P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.), ISBN 972-8692-27-7

Iterative system identification for the assessment and retrofitting of a historical pre-stressed concrete bridge in Berlin.

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ABSTRACT: The quality of the assessment and if necessary retrofitting of a historical structure depends primarily on the as close-to-reality identification and modelling of its static behaviour. This paper demonstrates the advantages of a hybrid approach to historic structures - the behaviour of which is often hybrid as well - using the assessment of one of the oldest pre-stressed concrete bridges of Berlin as an example. Built in 1958 with a span length of approximately 65 m, using the Freyssinet system for pre-stressing, it has been heavily used by the Berlin metro line for about 40 years. Notable cracks discovered in 2002 caused a thorough evaluation which was characterized by the combination of a comprehensive record of historical damage, a measuring programme for the determination of the state of stress of the external tendons, the development of a realistic FE model by calibration on the basis of the experimental results, excavations for the investigation of the actual condition of bearings as well as a one-year automated structural health monitoring program. As a result the bridge could be judged to be capable of bearing loads and to be sufficiently serviceable without the need for particular retrofitting.

1 REALITY AND MODEL

When applying the well-known canon for the treatment of historical structures - anamnesis, examination, diagnosis, therapy, prognosis and documentation -, it is primarily the first three phases of the medical procedure which are of basic importance for the quality of results. Only an identification of the extant system which is as close to reality as possible – be it as a technical diagram, documentation of damage or a static model – opens the possibility of appropriate and effective intervention. The close-to-reality identification is the *conditio sine qua non* of the assessment and retrofitting of historical structures. This not only applies to buildings and load-bearing structures erected before the historical watershed, which we characterise today as the beginning of scientific construction methods, but also for more recent structures which have been designed and detailed according to apparently reliable scientific rules and where statically modelling in the modern sense was applied in their conception.

Over the last two decades, measurement-based procedures have once again been gaining in importance as a method for system identification. These pick up on a concept for the derivation of measurement-based statements of safety which already belonged to the standard repertoire of engineers in the age of early iron and reinforced concrete construction of the 19th and beginning 20th century who used load-testing as a proof of load-bearing capacity. This current renaissance has in the mean time had its effect on various regulations in Germany (DB 1999, DAfStB 2000), whereas the European SAMCO-network is currently preparing monitoring guidelines (Rücker et al. 2005) and ISO Codes for structural health monitoring are in preparation (Mehdianpour et al. 2004).

Measurement programmes only become fully effective in the examination of historical structures when two important basic conditions are taken into consideration. They must firstly be proportionately anchored in the overall concept of the examination, which also fundamentally includes the assessment of the construction history, the structural survey in-situ or the static modelling. It is only this hybrid approach, the methodical triad of survey, measurement and calculation, which enables the model to achieve the aspired closeness to reality.

Secondly, both the measurements and the system identification must on principle be understood to be iterative processes. As a rule there is no clearly predictable solution at the beginning. Only the dialogue between the development of the calculated model and the forward projection of the measurement concept allows the closeness-to-reality being striven for in documentation of the structure to successively become concrete. If the system model for a new structure usually exists at the beginning, when dealing with historical structures it is achieved only at the end of an often long process of discovery. Similarly the phases of anamnesis, examination and diagnosis should not be seen as a rigid sequence, but rather as melting into a comparably iterative, gradual approach to the real state of the structure.

This paper demonstrates the potential for discovery of such a hybrid and iterative approach using the example of an approximately 50-year-old pre-stressed concrete bridge in Berlin.

2 THE PROBLEM – CRACKS IN SPITE OF PRE-STRESSING

2.1 The Structure

Erected in the late 1950s, the overpass of the Seidelstraße, is one of the oldest pre-stressed concrete bridges in Berlin. The skew bridge heavily used by the Berlin metro line No. 6 with a span length of approximately 65 m crosses a six-lane inner-city road. The frame structure consists of a strongly haunched hollow box, whose two cells are alternately shifted because of the skewed situation of the bridge in longitudinal direction. They were pre-stressed in the longitudinal and transverse direction using the Freyssinet system.

Figure 1: The Seidelstraße Bridge, just after completion in October 1959.

