Structural Engineering and Mechanics, Vol. 35, No. 3 (2010) 301-314
DOI: http://dx.doi.org/10.12989/sem.2010.35.3.301

Dynamic testing of a soil-steel bridge

Damian Beben[1*] and Zbigniew Manko[2]

[1]*Faculty of Civil Engineering, Opole University of Technology, Katowicka Street 48, 45-061 Opole, Poland*
[2]*Mechanics and Structures Engineering Division, Wroclaw University of Environmental and Life Science, Plac Grunwaldzki No. 24a, 50-365 Wroclaw, Poland*

(Received December 22, 2008, Accepted January 27, 2010)

Abstract. The paper presents the results and conclusions of dynamic load tests that were conducted on a road bridge over the Mokrzyca river in Wroclaw (Poland) made of galvanized corrugated steel plates (CSP). The critical speed magnitudes, velocity vibration, vibration frequency were determined in the paper. The dynamic analysis is extremely important, because such studies of soil-steel bridges in the range of dynamic loads are relatively seldom conducted. Conclusions drawn from the tests can be most helpful in the assessment of behaviour of this type of corrugated plate bridge with soil. In consideration of application of this type of structure in the case of small-to-medium span bridges, the conclusions from the research will not be yet generalized to all types of such solutions. The detailed reference to all type of such bridge structures would be requiring additional analysis (field tests and calculations) on the other types of soil-steel bridges.

Keywords: dynamic test; soil-steel bridge; corrugated plate; vibration velocity; vibration frequency; critical speed.

1. Introduction

The subject of this paper is soil-steel arch bridge, made of corrugated plates, over the Mokrzyca river in Wroclaw (Poland). The structure was subjected to thorough study (Manko and Beben 2004). The soil-steel bridge was build very fast (July-September 2003), and tested after three months from finished construction works (December 2003).

The authors created main test team, which carried out the examination on the bridge. Vertical and horizontal displacements as well as strains were measured at selected points and principal sections of the shell in two directions and in four basic stages as follows:

- During the soil compaction around the shell structure carried out five times for different numbers of layers. General, the steel shell was covered with 15 layers of backfill (Stage I);
- Bridge was under field static load tests (Stage II) as well as
- Dynamic load tests (Stage III); and
- In service examination (Stage IV).

Prior to commencement of the test, strain gages were attached to the steel shell and before placing the first soil layer should be protected (by polyurethane foam) before destructions or damages of the

*Corresponding author, Ph.D., E-mail: d.beben@po.opole.pl

strain gages. The inductive gages and dial gages were installed under the span, and the accuracy of all the gages and measuring apparatus specified for the test were checked (Manko and Beben 2004).

In the papers (Beben and Manko 2008b, Manko and Beben 2005) detailed descriptions of the similar bridge structures, applied measuring apparatus, the range of studies under the static load tests, the results obtained from measurements and calculations and their analysis as well as conclusions were presented.

Whereas, the analysis of deflections and strains (indirectly normal stresses) during construction, in particular the lateral backfill pressure in this soil-steel bridge, as well as during the field static load tests was described in the study (Manko and Beben 2004). Appropriate shell durability tests as a result of loads pressure exerted by the subsequent backfill layers were also showed in (Manko and Beben 2004). Analysis of the soil-steel bridge during construction is presented by Mohammed *et al* (2002).

Static analysis of such similar bridge structures is more frequently showed in papers e.g., (Abdel-Sayed and Salib 2002, Arockiasamy *et al*. 2006, El-Sawy 2003, Kang *et al*. 2008, Kim and Yoo 2005, Yeau *et al*. 2009), whereas the study of the soil-steel bridges in range of dynamic loads have been not so far widely analyzed (Manko and Beben 2006, Sezen *et al*. 2008).

The numerical simulations of moving force identifications from bridge dynamic responses were presented in paper written by Yu and Chan (2005). The series of experiments were also made in laboratory to evaluate the moving force identification methods.

Special manner of dynamic analysis of buried structure was presented by Dancygier and Karinski (2000). Moreover, the application of the Single Degree Of Freedom (SDOF) model to simulate of wave propagation at the buried structure was showed. The mathematical formulation and solution of applied model were also described.

The main aim of the this paper is to present the results of the research on the new bridge in the dynamic load test domain of studies (Stage III) as the basis upon which the quality of realization, durability, critical speed magnitude, velocity vibration, vibration frequency were determined.

Due to the important location of the bridge in the road network of Wroclaw, Poland (main road to the mine of sand) and considering its prototypical character as well as the comprehensive and thorough research on the structure together with the detailed analysis of the obtained results (from analysis of displacements, strains and dynamic effects), the conclusions derived from this complex study can be very helpful in engineering practice, especially in the control and acceptance field tests which carried out during construction of steel bridges made from corrugated or flat plates – particularly in bridges of similar geometric structure and similar material characteristics (Beben 2005, Beben and Manko 2008a,b, Manko and Beben 2005, 2006, Vaslestad 1990).

The results of dynamic tests along with their comprehensive analysis are extremely important, because such studies of soil-steel bridges in the range of dynamic loads are relatively seldom conducted. It should be add that the road sign of speed limit to 30 km/h is positioned on the bridge because of frequent exceeding its current carrying capacity by many vehicles. Therefore, the realization of experimental tests in the range of dynamic loads was necessary.

It should be add, that the behavior of soil-steel bridges under static and dynamic loads in comparison to the traditional reinforced concrete (or precast) box culverts is diametrically opposed (Abolmaali and Garg 2008). The special type of dynamic analysis of shell structures should be searched (Liu *et al*. 2005).

2. Description of the bridge structure

The bridge tested is a single span steel shell in the longitudinal section of effective length L = 6.320 m that is connected rigidly to a continuous footing. The shell is supported by means of steel unequal leg channels resting on two reinforced concrete continuous footings (Fig. 1).

