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Autor: König, Gert / Ötes, Atilla / Giegerich, Gerald
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Structural Integrity of Bridge Ulenbergstrasse in Düsseldorf

Aptitude au service du pont Ulenbergstrasse à Düsseldorf

Gebrauchsfähigkeit der Brücke Ulenbergstrasse in Düsseldorf

Gert KÖNIG
Professor Dr.-Ing.
Institut für Massivbau
Technical Unversity Darmstadt
FRG

Atilla ÖTES
Dr.-Ing.
König und Heunisch
Consulting Engineers
Frankfurt, FRG

Gerald GIEGERICH
Dipl.-Ing.
Institut für Massivbau
Technical University Darmstadt
FRG

Hans J. MIESSELER
Dipl.-Ing.
Strabag Bau AG
Köln, FRG

SUMMARY
The Bridge Ulenbergstraße in Düsseldorf is the first road bridge construction where prestressing is entirely provided by resin bonded glass fibre (Polystal) tendons. In order to verify the structural integrity under service conditions a long term monitoring program has been established. In the paper, integrity monitoring techniques applicable to concrete bridges are briefly reviewed and the special monitoring program for Ulenbergstraße is presented. Finally, the results obtained until now are discussed.

RESUME
Le pont Ulenbergstraße à Düsseldorf est la première construction de pont ou la précontrainte est fournie par des éléments de précontrainte en fibre de verre collés à résine (Polystal) entièrement. Afin de vérifier l'aptitude au service sous contrainte de service, un programme de contrôle sur plusieurs années a été établi. Les techniques applicables aux ponts en béton sont révisées et le programme de surveillance de l'aptitude au service du pont Ulenbergstraße est présenté. Les résultats obtenus jusqu'ici sont discutés.

ZUSAMMENFASSUNG
Die Brücke an der Ulenbergstraße in Düsseldorf ist die erste Straßenbrücke, bei der die Vorspannung gänzlich durch die Spannglieder aus dem Faserverbundwerkstoff Polystal aufgebracht ist. Um die Gebrauchsfähigkeit der Brücke über längere Zeit beobachten zu können, wurde ein entsprechendes Inspektionsprogramm aufgestellt. In dem Beitrag werden die auf Betonbrücken anwendbaren Überwachungsmethoden kurz besprochen und das spezielle Inspektionsprogramm für die Brücke Ulenbergstraße vorgestellt. Abschließend werden die bisher gewonnenen Ergebnisse diskutiert.

1. INTRODUCTORY REMARKS

The roadbridge Ulenbergstraße in Düsseldorf has been the first major bridge project of the joint venture Strabag Bau-AG and Bayer AG, where prestressing is entirely provided by resinbonded glassfibre tendons /1/.

Prior to the execution of the project in summer 1986 comprehensive investigations have been carried out on both the glassfibre material and the special questions regarding its application to concrete bridges. The material tests did not only deal with strength and stiffness properties but also focused on aspects like resistance to chemical attack and to physical damage. Regarding the application of the glassfibre material to prestressing tendons several questions pertaining to bond properties, resistance to the perpendicular pressure in anchorages, etc. had to be solved. Finally, an appropriate design concept has been developed to cope with the special features of the new material such as the relatively low modulus of elasticity ($E = 51000\ N/mm^2$) as well as the brittle type failure and the lower long-term strength.

The tests, in principle, proved the developed material to be adequate for prestressing of concrete structures. Nevertheless, for its first major application to a roadbridge with heavy traffic loads a systematic multiannual inspection program has been deemed to be indispensible.

In principle, the inspection aims at the identification of any change of the structural integrity in an early stage. Particular emphasis is laid on the inspection of the behaviour of the glassfibre tendons in order to evaluate their fitness for the purpose. In order to meet these objectives several monitoring and identification techniques have been incorporated. However, it should be remarked, that some of these methods currently is in research stage and necessitate detailed studies to be further developed.

2. INTEGRITY MONITORING OF CONCRETE BRIDGES

The ultimate objective of the regular integrity monitoring of concrete bridges is to identify and to quantify changes in the load carrying capability. Since cracks may significantly impact the stiffness as well as the durability of a bridge the attention is primarily directed towards monitoring of cracks and detection of their sources.

Regular visual inspection may help to identify cracks if they are visible. The human eye, however, does not have access to each part of the bridge. Consequently some cracks, e.g. in top of the sections on supports in multi-span bridge systems, may remain undetected under the paving. Not only the identification of unvisible cracks but also questions like

- Which are the sources of cracking?
- Which are the residual values for stiffness and loading carrying capacity of the structure?

call for additional monitoring tools. The answers to the above questions may urgently be needed to evaluate the structural integrity and in case to initiate measures for strengthening and repair.

