MATEC Web of Conferences **107**, 00013 (2017) DOI: 10.1051/matecconf/201710700013
DYN-WIND'2017

A comparison of spectral values obtained in bridge structures via radar interferometry and numerical calculations

Vlastislav Salajka[1,*], *Petr* Hradil[1], *David* Frybort[2] and *Michal* Glockner[3]

[1]Brno University of Technology, Faculty of Civil Engineering, Veveri 331/95, Brno, Czech Republic
[2]CONSULTEST, s.r.o., Sumavska 982/31a, Brno, Czech Republic
[3]Geodezie Ledec nad Sazavou s.r.o., Kozelska 225, Czech Republic

Abstract. Radar interferometry measurements were used to determine the dynamic response of two bridges. The dynamic excitation was performed via trucks crossing the road bumps placed upon each structure. From the relevant records we then determined the spectral values of the bridges. Detailed mathematical models enabled us to compute the natural frequencies and modes (shapes), and these were subsequently compared with their measured counterparts.

1 Introduction

In the monitoring of bridge structures, a basic observed quantity consists in the displacement of structural points caused by the response to the self-weight, traffic, and wind. At present, the static and dynamic behaviour can be also examined via a novel contactless method exploiting radar interferometry; in the wider sense, however, this approach is still being tested. A series of previous experimental measurements showed that the discussed technique can be applied in fast contactless defining of vertical deflections, with the accuracy of up to 0.01 mm in real time. Interestingly, the method is further characterized as suitable for the determination of vibration frequencies in particular objects [1]; as such frequencies may reach as high as 50 Hz, the approach naturally finds application in the monitoring of differently sized bridges, whose dominant vibration frequencies range between 0.5 Hz and 20 Hz.

Before using the method to monitor the static and dynamic motion of a structure, it is advisable to recognize not only the basic static values (deflections of the structure) specified within relevant calculations but also the main natural frequencies and vibration modes, or shapes. Such a set of data enables us to identify suitable positions for the radar reflectors, and it also facilitates the verification of or comparison between the measured values. In many cases, however, appropriate calculations are unavailable or lack the required data; this problem often associates with bridges built during previous decades and

* Corresponding author: salajka.v@fce.vutbr.cz

makes us estimate the positions of the reflectors merely based on common engineering practice.

Radar interferometry remains usable also in situations where the dynamic response is to be determined with respect to evaluating the effects induced by traffic and dynamic wind. The measured values are instrumental for the verification of the initial design and condition of the structure concerned, and they should agree with the results computed using models of the monitored structures.

To demonstrate the applicability of interferometry in measuring the responses of various bridges, we present the outcomes of measurement cycles performed in two markedly different bridges. Both the identification of suitable positions to place the radar reflectors and the selected force excitation procedure (via trucks) exploited design computations simulating the actual load test. We compared the measured and computed deflection values produced by the static testing; the records of the dynamic responses obtained during the excitation of the bridges through the vehicles then enabled us to determine the natural vibration frequencies to be correlated with the computed values.

2 Arch RC bridge

The bridge is a reinforced concrete structure with abutments in the slopes of the embankments, and it embodies a self-anchored arch system having an upper slab deck that rests on four inclined struts and rigid fixing at the crown of the arch. The total length of the structural frame equals 85.9 m, the width is 6.7 m, and the arch span corresponds to 51.3 m, at the rising height of 5.195 m (Fig. 1).

Fig. 1. A view of the discussed bridge with radar and reflectors.

