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Continuous Load and Condition Monitoring of a Highway Bridge

Surveillance continue de l'état et des charges d'un pont autoroutier

Dauerüberwachung für die Belastungs- und Zustandsbeobachtung einer Autobahnbrücke

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SUMMARY

The maintenance of structures and the protection of their serviceability requires a profound knowledge not only of their actual but also of their prospective condition. Consequently, it is convenient to observe the structure's conditions by means of permanent monitoring systems measuring all important parameters which can influence the structure's behaviour. Only the continuous and simultaneous measurement and control of certain data, like traffic loads, temperature distributions, etc., and their effect on the main structural parameters, provide for a reliable interpretation of changes in the structures behaviour.

RÉSUMÉ

Une bonne conservation des ouvrages et le maintien de leur aptitude au service exige non seulement une connaissance précise de leur état actuel mais aussi de leur fonctionnement futur. Cela implique une surveillance continue qui peut être réalisée aujourd'hui à l'aide de techniques modernes de mesures et d'évaluation. Seul le contrôle continu et simultané de différentes valeurs ayant une influence sur les paramètres principaux d'un ouvrage, par exemple les charges de trafic et les répartitions de température, permet d'interpréter de façon sûre les dégradations susceptibles de se manifester.

ZUSAMMENFASSUNG

Für die Erhaltung von Bauwerken und zur Sicherung ihrer Funktionsfähigkeit ist es notwendig, eine genaue Kenntnis sowohl des aktuellen als auch des künftigen Bauwerkszustandes zu haben. Dies ist eine Aufgabe der Dauerüberwachung, die heute unter annehmbaren Aufwand mit Hilfe moderner MeB- und Auswerttechniken durchführbar wird. Erst die gleichzeitige und kontinuierliche Beobachtung, Messung und Kontrolle verschiedenster Einflussgrössen auf relevante Bauwerksparameter, wie zum Beispiel Verkehrslasten und Temperaturverteilungen, ermöglichen eine sichere Interpretation von sich ankündigenden Zustandsänderungen.

1. INTRODUCTION

The guarantee of the functioning and serviceability of constructions, which are subject to the changing service loads and functional behaviour, where certain external effects are not predictable or the real bearing capacity ist not exactly known, is a very ambitious task. One contribution to solve this problem is to observe and assess permanently the loading and the condition of the structure by using automatically operating monitoring systems. In recent years at BAM Berlin such a system was developed and tested. In this paper the conception of the system and the kind of installation at a highway bridge in Berlin, Germany, is described and first results received with this system are presented.

2. CONCEPTION

The main task for the mission of a monitoring system is to extend the service time of a structure. To meet this aim amplitude and duration of the service loads will be observed continously. Based on this data possible changes of material properties which are not directly observable can be predicted using static and dynamic stress models. Beyond that the alteration of the structure, that is the decrease of bearing capacity, modification in the static system due to internal and external effects, corrossion etc. can be assessed by measuring static and quasistatic deformations, amplitudes of vibration, eigenvalues and mode shapes and the increase of known damages like cracks on certain positions at the structure. Results received from the monitoring data which will enable repair work at an early stage will extend the service life of the structure and give more security of the functional behaviour and load bearing capacity.

The monitoring system records the real loadings of the traffic. The results are given as load distribution functions. These are the data basis for the evaluation of load models, by which the fatique life of the structure can be computed by using well-known fatique models. The dynamic components of the traffic loads increase the level of loading and reduce the service life time due to fatique effects. The dynamic loading components are recorded in terms of the so-called dynamic factor, which is defind by $\varphi = \varepsilon_{stat+dyn} / \varepsilon_{stat}$.
Since the number of sensors for such measurements is limited, it is very important to know the location of maximum stress of the considered constructions. It is convenient to use modal analysis techniques for this purpose. First of all the eigenfrequencies f_i which are excited mostly by the traffic passing over the bridge have to be identified by means of long-term measurements due to the bridge's vibration. When these frequencies are known the modal shapes w_i belonging to f_i will be determined by an experimental modal analysis under artifical excitation. In certain cases it is also possible to extract modal shapes from measurements under traffic excitation. The areas of maximum stress can be evaluated by differentiating the modal shapes, using the relation $w_i''(x) \approx \varepsilon_i(x)$. It should be mentioned, that this approach requires sufficient close distances between the measurement points.