The load bearing structure was constructed as a shell assembled from the sheets of corrugated plate of corrugation depth of 140 mm, pitch of 380 mm (box culvert type) and plate thickness of t = 7.10 mm, connected together using high strength bolts $ø$ = 20 mm, covered with the layers of soil (about 0.20-0.30 m thick) properly compacted (in the Proctor Normal scale I_D = 0.95 for the soil connected directly with the steel structure and I_D = 0.98 for the remaining part of the backfill), allowing pavement to be laid on the broken stone base. The total height of the plate corrugation

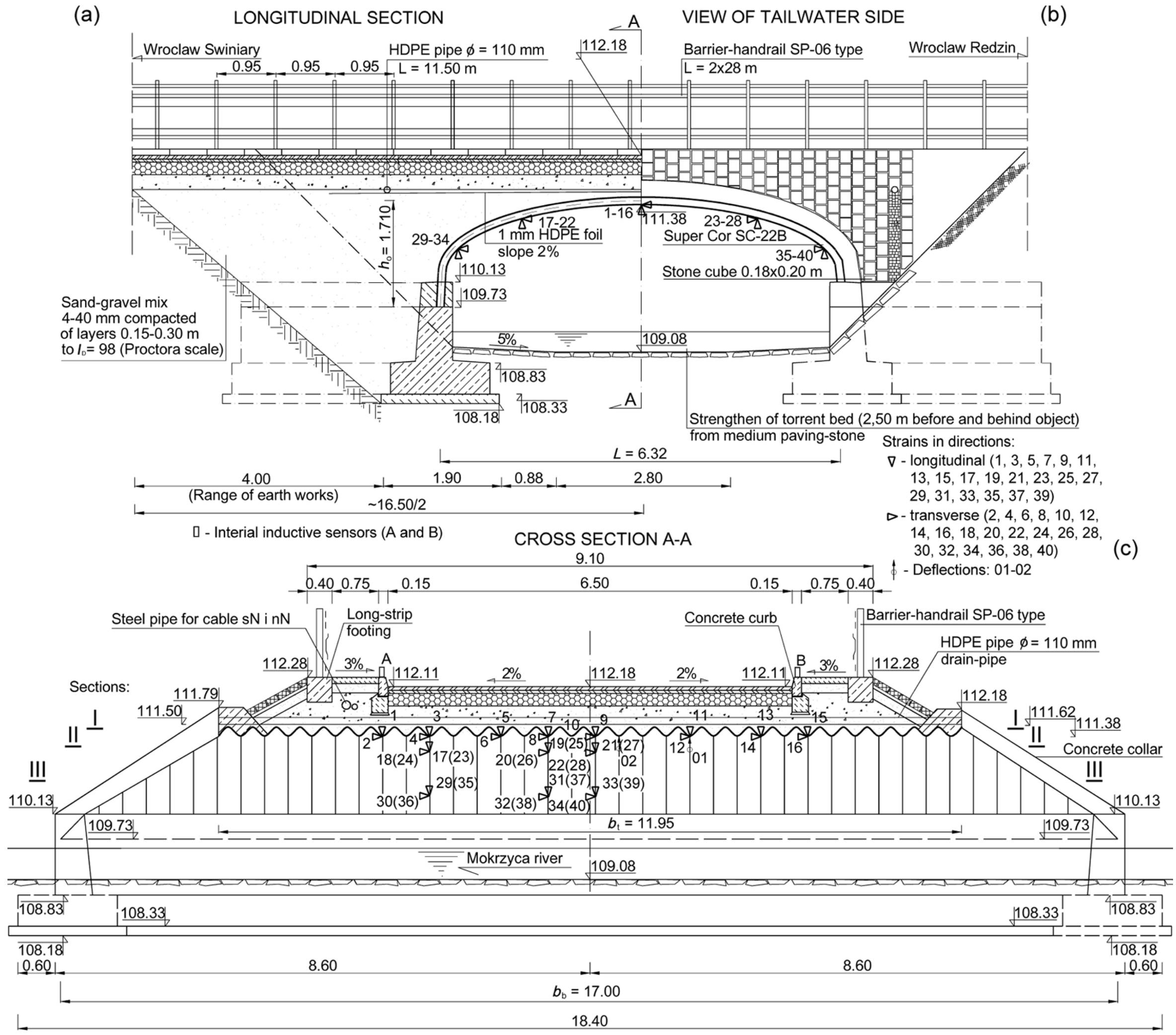

Fig. 1 Road bridge made of CSP in Wroclaw: (a) longitudinal section, (b) view of tailwater side, and (c) cross section A-A, together with location of gages the serving to dynamic measurements

(a) (b)

Fig. 2 The CSP bridge: (a) side view on object before beginning of dynamic tests, (b) passing the *Kamaz* vehicle on the bridge with speed of 20 km/h

amounts to h = 140 mm. The width of the bridge shell at the top is b_t = 11.95 m, whereas at the bottom is b_b = 17.00 m. In the plan view, the object is situated perpendicularly to the river current, and the rise amounts to h_o = 1.710 m. The bridge was designed on class *C* loads in accordance with the Polish Load Standard PN-85/S-10030, i.e., loading with vehicles having a total weight of 300 kN. The roadway on the bridge was 6.50 m and two-sided safety bands of 0.75 m. Under long strip footings the geogrid *Tenax LBO* type (2.50 × 20.00 m) was applied. It was used because the soil conditions were unfavourable. The basic shell of the bridge was reinforced in three places, i.e., the crown and in two corners at the continuous footings from the side of soil at both sides of the object by means of additional sheets of corrugated plate, so-called ribs (in the crown the reinforcing is continuous and in haunches the pitch is 380 mm) in order to assure greater transversal stiffness of the bridge span (Fig. 1). The soil-steel bridge after construction is showed on Fig. 2(a), whereas during dynamic field load tests on Fig. 2(b).

3. The range of conducted tests

For the dynamic tests (conducted for the evaluation of effects vehicles have on the magnitude of strains of corrugated plates and their deflections at selected cross sections of the shell), two inertial inductive sensors (A and B) PEVA 7225 type were fixed at the curb stones and reinforced concrete collar and strain gages 1-40 for strains measurements in the transversal and longitudinal directions of the bridge, located on top of the corrugated plates in three section of the bridge (Fig. 1), the time course of which have been registered on the PC computer. During field load tests the decision was taken of change the measured parameters of dynamic load diagrams, graduation device, and series of additional loads (repetition of the process). In order to make possible a comparison of obtained results all efforts were made to keep the almost similar route of the vehicle during its passing over bridge each time.

