. If the bridge was likely to have natural frequencies close to that of the pedestrian movement frequencies then vibration mitigation measures may be required if the response was excessive.

PROJECT DESCRIPTION

The MCCD Design Brief for the pedestrian bridge over the Yarra River required the following:

- Maximum density 1.5 persons/m^2 at an average of 0.75kN weight per person.
- Maximum dynamic vertical footfall load ± 33% of static load, corresponding to 0.25kN at 1.5Hz (the fundamental of the pacing frequency).
- Maximum lateral footfall load 10% of dynamic footfall load, corresponding to 0.025kN at 0.75Hz.
- For design, the number of people walking in phase with each other in any area is 1.645N$^{0.5}$, where N is the number of people on the bridge

Given the bridge dimensions with a length of 90m, span of 8m, with an expected load of 1,080 people walking randomly, the required design in phase load is 54 persons.

DESIGN REQUIREMENTS

Marshall Day Acoustics nominated the following performance criteria:

- Maximum permissible vertical acceleration 0.6m/s^2 RMS
- Damping ratio 6% of critical
- In phase people load 54
- Dynamic load per person 0.25kN
- Compliance with Clause 12 of AS5100.2-2004.

PRELIMINARY TESTING

As advised, a preliminary study was conducted on Kanes Bridge, Kew, Victoria to validate the prediction model accuracy. The results of the typical vibration amplitudes are presented in Figure 3. A picture of Kanes Bridge is provided in Figure 4.

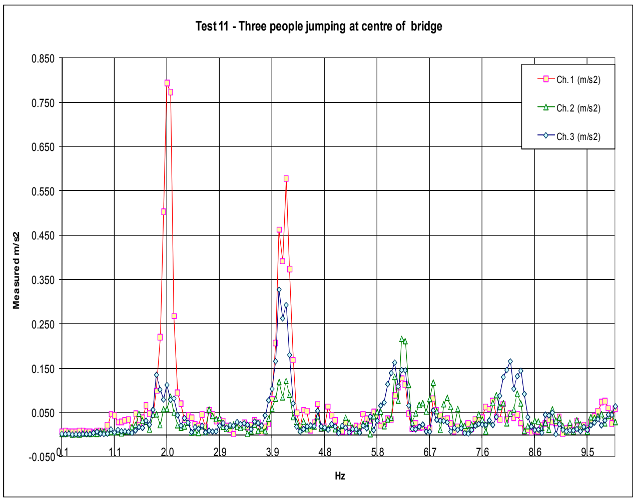

Figure 3 - Measured vibration amplitudes at centre of Kanes Bridge, Kew from spectral 3 people jumping at 2Hz frequency mid span

The vertical and horizontal modes of vibration and their amplitudes were found to correlate well with the Finite Element Model within the expected accuracy of 10-20%.

Figure 4 - View of Kane's Bridge, Kew Victoria

BRIDGE DYNAMICS

The span of a bridge is the dominant factor in determining the fundamental natural frequency. There is a simple generalised formula which may be used to obtain a rough estimate of the first natural frequency of a bridge (L = span, m).

$$f_1 = 33.6 \cdot L^{-0.73}$$

By plotting this function we can see that as the span of a bridge increases beyond 25m, there is only marginal decrease in its natural frequency, see Figure 5. As the walking frequency for a fast walk is approximately 2 Hz, the likelihood of problems arising is greatest when a bridge span exceeds 25m, and especially when the span is in the range 60-100m.

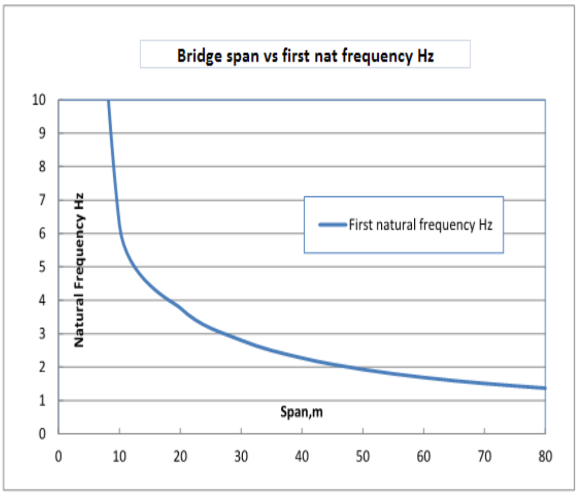

Figure 5 – The relationship between bridge span and the fundamental natural frequency

The material properties of a bridge can also affect the vibration response. A bridge of high stiffness will be more difficult to excite than a bridge of lower stiffness. For example, a steel bridge would usually have greater vibration amplitudes than a concrete bridge due to a lower value of internal damping. In addition, the bridge damping will determine the duration of the decay of the bridge to following any excitation (and hence the comfort for any pedestrians on the bridge) as it responds.

