THE ROLE OF MODULAR BRIDGE EXPANSION JOINT VIBRATION IN ENVIRONMENTAL NOISE EMISSIONS AND JOINT FATIGUE FAILURE

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Abstract

Modular bridge expansion joints (MBEJ's) are widely used throughout the world for the provision of controlled pavement continuity during seismic, thermal expansion, contraction and long-term creep and shrinkage movements of bridge superstructures. Modular Bridge Joint Systems (MBJS) are considered to be the most modern design of waterproof bridge expansion joint currently available. It was generally known that an environmental noise nuisance occurred as motor vehicle wheels passed over the joint but the mechanism for the generation of the noise nuisance has only recently been described [1].

Observation suggested that the noise generation mechanism involved possibly both parts of the bridge structure and the joint itself as it was unlikely that there was sufficient acoustic power in the simple tyre impact to explain the persistence of the noise in the surrounding environment. Engineering measurements were undertaken at Anzac and Georges River (Tom Ugly's) Bridges and the analysis of these measurements indicated that an environmental noise nuisance resulted from modal vibration frequencies of the MBEJ coupling with acoustic resonances in the chamber cast into the bridge abutment below the MBEJ. This initial acoustic investigation was soon overtaken by observations of fatigue induced cracking in structural beams transverse to the direction of traffic. A literature search revealed little to describe the structural dynamics behaviour of MBEJ's but showed that there was an accepted belief amongst academic researchers dating from around 1973 that a significant part of the load history was dynamic. In spite of this knowledge it would appear that almost all designers use a static or quasi-static design with little consideration of the dynamic behaviour, either in the analysis or the detailing.

Principally, this paper identifies the role of vibration in the generation of environmental noise complaints and links this vibration to the now endemic occurrence of structural fatigue failures of MBEJ's throughout the world.

Nomenclature

f_t	tyre pulse frequency (Hz)
f_p	wheel/beam pass frequency (Hz)
V	Vehicle speed (m/s)
G	Spacing between centre beams (m)
L_t	Tyre patch length (m)
b	Width of the centre beam top flange (m)
?	Forcing radian frequency (rads/s)
? $_n$	Natural radian frequency (rads/s)

Introduction

Whilst the use of expansion joints is common practice in bridge construction, modular bridge expansion joints are designed to accommodate large longitudinal expansion and contraction movements of bridge superstructures. In addition to supporting wheel loads, a properly designed modular joint will prevent rainwater and road debris from entering into the underlying superstructure and substructure. Modular bridge expansion joints are subjected to more load cycles than other superstructure elements, but the load types, magnitudes and fatigue-stress ranges that are applied to these joints are not well defined [2]. Modular bridge expansion joints are generally described as single or multiple support bar designs.

In the single support bar design, the support bar (beam parallel to the direction of traffic) supports all the centre beams (beams transverse to the direction of traffic). In the multiple support bar design, multiple support bars individually support each centre beam. **Figures 1 & 2** show typical single support bar and multiple support bar MBEJ's respectively. In Figure 1, the term "*Blockout*" refers to the recess provided in the bridge superstructure to allow casting-in of an expansion joint.

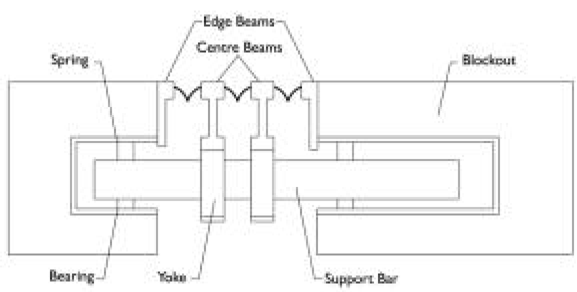

Figure 1 Typical Single Support Bar Design MBEJ

The MBEJ installed into the western abutment of Anzac Bridge consists of two interleaved single support bar structures that behave, in a dynamic sense, as independent structures. Previous experimental modal analysis studies [3] demonstrated only very light, almost negligible coupling between the two structures.

The MBEJ installed into the southbound carriageway of the bridge over the Georges River at Tom Ugly's Point is a typical multiple support bar design as shown in **Figure 2**.