In the opposite incident, change in the route of the vehicle in a cross section of the roadway makes it impossible for direct comparison of the obtained results.

Diagrams of dynamic load have been drawn in such a way to identify:
- influence of inertia and speed of moving load (vehicle);
- state of resonance caused in cycles of moving loads;
- influence of intensive braking of a loaded vehicle;
- influence of roughness threshold and roughness road surface; and
- natural frequency and logarithmic decrement of damping assigned by basic forms of natural vibration of examined structure span.

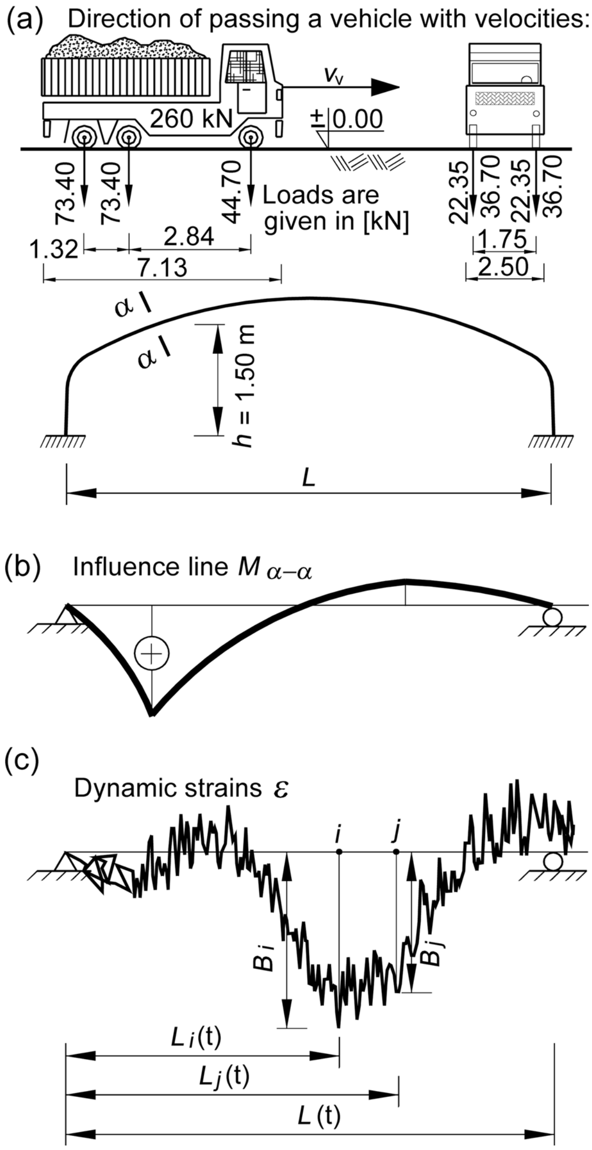

Fig. 3 Example graphs of the vibration in time for the selected cross section α–α and interpretation of results: (a) scheme of bridge and the vehicle dimensions and loads on wheels (axles), (b) influence line of bending moment $M_{\alpha\text{–}\alpha}$ at h = 1.50 m, (c) graphs of dynamic strains ε

During the dynamic research, a truck *Kamaz* type was used. The weighed front and rear axle loads together considerably exceeded the total weight of the vehicle (with its load included) of 260 kN. The technical specifications of the ballasting vehicle were as follows: the inter bumper length - 7.130 m, the width of the body - 2.500 m, the front wheel vehicle of 1.850 m, the front axle to first rear axle spacing - 2.84 m, the spacing between the rear axles - 1.32 m, the maximum weight of the vehicle with the load - 260.00 kN and without the load - 100.00 kN (the load capacity - 160.00 kN), the front axle load - 44.70 kN, and the weight per rear axles - 2 × 73.40 kN (Fig. 3(a)).

The speeds of the moving vehicle over the bridge (used earlier in the static tests (Manko and Beben 2004)) were estimated as follows 10, 20 and 30 km/h in both directions (schemes load I-VI) because of the road sign of speed limit to 30 km/h is positioned on the bridge. Moving of vehicle by threshold and during braking on the bridge was not conducted, because the weather conditions (unexpected fall of snow in this period of year) were very difficult and dangerous for the test crew and local people. The temperature during conducted tests was higher than the zero Celsius degree (positive).

The influence of changes in atmospheric conditions (mainly temperature) was eliminated through the use of compensation strain gages at all the measuring points. Taking into account the changeable weather conditions in this area, special quick-drying glue based on synthetic resin was used and the stuck on gages were coated with the protective weather- and mechanical damage-resistant compound. The stuck on gages were connected to the compensation gages (mounted on steel plates put against the structure next to the active strain gages) into half-bridge circuits.

4. The method of interpretation of tests results

Outlining the results of the dynamic tests is unusually labour consuming and arduous, and the registered values were taken usually in ordinary human handwritings. A characteristic result of the measurements is the common graph of vibration and movement and/or velocity and vibration frequency. Interpretation of results of measurements is very hard and a number of them can be ambiguous (not having unanimous implication).

Based on used apparatus and assumed test program, the final results are following:

1) Total dynamic maximum strains ($\varepsilon_{dyn}^{\max}$) – Fig. 3.

2) Frequency of natural vibration of the bridge.

3) Logarithmic decrement of damping Δ, which can be calculated from the formula (1):

$$\Delta = \frac{1}{r}\sum_{i=1}^{r}\ln\frac{\varepsilon_i}{\varepsilon_{i+1}} \tag{1}$$

were ε_i - i-th at particular amplitude of strain; ε_{i+1} - (i+1) amplitude of strain; r - number of addends.

It is necessary to mention that the measured strain include contributions from several modes of vibration. Thus, Eq. (1) is only relevant after filtering of the signal to isolate the mode of interest.

A special FFT (*Fast Fourier Transformation*) analyzer for filtering of the obtained signals was used by the test equipment and the natural frequency was finding automatically. During the dynamic load tests the courses of unit strains in time in the selected measurement points were measured and registered by *UMK*-10 channels switches (class precision 0.1, frequency 5 kHz, frequency range 0-1300 Hz, maximum sensitivity 50 μm) as well as digital meter *DMD* 20A type with accuracy 1×10^{-5} (frequency 225 kHz, total range ±20999 μm/m, frequency range 0-15 Hz, sensitivity ratio $k = 0.50$-19.99, analogue output for range ±1999 μm/m ± 2V, resistance > 10 kΩ). Amplifier *Spider*-8 from *Hottinger Baldwin Mebtechnik* has following characteristic: class precision 0.01, frequency 4.8 kHz and symmetrically enter from range 5-500 mV/V.

