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Identification of the Swiss Z24 Highway Bridge by Frequency Domain Decomposition

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Abstract

This paper presents the result of the modal identification of the Swiss highway bridge Z24. A series of 15 progressive damage tests were performed on the bridge before it was demolished in autumn 1998, and the ambient response of the bridge was recorded for each damage case. In this paper the modal properties are identified from the ambient responses by frequency domain decomposition. 6 modes were identified for all 15 damage cases. The identification was carried out for the full 3D data case i.e. including all measurements, a total of 291 channels, a reduced data case in 2D including 153 channels, and finally, a 1D case including 20 channels. The modal properties for the different damage cases are compared with the modal properties of the undamaged bridge. Deviations for frequencies, damping ratios and MAC values are used as monitoring variables. From these results it can be concluded, that frequencies and model shapes for the structure changed significantly during damage. Further, it can be concluded, that the spatial information gained by a large number of channels does not seem to result in significant better estimates of frequency and mode shape deviations.

Introduction to data and identification

This paper describes the modal identification of the old Swiss highway bridge Z24 at highway A1 between Bern and Zurich. The bridge was demolished in the autumn of 1998, but before demolition, a series of 15 progressive damage tests (PDT's) were carried out. The description of the PDT's can be found in Kramer et al. [1]. The damage cases can shortly be summarized as follows:

PDT02: 2nd reference measurement
PDT03: Settlement of pier, 20 mm
PDT04: Settlement of pier, 40 mm
PDT05: Settlement of pier, 80 mm
PDT06: Settlement of pier, 95 mm
PDT07: Tilt of foundation
PDT08: 3rd reference measurement
PDT09: Spalling of concrete, 12 m^2
PDT10: Spalling of concrete, 24 m^2
PDT11: Landslide
PDT12: Concrete hinges
PDT13: Failure of anchor heads
PDT14: Anchor heads #2
PDT15: Rupture of tendons #1
PDT16: Rupture of tendons #2
PDT17: Rupture of tendons #3

The data was measured in 9 data sets, 8 data sets with 33 channels and one with 27 channels (data set 5, the data from the middle of the bridge). Three reference sensors were used, one unidirectional, and one 3D sensor. All sensors measured accelerations with a sensitivity of 5 Volts/g. The bridge was loaded by natural loads and by the traffic passing under the bridge. Each data set consists of 10.9 minutes long time series sampled simultaneously at 100 Hz . Before analysis the time series were decimated by a factor three corresponding to an effective sampling rate of 33.3 Hz.

All data were analyzed using frequency domain decomposition (FDD) as described in Brincker et al. [2], however all data presented in this paper were estimated using the enhanced version of the FDD (EFDD), Brincker et al. [3]. All identifications were performed using the ARTeMIS *Extractor* software.

The full 3D data case

The first two data sets are shown in Figure 1. As it appears three sensors are keep as reference sensors at the same position in all data sets while the remaining sensors are moved along the bridge, one row at each side of the bridge,

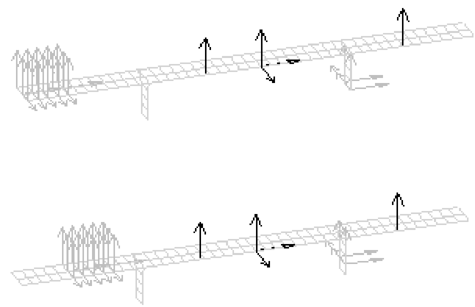

Figure 1. Reference sensors and moving sensors in the first two out of the nine data sets for the Z24 bridge.