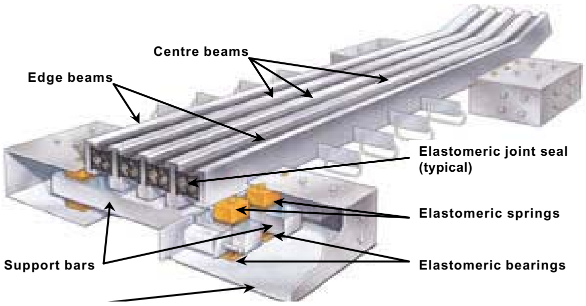

Figure 2 Typical Multiple Support Bar Design MBEJ

There was anecdotal evidence from environmental noise nuisance complaints received by the Roads and Traffic Authority of NSW (RTA) that the sound produced by the impact of a motor vehicle tyre with modular bridge expansion joints was audible at least 500 metres from the bridge in a semi-rural environment. This observation suggests that the noise generation mechanism involves possibly both parts of the bridge structure and the joint itself as it is unlikely that there is sufficient acoustic power in the simple tyre impact to explain the persistence of the noise in the surrounding environment.

Although it was generally known that an environmental noise nuisance occurred as motor vehicle wheels pass over the joint, the mechanism for the generation of the noise nuisance is not widely known. However, Barnard & Cuninghame [4] do point to the role of acoustic resonances. Studies were undertaken of the modular bridge expansion joints built into the Georges River (Tom Ugly's) Bridge and Anzac Bridge with engineering measurements made under operational conditions to determine how the noise nuisance originates and is subsequently propagated into the surrounding environment [1] [5] [6].

A literature search revealed little to describe the structural dynamics behaviour of MBEJ's but showed that there was an accepted belief amongst academic researchers from around 1973 that a significant part of the load history was dynamic [7].

Tschemmernegg [8] noted that "…*Although everybody knows that expansion joints of bridges are the heaviest dynamic-loaded components of bridges, the design calculations, if any, were of a static nature. The results are a lot of well-known problems of detail with high costs for repair, interruption of traffic, etc*…" Dexter *et al* [9] report that the poor performance of MBJS is in part due to the belief that they are often procured with inadequate specifications. Whilst there is reasonable International agreement on the distribution factor (percentage of load carried by a single centre beam), there is no common view on the extent to which the nominal quasi-static axle load should be augmented to account for the dynamic response. Dexter *et al* [2] favour a dynamic amplification factor (DAF) of 1.75 regardless of whether the design is single or multiple support bar whereas Crocetti & Edlund [10] advocate a DAF of 1.7 for multiple support bar designs and 2.0 for single support bar designs. Ancich *et al* [11] suggest that the prudent asset owner or specifier should consider setting the DAF at a minimum value of 2.5 for both single and multiple support bar designs. There is also a lack of agreement on the method of calculating the DAF with some approaches only considering the zero-to-peak (positive) displacement or strain from a moving vehicle as the dynamic contribution.

Schwammenhoefer [12] reports that the Federal Ministry of Transport (Austria) has experienced premature fatigue failure of MBEJ's and has replaced joints for both serviceability (fatigue) and noise protection (excessive environmental noise generation) reasons. MBEJ are also known to have been replaced in recent years in both Canada and the USA for predominantly serviceability reasons. Possibly the highest profile in-service failure involved the 3rd Lake Washington Bridge in Seattle, USA. Approximately 6 months after the bridge was opened to traffic in 1989, the asset owner (Washington State Department of Transportation) received numerous noise complaints about the expansion joints. Some relatively minor shim adjustments of the elastomeric bearings were undertaken but within one year, cracks in the centre beams similar to **Figure 3** were observed.

Figure 3 Centre Beam Cracking – 3rd Lake Washington Bridge (After [14])

The MBEJ's in the 3rd Lake Washington Bridge were manufactured in the US under licence to the German patent holder. The design is known as the swivel joist design and is essentially a variant of the single support bar design shown as **Figure 1**. Because of the *Buy American* requirement for this US federally funded bridge construction project, the original German centre beam section was replaced with a fabricated section sourced from a local hollow section and an extruded rail cap. Roeder [13] notes that "*…The tubular center beams clearly contribute to the fatigue problem because they cause local deformation and through-thickness plate bending stress…Despite the local deformation, fatigue would almost certainly have been a problem even if another section had been used for the center beams…*"

Kaczinski [15] believes that the 3rd Lake Washington Bridge joint failure was the result of very poor fatigue detail and the perception that no one even considered fatigue in the design.

