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Prestressed concrete bridges in Germany – overview of current new structures, re-analysis and research activities to preserve the existing infrastructure network

Oliver Fischer[a]*

[a]*Technical University of Munich (TUM), Chair of Concrete and Masonry Structures, Theresienstraße 90, 80333 Munich / Germany*

Abstract

Currently several major bridges are under construction in Germany, not only due to the construction of new roads and railway connections, but also because of the necessity to demolish and replace older bridges that no longer meet present requirements. Generally, the national infrastructure network is characterised by a relatively high average age of the existing bridges, a progressive increase in traffic volume (particularly with respect to the heavy traffic portion) and also a rise in weight of the individual vehicles and axle loads. In addition, several earlier design approaches for concrete bridges have been modified in modern codes, aiming to increase reserves in bearing capacity and to obtain more robust structures. Hence, an extensive assessment scheme was launched some five years ago, based on the so-called „Nachrechnungsrichtlinie“ (guideline for bridge re-analysis and assessment, latest release 04/2015), issued by the Federal Ministry of Transport and Digital Infrastructure, which provides a systematic staged re-analysis approach (four levels of analysis) adapted to the special demands of existing structures.
The present paper will firstly give a brief overview of selected new prestressed concrete bridges and related challenges and technical details in design and construction, including the utilisation of innovative materials and/or structural concepts. Subsequently, Germany’s assessment strategy for existing bridges will be explained and relevant overall results and findings gained from the re-analysis scheme will be presented and discussed. Finally, current research activities focusing on a more realistic assessment of both actions (e.g. bridge-specific traffic loads) and resistances, i.e. the bearing capacity (particularly regarding the transmission of shear), will be addressed. In view of limited financial resources and the negative consequences induced by civil works in busy traffic infrastructure, it is of utmost importance to only strengthen (or even replace) those bridges where such measures are unavoidable and absolutely necessary.

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Keywords: prestressed concrete bridges; innovative structures; re-analysis and assessment; shear capacity; bridge-specific traffic loads

* Corresponding author. Tel.: +49-89-289-23038; fax: +49-89-289-23030.
E-mail address: oliver.fischer@tum.de

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1. Introduction

The provision of an efficient, capable and fully functional traffic infrastructure network is of utmost importance in view of both guaranteeing mobility, transport and economic capability and preserving the people's quality of life. This particularly applies for countries with extensive trade relations and highly-developed industrial and economic activities. Hereby, critical points in infrastructure networks commonly are engineering structures such as bridges and tunnels, with unfavorable consequences arising from restrictions in service. Accordingly, the permanent preservation of unrestricted functionality and structural safety of these structures has to be pursued with highest priority.

In the following, a brief overview of selected new prestressed concrete bridges as well as related challenges and technical details (road and railway bridges) will firstly be given in section 2. Subsequently (section 3), Germany's re-analysis and assessment strategy for existing bridges will be explained and relevant overall results and findings gained from the re-analysis scheme will be presented and discussed. Finally, in section 4 current research activities focusing on a more realistic assessment of both actions (e.g. bridge-specific traffic loads) and load-bearing mechanisms and resistances, i.e. the bearing capacity (particularly regarding the transmission of shear), will be addressed.

2. New major bridges in Germany

In recent years and also today there are several major bridges under construction in Germany related to both the road and railway infrastructure network. On the one hand, structures are necessary because of new roads and railway connections, e.g. the new high-speed railway link Nuremberg – Halle/Leipzig, with some innovative slender bridges and the longest railway bridge in Germany (Saale-Elster viaduct, length of main bridge 6,465 m) or the HSR link connecting the cities of Stuttgart and Ulm with the new Filstal viaduct being one of the most challenging and spectacular German railway bridges. In addition there are also some measures on federal highways requiring bridges and engineering structures such as e.g. the extension of BAB A94 in Bavaria. On the other hand, there are also many locations along the existing network requiring the demolition and replacement of older bridges that no longer meet present requirements. In addition to some very old railway bridges (partially over 100 years) this applies for a series of roadway bridges in the course of highways, e.g. BAB A44, A61 and A3 (amongst others: bridge Heidingsfeld in the vicinity of Würzburg; Lahntal viaduct near Limburg [1], Fig. 1) and also to a couple of major river bridges, e.g. Leverkusen (cable-stayed bridge, severe fatigue problems) and Schierstein (steel and steel-composite beam bridges connecting Wiesbaden and Mainz, main span 205 m) across the river Rhine.

