EVALUATION OF THE STRUCTURAL HEALTH AND CONDITION FOR FUTURE MODIFICATIONS AND ENHANCEMENT OF LIFE CYCLE OF A STEEL BRIDGE IN MEXICO BASED ON THE EVOLUTION OF ITS DYNAMIC PROPERTIES

O. García D
Facultad de Ingeniería, UNAM, México

A.G. Ayala M
Instituto de Ingeniería, UNAM, México

S. López
Instituto de Ingeniería, UNAM, México

F. Bassolo
Ayesa México S.A. de C.V., México

The "Fernando Espinoza" bridge is located in northwest Mexico over the "Oblatos gorge", 130 m above the Santiago River, at Kilometer 11, of the Guadalajara-Zapotlanejo toll road. Its structure, currently the biggest steel frame in the country, has a 306 m span supported by 4 diagonal columns with a 45º inclination, which, alongside the central segment of 110 m, conform a rigid frame with two supports: one pinned and the other with unrestricted horizontal displacement. The bridge has an estimated weight of 2400 ton.

Due to its lightness and flexibility, the bridge has not an adequate performance neither for service nor for the significant wind pressures acting continuously on the site, presenting huge deflexions and strong vibrations which affect the safety and comfort of users. As a part of a recent national bridge program in which the most important bridges in the country were studied, a experimental study was performed in order to estimate the dynamic properties of the bridge, and, from these, develop and calibrate its structural model for the purpose of evaluating in detail the bridge behavior due to the static and dynamic demands for which it is subjected and the changes in this behavior associated to possible modifications in its service conditions.

The current study involved the execution of two measurement test campaigns. The first measurement campaign was carried out in 2001, starting with a dynamic test of ambient vibration caused by vehicular flow and wind pressures. Furthermore, a controlled passage test was done with a T3-S3 vehicle with the dimensions and weight specified by the mexican official normativity, in order to calculate the impact coefficient. The second measurement campaign was performed in 2010, and once again the vibration measurements due to similar load scenarios were recorded.

From the information obtained in the measurement campaign, the most relevant structural properties were determined: natural period, modal shapes and damping; that

were used to build a computer model in the SAP2000 program to estimate the bridge behavior for the demands for which it is subjected and also compare the change in vibration response throughout the time the two measurements were performed, for the purpose of conceiving a rehabilitation strategy and adequate maintenance programs. Some advice in this manner is also given in this text.

posgradoingcivil@cancun.fi-a.unam.mx

gayalam@iingen.unam.mx

fbasolo@ayesa.es

EVALUATION OF THE STRUCTURAL HEALTH AND CONDITION FOR FUTURE MODIFICATIONS AND ENHANCEMENT OF LIFE CYCLE OF A STEEL BRIDGE IN MEXICO BASED ON THE EVOLUTION OF ITS DYNAMIC PROPERTIES

O. García D
Facultad de Ingeniería, UNAM, México

A.G. Ayala M
Instituto de Ingeniería, UNAM, México

S. López
Instituto de Ingeniería, UNAM, México

F. Bassolo
Ayesa México S.A. de C.V., México

ABSTRACT: This paper presents a general description of the "Fernando Espinoza" bridge structure, the seismic instrumentation employed, the methodology and the measurements program aimed to the identification of the dynamic properties of the structural system. From the information obtained in the measurement campaign, the most relevant dynamic properties were determined: natural periods, modal shapes and damping ratios; all necessary to build a computer model in an analysis program used to estimate the bridge behaviour under current and future demands to which it may be subjected and also to compare the change in dynamic properties between the two measurement campaigns performed in 2001-2010, for the purpose of defining a rehabilitation strategy and adequate maintenance programs. For these particular matters some guidelines and recommendations are given.

1 BACKGROUND

The "Fernando Espinoza" bridge, fig.1, is located in west Mexico over the "Barranca de Oblatos" gorge, 130 m above the Santiago River, at Kilometer 11 of the Guadalajara-Zapotlanejo highway. This bridge, considered one of the most important of the federal highway system and the biggest steel frame in the country, has a 300 m span supported by 4 diagonal columns with a 45º inclination, which, together with the central segment of 110 m, form a rigid frame with two supports: one pinned and the other with unrestricted horizontal displacement. Both, columns and beams supporting the deck, are laterally braced by truss elements. The bridge has an estimated weight of 2400 ton.