The RTA has experienced premature fatigue failure of MBEJ's in two bridges. Fatigue cracks were observed in Pheasant's Nest Bridge on the Hume Highway (opened December 1980) and Mooney Mooney Creek Bridge on the F3 Freeway (opened December 1986). The MBEJ's installed into both bridges are multiple support bar designs and are essentially identical having been supplied by the same European manufacturer. **Figure 4** shows the typical locations for fatigue cracks in multiple support bar designs. Type A, B, & C cracks were observed at Pheasant's Nest and many developed into complete member failure. At Mooney Mooney, only Type B cracks were observed of which some developed into complete member failure. Several weld repair exercises were attempted at both bridges but these proved to be only stopgap solutions as fatigue cracks continued to develop. The Pheasant's Nest joints were replaced in 2003 and the Mooney Mooney joints are scheduled for replacement in 2004.

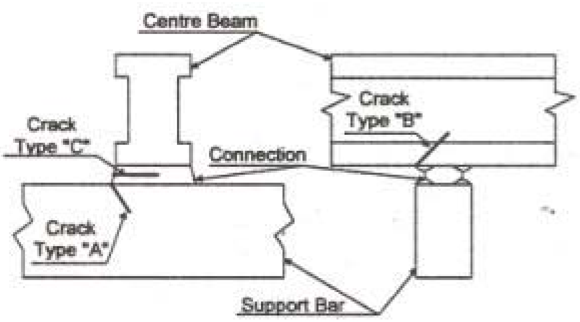

Figure 4 Established Fatigue Crack Patterns – Multiple Support Bar Designs

The Noise Issue

Noise measurements and analysis [1] [6] confirmed the hypothesis that an environmental noise nuisance resulted from the interaction of vibration of the modular bridge expansion joint with acoustic resonances produced inside the abutment void space below the joint. It was considered that cost-effective noise abatement could be undertaken by:

1. Modifying the dynamic behaviour of the joint to shift the natural frequencies so that they no longer co-incide with acoustic resonances.
2. Reducing the overall dynamic response by additional modal damping. This option included the trial use of tuned mass dampers (TMD's).
3. Providing acoustic absorption and limited screening, adjacent to the joint, to reduce noise propagation.
4. Modifying the acoustic absorption properties of the void space to eliminate or reduce the incidence of acoustic resonances.

The above strategies represented both "*new construction*" and "*retro-fit*" options. However, their efficacy and cost-effectiveness was still to be established by engineering measurement.

There were initial plans to design and test Option 2. However, this option was ultimately not pursued. Although TMD's would likely provide an effective noise reduction, these devices were not strongly advocated due to the high number of natural modes present and hence a high number of TMD's needing to be fitted and tuned. An alternative to the TMD concept would be the use of broadband damping coupled mass absorbers.

The perceived disadvantage of this approach being the requirement for a significant mass attachment to each centre beam. An array of damping coupled mass absorbers was subsequently trialled at Anzac Bridge to reduce the risk of fatigue failure but elaboration of that work is beyond the present discussion.

Due to resonances within the void space, the use of acoustic absorption and limited screening, adjacent to the joint was not considered practical. Consequently, only Option 4 was investigated. The chosen approach involved the construction of a Helmholtz Absorber within the void space of Tom Ugly's Bridge. The internal dimensions of the Helmholtz chambers were calculated to co-incide with the dominant acoustic frequencies. The Helmholtz Absorber panels were designed to target the critical frequencies shown in **Table 1**.

Table 1. Helmholtz Absorber Modules Target Frequencies

Segment	Design Centre Frequency of Helmholtz Chambers, Hz					
	1	2	3	4	5	6
Frequency	64	80	90	105	110	120

The "*Before*" and "*After*" noise measurement results showed that the benefit is most obvious in the frequency range of 50 to 200 Hz that encompasses all the natural vibration modes. The noise reduction provided by the Helmholtz Absorber installation is of the order of 10 dBA.

Vibration Induced Fatigue

In an almost universal approach to the design of modular bridge expansion joints, the various national bridge design codes do not envisage that the embedded joint may be lightly damped and could vibrate as a result of traffic excitation.

These codes only consider an amplification of the static load to cover sub-optimal installation impact, poor road approach and the dynamic component of load. The codes do not consider the possibility of free vibration after the passage of a vehicle axle. Codes also ignore the possibilities of vibration transmission and response reinforcement through either following axles or loading of subsequent components by a single axle. Ancich *et al* [3] showed that, for the measured MBEJ, the number of effective cycles of load, due to vibration, for each vehicle passage was quite high. It was found that each heavy vehicle passage, of the load configuration of the 42t GVM test vehicle, produced around 30 vibration cycles where the dynamic strain equalled or exceeded the quasi-static strain of 100 $\mu\varepsilon$ (0-Pk). Whilst these measurements relate to one particular MBEJ, they are considered to be generally representative of the single support bar design. The data must surely be of concern to MBEJ designers and specifiers who assume a single quasi-static load calculated from their national maximum permissible axle loading.