Fig. 1. Lahntal bridge, (a) balanced cantilever erection with auxiliary pier; (b) twin-box cross-section (width 21.44 m) before closure at midspan

Besides new major bridges and viaducts there are also smaller ones with interesting details mostly focusing on an enhancement of maintenance and durability. One example is the new flyover near Greißelbach being characterized by a separation of the load-bearing systems, with a precast steel-composite frame (‘VFT’) as main structural system and prestressed segments with subsequent longitudinal internal post-tensioning (w/o bond) forming the bridge deck, separated from the frame by a sliding plane. Because of this structural concept and many innovative details, laboratory tests, expert’s reports and approvals were necessary prior to erecting the flyover which is also presented in de-tail in [10]. In addition and in view of gaining valuable information for future application of this type of bridge, the construction works were are accompanied by a comprehensive scientific supervision, provided by the TUM Chair of Concrete and Masonry Structures, including a loading test on the completed structure, e.g. see Fig. 2(b).

Fig. 2. (a) Filstal viaduct (computer animation, DB Netz AG); (b) Greißelbach bridge with segmental roadway slab (here: loading test)

3. Re-analysis and assessment strategy in Germany

Similar to many other countries, the German infrastructure network is characterised by a huge number of existing bridges with a relatively high average age and a progressive increase in traffic volume, particularly with respect to the heavy traffic portion. By only taking into account the federal roads and highways there is an overall number of more than 39,000 bridges and viaducts (some 51,000 individual structures) representing a total deck area of some 30 million sqm. In relation to the deck area the majority of the structures (i.e. 87,2%) are prestressed or reinforced concrete bridges with a huge portion being erected between 1960 and 1980. At the moment there is an average age of some 45 years with more than 65% of the existing structures exceeding 30 years. In 2011 the so-called “Nachrechnungsricht-linie” (NaRil) [2] was recommended for application by the Federal Ministry of Transport in order to implement a systematic staged re-analysis approach (four stages of analysis)[†] for re-analysis and assessment adapted to the special demands of existing structures. Since then all states, with varying intensity and starting with selected pilot applications, have undertaken and still do undertake bridge assessments according to the new guideline.

Current experience gained from application of the staged guideline to more than 350 bridges shows, that only some 20% entirely can fulfil all requirements upon finalisation of stage 2 (only 2,7% in stage 1) whereas more than 60% of the bridges exhibit relevant or severe calculatory deficits. A detailed overview on re-analysis results for German bridges as well as an evaluation of typical deficits can be found in the BASt research report B 124 [6], please also refer to [4,8]. Besides the age, the general structural condition of the bridges and the continuously increasing traffic loads the deficiencies may also be attributed to modified codes and regulations; several earlier design approaches for concrete bridges have been modified in modern codes (targeted on the design of new bridges), aiming to increase reserves in bearing capacity and obtain more robust structures. Further, there is quite a number of bridges erected in

[†] In NaRil stage 1 the bridge is analysed in accordance with current codes, whereas stage 2 allows certain modifications in terms of input parameters and/or limit values, e.g. regarding partial safety factors or the shear design concept. If there are still deficiencies upon completion of stages 1 and 2, the guideline defines two additional levels 3 (measurement-based assessment) and level 4 (re-analyses utilising scientific methods such as physically non-linear numerical models or probabilistic approaches).

the early days of prestressing exhibiting systematic weaknesses (e.g. cracks and fatigue at tendon coupling/structural joints, pt-steel sensitive to stress corrosion cracking) and – because of the former general tendency towards a material saving design, there are only little structural reserves for changing boundary conditions.