A monitoring technique which is nondestructive and capable to recognize both the damage as well as its source in an early stage and to quantify it in a reliable way would constitute a perfect inspection tool. However, considering the appreciable size of a bridge structure, the diversity and inhomogenity of the materials and the various environmental effects such as traffic flow, temperature, humidity, etc., it can easily be recognized that monitoring of a concrete bridge is not only associated with expenses but also with serious limitations and uncertainties.

A further basic problem in damage source detection stems from the fact that the measured quantities, in general, pertain to physical effects which result from the damage source but not necessarily reveal it directly. For example, the rupture of a prestressing tendon may lead to such a local increase of tensile stresses that concrete cracks but the rupture itself may still remain unrecognized.

In addition to these general problems also some special phenomena like the interaction of the superstructure with nonstructural and substructural elements may pose further serious questions regarding the interpretation of the measured data.

Despite all these difficulties techniques developed for integrity monitoring of concrete bridges should satisfy the following requirements:

- predicative
- objective and reproducible
- reliable
- nondestructive

and

- economical.

In the following, the potential monitoring techniques applicable to integrity monitoring of concrete bridges are discussed in the light of the above listed criteria:

- Visual inspection:

  Performed by well-trained human eye it is a highly reliable inspection technique and is inexpensive. If carried out at regular intervals the crack propagation can be recognized. However, the method is neither capable to give clear indications on the source mechanisms nor does it provide any direct means to evaluate the residual integrity quantitatively. Furthermore, it can be viewed to be useless for cases with brittle-type failure.

- Deformation and strain measurements:

  Sensitive measurements of the deformations under dead loads along both the bridge spans as well as the bridge sections carried out at regular intervals may indicate changes of the overall stiffness properties.
  To eliminate the influence of the environmental effects, special measurements under well-defined static loads can be carried out. Comparing the measured data with analytical results, the overall stiffness properties can be quantified.
  Since the deformation increase reflects an integral value of the contributions of all bridge sections, the method doesn't offer a direct means to localize the cracks effectively. It may well give indications on potential crack zones but does not allow to quantify the cracks individually. Hence, it is not suitable for identification of crack source mechanisms.
  The capability of deformation monitoring can considerably be improved by strain monitoring. Concrete surfaces in critical zones, prestressing tendons

or reinforcing bars can be effectively monitored using appropriate strain gauges. In connection herewith, also the use of load cells should be mentioned. For example, monitoring the prestressing force in a tendon, which is not bonded with concrete, by using a load cell can be helpful to recognize changes in the overall behaviour.

- Vibration monitoring (dynamic system identification):

Systematic vibration monitoring aiming at the identification of dynamic parameters such as natural frequency, damping and modal shapes may offer substantial means to quantify the stiffness changes and to localize their sources.
If events like overloading, restraint or loss of prestressing result in cracks or high stress concentrations, stiffness and damping properties of the vibrating system change. With increasing damage the natural frequencies decrease wheras the damping values increase. Furthermore, modes which have large relative rotations in damaged zones exhibit a higher relative change in their eigenfrequencies and thus give indications on potential damage zones. Since many mode shapes can be excited and checked with regard to their properties, for the detection of damages dynamic monitoring provides a much larger data basis than the static displacement measurements.

Vibrations can be induced either by artificial excitation or by ambient vibrations. In any case, system identification tests are conducted at very low-level excitations since testing may not cause any damage to the structure. Hence, sensitive transducers are needed to capture the dynamic response of the structure.
Having identified the dynamic properties of a bridge shortly after construction, a representative mathematical model can be developed by fitting its parameters to those gained from the experimental data. Evaluating the data from periodically performed measurements the eigenfrequencies, damping values and mode shapes can be determined and compared with the reference values of the first measurement (nonparametric identification). If changes are identified, adequate methods must be implemented to fit the mathematical model to the new data (parametric identification) /2/. This step is necessary to determine the change of structural properties such as stiffness, mass and stresses which are essential to draw conclusions concerning the state of the structure.

For an effective use of this monitoring technique following prerequisites must be considered:

- Adequate equipment: wide-band exciter, sensitive accelerometers, highly capable data acquisition system
- For interpretation and pattern recognition: profound knowledge on nonlinear force-deflection characteristics of R/C bridges with emphasis on cracking and its effects on stiffness and damping properties.
- Additional measurements and experience in pattern recognition for environmental, nonstructural and substructural interactions.