Due to the lightness and flexibility of its structure, the bridge has huge deformations and strong vibrations under vehicle traffic, which are thought to be pathogenous to its serviceability and ultimately to its structural health. For this reason, and as a part of a federal bridge program in which the most important bridges in the country were evaluated, a first experimental study aimed to the determination of the dynamic

properties of the bridge was performed 9 years ago, and, from these, develop and calibrate its structural model for the purpose of evaluating in detail the bridge performance under both static and dynamic demands.

Figure 1. Fernando Espinoza bridge.

This paper presents the results of a new vibration measurement campaign aimed to the identification of the current dynamic properties of the Fernando Espinoza bridge, necessary to investigate its present structural condition. For this purpose a structural model of the bridge was constructed, matching the dynamic properties obtained from the measurement campaign. To identify the changes in structural behaviour during the time elapsed between the first and this measurement campaigns a comparison of the corresponding dynamic properties was carried out.

2 EXPERIMENTAL DETERMINATION OF THE DYNAMIC PROPERTIES

It is generally recognized that the results derived from measurement campaigns allow the determination of realistic dynamic properties of an existing structure, which is not generally possible to do with any known analytical approach, mainly due to numerous uncertainties attached to the properties of the structural elements, their condition and the mass of the system which are the aspects that define its dynamic response and, ultimately, its performance under design conditions. For this reason, it is essential to perform site vibration measurements to evaluate, in a reliable manner, the characteristics of existent structures.

In general, the dynamic properties obtained from measurement campaigns are: 1) the periods or frequencies of vibration; 2) the corresponding modal shapes; and 3) the modal damping ratios. These properties are obtained by measuring the vibration of the structures subjected to actual demands. Considering that the most important source of excitation under operational conditions of bridge structures is vehicle traffic, it is essential to evaluate their dynamic properties under this condition.

2.1.1 Characteristics of the measurement equipment

For both measurement campaigns, the vibration signals were obtained using Terra Technology accelerometers. These instruments register accelerations in three orthogonal directions (two horizontal and one vertical), calibrated to a 2.0g maximum acceleration level and able to cover a range of accelerations spanning from those characteristic of ambient vibrations to those of severe ground motions such as earthquakes. Previous works have shown that these instruments are well suited to record the low amplitude vibrations caused by sources such as vehicle transit, wind action, miscellaneous equipment operation, etc.

2.1.2 Design of the recording strategy

The adequate definition of the measurement spots in a structure allows for correct identification of its properties, thus, in these campaigns special attention was placed on the in the selection of these spots partly based on the experience acquired from the numerous measurement campaigns carried on by the authors of this article and on the results of a preliminary model of the structure constructed to understand its behaviour. The results of the first measurement campaign of the Fernando Espinoza Bridge were particularly useful in the definition of the strategy to follow in the second campaign. In this campaign, for the identification of the dynamic properties associated to the vertical, longitudinal and transversal modes of vibration of the bridge, 4 measurement arrays were designed involving fourteen measurement spots, distributed in the thirds and halves of the three spans.

In array No 1, fig. 2, 5 measurement instruments were used, placing 2 on the thirds of span L1 (instruments identified as 4 and 6), 2 on the thirds of span L2 (instruments 1 and 2) and instrument 3 over the left column (column 1). This distribution allowed the identification of not only the dominant modes, but also other higher modes. Arragement No 2 involved three instruments; instrument 2 was placed on the halve of the left span, instrument 4 on the halve of the central span, and instrument 3 over column 1. The purpose of this array was to identify the dominant modes associated to the transversal and vertical directions. The location of instrument 3 on arrays 1 and 2 was chosen to trigger the other instruments for the synchronous recording of the signals. Array No 3 consisted of 11 measurement points placed in the halves and thirds of the three spans, and an independent instrument with the highest resolution (instrument 6). This array was defined to validate the results obtained from arrays No 1 and No 2. Array No 4, fig. 3, was used to identify the frequencies associated to torsional modes in the 3 spans. For this purpose, two instruments were placed on the halves of each span; one on the central curb and the other in the parapet.

2.1.3 Recording of acceleration vs. time signals

For this study, signal samples, 5 to 10 minute duration, were obtained from each instrument. These signals were stored in the solid state memory of the instruments and subsequently transferred to a computer for its analysis and processing.