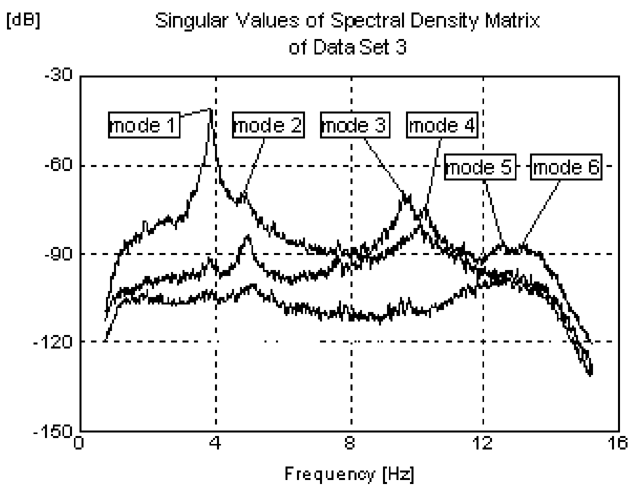

Figure 2. Modes identified in all tests of the Z24 bridge

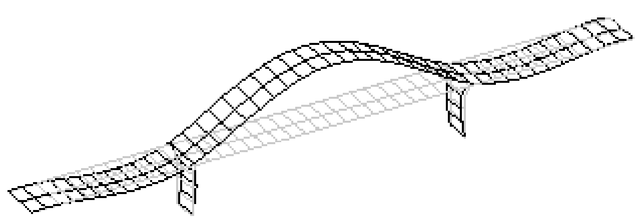

Figure 3. Mode 1, Vertical bending.

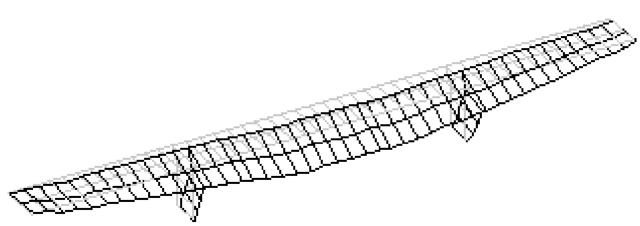

Figure 4. Mode 2, Transversal rocking, horizontal bending.

one row in the middle. There were 120 measurement points on the bridge deck, 30 in each row, and 16 on the piers, 8 on each of the two piers. Thus, the total number of measurement points was 136. It is assumed that the transverse and longitudinal horizontal movement of the bridge deck is the same over the cross section of the bridge deck. Using this assumption, the 3D movements can be estimated in all the 136 measurement points resulting in a modal model with 408 degrees of freedom.

The 6 modes estimated in all tests are indicated in Figure 2. The results of the identified frequencies and damping ratios for all PDT's are listed in Table 1 and Table 2 respectively. Typical mode shapes are shown in Figures 3-8. The details of the bridge deformations are determined rather well, denote the clamped behavior between pier and bridge deck as shown in Figure 9.

Table 1. Identified natural frequencies in Hz

PDT	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
02	3.876	5.021	9.828	10.28	12.70	13.48
03	3.871	5.059	9.836	10.30	12.83	13.41
04	3.858	4.926	9.770	10.23	12.46	13.20
05	3.763	5.003	9.397	9.801	12.17	13.21
06	3.686	4.917	9.253	9.681	12.12	13.05
07	3.842	4.648	9.705	10.16	12.11	13.13
08	3.856	4.886	9.783	10.31	12.50	13.10
09	3.869	4.853	9.819	10.30	12.33	13.31
10	3.860	4.871	9.789	10.33	12.29	13.31
11	3.853	4.696	9.799	10.32	12.11	13.17
12	3.846	4.678	9.735	10.21	11.72	13.17
13	3.847	4.715	9.747	10.21	11.73	13.21
14	3.842	4.689	9.754	10.20	11.70	13.21
15	3.846	4.648	9.764	10.24	11.60	13.05
16	3.830	4.689	9.739	10.21	11.66	13.11
17	3.825	4.720	9.720	10.18	11.71	13.18

Table 2. Identified damping ratios in %

PDT	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
02	0.85	1.40	1.21	1.23	1.17	0.86
03	0.65	1.30	1.29	1.08	1.27	1.32
04	0.79	1.71	1.23	1.20	1.80	1.24
05	0.78	1.31	1.20	1.04	1.90	1.44
06	0.87	1.48	1.34	1.13	2.14	1.31
07	0.75	1.74	1.23	1.12	1.70	1.73
08	0.79	1.61	1.26	1.36	1.36	1.65
09	0.86	1.60	1.23	1.13	1.37	1.16
10	0.86	1.65	1.11	1.23	1.51	1.04
11	0.91	2.23	1.37	1.17	2.15	2.07
12	0.79	1.73	1.31	1.12	2.10	1.64
13	0.91	2.10	1.33	0.98	2.18	1.56
14	0.98	2.31	1.34	0.93	2.24	1.39
15	0.99	2.29	1.35	1.17	2.33	1.08
16	0.90	1.99	1.30	1.08	2.34	1.36
17	0.88	1.98	1.37	1.12	2.29	1.38