The current state of practice is such that considerable additional work is necessary for both to further develop the identification technique as well as to determine the limits of application to bridges quantitatively.

- Monitoring using optical sensors:

Inaccessible parts of the bridges, e.g. the prestressing tendons can be effectively monitored by means of optical fibres. If appropriately attached to the tendons or even integrated in the tendons as in the case of glass-fibrons tendons, the optical fibres may offer the possibility to observe the tendon deformations remotely. If appropriately designed and reliably measured, the fibres can serve a dual purpose: First, they indicate the elongation of the prestressing tendon by the decrease of the transmissibility of the light, which is due to the fact that the transverse strains reduce the fibre section. Secondly, fracturing of the fibre can either indicate a given stress level or the fracture of the tendon, both causing a loss of the light at the detector. Measuring the reflection, the location of the fracture can be determined.
Problems may arise in connection with transverse stresses in the anchorage zones as well as at the bends of the tendons. Current studies are quite promising /3/.

- Crack monitoring by acoustic emission analysis:

Microcracking, local deformation, friction and plastification in inaccessible parts of a concrete structure, in principle, can be captured detecting the stress waves released from such sources by piezoelectric sensors /4/. Parameters such as energy, wave amplitude, duration and frequency content may comprise useful information about the source mechanisms. Crack initiation and growth can only be captured through permanent monitoring whereas the energy release due to friction effects may also be detected by inspections at regular intervals provided that a dynamic situation exists. Questions pertaining to problems such as the environmental noise, the attenuation of the waves and the small amplitude of the stress changes are currently dealt with in systematic investigations /3/.
In any case, for a rational monitoring of a bridge the method should be considered in a later step, namely if the techniques presented before indicate that a deterioration has occured. Having a first estimate about the location of the defect the acoustic emission analysis can be implemented to detect the damage and, if possible, to measure its size.

- Ultrasonic testing

Ultrasonic testing techniques are widely used to detect cracks and material defects /5/. In concrete, however, the reduction of the transmitted ultrasound and reflected echoes is much more emphasized than in metallic materials. Because of the porosity of the material the absorption and particularly scattering may become so high that the signals for defects cannot be recognized. In order to reduce scattering wave lengths must be increased. This measure, however, results in an increase of divergence of the sound and complicates the identification of the defect size.
The frequency range for application to concrete is 50 - 150 kHz. In this range the transmission technique can be used to detect cracks and flaws by changes of the transmission velocity.

3. INTEGRITY MONITORING OF BRIDGE ULENBERGSTRASSE

Bridge Ulenbergstraße is a two-span roadbridge designed for the load class 60/30 (tons) according to DIN 1072 (Fig. 1). In the longitudinal direction the bridge is prestressed with 59 glassfibre tendons, each composed of 19 dia 7,5 mm tendon rods and providing a tensile working force capacity of 600 kN per unit.

The serviceability requirements for partial prestressing according to DIN 4227, part 1 governed the determination of the number of tendons. The amount of the ordinary reinforcement is sufficient to cope with an increase of stresses due to cracking of concrete without yielding. The ultimate load carrying capacity is 30 % higher than required by the design provisions. Additional safety is provided by nonprestressed steel tendons which are conceived as "emergency belts". In case of large deformations of the structure they would automatically be activated and would contribute to the load carrying capacity. Further, space is preserved for additional steel tendons to be installed at an advanced level of damage in order to suppress the cracks and thus to rehabilitate the bridge /5/.

Under service conditions no cracking is supposed to occur. The analysis shows that quite a number of prestressing tendons may fail without causing a visible crack in concrete. This specific aspect clearly states the need for a monitoring tool for early warning.

Since the modulus of elasticity of glassfibre is much lower than of steel, cracking is assumed to result in larger deformations exhibiting wider crack openings. Test on beam specimens have clearly confirmed this phenomenon. For the inspection task this fact certainly means a simplification but considering the consequences of large cracks one can easily realize that a quick and effective source detection is of paramount importance. Hence, adequate monitoring techniques are needed which are capable to evaluate both the magnitude and the consequences of the damage. In connection herewith, the review of design assumptions and further analytical investigations, within certain limits, may help verify the quantitative findings by the measurements.

Finally, for the advanced level of a damage where repair or strengthening measures must be taken, effective methods are needed to answer questions like whether the damage in the tendons is a local phenomenon or whether it is propagating or not.