2.1.4 Signal processing

The dynamic properties of the bridge under study were obtained using the theory of signal analysis in the frequency domain. This theory is based on the original concept of the Fourier transform given by Eq.1 and in particular using the discrete version of it.

$$x(t) = \int_{-\infty}^{\infty} F(f) e^{j2\pi f t} df \qquad F(f) = \int_{-\infty}^{\infty} x(s) e^{-j2\pi f s} ds$$

(1)

where x(t) is the given time signal and F(*f*) is its corresponding Fourier transform in the frequency domain. In structural system measurements, the signal x(t) is obtained by converting the analog signals recorded by the instruments digital format. Hence, the calculation of the Fourier Transform is carried on in a discrete form over a given duration.

The analysis of the signals obtained in this study was executed with a virtual spectrum analyzer developed by the authors in LABVIEW (Laboratory Virtual Instrument Engineering Workbench). This system is a representative tool of the state of the art of signal analysis and has been repeatedly used and validated in identification projects for bridges and buildings, amongst other types of structures.

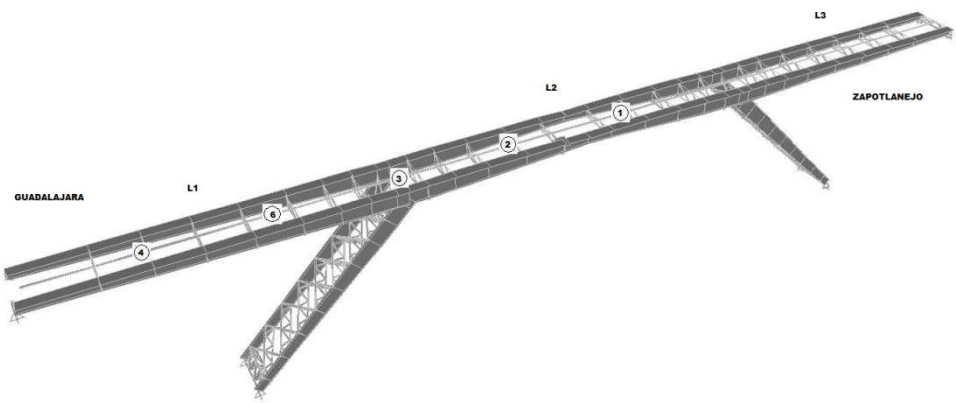


Figure 2. Equipment array No 1

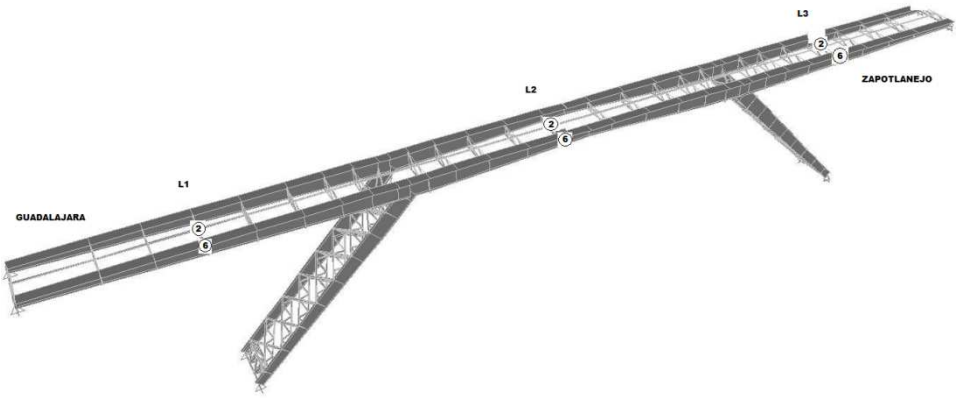


Figure 3. Equipment array No 4

2.1.5 Dynamic Properties

From the analysis of the signals obtained, fig. 4, it was found that the response of the bridge is defined by two dominant modes in vertical bending, two in transversal bending and one in longitudinal torsion, fig.5. The modes in vertical bending have frequencies in the range of 0.96 to 0.99 Hz, for modes associated to the deformation of the central

span, and 1.25 Hz for a mode corresponding to the deformation of the edge spans; the modes in transversal bending, are associated to frequencies of 0.68 Hz (2001) and 0.74 Hz (2010), which corresponds to the fundamental mode, and 1.56 Hz. The torsional mode of the bridge has a frequency of 2.34 Hz.