Observing and assessing the global state as well as local properties and possible changes of the structure is the main aim of conditional monitoring. Changes in the bearing capacity are normally caused by changes in the vital members of the structure due to cracks or changes in the support of the structure. Alteration of that kind modifies the dynamic behaviour of the structure, i.e. the modal parameters are changing. In order to detect changes in the structural behavior at an early stage relevant natural frequencies and related modal shapes are used as indicator values or functions. In [2] results are given which show that especially for statically

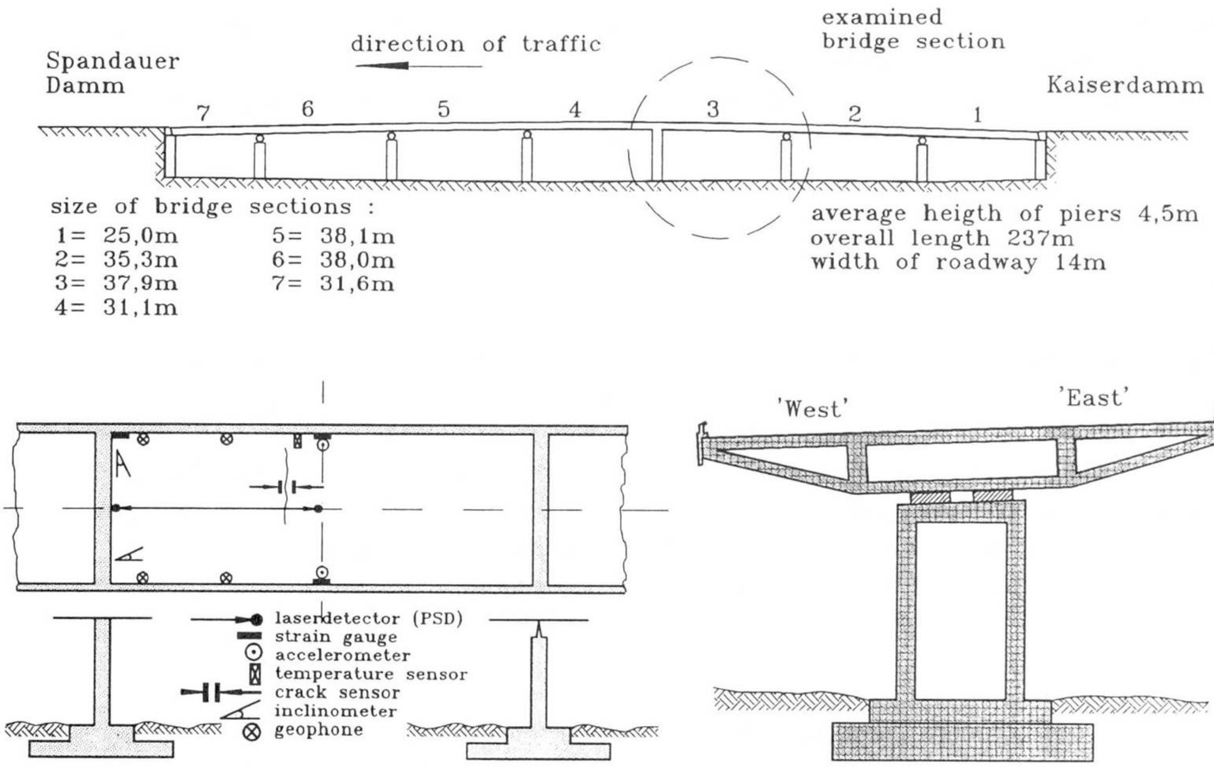

Figure 1: Highway Bridge Westend
Profile of the bridge (above), Location of sensors (left), Cross-section (right)