The computational model of the structure to facilitate static and dynamic calculations was set up using the ANSYS system. The full-scale computational model is predominantly based on SOLID187 spatial ten-node finite elements; however, SURF154 and SHELL281 eight-node surface and shell elements, respectively, were also exploited to a large extent. Reinforced concrete is assumed as an isotropic linear elastic material, exhibiting the elastic modulus of E = 33 GPa and the coefficient of lateral contraction equalling ν = 0.2. The specific weight of the material is estimated to be 2 500 kgm^{-3}; the real data are unknown. The specific weight of the reinforced concrete components of the ledges, including the railings, is assumed as 2 600 kgm^{-3}; the corresponding presumed weight of the road then amounts to 2 000 kgm^{-3}. The selected elastic modulus of the ledges is several orders of magnitude lower to prevent the structure from affecting the stiffness of the

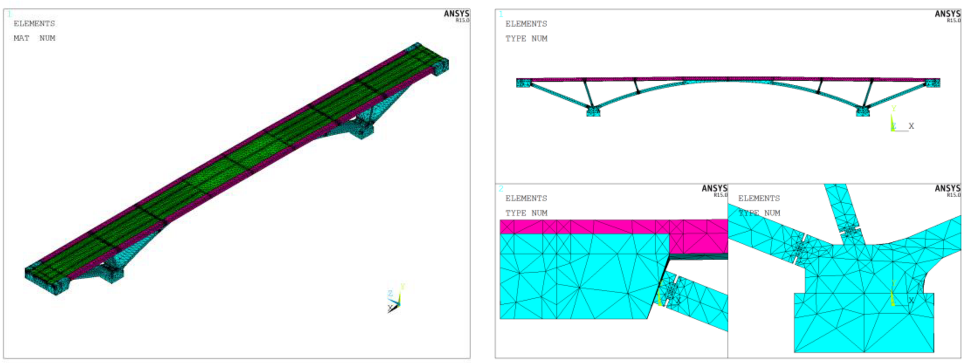
 DOI: 10.1051/matecconf/201710700013

bridge. The elastic modulus of the road is also selected to be lower, namely 5 GPa. The bearing system is designed as partially pliable.

The static testing comprised two measurement cycles correlated with the positions of two vehicles stationed upon the bridge; their weights, 22.150 Mg and 18.720 Mg, were adopted from relevant weight certificates.

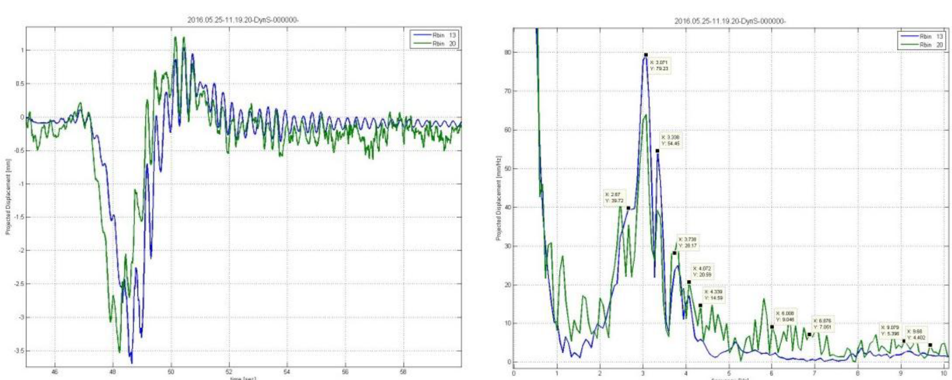
In the actual computation, the two above-indicated values corresponded to the total static load of 400.935 kN, which had been set within the proportional action of the individual wheels.

The measurement records showed the maximum deflection in the central section of the bridge equalling 4.32 mm and 4.20 mm during the first and second test, respectively; the computation-based rate that corresponds to these two values is 4.516 mm. The experimentally obtained deflection at the level of the ledges ranges between 4.41 mm and 4.68 mm, with the computed value being 4.606 mm.



a) The axonometric representation of the model; b) the detailed struts and Freyssinet hinges.
Fig. 2. The mathematical model of the arch bridge.

The dynamic test, involving the heavier vehicle advancing along the structure, produced two measurement sets; we monitored the displacement at both the ledges and the centre of the arch. The excitation was performed via the given vehicle crossing a road bump, whose various locations had been determined from the preliminarily computed natural shapes of the vibrations. In total, twenty four measurement records were acquired; the patterns related to the measured displacement and spectral values are exemplified in Figure 3a) and 3b).



a) The dynamic response patterns; b) the spectral response record.