Considering the above design aspects as well as the conceivable damage patterns and levels a multiannual monitoring program has been set up. The monitoring techniques chosen are viewed to support each other (Table 1). In the following, for each of the monitoring techniques the special aspects regarding the implementation and the results obtained from the measurements until now are presented:

- Visual inspection: No cracking could be observed during the visual examinations carried out hitherto.

- Deformation measurements: The vertical displacements under dead loads and well-defined truck loads (2 x 22 = 44 tons) have been measured in 24 points using a level. 2 x 9 points are located on the superstructure reflecting the bending modes in longitudinal as well as perpendicular directions. On each of the supports two points have been monitored in order to separate the relative deformations from the overall displacements. The accuracy of levelling performed until now is approximately 1 mm which is of the same order as the

maximum displacements under truck loads. Since the geometry of the prestressing tendons is such that no compressive forces act at the level of the tendon, creep effects on displacement can be neglected. In order that the temperature effects remain negligable, the measurements have been carried out at about 5 a.m.
Until now the measurements did not indicate any change of the deformation characteristics.

- Monitoring of unbonded tendons: Permanent measuring of the prestressing force in three unbonded glassfibre tendons by load cells provides a further tool to recognize major changes in the structural behaviour. Since the force change is controlled by the global deformations of the bridge, local changes cannot be captured sensitively. However, any integrity change of the prestressing tendon itself can easily be captured.
  Until now no indication on integrity loss could be observed.

- Dynamic system identification: Prior to the application of this method various analytical models for the bridge superstructure have been studied with regard to modal parameters such as natural frequencies and mode shapes. A simple beam model has been quite sufficient to reflect the bending modes but because of the high width/span ratio of the superstructure it has beennecessary to develop a 3D-model which captures the geometry entirely.
  Based on these analytical estimates the optimal locations for artificial excitation as well as measurement points have been established. For the excitation such positions have been selected which are far enough from the contraflexural sections of all the modes of interest. For the measurement points an appropriate grid size has been chosen which offers the possibility of capturing of all the modes effectively (Fig. 2). In meeting the decision about the number of the measurement points also economical aspects have been considered, since only a limited number of transducers are available.
  The bridge has been excited dynamically using a hydraulic actuator mounted on a concrete block and placed on the superstructure (Fig. 3). Accelerating the mass (460 kg) on the jack with a random noise in the range of 0 - 64 Hz, vertical forces have been applied to the structure. In order to avoid any damage to the structure the force level has been limited to 15 kN. Some of the basic criteria which led to this type of excitation are:

  - As the number of available transducers is significantly smaller than the number of measuring points, an excitation technique is needed which is capable of exciting a wide range of frequencies and can reliable be reproduced multiple times. The latter feature is essential to satisfy the requirement for constant excitation during the stepwise identification of the entire measuring grid.
  - The applied force can be kept almost constant over the entire frequency range and be controlled easily. In case, the level of the forces as well as the range of frequency can be adjusted to the specific boundaries to achieve a better identification.

  The dynamic response of the bridge has been recorded using sensitive seismometers wherby in each configuration three measuring points and one reference point (top of exciting mass) have been recorded. The signals have been amplified and transferred to a 4-channel FFT analysator. Autospectra and transfer functions have been calculated and stored. Using the software package MODAL PLUS the modal values of the structure have been obtained (Table 2). In Figure 4 the corresponding mode shapes are presented.

Referring to the results summarized in Table 2 following statements can be made:

- The comparison between the first and second measurements clearly shows an increase of the natural frequencies. The increase in modes corresponding with bending are smaller than in modes associated with torsional modes. The increase in general can be explained by the ongoing increase of the Young's modulus of concrete after construction as well as by the reduction of mass due to loss of water in concrete. Furthermore, since the loss of water in the cantilever parts may be more pronounced, the torsional modes reflect a higher change of eigenfrequencies.

- The discrepancy between the results derived from the measurements and those obtained by analytical models is partly due to the fact, that the mathematical model is not an ultimately refined model. Nevertheless, uncertainties associated with the simulation of nonstructural elements, bearings and interactions with the substructure are viewed to pose serious questions with regard to analytical prediction as well as with regard to interpretation of any measured change in the structure.

It can be concluded that both procedures, namely the evaluation of the measured data as well as the mathematical modelling including the parametric identification necessitate further thorough work. Studies on damage assessment modelling are planned to investigate the relationship between the damage parameters and the modal properties. The outcome will help to quantify the sensitiveness of this monitoring technique.