Based on the re-analysis findings mentioned above, in many cases at least additional in-depth investigations (e.g. stage 4 analyses) would be required and for a rather big portion of bridges it would be necessary to design strengthening measures or even to replace the existing bridge by a new one. As expected and shown in detail in [6] the main deficiencies particularly are related to longitudinal shear (56,5% of the bridges) and combined shear/bending action at the connection of webs and slabs (43%), to missing longitudinal torsion reinforcement (29%) and to fatigue problems at coupling joints (41%). Especially the insufficient shear capacity is in direct relation with the bridge age and corresponding standards, respectively. Thus, almost 90% of the prestressed concrete bridges built before 1966 exhibit dramatic deficiencies in shear, mainly because of a systematic minimum shear reinforcement criterion missing in the former DIN 4227:1953, whereas bridges completed 1980 and later rarely exceed shear design criteria according to NaRil stage 1/2 with deficiencies being limited to small values in case of exceedance (< 20%).

Despite there are many severe calculatory deficiencies only few cracks can be detected at those bridges. Therefore, it seems that either there are more favourable load-bearing mechanisms in real structures, which are not reflected sufficiently in current engineering models, or/and traffic loads do not reach the levels taken into account in numerical analyses. In order to achieve a more realistic assessment and hence to reduce the huge number of bridges with calculatory deficits, the "Bundesanstalt für Straßenwesen" (BASt), the research coordinating unit of the Federal Ministry of Trans-port, has initiated several research projects focusing on a provision of additional (simplified) stage 2 design formats which have been incorporated in the latest revision (i.e. 1st NaRil supplement) of the guideline [3]. In this context, investigations on the shear and torsional capacity [5] ("short-term solutions"), the load-bearing behaviour at the web/slab connection and fatigue effects, impact loads to be considered on bridge parapets [9] and traffic loads in temporary 4+0 traffic situations during heavy maintenance and/or construction works, shall be mentioned exemplarily. Comprehensive commentaries on the revised NaRil guideline including details on the extended design formats and the mechanical and technical background can be found e.g. in [4].

4. Current research activities (realistic assessment of existing bridges)

The current revision of NaRil [3] provides several extended design concepts (e.g. evaluation of the shear capacity of prestressed concrete bridges on the basis of a principal tensile stress criterion). However, with regard to future re-analyses and assessments reflecting the load-bearing behavior and failure modes as realistic as possible there seems to be still further potential, as can be seen from scientific investigations and several experts reports on existing bridges. Therefore, additional theoretical and experimental research activities have been launched aiming to further improve the re-analysis methodology (i.e. realistic assessment) and to provide practice-oriented engineering models based on scientifically verified basics. Exemplarily, please refer to a major current BASt research project on shear and on torsion (FE 15.0591/2012/FRB), with four research partners and extensive laboratory experiments on prestressed continuous beams. The project particularly comprises investigations on the influence of different loading scenarios and cross-sectional geometry (e.g. varying slenderness ratio of web and flange). Hereby, static and dynamic loads as well as different shear reinforcement concepts (in terms of content and shape of the stirrups) are included with special attention being paid on the permissibility to take into account special types of stirrups and shear rebars no longer accepted in modern codes. In experimentally assessing the effectiveness of not closed types of stirrups or rebars with insufficient lap length it is import to gain precise information on the internal load-bearing mechanism and the bonding behavior between reinforcement and concrete. In the research project special fiber-optic measurement systems are utilized offering both a distinctively higher resolution and precision compared e.g with conventional camera-based systems and the possibility to continuously record strains within structural members (fibers applied to rebars) and on the outside concrete surface [13], see Fig. 3. In addition to loading tests with continuous beams (length 12.0 m, height 0.80 m) an innovative experimental setup is developed enabling a realistic testing of concrete beams at a reduced length (substructure technique) with arbitrary stress states being applied by external jacks [11]. Hereby, also scale effects are investigated by testing beams with varying height of up to 1.50 m.