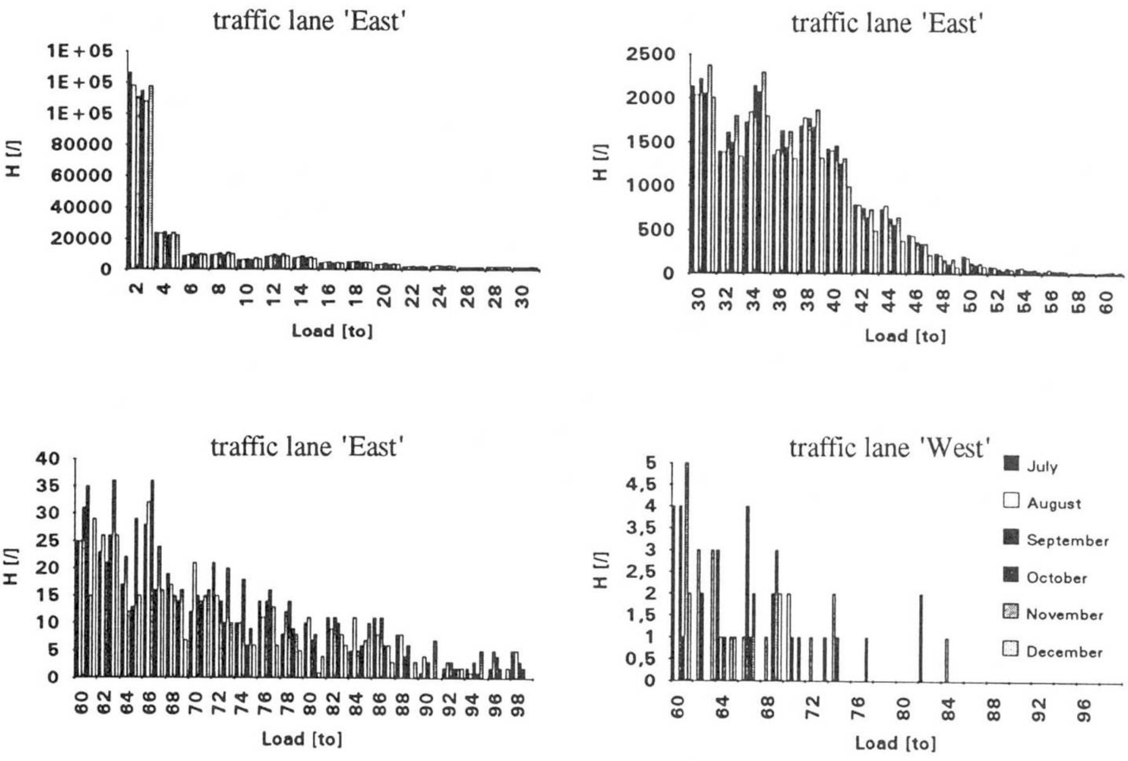

Figure 2: Frequency H of static traffic loads P_{stat} from 6 months (July - December 1994)

indeterminated systems the modal shapes are much more sensitive indicating alteration of the structural behaviour then natural frequencies.
In order to record the influence of temperature variations to the static and dynamic behaviour of the bridge, two sensors measuring the structural temperature are also included in the monitoring system.

3. STRUCTURE AND SENSORS

This 30 year old prestressed bridge (figure 1) has had a lot of cracks occurring at the floor slab of the hallow box, at the cross girder above the columns and at the longitudinal main beams. There was no clear explanation for these cracks. So the supervising authority decided to repair the bridge first and then to install a monitoring system to surveille the bridge by measuring the service loads and the conditional behaviour permanently. Positions and types of 15 sensors attached inside the bridge is shown in figure 1. The traffic loadings are measured with strain gauges attached at the middle of the main beam and above a support.

4. RESULTS

From the amount of existing monitoring data some selected results will be discussed. At first we discuss the results of loading control. The common approach to simulate traffic loads, Riera et. al. described in [3], is a composition of assumptions about vehicle characteristics, mean velocities and traffic composition. In connection with a numerical model this loads result in desired dynamic responses. In our approach we directly measure the dynamic responses and then based on this data develope an artificial loading model for the bridge. Assuming linear conditions the bridge was calibrated first by measuring the maximum midspan strains at the girders of the described span due to a heavy truck of known weight travelling along the bridge on different lanes. The monitoring system then is measuring continously the loading conditions under normal traffic.Within a certain time window the maximum value of measured strains is stored.This will be done before and after a low pass filtering of the signal. In relation to the results of the calibration data each of these strain values belong to an artificial vehicle load due to each traffic lane. So in certain periods of time an averaged passage frequency classified by vehicle loads is developing, which is as stable as the measuring time is long enough. Figure 2 shows representative results of the load density function for a observation time of 6 months.
Long-time monitoring is able to show the monthly deviations of the load distributions. Comparing the results of figure 2 with those of the theoretical results in [3] a recognizeable difference is that the measured loads does not fulfill a normal distribution.