Table 1 shows the frequencies obtained from the spectral analyses of the signals and the correlation between them corresponding to the arrays of the measurement equipment.

The calculation of the damping ratios was performed with the method of Kawasumi & Shima (1965), based on the use of amplitudes of a clearly defined power spectrum, with good resolution and assuming white noise conditions. Table 2 shows the average values of damping ratios associated to the first identified frequencies of modes in the vertical, transversal and torsional directions.

Table 1. Vertical, transversal and torsional vibration frequencies obtained in 2001 and 2010

Mode	Type	Experimental Frequency(Hz) year 2001	Experimental Frequency(Hz) year 2010	Theoretical Frequency (Hz) year 2001
1	Transversal bending	0.680	0.72-0.74	0.689
2	Vertical bending, central span	0.980	0.96-0.99	1.000
3	Vertical bending, edge spans	1.270	1.24	1.23
4	Transversal bending	1.560	1.560	1.49
5	Vertical bending in 3 spans	1.610	1.62	1.563
6	Vertical-longitudinal bending	2.290	2.24	2.17
7	Transversal-torsional bending	2.490	2.34	2.44

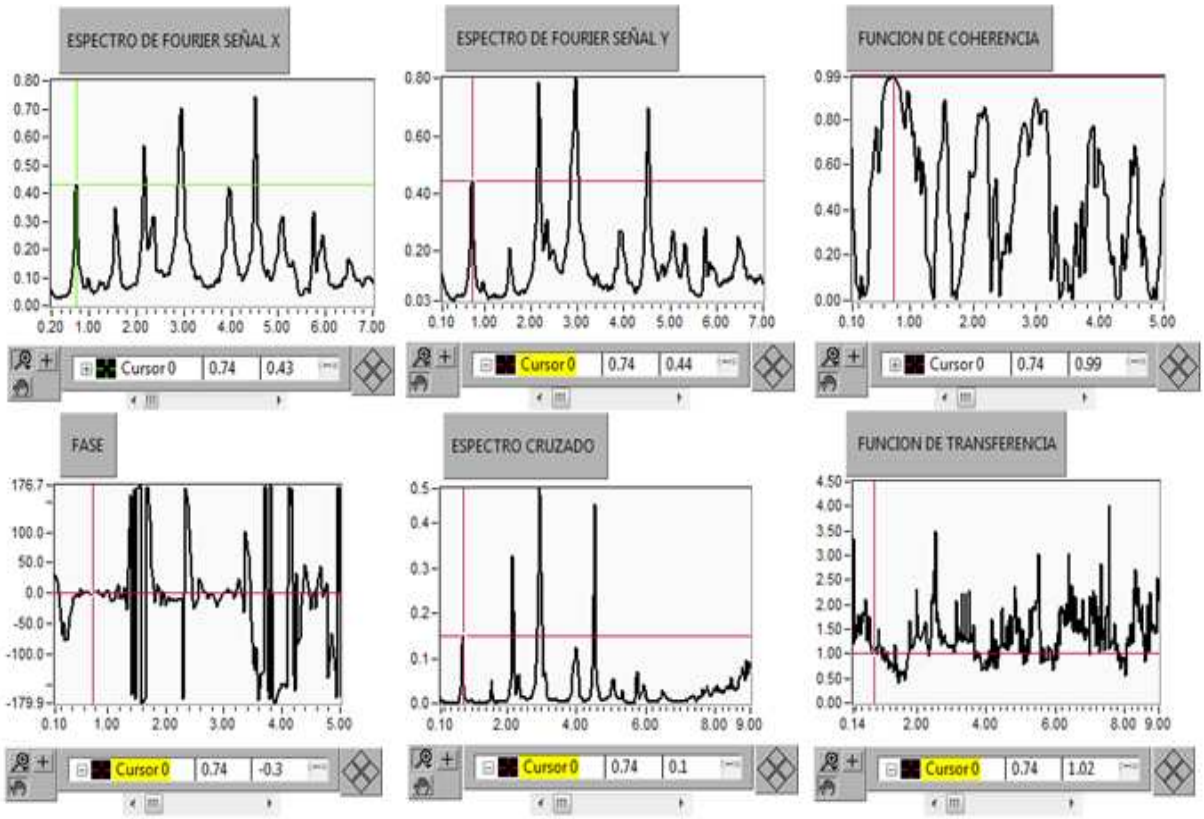
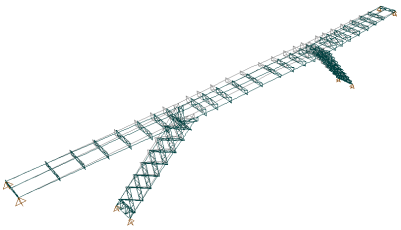
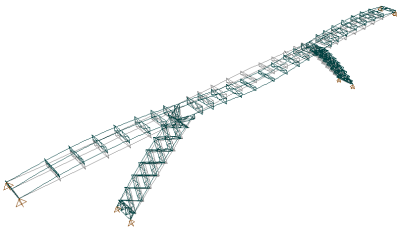