According to velocity measurement it is necessary to mention that measurements were made under definite size of sampling (in analyzer from frequency in range 400-500 Hz and hence the resulting from here recording times of signals carried out respectively from 50 to 120 seconds) which was set on the measuring apparatus. And only for practical information it was also changed for other number of sampling. In both cases of sampling the considered results were almost the same. But it necessary to add also that conducted research has had wider range than an engineering level during a classical field load tests.

In the case of measurement of displacement, the above given characteristics are determined based on their measured values in given time.

The calculation procedure of stresses is following: value of obtain strain were multiplied by Young modulus for steel (205 GPa). This was made only in aim the estimation of stresses level in steel shell structure.

5. Results and analysis of the research

All the graphs obtained from the strains ($\varepsilon_{dyn(x)}^{\max}$, $\varepsilon_{dyn(y)}^{\max}$) and vibration velocity (v_A, v_B) courses in time as well as the corresponding natural velocity frequencies (f_A, f_B) and also the dynamic deflections (u_A, u_B) of the vehicle in its various crossings are presented in the Fig. 4. In all, 6 dynamic load schemes were realized (I-VI).

Analyzing the obtained graphs, the vibration velocity in time as well as the amplitude values and natural frequency of steel shell of the bridge during the passing of the vehicle, it was confirmed that (Table 1 and Fig. 4):

1. The largest amplitude of vibration velocity measured in measurement point A amounted to $v_A = 0.078$ m/s with the vibration frequency equal to $f_A = 28.562$ Hz and dynamic deflections amounted to $u_A = 0.43 \times 10^{-3}$ m. Whereas in the point B, the amplitude of vibration velocity

Table 1 Dynamic characteristic of bridge obtained from inertial inductive sensors during passing a vehicle with various speeds

Speed of vehicle v_v in (km/h) and load schemes		Gages A			Gages B		
		v_A (m/s)	f_A (Hz)	u_A (10^{-3} m)	v_B (m/s)	f_B (Hz)	u_B (10^{-3} m)
10	I (II)	0.040	15.500	0.41	0.029	15.000	0.31
20	III (IV)	0.069	25.250	0.44	0.071	25.562	0.44
30	V (VI)	0.078	28.562	0.43	0.082	24.250	0.54

Notes: u – dynamic deflection, f – vibration frequency, v – vibration velocity

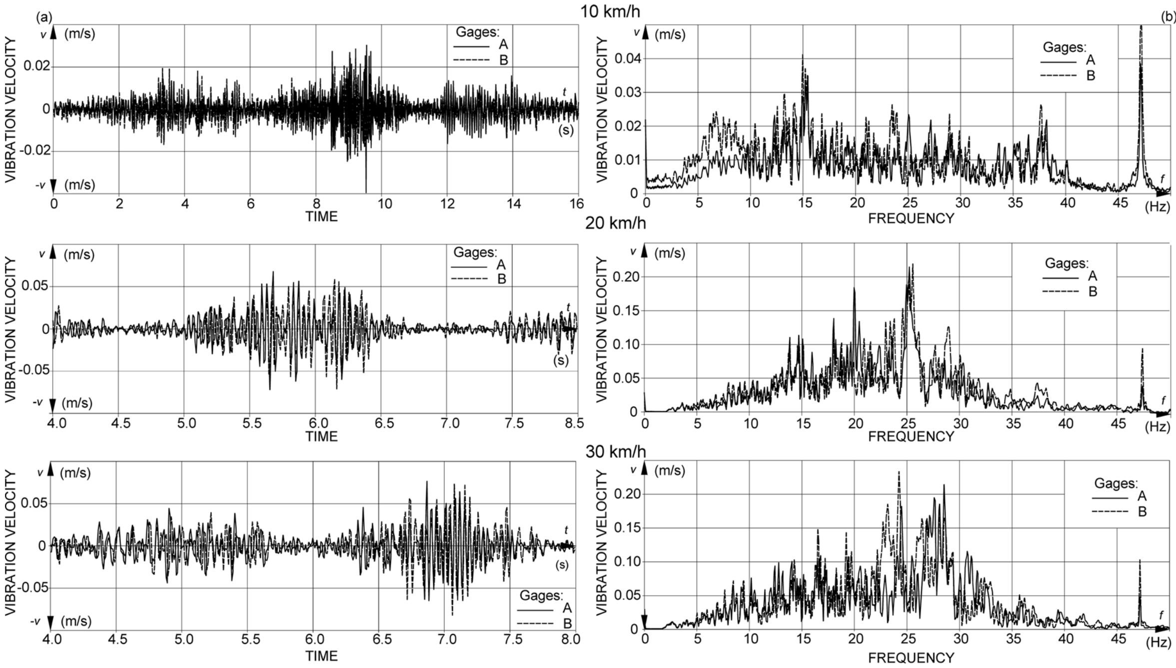

Fig. 4 Courses: (a) vibrations velocity in time, (b) vibrations frequency of the structure in selected points (A and B) during passing a vehicle with the speeds v_v = 10, 20 and 30 km/h, respectively

equals to $v_B = 0.082$ m/s with a frequency $f_B = 24.250$ Hz and dynamic deflections equal to 0.54×10^{-3} m which was simultaneously obtained during the passing of the vehicle with a speed of about 30 km/h.

2. The largest amplitude of vibration velocity measured in measurement point A during passing a vehicle a speed with 20 km/h amounted to $v_A = 0.069$ m/s with the vibration frequency equal to $f_A = 25.250$ Hz and dynamic deflections amounted to $u_A = 0.44 \times 10^{-3}$ m. Whereas in the point B, the amplitude of vibration velocity equals to $v_B = 0.071$ m/s with a frequency $f_B = 25.562$ Hz and dynamic deflections equal to 0.44×10^{-3} m.
3. The largest amplitude of vibration velocity measured in measurement point A during passing a vehicle a speed with 10 km/h amounted to $v_A = 0.040$ m/s with the vibration frequency equal to $f_A = 15.500$ Hz and dynamic deflections amounted to $u_A = 0.41 \times 10^{-3}$ m. Whereas in the point B, the amplitude of vibration velocity equals to $v_B = 0.029$ m/s with a frequency $f_B = 15.000$ Hz and dynamic deflections equal to 0.31×10^{-3} m.