vehicle loads [to]	West	East
0 - 29	99.466 %	94.35 %
30 - 59	0.530 %	5.55 %
40 - 90	0.004 %	0.10 %
total	1209769	1255124

Table 1: The distribution H of the classified passages

The dynamic factor φ is shown in figure 3. The distribution due to each respective loading class is different. Up to the value $\varphi=1.25$ the relative frequency H_r in each loading class and traffic lane is equal. For values $\varphi > 1.25$ on the traffic lane 'West' in comparison with

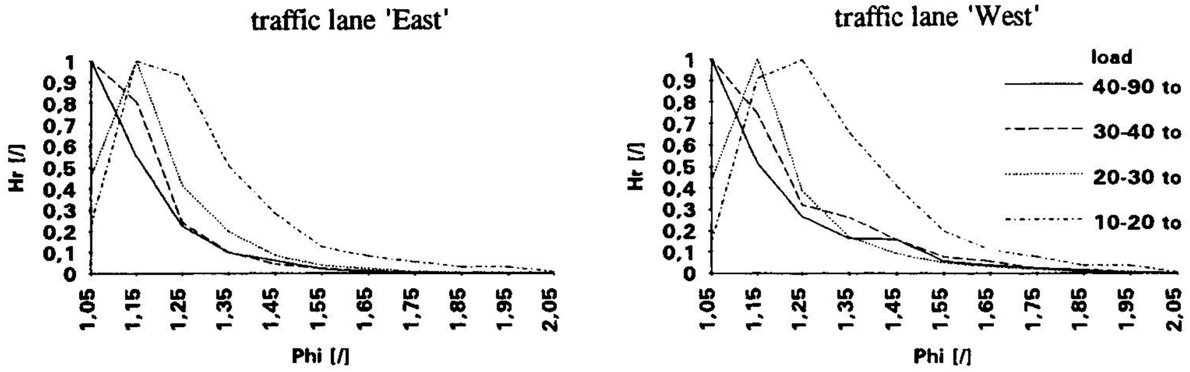

Figure 3: Relative frequency H_r of the dynamic factor φ measured during July 1994

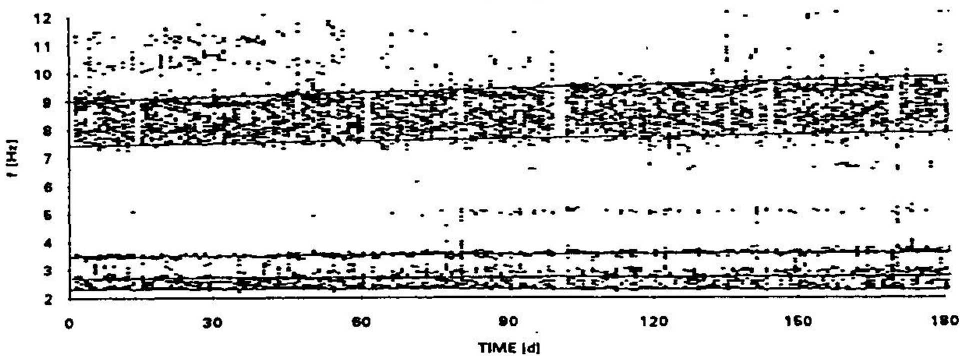

Figure 4: Dominant frequencies f_i measured during t=6 months (July - December 1994)