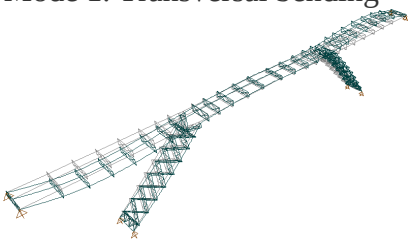
Figure 4. Array 1. Equipment E2/E1 (Y/X). Record 1. Transversal Direction Frequency 0.74 Hz



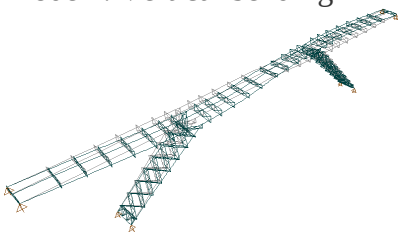
Mode 1. Transversal bending



Mode 2. Vertical bending



Mode 3. Vertical bending



Mode 4. Transversal bending

Figure 5. Transversal, vertical y torsional vibration modes experimentally obtained.

Table 2. Mean damping ratios experimentally obtained

Modal shape	Damping ratio (%)
Vertical	3.0 %
Transversal	7.0 %

Torsional	2.0 %

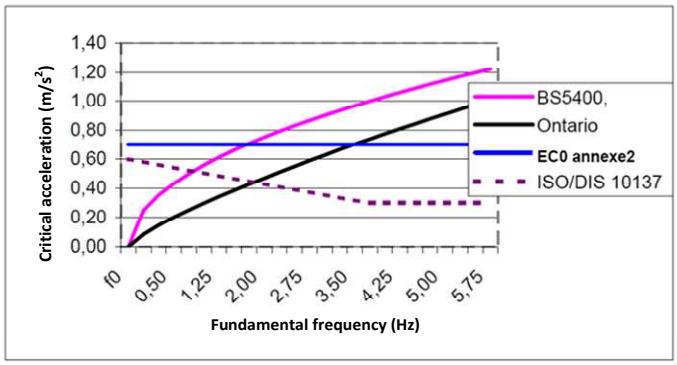


Figure 6. Critical vertical acceleration limits as a function of frequency.

From the measurements obtained in the second campaign, the peak acceleration levels were identified. As shown in fig. 6, the maximum acceleration in the vertical direction was 4.7 m/s^2. This acceleration level exceeds considerably the recommended values by various international codes, *e.g.*, BSI (1987,1992) and ISO (1997) thus, the bridge does not comply with the serviceability criteria, stated by international regulations.

3 STRUCTURAL MODEL OF THE BRIDGE

The structural model of the bridge, fig. 7, was built to be executed in the analysis program SAP2000 V14.0.0, CSI (2004) with the following characteristics:

- The sections were modeled according to the plans of the geometrical layout of the structure performed by AYESA SA de CV in 2010.
- The structural stiffness of the bridge was estimated considering the contribution of the metallic deck and the bracing truss systems of the frame.
- Due to the considerable depth of the primary beams and columns of the bridge, the eccentricity between the primary element and the bracing trusses was considered. This condition using rigid elements to connect the neutral axis of the primary elements to the axis of the truss chords.
- The secondary beams of the reticular system, *i.e.*, transversal beams, were only considered in the estimation of dead loads, because, due to their dimensions and orientation, do not provide significant lateral stiffness to the system.
- All steel elements of measurable dimensions were considered in the estimation of dead loads.