Analyzing the graphs of extreme amplitudes and vibration frequencies obtained from the strains measurements values of the steel shell of the bridge, it was confirmed that (Table 2 and Figs. 5-7):

1. The largest dynamic strains in the bridge shell measured at point 22 in transversal direction of the bridge $\varepsilon_{dyn(x)}^{\max} = 34.50 \times 10^{-6}$ with maximum total magnitude range of displacement (positive and negative) $\Delta\varepsilon_x = 39.50 \times 10^{-6}$, which is $\sigma_x = 8.90$ MPa, therefore at point 13 strains in the longitudinal direction of the span were $\varepsilon_{dyn(y)}^{\max} = 18.00 \times 10^{-6}$, and their suitable range $\Delta\varepsilon_y = 20.50 \times 10^{-6}$ which is equivalent to $\sigma_y = 4.20$ MPa, that was obtained during the passing of the vehicle across the bridge with a speed $v_v = 10$ km/h (Fig. 5).

Table 2 The dynamic characteristics calculated on the basic of strains (10^{-6}) measured during passing the vehicle across a bridge with various speeds

Values	Number of gages																			
v_v = 10 km/h	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**
$\varepsilon_{dyn(x)}^{max}$	9.00	16.00	22.00	24.00	–	27.50	21.00	15.00	5.10	17.00	34.50	12.00	17.50	18.50	12.00	15.00	26.00	10.50	11.00	23.00
Δ	0.182	0.207	1.011	1.098	–	1.299	1.252	0.143	0.071	0.693	0.245	0.405	0.259	0.114	0.233	0.310	0.080	0.336	0.318	0.362
	1	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**	**25**	**27**	**29**	**31**	**33**	**35**	**37**	**39**
$\varepsilon_{dyn(y)}^{max}$	6.00	4.00	9.00	12.00	7.00	13.00	18.00	8.00	4.00	12.00	9.00	4.00	–	7.50	7.50	5.10	8.50	–	–	–
Δ	0.087	0.133	0.251	0.875	0.336	1.178	0.057	0.133	0.133	0.233	0.057	0.287	–	0.405	0.068	0.125	0.125	–	–	–
v_v = 20 km/h	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**
$\varepsilon_{dyn(x)}^{max}$	12.00	19.00	24.50	26.50	–	23.00	18.00	12.00	6.50	18.00	28.00	17.00	16.50	23.00	4.50	6.50	9.50	7.00	4.50	21.00
Δ	0.980	0.546	1.058	1.405	–	1.056	0.693	1.791	0.167	0.117	2.079	0.530	0.164	0.427	0.057	0.262	0.054	0.074	0.811	0.048
	1	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**	**25**	**27**	**29**	**31**	**33**	**35**	**37**	**39**
$\varepsilon_{dyn(y)}^{max}$	7.50	2.50	7.00	7.00	4.50	7.00	16.50	6.50	4.00	12.50	6.50	4.00	–	6.00	7.00	4.50	3.50	–	–	–
Δ	0.068	0.223	0.441	0.336	0.117	0.559	0.062	0.485	0.133	0.916	0.080	0.133	–	0.405	0.074	0.405	0.174	–	–	–
v_v = 30 km/h	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**
$\varepsilon_{dyn(x)}^{max}$	10.00	16.00	20.00	22.50	–	24.00	21.00	16.00	7.50	15.50	29.00	13.50	18.50	17.00	11.50	13.50	19.00	13.50	7.50	24.00
Δ	0.693	1.519	0.916	1.098	–	1.306	1.435	1.386	0.511	0.101	0.969	0.523	0.720	1.329	0.650	0.656	0.998	0.587	0.405	0.182
	1	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**	**25**	**27**	**29**	**31**	**33**	**35**	**37**	**39**
$\varepsilon_{dyn(y)}^{max}$	5.00	4.00	4.00	4.00	8.00	10.50	12.00	4.00	6.50	8.50	6.50	3.50	–	9.00	6.00	6.00	13.00	–	–	–
Δ	0.223	0.133	0.133	0.064	0.287	0.646	1.386	0.133	0.367	0.635	0.080	0.154	–	0.057	0.287	0.287	0.424	–	–	–

Note: gages No. 10, 25, 35, 37, and 39 did not move correctly in whole test period