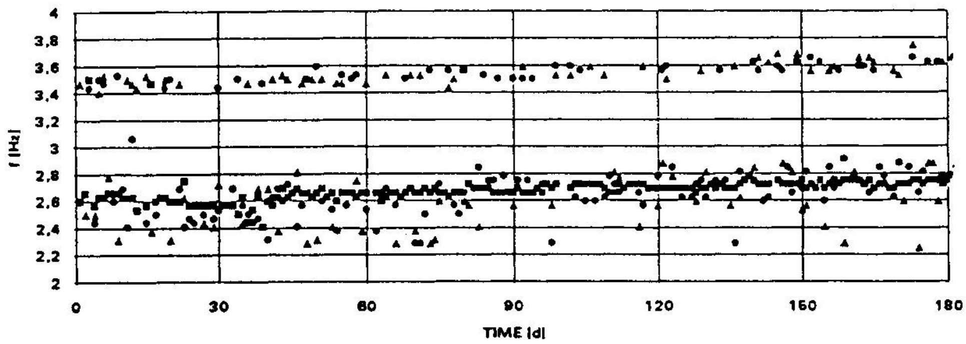

Figure 5: Changes of 2 natural frequencies f_i of the bridge (zoomed from figure 4) due to temperature variations

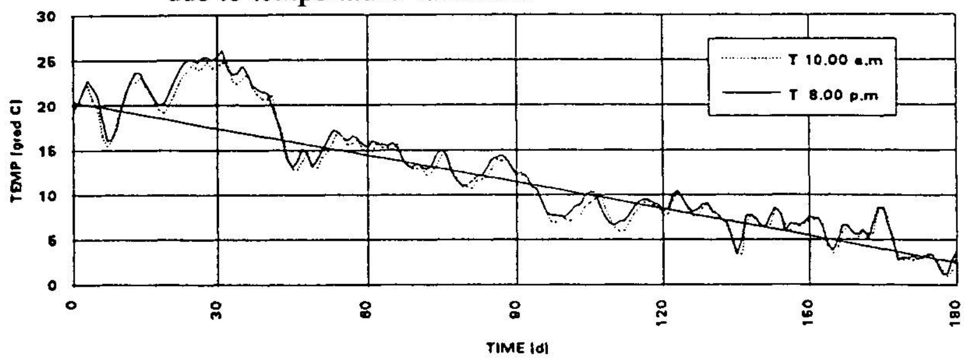

Figure 6: Structural temperature T measured during t=6 months (July - December 1994)

with 'East' (figure 3) we can find a greater amount of vehicles in all load classes with higher dynamic loading parts due to their higher velocities.

As part of the condition monitoring figures 7 and 8 present results of monitored changes of the natural frequencies at certain measurement points of the bridge. The approach of getting this results is measuring permanently the vibrations of the bridge, evaluating the frequency spectra and picking from that a certain amount of frequencies which belong to dominant amplitudes. Marking these frequencies daily in the diagram the results are presented in figure 4. In case of unchanged structural conditions natural frequencies can be detected as horizontal lines within the amount of all frequency points. The natural frequencies determined by means of modal analysis can also be identified but in a noisy environment.This effect is predominant the influence of the changing constitutions of traffic relating to bridge excitations. Figure 4 shows one of the results of condition monitoring during the period of 6 months. Here the values of the natural frequencies are increasing, what means that the structural stiffness is increasing. Zooming figure 4 into figure 5 this trend is visible as a linear function and will be caused by the change of the structural temperature (figure 6). The correlation between both indicates a relationship approximatly $\Delta f \cong 1/100 \cdot \Delta T$. The physical background of this effect is exactly not yet known, but the consequences are not negligible. Variations of the structural stiffness within an adjusted finite element model for the bridge have shown, that the difference $\Delta f = 0.2$ Hz of the natural frequencies f_1 and f_2 due to the change of the temperature between summer and winter corresponds to a change of stiffness of more than 50% of one whole span. This effect shows that monitoring additional environmential parameters is not of secondary significance.

5. CONCLUSIONS

This contribution introduces an automatically working monitoring system for loading and condition monitoring of bridges. The loading control includes determination and classification of equivalent vehicle loads outgoing from continously measured static and dynamic strains at the structure. The condition monitoring supplies criteria about the actual local and global structual conditions under the control of different sensitive parameters like deformations, dynamic quantities and environmential parameters. Results of the system which has been working since more than 2 years at a highway bridge in Berlin are presented.

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