Cracks were first discovered as early as 1981 in areas which had, according to plan, been fully pre-stressed. In 1997 finally the bridge was strengthened by adding an external pre-stressing within the two cells of the hollow boxes to recreate the originally intended, but in fact no longer existing condition of fully pre-stressed structure.

2.2 New Cracks in theoretically fully pre-stressed areas

Within the scope of a bridge inspection in 2002 notable new cracks were discovered with breadths between 0.05 and 0.15 mm in those areas in which cracks had been already documented in 1981 – perpendicular to the longitudinal axis of the bridge below the crown, precisely where they should actually no longer have appeared after the insertion of the external pre-stressing. Despite the retrofitting of 1997, the condition of full pre-stressing had manifestly still not been achieved.

Figure 2 – The load-bearing structure of the bridge on Seidelstraße
with the subsequently added external pre-stressing in the two cells of the boxes

Albeit the results of a first study of robustness carried through in connection with the retrofitting in 1997 had warned that a possible loss of stress, for example through the failure of individual strands caused by stress corrosion, would be shown exactly through new cracking, an initial evaluation concluded now that the probability of a sudden collapse nevertheless should be considered low. The bridge had apparently not been pre-stressed by the Sigma Steel 145/160 which commonly had been used in West Germany particularly in the 1950s and is known to be especially susceptible to stress corrosion (Wölfel 1992, Isecke et al. 1995, Bertram et al. 2002). In addition it was proven to be favourable that distributed tendons with strands had been used, which are able to perform quite well in the case of eventual damages (Vill et al. 2005). Last not least the indeterminate system has redundancies which raise the load-bearing capacity.

Nevertheless the actual level of safety was dubious. In spite of the apparent retrofit the danger remained that the construction no longer maintained an adequate level of pre-stressing, that the load-bearing capacity was unacceptably reduced and that the overpass – in accordance with the advanced notice of the cracking – could collapse at worst precisely when a train was crossing. The authorities thus had to accept that the structure was potentially endangered while being used; even the demolition of the still relatively young bridge was considered. After preliminary examinations and provisional shoring a decision was made to commission a new and thorough evaluation of the real load-bearing capacity of the supposedly already retrofitted structure – not least as various signs indicated that so far the behaviour of the existing structure not had been understood accurately.

3 SURVEY, MEASUREMENT, CALCULATION – ITERATIVE IDENTIFICATION

3.1 Integral approach

The obvious urgent need for a reliable diagnosis was hampered by the difficulty of providing one. In particular the condition of the pre-stressed steel of 1958 resisted a straight-forward evaluation. In order, however, to reach a conclusion on the level of safety two different approaches generally are possible. The first is the direct pin-pointing of possible wire and strand breakages through appropriate procedures. This approach notwithstanding of good results in some newer research can contain uncertainties under certain circumstances (Mietz and Fischer 2005a, b). The second method comes to conclusions indirectly by analysing specific indicators such as local strains and deformations and the differences of their actual behaviour from that under ideal conditions. An integral approach like this, which was chosen finally, allows for questioning all previously apparent certainties about the system's performance in order to reach an entirely new and best-possible system identification.

3.2 Initial approach – Short- term- measurements of the strain and deformation behaviour

In an initial reaction to the diagnosed cracks a short-term measurement of the strain and deformation behaviour was carried out at specific reference points in autumn 2002. The goal of this first approach was to document the behaviour of the cracks more exactly and to recognize possible marked features of deformation. The measurements were taken both under conditions of normal traffic as well as during the nocturnal period of suspension of service using the defined load of a particularly heavy track-grinding machine. The measured data confirmed the critical results documented visually. The diagnosed tension cracks actively reacted to both load scenarios. The full pre-stressing aimed for in the retrofitting of 1997 was in fact no longer extant. The static model and the real condition of the structure significantly differed from each other. A more exact and fundamental assessment was unavoidable.