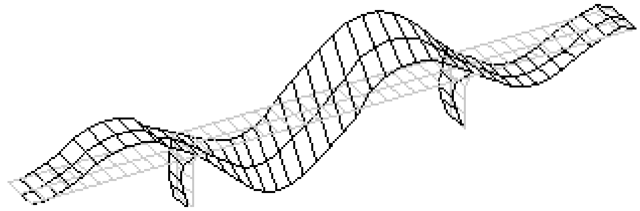

Figure 5. Mode 3, Vertical bending and torsion.

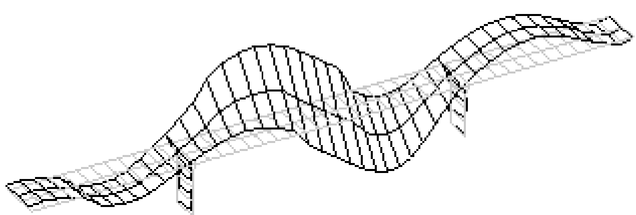

Figure 6. Mode 4, Vertical bending and torsion.

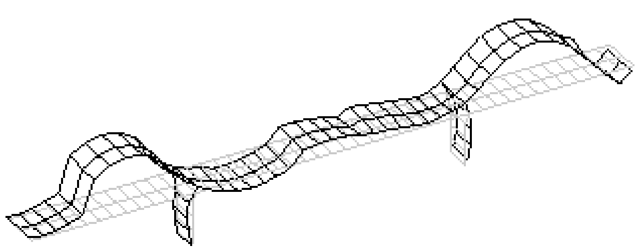

Figure 7. Mode 5, Vertical bending.

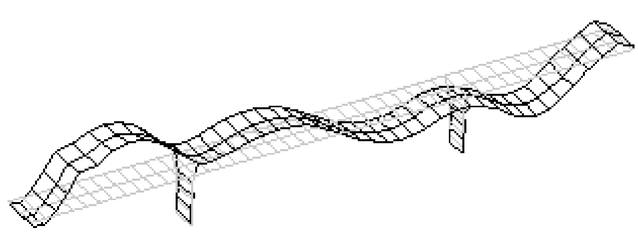

Figure 8. Mode 5, Vertical bending.

The 2D data case

Removing a large part of the measurement points and discarding all longitudinal sensors creates the 2 dimensional case. In this case only the vertical and the transverse horizontal movements of the bridge are determined.

This leads to a case with a total 153 channels distributed in the 9 data sets, 36 measurement points on the bridge deck, one row at each side, and all measurement points kept on the piers. A total of 52 measurement points each with 2 degrees of freedom, thus, a case with a total of 104 degrees of freedom.

The placement of sensors for the first two data sets are shown in figure 10, and typical mode shapes for the first two modes are shown in Figure 11 and 12 respectively.

All natural frequencies and damping ratios determined in the 2D case were rather close to the estimated values for the full 3D case. The standard deviation of the differences between the natural frequencies for the two cases was determined to 0.04 Hz, and the standard deviation of the difference between damping ratios for the two cases was determined to 0.20 %.

The 1D data case

By removing all horizontal sensors and keeping only 2 measurement points in the side spans and 4 in the mid span creates the 1D case. In this case, the vertical displacements of all supports are assumed to be zero.

Still all 3 reference sensors was kept, but only the data sets 2, 4, 6 and 8 were applied for this analysis. This leads to a case with a total of 20 channels distributed in 4 data sets, 8 measurement points each with one degree of freedom, thus a total of only 8 degrees of freedom.