Fig. 3. The analyzed load case (L5) – a dynamic response pattern – the first set of measurements.

 DOI: 10.1051/matecconf/201710700013

The sought frequency values constitute the average of those from the spectral records; the thus obtained values of three frequencies are presented in Table 1.

The same model for the computation of the static response was used to compute the fifteen lowest natural frequencies and modes (shapes). The first five specified natural frequency values complemented with the description of the related vibration shapes are shown in Table 1. For completion, Figs. 4 to 7 display the natural vibration shapes of the first four natural frequencies.

Table 1. The natural frequencies: measurement and computation.

Frequency No.	Computed [Hz]	Measured [Hz]	Vibration shapes
1	**2.675**	**2.460**	1st transverse
2	**3.182**	**3.056**	1st symmetric flexural
3	**3.363**	**3.309**	1st antisymmetric flexural
4	4.158		2nd symmetric flexural
5	5.089		1st torsional

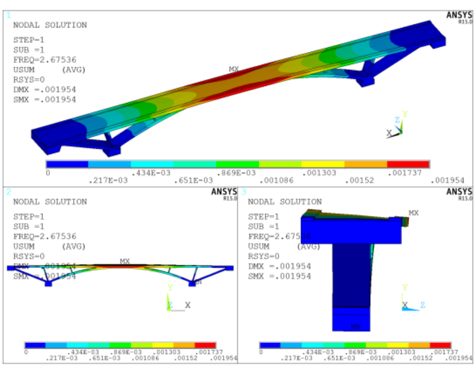


Fig. 4. Natural vibration shape: $f_1 = 2.675$ Hz.

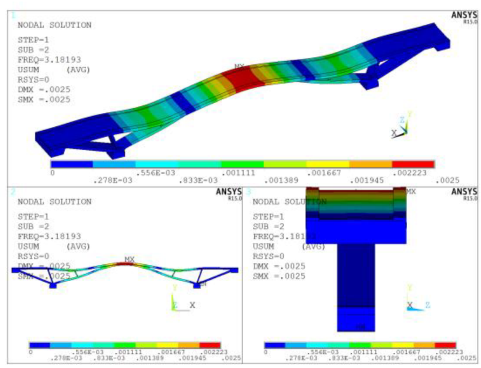


Fig. 5. Natural vibration shape: $f_2 = 3.182$ Hz.

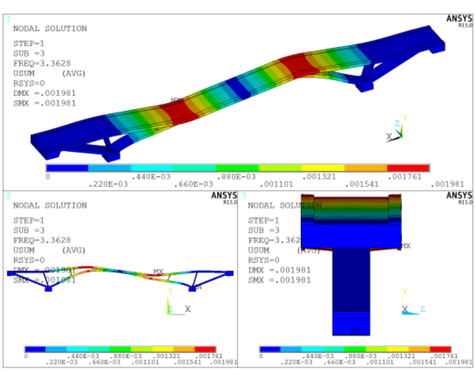


Fig. 6. Natural vibration shape: $f_3 = 3.363$ Hz.

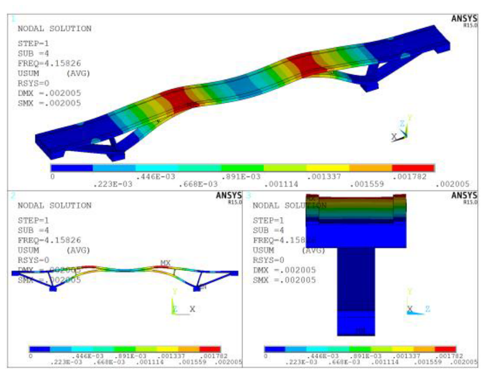


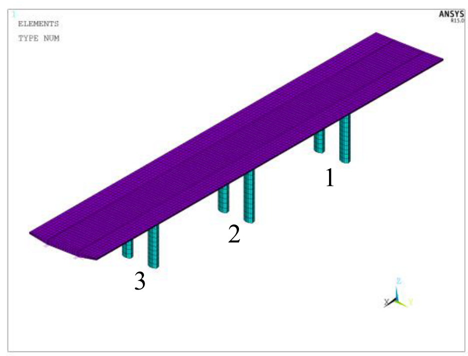
Fig. 7. Natural vibration shape: $f_4 = 4.158$ Hz.