- Integrity monitoring using sensors:

  For the purpose of monitoring the glassfibre tendons in a direct manner, optical sensors have been used. Three arbitrarily chosen tendons have been equipped with special lightwave-conductors developed by Felten & Guilleaume, Köln (Fig. 5). As briefly described in the preceeding chapter, any change of the axial strain in the conductor also results in a change of the fibre section. The transverse compression is amplified by using a spiral wire wrapped around the conductor. If the glassfibre tendon is subject to elongation, the section of the optical fibre is reduced under the pressure of the wire and as a consequence of this the transmissibility of light decreases (damping effect).
  Tests clearly proved that the relationship between elongation and damping is characterized by a constant value independent upon the number of test cycles (Fig. 6). Furthermore, through implementation of the impulse reflection technique the location of any rupture in the fibre can be determined with an accuracy of $\pm$ 10 cm.
  One further tendon has been equipped with an alternative sensor type, a copper wire, the capacitance of which can be measured and used for the identification and location of a possible rupture.
  Investigations on both sensor techniques are underway within the framework of an integrated research effort (BRITE) aiming at development of nondestructive techniques for concrete structures /3/.
  Until now none of the sensors gave any indication on a significant change of the force and geometry of the tendons they are embedded in (Fig. 7).

- Acoustic emission analysis

  This method is also dealt with as a subproject within the BRITE research program. Systematic investigations focussing on parameters for damage detection are currently carried out by "Fraunhofer Institut für zerstörungsfreie Prüfverfahren" in Saarbrücken.
  Since this monitoring technique, in principle, is conceived for implementation in an advanced level of damage, so far no need has been recognized for application to the Bridge Ulenbergstraße.

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TIME (quarter year)	Completion of construction	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Visual inspection	Initial measurement	x	x	x	x	x	x	x	x		x		x		x		x				x				x
Deformation measurements	"	x	x		x				x				x												x
Dynamic monitoring	"	x	x		x				x				x												x
Monitoring of unbonded tendons	"	x	x	x	x	x	x	x	x		x		x		x		x				x				x
Monitoring using sensors	"	x	x		x				x				x												x

Table 1 Monitoring program for Bridge Ulenbergstraße

Mode No.	2D-Model (Beam elements) for the bare	3D-Model (Shell elements) superstructure	1st Measurement	2nd Measurement	Mode type
1	4.45	4.412	4.95	5.11	bending
2	7.71	7.661	7.07	7.42	bending
3	--	13.238	9.92	10.16	torsion
4	--	16.257	11.53	12.46	bending in transversal direction
5	17.08	16.836	18.94	20.79	- " -
6	25.27	24.153	21.62	22.55	bending + torsion

Table 2 Eigenfrequencies (Hz)