All natural frequencies and damping ratios determined in the 1D case were rather close to the estimated values for the full 3D case. The standard deviation of the differences between the natural frequencies for the two cases was determined to 0.06 Hz, and the standard deviation of the difference between damping ratios for the two cases was determined to 0.33 %.

Damage Monitoring

Before damage can be detected and identified, the modal estimates must be combined with other sources of information to determine whether or not the structure has been subject to any significant physical changes.

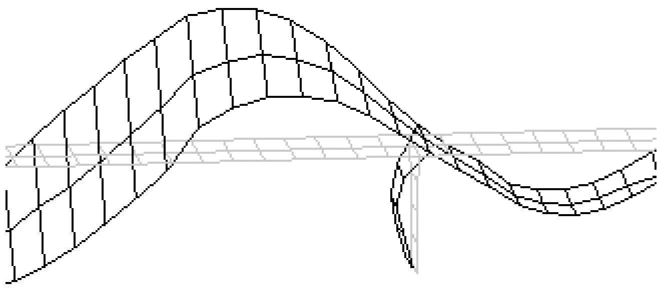

Figure 9. Close-up of mode shape for mode 3 showing the stiff connection between pier and bridge

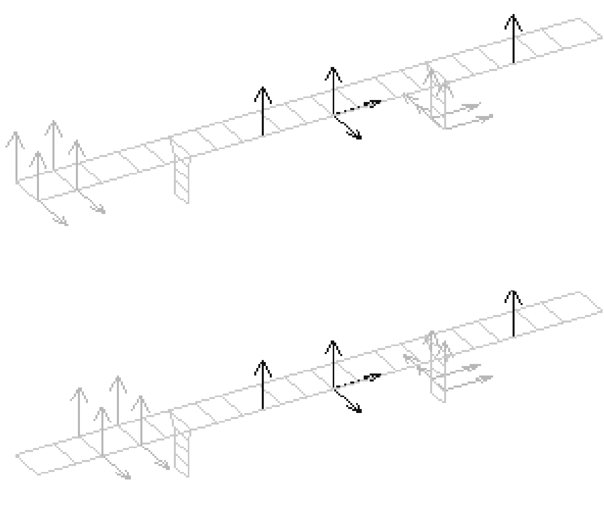

Figure 10. The two first data sets for the reduced 2D case.

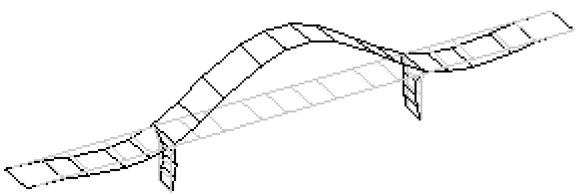

Figure 11. Mode 1 for the 2D case.