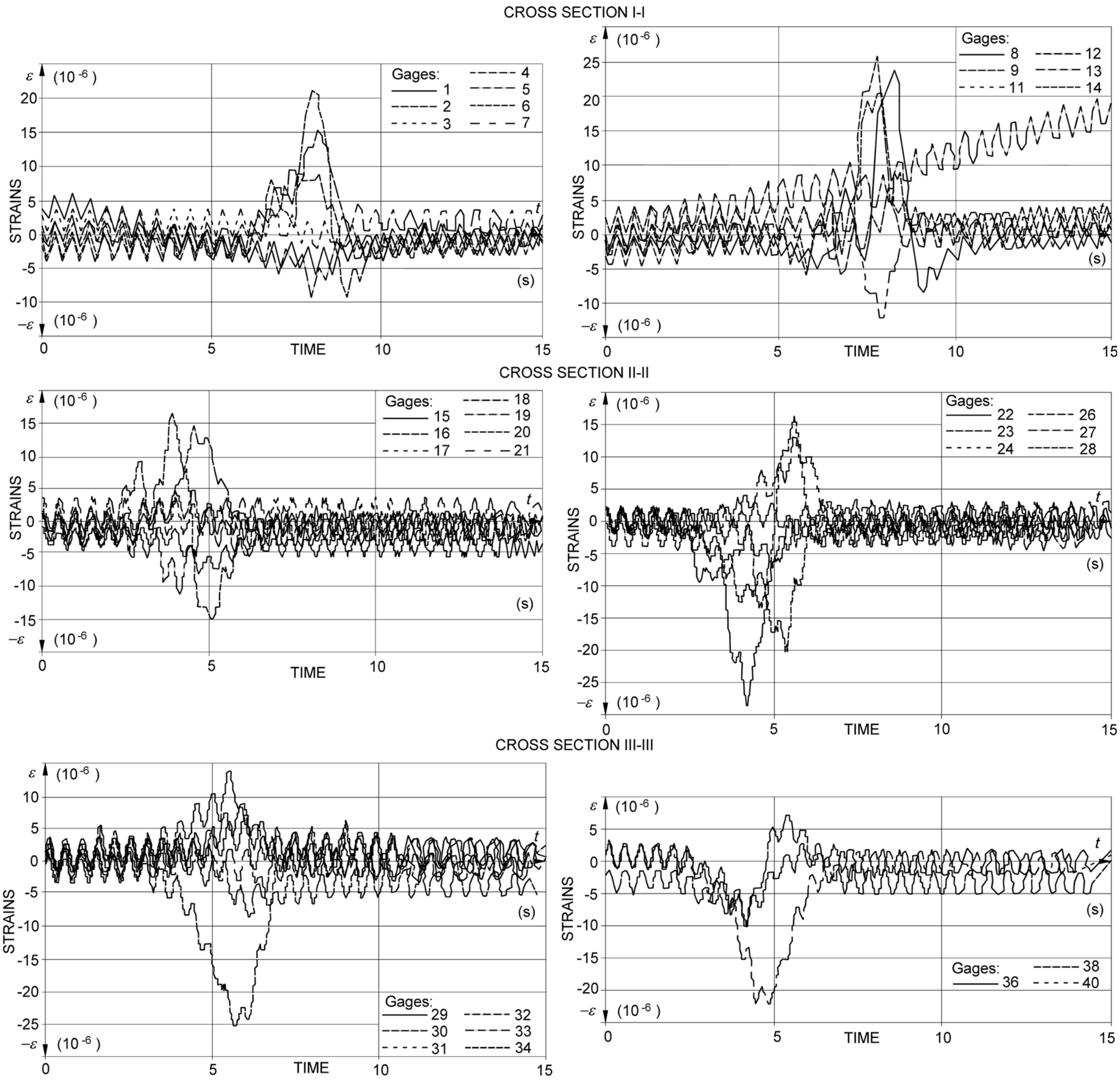

Fig. 5 Courses of strains in time in selected points (cross sections I-I, II-II and III-III) of steel shell structure during passing a vehicle with a speed $v_v = 10$ km/h

2. In next load schemes, e.g., during passing of vehicle with a speed $v_v = 20$ and 30 km/h the values of dynamic strains were less. Simultaneously one should add that dynamic strains obtained in the same measured points 22 and 13 (Figs. 6, 7 and Table 2).

In case of logarithmic decrement of damping values which were calculated from Eq. (1) for the analyzed dynamic load schemes during the experimental tests of this bridge were comprised in range 0.057-1.299 for speed of vehicle passing $v_v = 10$ km/h (I-II load schemes), whereas in the next load schemes III-IV (v_v = 20 km/h) in range 0.048-2.079, and for v_v = 30 km/h (V-VI load schemes) in range 0.057-1.519. The largest value Δ = 2.079 was received during vehicle passing