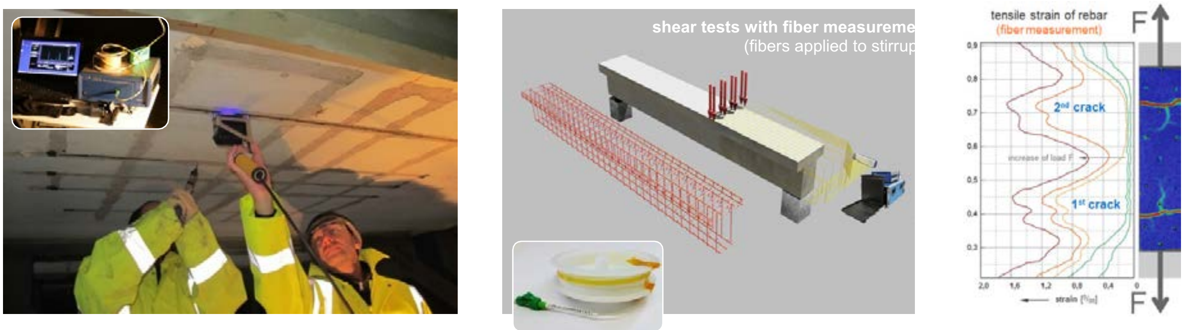

Fig. 3. Continuous high-precision fiber-optic strain gauges (a) applied to a concrete roadway slab (in-situ strain measurement), (b) applied to reinforcement: shear tests (middle), test setup with individual rebar under tension embedded in concrete (right)

Besides in-depth investigations on load-bearing mechanisms and structural capacity ("resistance") there are also several research projects focusing on additional reserves arising from overestimated live loads (i.e. deriving bridge-specific loads taking into account the real traffic). NaRil generally allows to adapt the loading level to the local traffic situation. At the moment however, possible adaptions are limited to a relatively conservative level and all federal road and highway bridges have to be re-analysed using load model LM 1 as target value – regardless of the actual traffic. In contrast to this, rather big differences between theoretical and actual heavy traffic (overall weight, axle loads) can be detected in the road infrastructure network in Germany. Further, also the intended/required (remaining) service life of the individual bridges directly influences the calculatory live loads derived from probabilistic models, an effect which is not considered in current design concepts. Therefore, the development of an enhanced concept towards route- and bridge-specific load models both could lead to a distinct reduction of the maximum live load to be included in bridge re-analyses and would provide important information in view of developing optimized maintenance and modernization strategies for individual bridges and the infrastructure network. First numerical analyses on specific bridges with a relatively low heavy traffic portion clearly confirm that there is a considerable potential in adopting this concept, please refer to e.g. [14, 15]. In this context, I would like to also draw the attention to a current research project of the TUM Chair of Concrete and Masonry Structures [12] (research grant by Highways Authority of Southern Bavaria), aiming to develop site-specific traffic load models and evaluate their potential of application within the scope of re-assessment for an exemplary route, the federal highway BAB A92 in Germany. Extensive numeric parameter studies estimating extreme load effects on a large set of different structures and traffic constellations are performed, to gain a better understanding of the underlying correlations, and hence support the development of strategies to identify those sections of the highway network promising the highest potential for the application of site-specific load models in bridge re-analyses. The research project also includes investigations on appropriate and efficient monitoring concepts applied to survey if relevant assumptions, such as traffic data, are still valid in the long term (e.g. definition of warning, limit and alarm values).

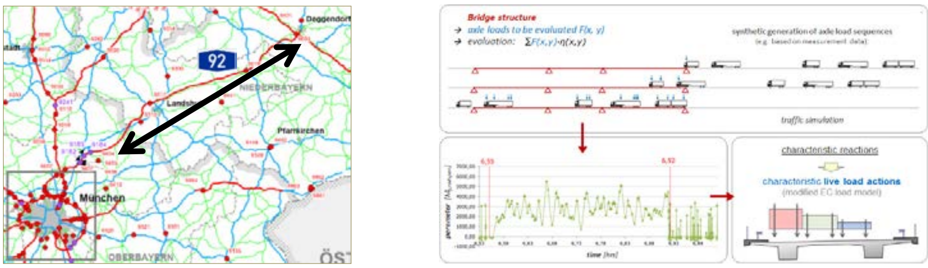

Fig. 4. (a) Traffic counting and WIM locations, here: Munich and A92; (b) derivation of route- and/or bridge-specific load models

In addition to monitoring changes in live load actions or/and structural responses there are also several research projects focusing on innovative (”intelligent”) monitoring strategies and a direct linkage of measuring data with numerical prognosis models culminating in a reliability-based assessment of the actual safety level of bridge structures, see e.g. [16]. In this context, there is also a series of research projects conducted within the framework of the priority program of the Bundesanstalt für Straßenwesen (BASt) „Smart Bridge“, for details please refer to [17].

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