The average walking frequency of people can be modelled as a normal distribution with a mean walking rate of 2 Hz with a standard deviation of 0.173 Hz. Any undesirable response occurring as a result of resonance will require additional damping. However, some consideration of uncertainty is required as the behaviour of pedestrians on footbridges is variable and the dominant characteristics are:

- Walking rate
- Step length
- Step force and direction
- No. of persons walking in phase.

MODELLING SCENARIOS

The results of the MCCD bridge FE modelling are presented in Table 1 and Figures 6 & 7 attached. As Figure 5 indicates bending modes normally dominate the bridge vibration below 2Hz. In the case of this bridge, dampers for bending modes 1 and 2 should be tuned for 1.6Hz and 2.3Hz respectively.

A twisting mode such as the one at 1.6-1.8Hz may also be significant. Vibration dampers located mid span and on each side can be designed to attenuate both bending and twisting modes by installing at the position of maximum displacement at the bridge mid span.

In circumstances where large discrepancies exist between modelled or theoretical results, preliminary vibration testing of the partially completed bridge is recommended to tune the FEM model and confirm the actual modes for specification of any dampers that may be required.

Table 1 MDA FEM Modelling and check comparison results

Mode	MDA FEM results		Check results	
	Natural frequency	**Mode shape**	**Natural Frequency**	**Mode shape**
1	1.47	Twist	1.56	Bending
2	1.79	Bending	1.83	Twist
3	2.39	Bending	2.23	Bending
4	2.45	Twist	2.37	Bending
5	2.55	Twist	2.55	Bending

The variation in the results show that, depending on the method of constructing the model and the elements employed, some modes are more readily identified than others. In the case of the Millennium bridge, this could explain why the lateral mode was not identified or considered to be critical at the design stage.

VIBRATION PREDICTIONS

Items 1, 2 & 3 in Table 2 are dampers that were selected to be located at the centre of the bridge (L/2) below the centreline of the pedestrian walkway. Damper 4 could be supplied in two parts each half located at L/4. Item 3 which controls torsion were proposed to be supplied in 2 parts (each 1.5 x 104kgs) located at the bridge extremities.

Table 2 MCCD Bridge TVA Specification

Mode (direction)	**Tuned Frequency (Hz)**	**Qty**	**Damper Mass (kg)**	**Damper spring stiffness (kN/m)**	**Damping (Ns/m)**	**TVA mass displacement (mm)**
						Operational
1 (trans)	2.0	1	203	33	100	±35
2 (vert)	1.5	1	6.730	595	15,800	±15
3 (twist)*	1.8	1	$3.0x\ 10^4$ (kgm^2)	3.8×10^6 (Nm/rad)	$6.0x\ 10^4$ (Nm/rad)	±0.01 radian
4 (vert)	2.6	2	274	70	184	±40

frequency of 1.3Hz was installed at the bridge mid span, supplied in two halves, used to control vertical mode bending and twisting. It was decided that if further problems arose the additional dampers could be retro-fitted if necessary.

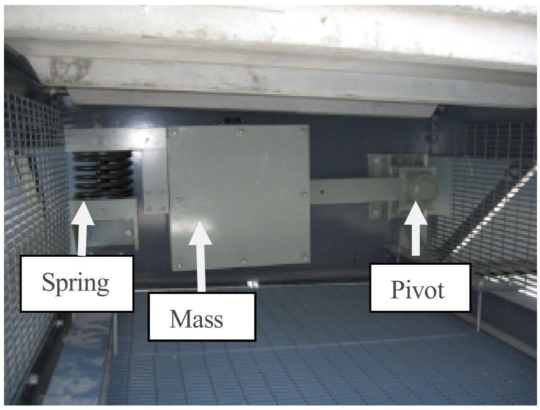

Figure 6 - Installed TVA showing spring, mass elements

MEASURED RESULTS

The commissioning tests conducted at the MCCD pedestrian bridge indicated the following vibration results as given in Table 3. Tests were conducted with groups of 6, 12 and 24 persons walking in phase, with the 1.3Hz damper operating and disabled (no motion).