Heywood *et al* [17] identify the role of road profile unevenness in bridge damage. The unevenness of the approach pavement to a MBEJ will determine the quantum of the peak dynamic wheel force applied to the joint and this may be controlled to some extent by maintaining the road profile within predetermined International Roughness Indices (IRI) or NAASRA Roughness Counts.

However, the quantum of the peak dynamic wheel force applied to the joint will only determine the amplitude of the initial displacement. The response of the MBEJ to this dynamic force input will be principally determined by the structural dynamics behaviour of the joint.

It is likely, however, that the dynamic response of the joint is "*moderated*" by the presence of the tyre.

Figure 5 shows a typical heavy vehicle response to a deliberately introduced 40mm high vertical discontinuity in the pavement. It should be noted that the vertical scale for the road profile, axle movement (axle-hop), and body movement (body-bounce), is distorted for illustration. The abbreviations SWF and PDWF refer to the static wheel force and peak dynamic wheel force respectively.

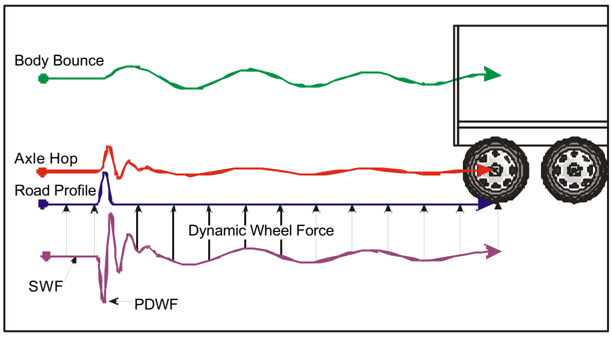

Figure 5 Axle-hop, body-bounce movements and tyre forces induced by a 1.5 m long 40 mm high hump – quarter truck simulation at 80 km/h (After [17])

Heywood *et al* [17] measured axle movement (axle-hop) frequencies generally in the range 8 – 12 Hz, and body movement (body-bounce) in the range 1.2 – 4 Hz. Consequently, if both the MBEJ and vehicle were lightly damped, vibration resonance between the two systems could potentially lead to very large vibration amplitudes. Work by Boyd *et al* [18] suggests that provided the forcing frequency is less than one quarter of the natural frequency of the lowest mode of the MBEJ then resonance effects may be ignored ($?/?_n \ll 1$). In the present study, the highest vehicle related frequency of 12 Hz is considerably less than one quarter of the lowest measured modal frequency (either bending or translational). However, resonance effects may not be totally ignored. If the beam pass frequency (f_p) is examined, it is obvious that some vehicle speed ranges will co-incide with modal frequencies. The beam pass frequency (f_p) is calculated as follows:

$$f_p = \frac{V}{G+b} \qquad (1)$$

Figure 6 shows the calculated resonance speeds for the single support bar MBEJ at Anzac Bridge over a range of centre beam spacings. Resonance effects are further complicated by a second, speed related, frequency described as the tyre pulse frequency (f_t).

The impact time or duration of loading for a wheel impact load may be expressed as a function of the vehicle speed, tyre patch length and the width of the centre beam top flange. The shape of the loading function may also be conveniently approximated by a half-sine wave (see **Figure 7**).

$$f_t = \frac{V}{L_t + b} \qquad (2)$$

For the legal speed limit at Anzac Bridge of 70 km/hr, a heavy vehicle tyre patch length of 200mm and a centre beam width of 75mm, the tyre pulse frequency f_t = 71 Hz. This is precisely the frequency identified by Ancich *et al* [3] [19] for a predominantly translational mode in the Anzac MBEJ. As **Figure 8** shows, 71 Hz is also the frequency at which most traffic induced vibration occurs.