3 Continuous multi-span RC slab bridge

Another monitored structure is a bridge whose horizontal portion consists in a continuous prestressed concrete deck having four fields with the span of 13.0 + 17.0 + 17.0 + 13.0 m and obliquely seated on supports. Within the transversal section, the deck is designed in all its fields as a plate of variable thickness. End cross beams are fixed above the abutments. The width of the carrying frame equals 10.05 m, and the frame rests on elastomeric bearings in all the supports. The inner supports are pairs of piers exhibiting different heights.

In this structure too, the model for static and dynamic computations was set up in ANSYS, mainly from SOLID185 spatial eight-node finite elements; these were used to model the piers and the deck. Further, the model exploited SHELL181 four-node shell elements combined with the SOLID185 ones to simulate the distribution of the forces transferred by the modelled bearings, and it also comprised COMBIN14 two-node finite elements to model the stiffnesses of the bearings.

The same material model of reinforced concrete was used; the estimated specific weight of the deck, including the non-carrying frames, amounts to 2 500 kgm^{-3}, and the specific weight of the piers is 2 400 kgm^{-3}.



a) The carrying frames of the bridge; b) the computational model of the bridge, with the piers numbered.

Fig. 8. The axonometric representation of the overall model: subdivision into components.

The static testing comprised two measurement cycles correlated with the positions of two vehicles stationed upon the bridge; these vehicles were positioned between the second and third pairs of pillars. We obtained the values of deflection at the centre of the span of the second field (between pillars 2 and 3), at the ledges, and at the centre of the bottom face of the deck. The weights of the vehicles, 27.580 Mg and 17.900 Mg, were adopted from relevant weight certificates.

In the related computation, the two above-indicated values corresponded to the total static load of 446.159 kN.

The measurement records indicated the maximum deflection in the central section of the bridge being 1.96 mm and 1.98 mm for the first and second vehicles, respectively; the computation-based rate that corresponds to these values is 2.054 mm. The experimentally acquired deflection at the level of the ledges ranges between 1.98 mm and 2.13 mm, with the computed value within the interval from 1.977 mm to 2.271 mm. The larger difference at the ledge on the walkway side can be explained via simplification in the modelling procedure. The stiffness of the sidewalk was not considered in the computation.

In the dynamic test, we measured the deck motion values at locations identical with those observed during the static monitoring. The bridge was excited by the heavier vehicle crossing the applied road threshold at various speeds (30 and 50 km/h). The threshold was positioned to lie either on the axis of the bridge or at its edge, progressively in the second and first fields. The positions had been determined from the preliminarily computed natural vibration shapes. The vehicle was driven on both sides of the bridge, and we obtained 16 measuring records in total.

The first eight specified natural frequency values complemented with the description of the related vibration shapes are shown in Table 2. For completion, Figs. 9 to 14 display the natural vibration shapes of the first five and seventh natural frequencies.

Table 2. The natural frequencies: measurement and computation.