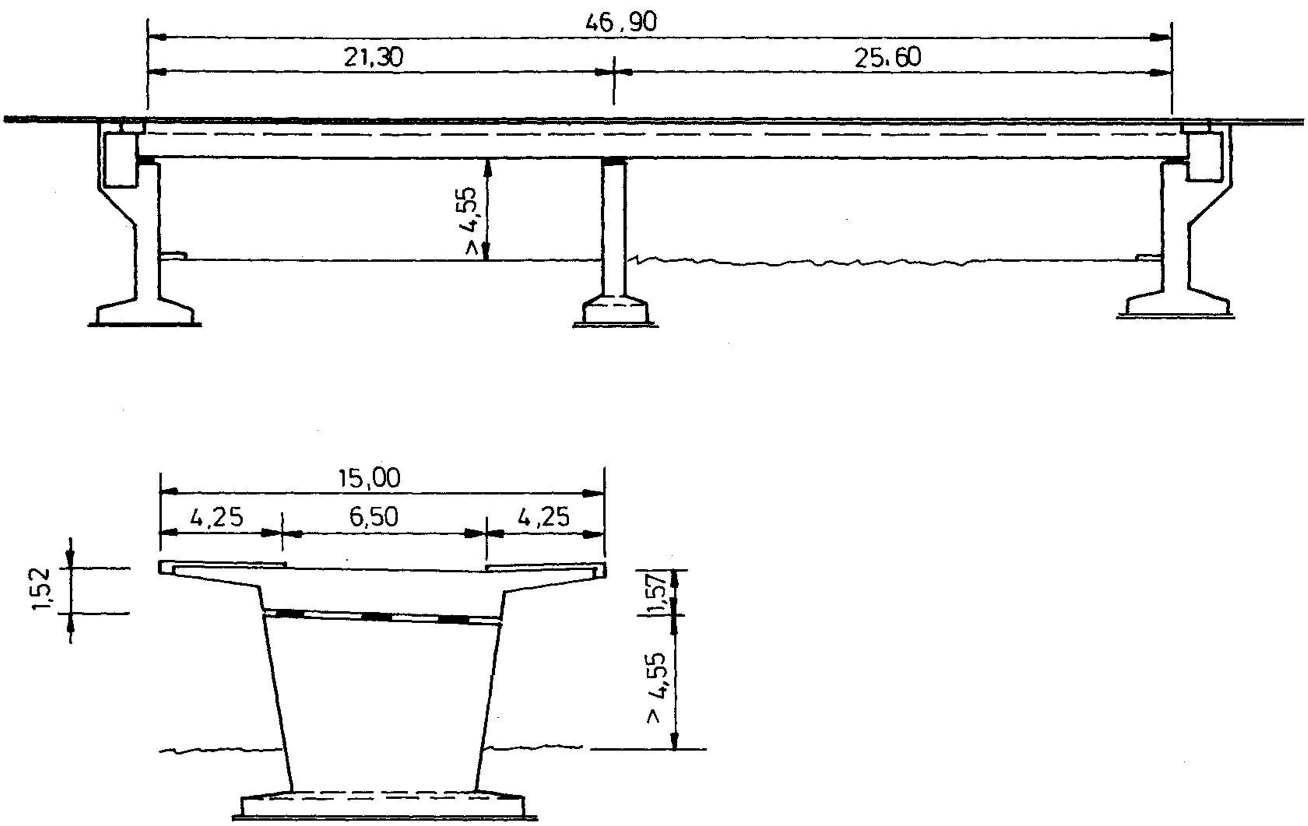

Fig. 1 Bridge Ulenbergstraße, Longitudinal and cross sections

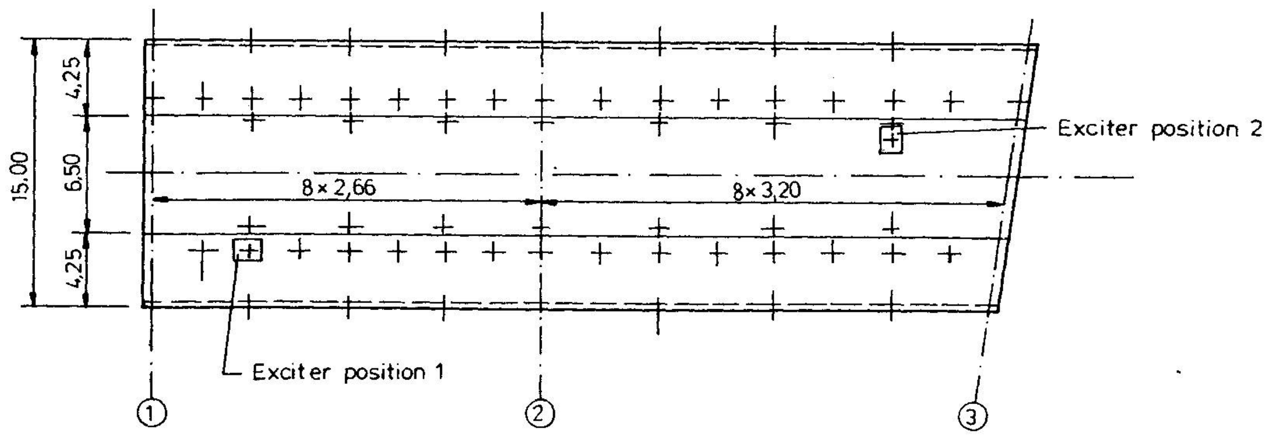

Fig. 2 Bridge Ulenbergstraße, Plan view
Exciter positions and measuring grid

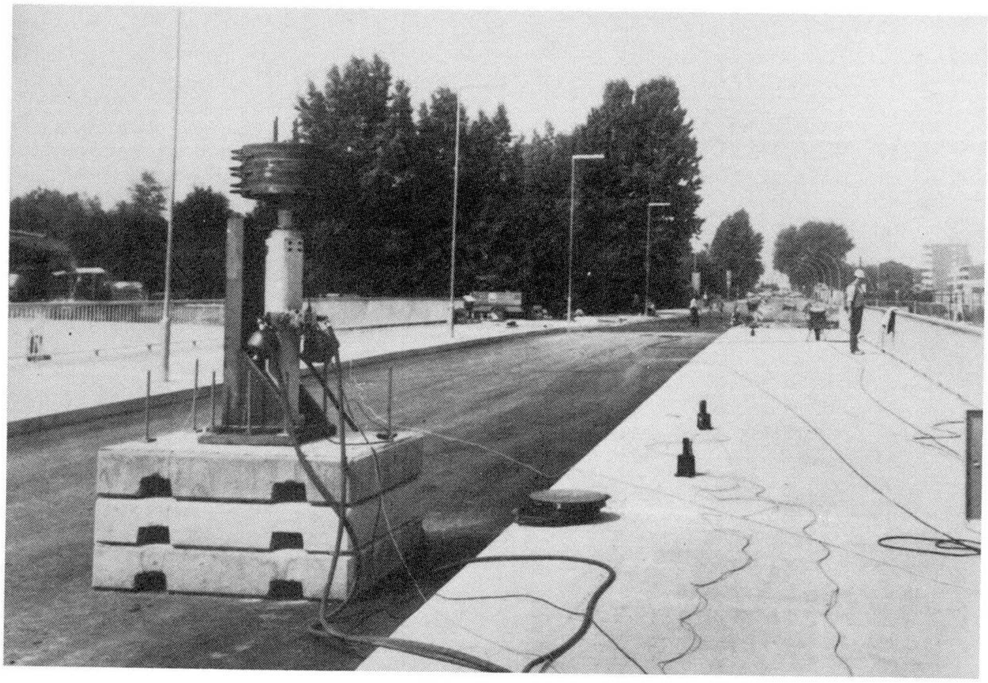