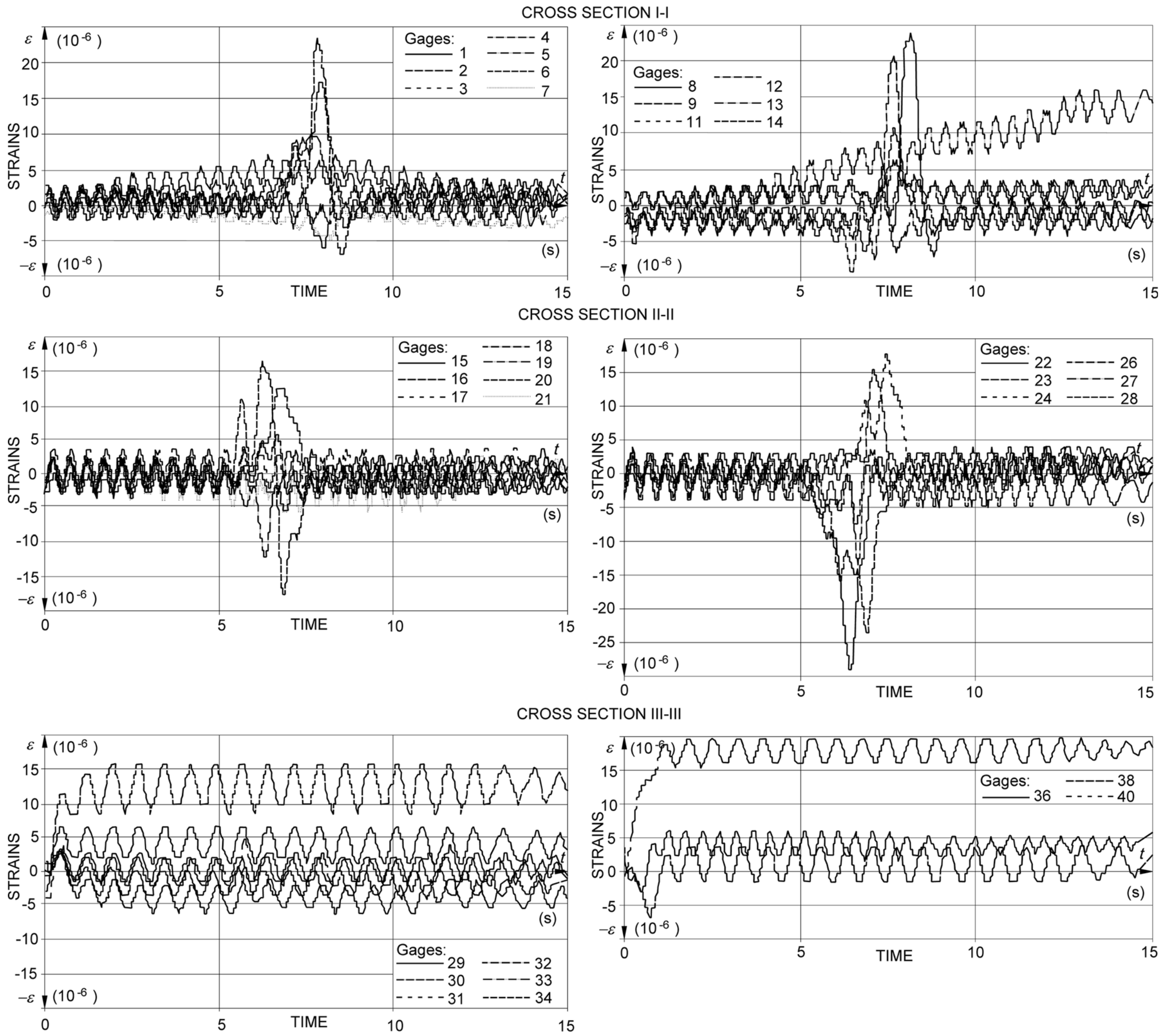

Fig. 6 Courses of strains in time in selected points (cross sections I-I, II-II and III-III) of steel shell structure during passing a vehicle with a speed v_v = 20 km/h

with speed v_v = 20 km/h in load scheme III (Table 2). From the executed calculations and analysis results that the values of logarithmic decrement of damping of for soil-steel bridges seem to be considerably larger in comparison to magnitudes obtained in the case of traditional steel bridges (e.g., plate-girder and/or box girder, etc.). However having on an attention other the conducted tests by authors thereon type bridges there was possible to recognize these results as the similar values (Beben 2005).

6. Conclusions

Practical experiences obtained from the dynamic tests of the soil-steel bridge, which were

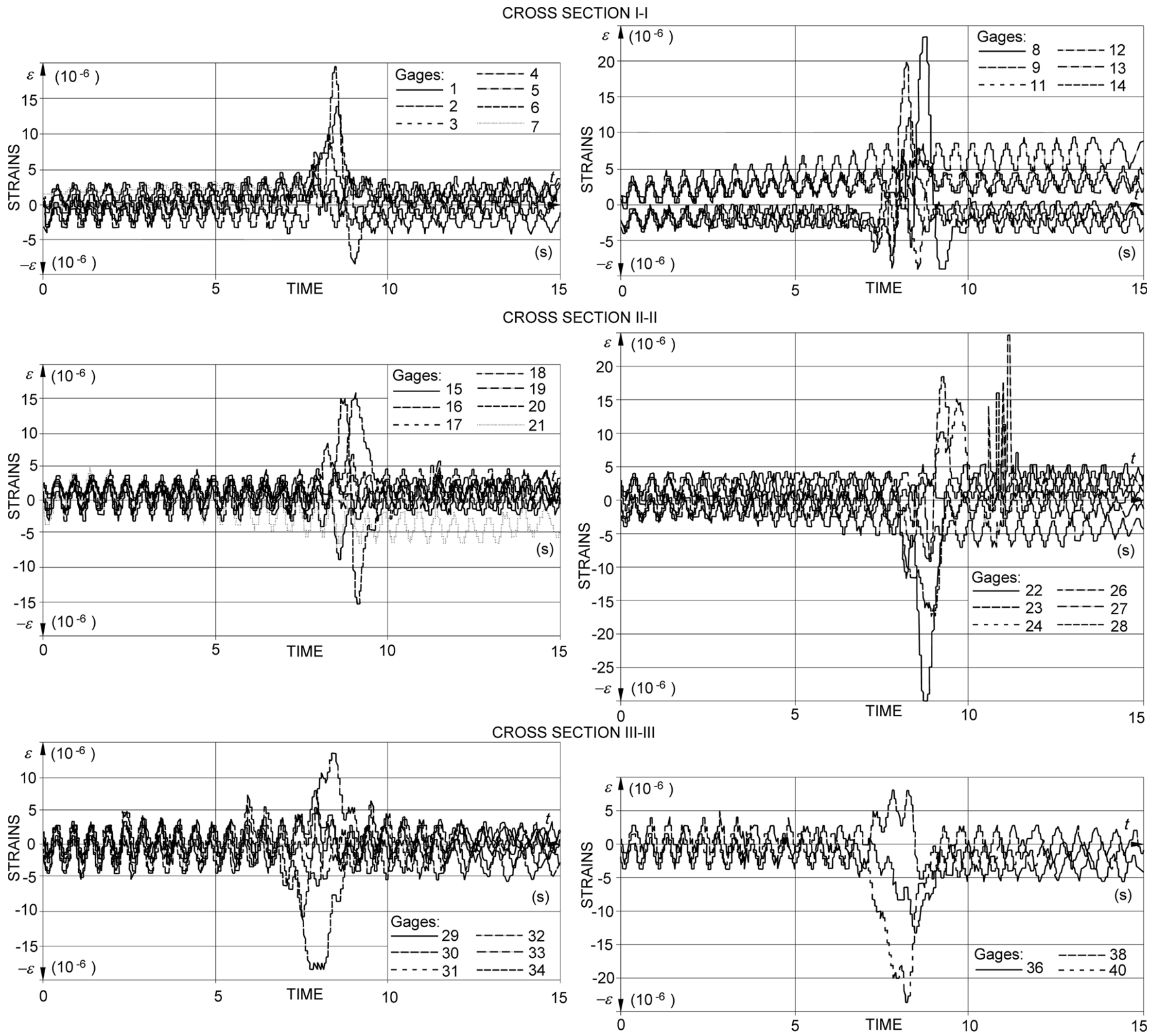

Fig. 7 Courses of strains in time in selected points (cross sections I-I, II-II and III-III) of steel shell structure during passing a vehicle with a speed v_v = 30 km/h

continuations of previously conducted static tests (Manko and Beben 2004), carried out with the intension of gaining complete view of the behaviour of bridge span and how to find relatively new structural solutions to them. The observations of the structure's behaviour as well as comprehensive analysis of obtained results and their comparison with calculated results allow for formulation of the following conclusions:

1. The critical speed has been determined in this case on the level $v_{cr.}$ = 30 km/h. It was one should add on it the certain limitation with regard on lack of realization possibility during experimental tests of higher speeds of vehicle passing (the sign of speed limit to 30 km/h).