Frequency No.	Computed [Hz]	Measured [Hz]	Vibration shape
1	0.982		Longitudinal
2	3.979		1^{st} transverse
3	**5.386**	**5.518**	1^{st} antisymmetric flexural
4	**7.094**	**7.214**	1^{st} symmetric flexural
5	8.106		1^{st} flexural - support
6	8.115		1^{st} flexural - support
7	**9.360**	**9.445**	2^{nd} antisymmetric + flexural longit.
8	9.398		1^{st} flexural - support

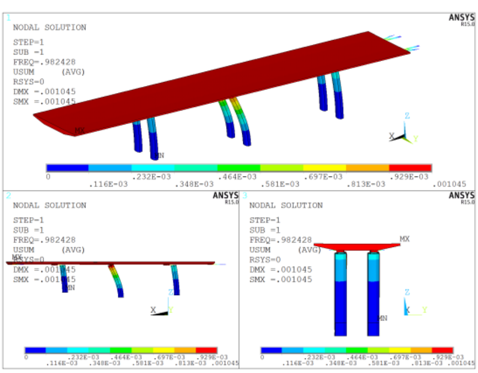


Fig. 9. Natural vibration shape: f_1 = 0.982 Hz.

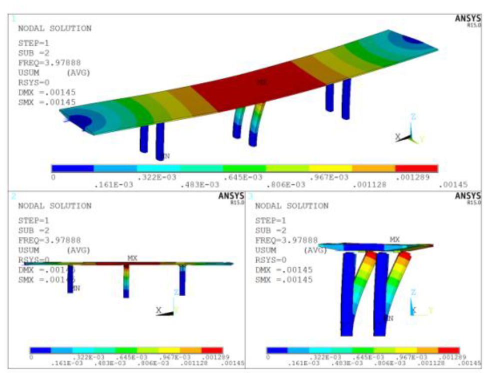


Fig. 10. Natural vibration shape: f_2 = 3.98 Hz.

DOI: 10.1051/matecconf/201710700013

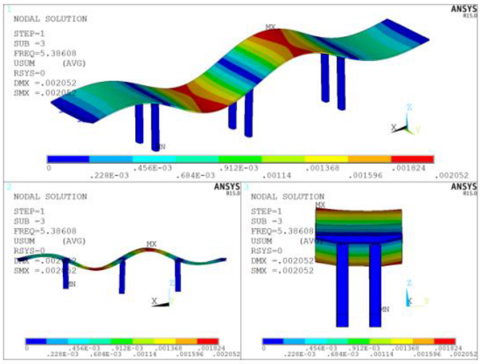


Fig. 11. Natural vibration shape: f_3 = 5.386 Hz.

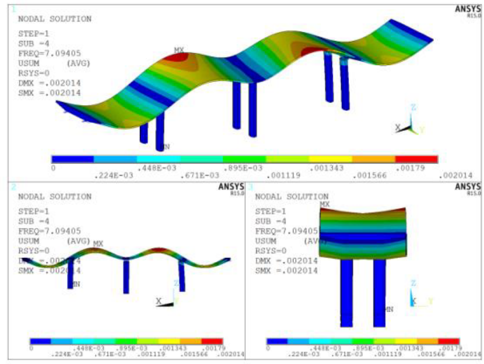


Fig. 12. Natural vibration shape: f_4 = 7.094 Hz.

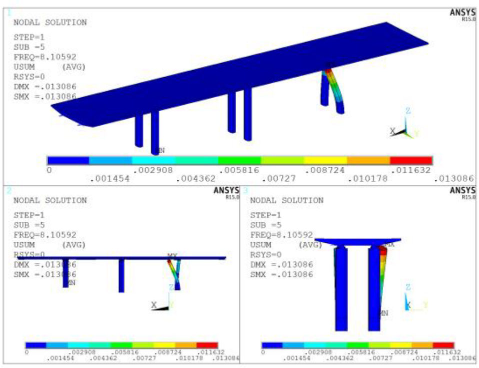


Fig. 13. Natural vibration shape: f_5 = 8.106 Hz.