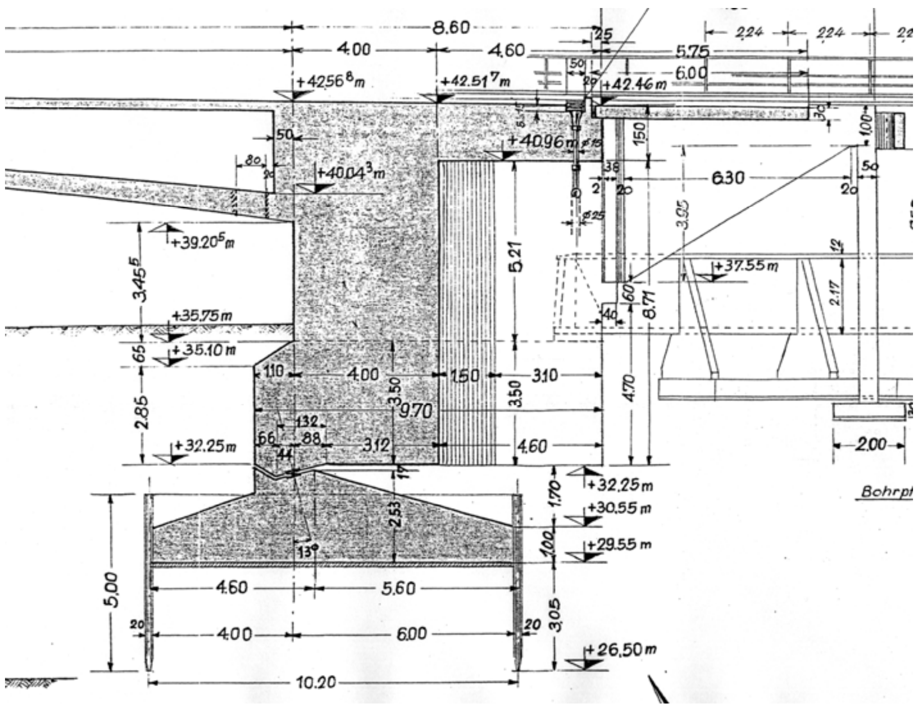

Figure 3 – Portal frame leg with hinge bearing, design drawing, 1957

3.3 Second approach - Anamnesis

It is common knowledge that a well-founded medical diagnosis cannot be reached without a detailed anamnesis. This applies accordingly for the current state and damage assessment of a historical building. At the Seidelstraße bridge the anamnesis revealed three interesting results.

Firstly the bridge had been subject to numerous and varied surveys in the course of its short service history of almost half a century. The reason for this was not only the damage observed but also the continuously growing general knowledge of pre-stressed concrete structures and the resulting new technical regulations. Secondly the first structural model used to describe the system as well as the action effects not had been questioned seriously in none of these numerous examinations – regardless of the quite complicated geometry of the bridge with its combination of skewing, lower flange curvature, staggered supports and eccentrically laid track-way, facts which, using the methods available at the end of the 1950s, could only have been recorded in a radically simplified form. Nonetheless, later experts had not looked beyond the modeling of a simple strut-and-tie model. Thirdly none of the later surveys had questioned the hinged bearings of the portal frame as one of the most important system assumptions inherent in the model – notwithstanding that the structure lying 4 meters below ground must have been particularly susceptible, though no-one knew what this actually looked like as no visual access was possible (Fig. 3). A discrepancy between the model and the actual construction, however, caused by an obstruction of the turning of the bearing, would possibly have had great effect, according to initial static analysis. In this case the rigid restraint of the portal frame would have the effect of considerably neutralizing the external pre-stressing in the horizontal frame member and lead to considerable squeeze-stressing in the stiffer system under conditions of regular warming or cooling.

3.4 Third approach - Development of a refined static base model

As first step on the way to creating a close-to-reality structural model, a refined base model was developed, which reacted to the observed flaws in the previous one and contained various adjusting screws which allowed different influencing conditions to be varied within conceivable limited situations. Characteristic for this base model were among others:

- The modelling of the bridge as a spatial folded FE-structure
- The generation of internal pre-stressed elements along its length on the basis of the available reinforcement drawings from 1957
- The possible variation in the bearing conditions.