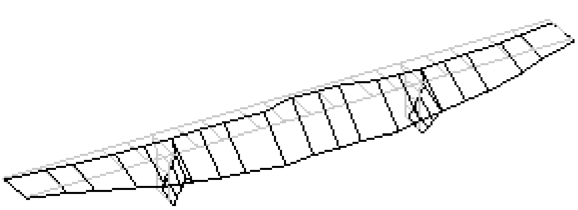

Figure 12. Mode 2 for the 2D case

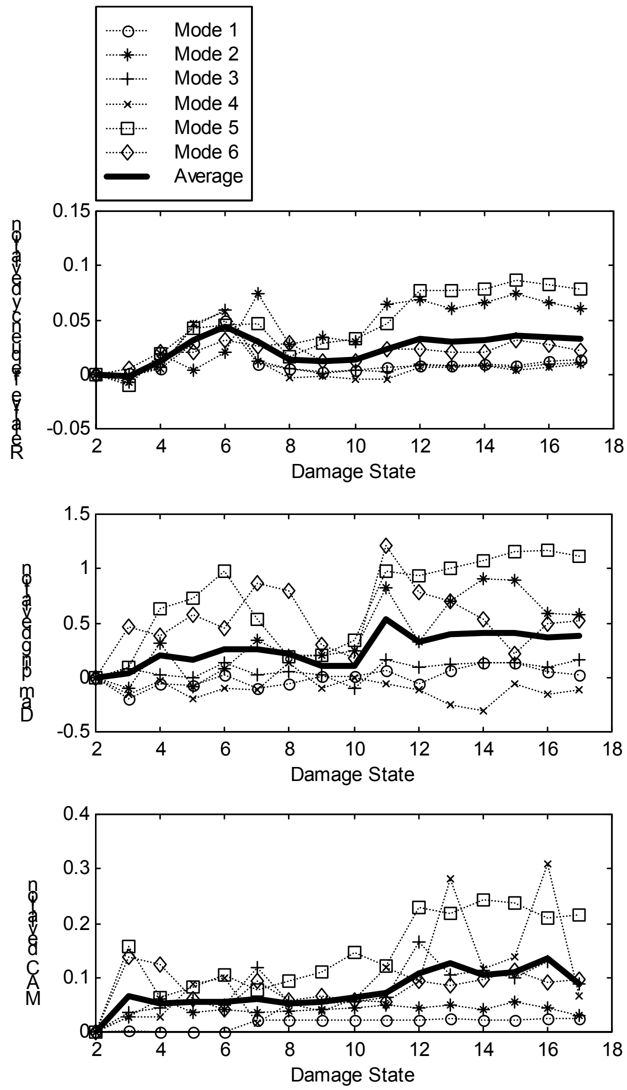

Figure 13. Monitoring variables for the 3D case

For that purpose three simple monitoring variables were estimated: frequency deviation, damping deviation, and finally mode shape deviation.

The frequency deviation was calculated as the relative frequency drop, i.e. the drop of natural frequency between the specific PDT and the reference test divided by the natural frequency of the reference test. The mode shape deviation was calculated as the deviation of MAC value from unity.

The monitoring variables were calculated for the 3D, the 2D and the 1D cases, and the results are shown in Figures 13, 14 and 15.