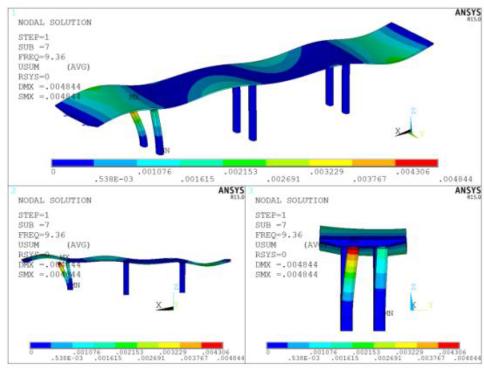


Fig. 14. Natural vibration shape: f_7 = 9.360 Hz.

4 Conclusions

We used the finite element method to set up two similarly designed spatial computational models of two different structures, namely, the reinforced concrete expressway bridges joining the municipalities of Velké Albrechtice and Studénka and urban districts of Polanka nad Odrou and Václavovice (bridge registration codes D1-412.2 and D1-430.2, respectively). All the residential areas are situated in northern Moravia, the latter two being districts within the city of Ostrava.

The static response and natural shapes of vibration were computed in both of the structures. Relevant preliminary calculations enabled us to determine the positions to place the trihedral corner reflectors during the static and dynamic load tests, performed using radar interferometry.

This method was employed to yield the deflection values observed under the load generated by the vehicles used, and it also facilitated the measurement of the dynamic response to a heavy vehicle on the bridge structure. To increase the dynamic effect, the vehicle repeatedly crossed the applied road bump, and the recorded dynamic responses were instrumental for determining the sought frequency spectra.

A comparison of the experimental and computational static response results showed that radar interferometry can be advantageously utilized in static tests and pointed to the high quality of the bridge models set up via the finite element method.

The FEM-based models were exploited in the computation of the natural frequencies and modes (shapes) of the vibrations. For each model, we registered a frequency spectrum of fifteen natural vibration frequencies and shapes; these spectra were then compared with those acquired through measurement. In both cases, the three lowest measured natural frequencies were successfully associated with the calculated ones having corresponding natural vibration shapes.

If we compare the measured and computed values, it becomes obvious that, on condition that the natural frequencies were correctly paired, the results exhibit very good agreement. This type of operation, however, remains an issue hitherto not fully resolved; it would beneficial to create a methodology for processing the time records such that we could clearly determine the natural vibration shapes to which the frequencies found should be assigned.

Significantly, the time records of the dynamic response displacement are normally obtainable and can be employed as the basis for further analysis of the monitored structures. The present paper, comparing the related experiments and computations, proposes that the diagnostics of bridge structures is suitably performable via radar interferometry; this approach, however, could be improved by using multiple radars to suppress the deficiencies arising from the shadowing of parts of the structure.

In terms of the dynamic behaviour, the diagnostics have to be completed with an evaluation methodology to facilitate the assignment of frequencies to corresponding vibration shapes; otherwise, similarly to other relevant methods, it is invariably necessary to rely on computation.

Measurement was performed using interferometric radar IBIS-S, high precision total station Sokkia Net 1AX, videorecorder SONY HDR-CX115 and weather station Conrad D152.

This paper was created with the financial support of project GACzR 17-23578S “Damage assessment identification for reinforced concrete subjected to extreme loading“.

References

1. M. Talich, M. Glockner, *A novel approach to defining vertical deflection in railway bridges via terrestrial radar interferometry* (Železniční mosty a tunely, Praha, 2015, in Czech)
2. V. Salajka, *Preparing data for radar interferometry measurements and comparing the measured and computed results* (Technical report, Consultest, Brno, 2016, in Czech)
3. P. Kohnke, ANSYS mechanical APDL Theory Reference, Release 15.0, (ANSYS Inc., 2013)
4. J. Kala, P. Hradil, V. Salajka, V. Juttner, Dynamic response of cable stayed steel bridge with tuned mass damper installed - Numerical and experimental approach, 10th International Conference on Modern Building Materials, Structures and Techniques, Vilnius (2010)
5. V. Salajka, J. Kala, Z. Cada, P. Hradil, Modification of response spectra by probabilistic approach, Proceedings of the European safety and reliability conference, Wroclaw, (2004)