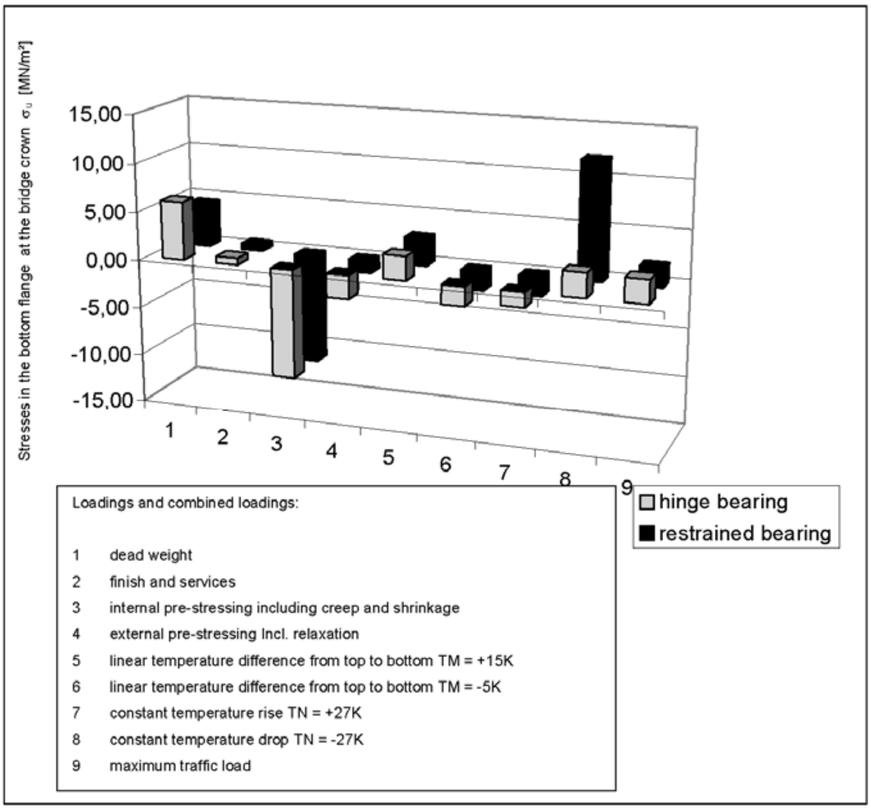

Figure 4 : Stresses in the bottom flange at bridge crown
as caused by important loadings respective to the type of bearing.

The calculations comparing hinge bearings and rigid restraints showed that the variations had in fact a significant effect on the resulting dimensions of the internal stresses under certain load conditions. Whereas the results of the FE calculations for the pin-joint bearings are more or less the same as those from 1997, they differ in some respects noticeably in the case of rigid restraints. The effect of the external pre-stressing in the hollow boxes is clearly reduced when creeping and shrinkage are taken into account; in the case of constant temperature drop extreme tension stresses are created. Figure 4 demonstrates the effects using the example of the stress in the crown of the underside of the lower chord.

The results thus contained a robust hypothesis for the damage: the cause of the observed cracks could be an obstruction in the pivoting in the buried bearing points. A more precise calibration of the model based on the measurements was necessary in order to verify this hypothesis.

3.5 Fourth approach - Measurements of the effectiveness of the external pre-stressing

To investigate the two influencing values recognized as significant in the FE analysis – changes in temperature and the actual effect of the external pre-stressing - a measurement programme within a 48-hour period was carried out in June 2003 which not only continually measured changes in temperature over the height of the structure, but also checked the external pre-stressing tendons in both hollow boxes while completely unstressed and then once again under stress.

The measured data confirmed that although the external pre-stressing had been carried out properly and maintained the planned pre-stress force, the calculated pressure-stressing in the centre of the bridge had not been achieved. A considerable part of the pre-stressing force was in reality being absorbed by the clearly not hinged, but stiffly restrained portal frame struts.

3.6 Provisional appraisal - First calibrations, first statements on safety, remaining doubts

The results allowed the first calibration of the base model to be carried out and the first identification of the degree of restraint to be made. Turning springs with a spring constant of 50.000 MNm/m were attached to the portal frame bearings. The internal forces and deformation indicated by the calibrated system model allowed an initial statement to the level of safety to be derived which approached the real state of the structure for the first time. It could be shown that the bridge, even when considering fatigue of material, maintained a sufficient load-bearing capacity, although the serviceability is no longer given as unrestricted.