The masses and structural properties of the elements of the initial model were tuned to reproduced the dynamic properties of the bridge. This final model was subsequently used to perform the structural evaluation of the original structure and the structure with modifications. The results of these analyses fall out of the scope of this paper.

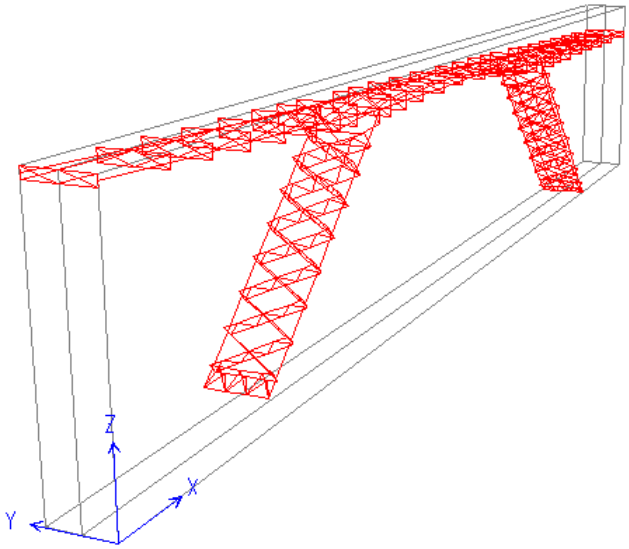


Figure 7. Structural model of the bridge

4 CONCLUSIONS

4.1 General

This paper has illustrated the methodology used in the estimation of the dynamic properties of the Fernando Espinoza Bridge. The calibration of the mathematical models was carried out using the dynamic characteristics experimentally obtained and the results of the eigen value analysis of the mathematical model of the bridge structure. The objective of this paper is to show the importance of these experimental studies to adjust the properties used in the mathematical models of the structure, *i.e.*, to match those dynamic properties of the real structure. This information is important in the definition of structural modifications to the original structure, in evaluating its structural health and consequently in defining maintenance and conservation programs, This particular study provided valuable information on the time evolution of the elastic properties of the bridge which could had been of interest if the detected changes were associated to a structural damage otherwise visually undetected.

4.2 Comments on the current operation conditions of the bridge

The experimental results obtained show that the Fernando Espinoza Bridge has considerable deformations and strong vibrations that exceed the tolerable limits of serviceability both for pedestrians and vehicles, according to international regulations. The opinion of the personnel involved in this study is that increasing the number of lanes, as original planned, will lead to even larger levels of deformation and vibrations. It is important to define a structural modification that reduces this performance levels beyond those accepted by the codes before actually designing the structure to withstand an increased demand.

5 REFERENCES

Ayala, A.G., García, O., Reyes, R, and Alvarez, C. 2002. Structural model and dynamic vibration measurement of the "Fernando Espinoza" bridge, (In Spanish), XIII National Congress on Structural Engineering, SMIE, Puebla, Mexico.

Bachmann, H. 1995. *Vibration Problems in Structures - Practical Guidelines*, Birkhäuser, Basel

Bendat, J.L. and Piersol, A.G., 1993, *Engineering applications of Correlation and Spectral Analysis*, John Wiley and Sons, New York, N.Y.

BSI. 1987. Measurement and evaluation of human exposure to wholebody mechanical vibration and repeated shock. BS 6841, London.

BSI. 1992. Guide to evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz). BS 6472, British Standards Institution, London.

CSI 2009. SAP2000 *Integrated Software for Structural Analysis and Design - User Manual*, Computers and Structures Inc, Berkeley CA.

ISO. 1997. Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 1: General requirements. International Standard ISO 2631-1.

Kawasumi H. and Shima E. (1965) Some applications of a correlator to engineering problems, III WCEE, New Zealand, Vol 2, II-298 a II- 320.

Price TE, and Smith RC. 1991. Serviceability vibration evaluation of long floor slabs. ASCE Structures Congress, Washington DC, 21-23.

Hanagan, LM, and Kim, T. 2001. Development of a simplified design criterion for walking vibrations. ASCE Structures Congress, Washington DC, 21-23.

Leonard, DR. 1966. Human tolerance levels for bridge vibrations, Ministry of Transport, Transport and Road Research Laboratory, Report, No 34, Harmondsworth.