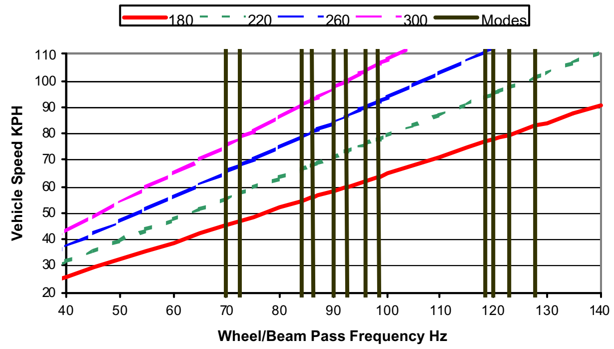

Figure 6 Calculated Beam Pass Frequencies for a Range of Expansion Joint Spacings

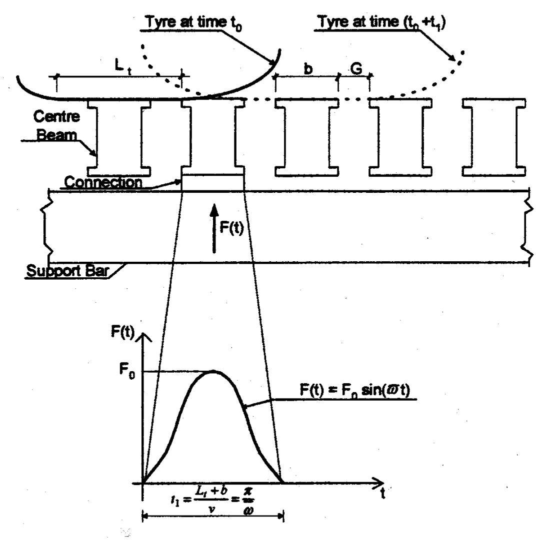

Figure 7 Characteristic Half-Sine Wave Impulsive Load

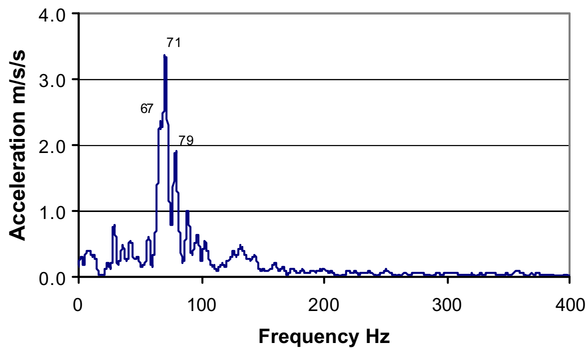

Figure 8 Centre Beam Vibration Spectrum – Anzac Bridge

Conclusions

Noise and vibration measurements have been undertaken at Anzac and Georges River (Tom Ugly's) Bridges. The analysis of these measurements supported the hypothesis that an environmental noise nuisance results from the interaction of vibration of the modular bridge expansion joint with acoustic resonances produced inside the void space below the joint. The trial installation of a Helmholtz Absorber at Tom Ugly's Bridge reduced the modular expansion joint induced low frequency "booming" noise emissions by up to 10 dBA. The character of the noise emission from the underside of the bridge deck would no longer be characterised as tonal and hence the likelihood of modular expansion joint related noise complaints has been significantly reduced. The use of Helmholtz Absorbers at other bridges with modular expansion joints is considered to be viable as an engineering method of noise control.

High vibration levels were also considered largely responsible for premature fatigue failure. Experimental modal analysis and operational response shape studies were performed on a hybrid MBEJ installed in Anzac Bridge. The studies showed that for this joint:

- The joint is very lightly damped (<2% of critical damping).
- The bwest frequency mode excited was a quasi-translational (bounce/bending) mode at 71 Hz.
- Due to access restrictions, horizontal modal data could not be acquired in sufficient detail to identify horizontal bending or torsional modes.
- The support bars and centre beams were acting dynamically as if simply supported.
- There was good agreement between the experimental modal analysis and the operational response shape studies.

It is considered that the dynamic response of this MBEJ is mainly due to coupled centre beam resonance and this is seen as a design characteristic of all single support bar designs. Static and dynamic strain gauge studies showed that for this joint:

- The DAF is up to 4.6 for the fully laden test vehicle
- This DAF is not necessarily the worst case as every possible vehicle speed and joint opening combination was not tested
- Damping is important in the dynamic behaviour
- The number of effective cycles of load, due to vibration, for each vehicle passage is very high
- High uplift forces are generated within the joint under vehicle loading

These results should be of concern to bridge asset owners, bridge designers and modular joint suppliers. The normal assumption of quasi-static behaviour for both the single and multiple support bar design MBEJ's (and variants thereof) is not sustainable and both bridge designers and modular joint suppliers must think in terms of a fully dynamic system. The lack of International agreement for the method of calculating and assessing the dynamic amplification of load is seen as an impediment to this process.