The safety statements derived from the present system identification must, however, rely on the assumption that the internal pre-stressing dating from 1959 in fact had remained undamaged to a large extent. Other hypotheses based on the levels of knowledge available at this time were also only reliable to a certain extent. For example the influence of seasonal changes in temperature, recognized as theoretically dominant, could not be confirmed by the measured data. A more extensive permanent system of measurement seemed urgently needed to corroborate and fine-tune the calibration of the system model.

3.7 Fifth Approach - Monitoring to document long-term influences

A permanent measurement system was installed on the bridge in January 2005 for this purpose which was primarily designed to serve three aims: to confirm the particular significance of seasonal changes in temperature on the strain and deformation behaviour of the bridge worked out in the theoretical model, to generally observe the bridge over a one-year period and additionally to react quickly to possible unexpected conditions in the structure, through the implementation of an early-warning system.

The monitoring programme designed for 12 months continually recorded data through a total of 20 measurement channels on strains, width of cracks, deflection, inclination and characteristic temperature data, vibration recorders were added during some periods. Especially the high quality sensors measuring inclination on one axis on the portal frame legs proved to yield particularly interesting data.

The permanent measurement over the course of the year emphatically underlined the prognosis for the long-term behaviour of the cracks and the dominating influence of the temperature parameter. The correlation, for example, between the temperatures in the centre of the structure and inclination of the portal frame legs are excellent (Fig. 5). The calibration of the FE model was able to be further refined by taking into account the significant long-term influencing values. It was demonstrated that the degrees of restraint still clearly lay outside the values delivered by the short-term measurements. The eastern leg even must be considered to be almost entirely restrained. (Fig. 6).

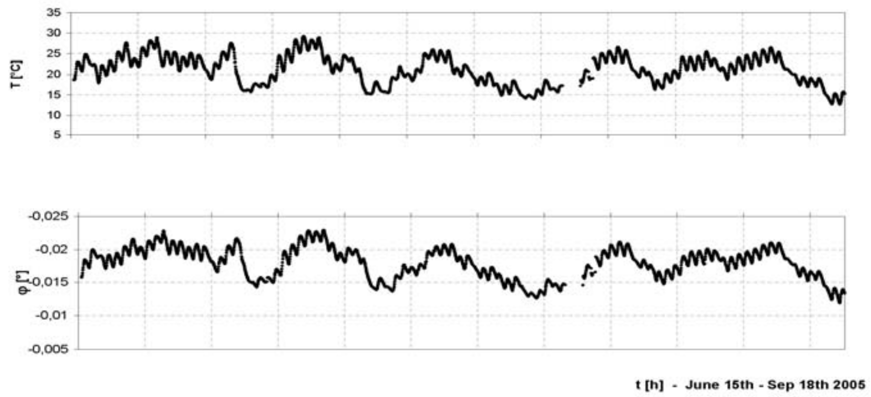

Figure 5 – Correlation between inclination at east portal frame leg and temperature in the bottom flange from June 15th to Sep 18th 2005