Table 3 Measured vibration levels on MCCD bridge from pedestrians walking in phase (m/s^2)

Test Condition	North -south motion			South-north motion		
	6 People	**12 people**	**24 people**	**6 people**	**12 people**	**24 People**
Dampers On (free)	0.16	0.17	0.47	0.14	0.06	0.28
Dampers off (retrained)	0.11	0.11	0.20	0.08	0.09	0.10

As the tests with a crowd of only 24 persons indicated the criterion (0.6m/s^2) could potentially have been exceeded with a larger crowd, we investigated the predictions for the larger crowd size walking in phase, for the average and maximum acceleration scenarios.

The predictions were conducted in several ways using the loading factor in Section 3.0 (1.645N$^{0.5}$) or by extrapolating the test results for 6, 12 or 24 persons to determine the expected response for larger crowds.

Using the average of the N-S and S-N walking direction results for 24 persons with the TVA switched off (restrained) scenario, (0.15m/s^2) we predicted the average bridge vibration level with 54 persons would be between 0.42 - 0.49 m/s^2 depending on the extrapolation method chosen. Given that the maximum vibration is up to 30% higher than the average then the predicted full load case would also increase by the same margin. Accordingly, there was some risk that the project vibration criterion of 0.6 m/s^2 might have been exceeded under full load conditions with 1,080 people on the bridge.

As a result, the TVAs were retuned as noted below and the response tests repeated.

CONCLUSION

Table 3 shows that the least vibration occurred when the dampers were turned off or disabled, (i.e. chocked). The variation in results occurred to some degree owing to the difficulty in keeping the test subject walking consistently in phase. Since the dampers were originally tuned to 1.3Hz and the first mode of vibration was at 1.6Hz, the dampers initially made the bridge vibration response worse rather than better. As there was a likelihood that the vibration criteria could be exceeded with the 1.3Hz dampers either on or off, the dampers were adjusted and tuned to 1.6Hz to perform as designed and compliance with the nominated brief was achieved.

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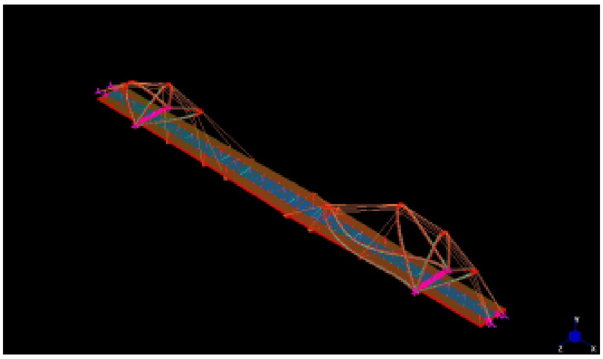

Figure 7 - Mode 1 - 1.47Hz

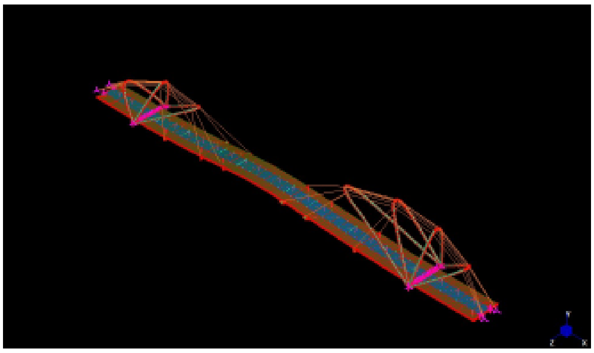

Figure 8 - FEM Mode 2 deflection shape - 1.79Hz

Figure 9 - In situ test setup

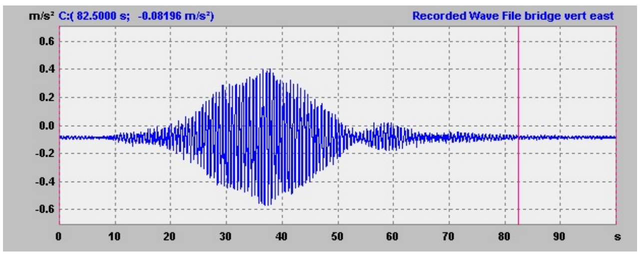

Figure 10 - Samples time trace from mid span of bridge due to 24 people walking across the bridge at 1.6Hz pacing speed