Acknowledgement

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References

[1] Ancich E.J. & Brown S.C.: "Modular Bridge Joints – Reduction of noise emissions by use of Helmholtz Absorber", *Proc. 5th Austroads Bridge Conference*, Hobart, Tasmania, Australia (2004).

[2] Dexter R.J., Connor R.J. & Kaczinski M.R.: "Fatigue Design of Modular Bridge Expansion Joints", *NCHRP Report 402,* Transportation Research Board, National Research Council, Washington, DC, USA (1997) 128 pp.

[3] Ancich E.J., Chirgwin G.J. & Brown S.C.: "Dynamic Anomalies in a Modular Bridge Expansion Joint", *J. Bridge Engrg*., ASCE, (Submitted).

[4] Barnard C.P. & Cuninghame J.R.: "Improving the Performance of Bridge Expansion Joints: Bridge Deck Expansion Joint Working Group Final Report", *TRL Report 236*, Transport Research Laboratory, Crowthorne, Berkshire, UK (1997) 92 pp.

[5] Ancich E.J.: "A Study of the Environmental Noise Generation & Propagation Mechanisms of Modular Bridge Expansion Joints", RTA *Environmental Technology Report No. 000203*, Roads & Traffic Authority, Sydney, NSW, Australia (2000) 9 pp.

[6] Ancich E.J. & Brown S.C.: "Engineering Methods of Noise Control for Modular Bridge Expansion Joints", *Acoustics Australia*, (Submitted).

[7] Tschemmernegg F.: "Messung von Vertikal- und Horizontallasten beim Anfahren, Bremsen und Überrollen von Fahrzeugen auf einem Fahrbahnübergang (Measurement of Vertical and Horizontal Loads due to Accelerating, Braking, and Rolling Vehicles on an Expansion Joint)", *Der Bauingenieur*, 48, Heft 9, Springer-Verlag, (1973) 326-330 (In German).

[8] Tschemmernegg F.: "The Design of Modular Expansion Joints", *Proc. 3rd World Congress on Joint Sealing and Bearing Systems for Concrete Structures*, Toronto, Ontario, Canada, (1991) 67-86.

[9] Dexter R.J., Osberg C.B. & Mutziger M.J.: "Design, Specification, Installation, and Maintenance of Modular Bridge Expansion Joint Systems", *J. Bridge Engrg*., ASCE, (2001), 6(6), 529-538.

[10] Crocetti R. & Edlund B.: "Fatigue Performance of Modular Bridge Expansion Joints", *J. Perform. Constr. Facil*., ASCE, (2003) 17(4), 167-176.

[11] Ancich E.J., Brown S.C. & Chirgwin G.J.: "Dynamic Design of Modular Bridge Expansion Joints by the Finite Element Method", *J. Bridge Engrg*., ASCE, (In Preparation).

[12] Schwammenhoefer F.: Personal Communication (2001).

[13] Roeder C.W.: "Fatigue Cracking in Modular Expansion Joints", *Research Report WA-RD 306.1*, Washington State Transportation Center, Seattle, Washington, USA (1993) 53 pp.

[14] Roeder C.W.: Personal Communication (2004).

[15] Kaczinski M.R.: Personal Communication (2004).

[16] Roeder C.W.: "Field Measurements of Dynamic Wheel Loads on Modular Expansion Joints", *Research Report WA-RD 369.1*, Washington State Transportation Center, Seattle, Washington, USA (1995) 66 pp.

[17] Heywood R., Prem H. & McLean J.: "Guide to Road Profile Unevenness and Bridge Damage", *Report AP-T13*, Austroads Inc., Sydney, NSW, Australia (2002) 33 pp.

[18] Boyd A.L., Schmidt B.R. & Thornton P.B.: "Loading and Impact Effects on Mine Haul Road Bridges" *MWP Technical Quarterly No. 4*, Macdonald Wagner & Priddle Pty Ltd (now Connell Wagner Pty Ltd), Sydney, NSW, Australia (1982) 7-15.

[19] Ancich E.J., Brown S.C. & Chirgwin G.J.: "Modular Deck Joints – Investigations into structural behaviour and some implications for new joints", *Proc. 5th Austroads Bridge Conference*, Hobart, Tasmania, Australia (2004).