Fig. 3 Bridge Ulenbergstraße, hydraulic exciter (1st measurement)

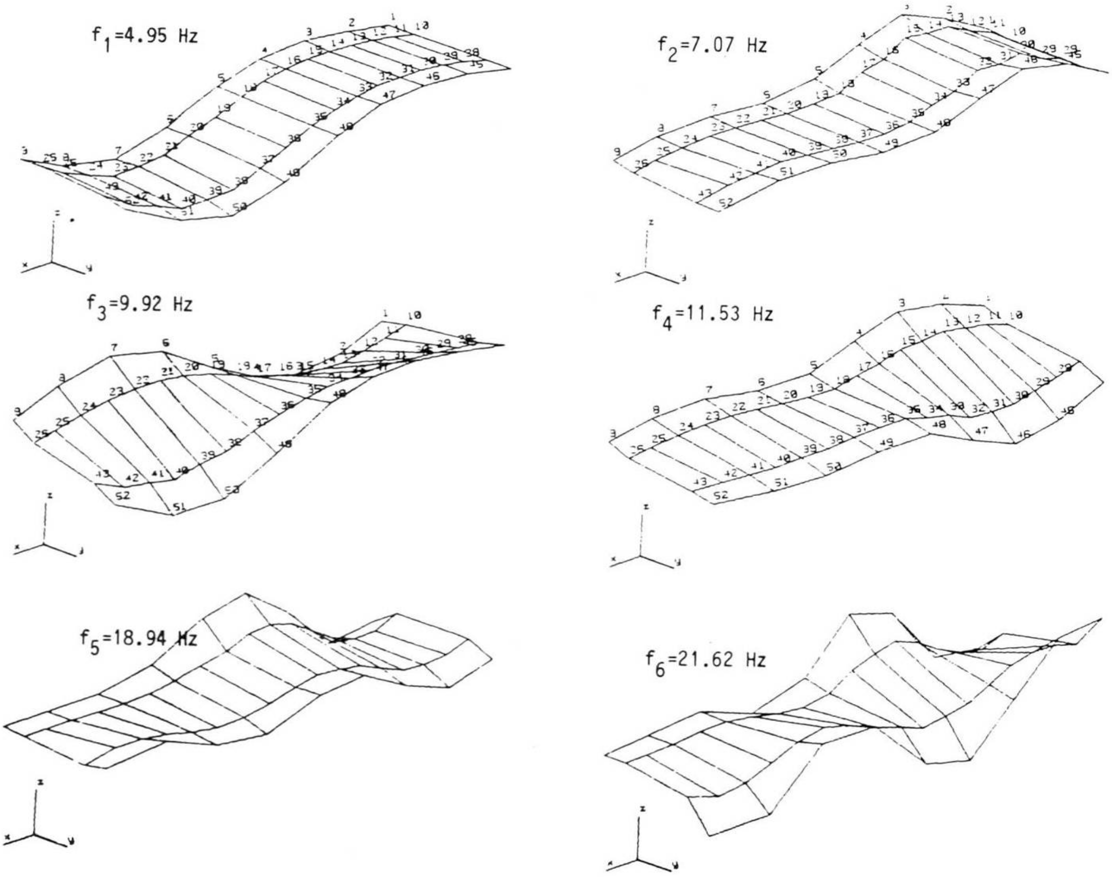

Fig. 4 Mode shapes extracted from the measured response

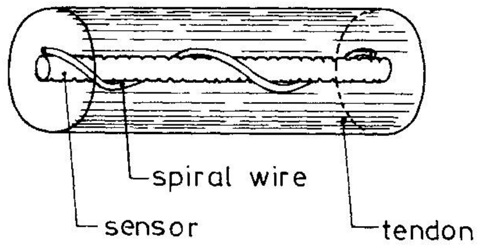

Fig. 5 Optical sensor (Felten & Guilleaume)