2. The values obtained from dynamic analysis of this bridge distinctly prove that it is possible to allow the bridge to be serviced according to the design purpose i.e., loading with vehicles having a

total weight of 300 kN. The possibility of ride of heavier vehicles requires the additional tests, what will be done.

3. It was noticed that the dynamic results are various depending on the type of element, dynamic load scheme, speed of the loaded moving vehicle and above all, on the location of the point of measurement on the bridge shell, flexibility of steel shell structure and the soil properties (i.e., cohesion, density, internal friction angle, compaction degree, Poisson ratio, elasticity modulus) as well as the soil-steel interaction phenomena (Table 2).

4. The logarithmic decrement of damping values Δ calculated on the basis of the strains obtained from the experimental tests of bridge for all realized dynamic load schemes seem to be on the suitable level as for this type of objects. However it would belong to conduct the next tests of this bridge for higher speeds and heavier of vehicles passing, what in this case was made impossible with a regard of object safety and people with an attention on existing weather during tests conditions (it was snowed).

5. In the process of the research on dynamic load effects on bridge, no observation of irregularity of the steel structure under different load schemes was made. Only during some of the rides of the vehicle, the obtained results (velocity amplitude and vibration frequency) from velocity vibration gages could be seem too large in comparison with results obtained in researches made in typical steel bridges. Taking into consideration however, certain rough surfaces occurring on the contact the gage with the road surface as well as type of the tested structure and also nearness of the vehicle in relation to the installed gages which could have had some influence on the obtained results. However, it did not show any danger effects on the bridge, especially as their values did not exceed the calculated values (Manko and Beben 2004). The conducted wide range of dynamic tests caused to comprehensive effort, behaviour and evaluation of the each element in the shell structure of this bridge. The present conclusions also confirmed the observations taken from the tests under static loads (Manko and Beben 2004). In effect, total analysis gave rise to basis on which the bridge was qualified for normal service in accordance with the Polish Standards in bridges (similarly as in the Swedish Standards).

The above summary and final conclusions refer to a structure of tested bridge of given geometrical characteristics and rigidity of various elements as well as specified effective span. In order to be able to directly apply the results obtained in the research of dynamic load effects on bridges (among others, critical speed $v_{cr.}$) to other types of bridges, additional tests must be conducted on other bridges, consisting mainly of spans with different geometrical longitudinal cross section, different backfill thickness, different kinds of steels of different span structures as well as different proportions of rigidity of various elements e.g., different types of dimensions, corrugations, and strengths.

Acknowledgements

The paper is co-financed by the European Union in frames of the European Social Found.

References

Abdel-Sayed, G. and Salib, S.R. (2002), "Minimum depth of soil cover above soil-steel bridges", *J. Geotech.*

Geoenviron., **128**(8), 672-681.

Abolmaali, A. and Garg, A.K. (2008), "Effect of wheel live load on shear behavior of precast reinforced concrete box culverts", *J. Bridge Eng-ASCE*, **13**(1), 93-99.

Arockiasamy, M., Chaallal, O. and Limpeteeprakarn, T. (2006), "Full-scale field tests on flexible pipes under live load application", *J. Perform. Constr. Fac.,* **20**(1), 21-27.

Beben, D. (2005), *Soil-Structure Interaction in Bridges Made from Steel Corrugated Plates*, Faculty of Civil Engineering, Opole University of Technology, (Ph.D. thesis), Opole, Poland.

Beben, D. and Manko, Z. (2008a), "Experimental tests and finite element modelling analysis of behaviour of unconventional steel-soil structure", *Proceedings of Transportation Research Board of National Academies*, Washington, D.C., January.

Beben, D. and Manko, Z. (2008b), "Static load tests of a corrugated steel plate arch with relieving slab", *J. Bridge Eng-ASCE*, **13**(4), 362-376.

Dancygier, A.N. and Karinski, Y.S. (2000), "A model to analyze a buried structure response to surface dynamic loading", *Struct. Eng. Mech.*, **9**(1), 69-88.

El-Sawy, K.M. (2003), "Three-dimensional modeling of soil-steel culverts under the effect of truckloads", *Thin Wall. Struct.*, **41**(8), 747-768.

Kang, J., Parker, F. and Yoo, C.H. (2008), "Soil-structure interaction for deeply buried corrugated steel pipes. Part I: Embankment installation", *Eng. Struct.*, **30**(2), 384-392.

Kim, K. and Yoo, C.H. (2005), "Design loading on deeply buried box culverts", *J. Geotech. Geoenviron.,* **131**(1), 20-27.

Liu, Z.S., Lee, H.P. and Lu, C. (2005), "Numerical study of dynamic buckling for plate and shell structures", *Struct. Eng. Mech.*, **20**(2), 241-257.

Manko, Z. and Beben, D. (2004), *The Study of Road Bridge Structure of Steel Corrugated Plates Under Static and Dynamic Loads*, Scientific-Research Centre for Development of Bridge Industry MOSTAR, Wroclaw, Poland.

Manko, Z. and Beben, D. (2005), "Static load tests of a road bridge with a flexible structure made from Super Cor type steel corrugated plates", *J. Bridge Eng-ASCE*, **10**(5), 604-621.

Manko, Z. and Beben, D. (2006), "Behaviour of steel-soil bridge structure made from corrugated plates under field load tests (Part II: Dynamic research)", *Eng. Trans.,* **54**(1), 71-86.

Mohammed, H., Kennedy, J.B. and Smith, P. (2002), "Improving the response of soil-metal structures during construction", *J. Bridge Eng-ASCE*, **7**(1), 6-13.

Sezen, H., Yeau, K.Y. and Fox, P.J. (2008), "In-situ load testing of corrugated steel pipe-arch culverts", *J. Perform. Constr. Fac.,* **22**(4), 245-252.

Vaslestad, J. (1990), "Long-term behaviour of flexible large-span culverts", *Transportation Research Record No. 1231*, Transportation Research Board of the National Academies, 14-24, Washington, D.C.

Yeau, K.Y., Sezen, H. and Fox, P.J. (2009), "Load performance of in-situ corrugated steel highway culverts", *J. Perform. Constr. Fac.,* **23**(1), 32-39.

Yu, L. and Chan, T.H.T. (2005), "Moving force identification from bridge dynamic responses", *Struct. Eng. Mech.*, **21**(3), 369-374.