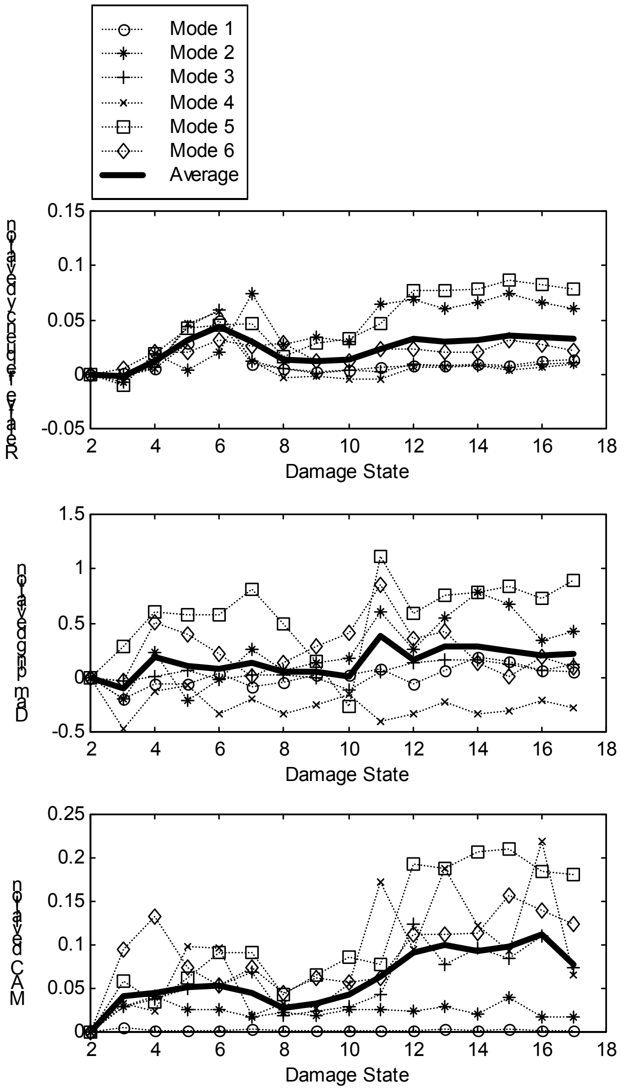

Figure 13. Monitoring variables for the 2D case

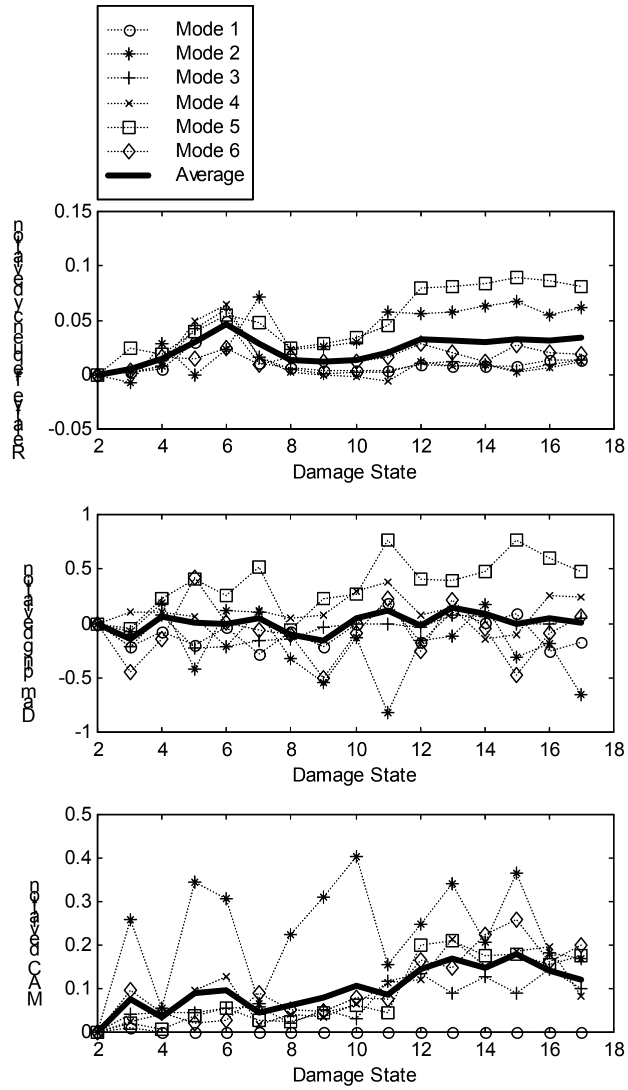

Figure 14. Monitoring variables for the 1D case

As it appears from the results of the monitoring investigation, a clear frequency drop for all 6 modes can be detected for damage states 4-6. For later damage states a somewhat smaller but significant drop can be detected. Regarding frequency deviation no significant difference can be seen between the 3D, the 2D and the 1D case.

For damage states 11-12 and later, a significant increase in the damping ratio can be detected for the 3D and the 2D case, however, a similar increased cannot be seen for the 1D case.

Some increased in mode shape deviation can be seen for all damage states. However, since the deviation is one-sided, some of the deviation is due to random errors, and not necessarily due to physical changes. Later states 12-17 show a clear increase in the deviation indicating that damage has been introduced. The later mode shape deviation is stronger in the 2D and 1D case than it is for the 3D case.

Conclusions

With the frequency domain decomposition technique it was possible to detect all 6 bending/torsion modes in the frequency range from 0-16 Hz for the full 3D case including 408 degrees of freedom, for the 2D case including 104 degrees of freedom, and the 1D case including 8 degrees of freedom.

Natural frequencies and damping ratios was practically the same for the 3D, 2D and the 1D case.

Monitoring of the data was performed using frequency, damping and mode shape deviations. All three deviations clearly indicated that damage had been introduced, however, the clearest indication is believed to be based on frequency deviation.

Monitoring based on the 3D, 2D and the 1D case showed that there is only a very little difference between the monitoring of the three cases. Thus, in practice when a structure is to be monitored, the results of this investigation suggests that a good monitoring can as well be based on a limited number of sensors.

Acknowledgements

The main part of the elaborate work of performing all the identifications were done in Oslo in the kitchen of Ingunn Mari Eide. Her company and support is gratefully acknowledged.

References

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