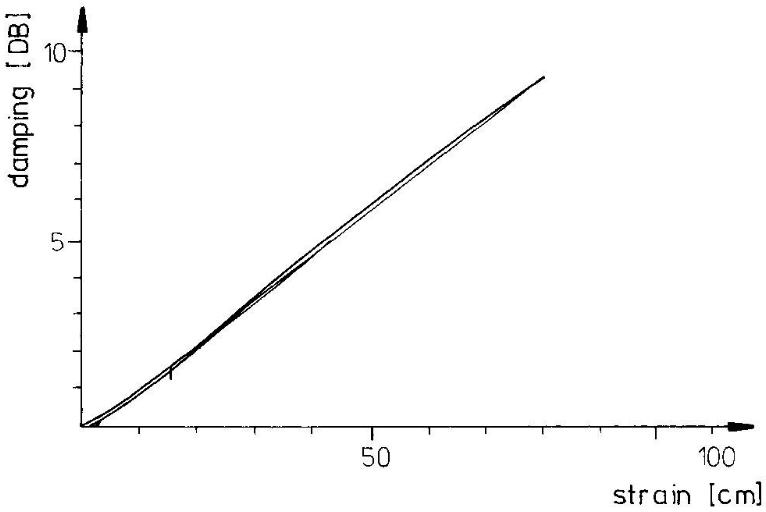

Fig. 6 Damping-strain relationship of the optical sensor

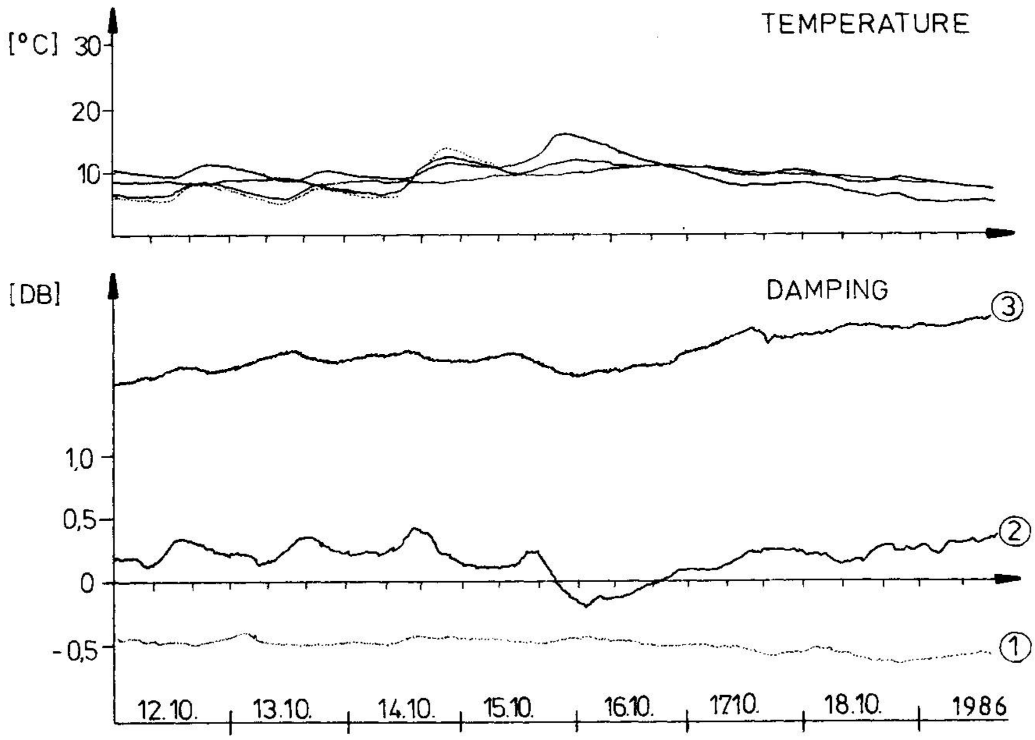

Fig. 7 Optical sensor monitoring on Bridge Ulenbergstraße

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