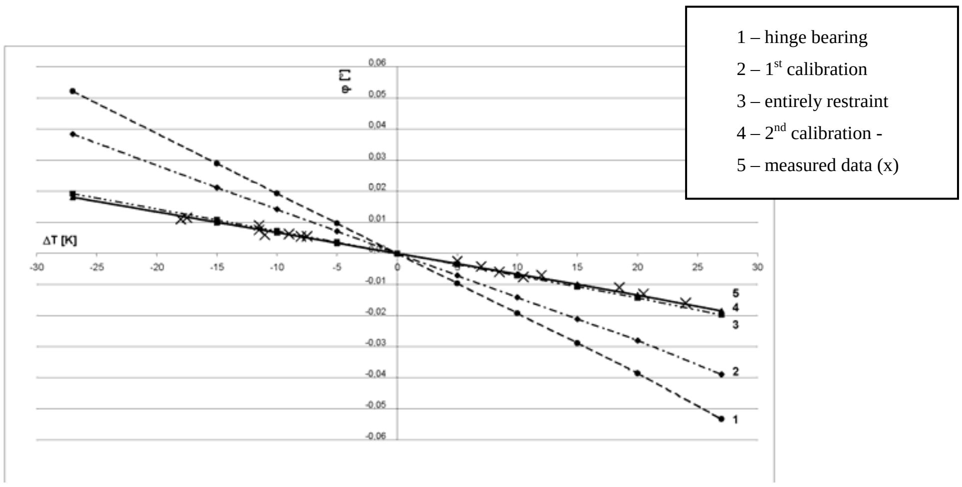

Figure 6 – Correlation between the measurements and the various system models using the inclination of the eastern portal frame leg caused by temperature changes as an example

3.8 Sixth approach: excavation for the survey of the bearing

Once all of the measurements had confirmed the working hypothesis, namely that the bearings buried at a depth of four meters were no longer fulfilling their function and that this obstruction must be the cause of the observed cracks, a partial excavation of the eastern leg was intended to conclusively show how the bearing had been constructed in reality, what the cause of the obstruction was and whether the originally planned type of bearing could with reasonable effort be reliably reconstructed. The excavation carried out in October 2005 demonstrated that the actual construction of the bearings corresponded very closely to the building plans (Fig. 3), but the planned 7 cm, in reality 6 cm thick gap between the leg and the foundations had been completely filled with bitumen-covered cork grains.

The filling-in of the gap with cork grains or cork-grain plates, only a small change from the planned design, is the real construction flaw in the structure and responsible for the damage observed. According to all of the results, the portal leg strut was constructed of concrete cast in-situ and thus the bitumen-covered cork granules were placed in advance into the geometrically demanding 7 cm gap to act as a buffer. The considerable pressure from the fresh concrete added from a height of 3.50 m then compressed the filling material to the current thickness of 6 cm. The pre-distortion of approximately 15% when added to the heavily obstructed lateral strain led to a high resistance to further compression and almost completely prevented the planned inclination of the portal leg strut. The hinge had become a restraint.

4 CONCLUSIONS

The analysis of the bridge on Seidelstraße, carried out iteratively by combining various approaches gave no indication that the diagnosed tension cracks in the crown of the bridge could be traced back to any possible wire or strand breakages. The cause was far more the considerably obstructed pivoting of the bridge bearings which could be proven in contrast to all previous statical modelling and could be traced back to a small but wide-reaching flaw in the original construction. The load-bearing behaviour of the almost entirely restrained system differs significantly from the hinged frame above all under changes in temperature; the cracks observed are a reaction to the constraining forces engendered during cooling. The external pre-stressing added later was demonstrated to have little effect considering the actual state of the bearings.

The newly identified structure is judged to be capable of bearing loads and to be sufficiently serviceable regardless of the cracks observed. The load-bearing capacity can be proven in terms of the new German regulations for states of limited pre-stressing. The serviceability can be deemed proven on the basis of the minimal breadth of cracks and minimal changes in the breadth of cracks detected in the year-long monitoring period. In the light of the level of knowledge now attained one of the oldest pre-stressed concrete bridges in Berlin can continue to serve its purpose in the transportation network of the Berlin Metro without the need for particular retrofitting. The proprietors are simply advised to maintain a more intensive level of observation of the structure and in particular of the cracks.

The investigations were carried out between 2002 and 2006 from the *Prof. Dr. Lorenz & Co. Bauingenieure GmbH, Berlin* in collaboration with *The Society for Technical Control – TÜV, Rheinland / Berlin-Brandenburg* (measurement programmes in autumn 2002 and summer 2003) and *the Federal Institute for Materials Research and Testing – BAM, Berlin* (monitoring in 2005 including additional short-term measurements). The author wishes to thank all partners involved for their cooperation in reaching a successful conclusion. Above all the author wishes to thank the commissioner *Berlin Transport Company (BVG)* for his support of the proposed successive approaches and the patience implicit in this. It was *the BVG* which allowed the planners the possibility of successfully implementing a methodical approach which could then be of general interest beyond the concrete project in hand.

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