EAN 2012
50th annual coference on experimental stress analysis

Existing structures: old and disused? Experimental approaches for extension of lifetime

Marc Gutermann[1] & Carsten Schröder[2]

Abstract: Experiments are part of the history of engineering science. They were used to validate theoretical assumptions and to understand the load bearing behavior of new constructions. During the last decades several approaches were developed to use experiments for assessment of the actual load carrying capacity of existing structures. The field of application goes from investigation of material properties, long-term measurements to in-situ load tests. This article shall give a short overview over existing methods and it shall show experiences gained in practice: experiments may be used to explore the actual structural behavior and can lead to proof sufficient load carrying safety for modern utilization. As a result the lifetime of existing structures can be extended without reducing the permitted service load. Time and cost consuming building measures are avoided.

Keywords: experimental safety evaluation, structural health monitoring, in-situ load test, loading vehicle

1. Introduction

The progress in engineering sciences is based on empiricism. In the late 19th century experiments were used to understand the complex correlation of material and mechanical behaviour as well as recommendations for structural design. As a result the first German recommendations, e.g. DIN 1045 (1925) for reinforced concrete, contained even instructions for in-situ load tests of massive constructions.

The second half of the 20th century was affected by the introduction of electronic data processing. The finite element method (FEM) appeared to be capable of solving every engineering problem. In this period the main focus of civil engineering was the development and building of new infrastructure, so that experimental approaches became less important.

Today more and more existing structures have to be assessed which requires input data concerning the actual properties of the structure and the mechanical boundary conditions. These preconditions couldn't always be met so that not any calculated proof is successful. Possible reasons are an incomplete documentation, unknown effects of structural faults, and uncertainties in the modelling of the structural system with the appropriate boundary conditions. Another problem occurs

[1] *Prof. Dr.-Ing. Marc Gutermann, University of Applied Sciences Bremen, Institute for Experimental Static, Neustadtswall 30, 28199 Bremen, Germany; ifes@hs-bremen.de*
[2] *Dipl.-Ing. Carsten Schröder, University of Applied Sciences Bremen, Institute for Experimental Static, Neustadtswall 30, 28199 Bremen, Germany; ifes@hs-bremen.de*

if the structures have a historic design: the current recommendations are made for building of (new) structures and doesn't meet the requirements to assess historic designs. The safety evaluation based on experiments is a powerful tool if demolition and new building should be avoided.

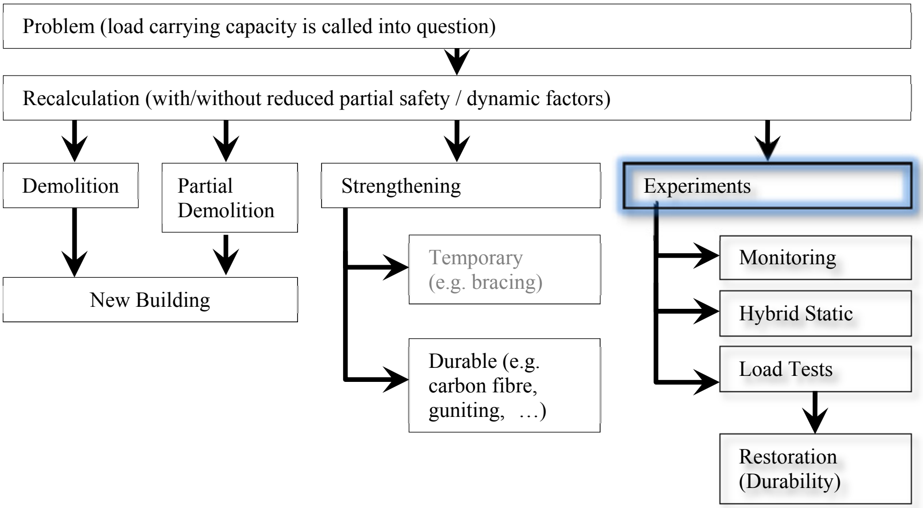

Fig. 1. Solution Strategies

The common procedure is shown in Fig. 1. After an unsuccessful recalculation, caused e.g. by the facts mentioned above, the further proceeding is dependant of several factors. However, the decision which solution is applicable depends on the problem, the involved parties and the area of conflict:

- The owner wants to use the structure soon, sometimes with increased loads and every time with low costs
- The building contractor want's to generate a high turnover to save jobs and to realise profit
- The structural engineer is (in Germany) paid dependant of the turnover and has nearly the same motivation than the contractor
- Sometime involved politicians have special goals, motivated by higher aspirations or imminent elections
- The user (e.g. inhabitants) won't be disturbed and don't like any emissions (e.g. dust or noise)

In the following chapters we want to show which experimental approaches exist and how they may help to find a suitable solution how to extend the lifetime of structures without reducing the level of loading od safety. Demolition and new building is not part of these considerations.

2. Recalculation

“A mathematical or mechanical model may be nearly perfect – it stays a model“. This citation from Prof. Opitz (TU Dresden) points to the reality: many students and even some engineers believe in computational results since a computers calculation is always correct. The truth is that the results are as good as their assumptions which lay hopefully always on the safe side.

If we want to describe the physical reality, we need additional information that may be gained by experiments e.g. non-destructive testing, monitoring or load-tests. This may be cost and time consuming, but sometimes a little effort may have a great effect. Recommendations exist in Germany, i.e. [1], that the partial safety factors may be reduced if additional information of existing structures is available (Fig. 2). This procedure is consistent with the present probabilistic safety theory that considers apart every parameter. For example, building and material construction of an existing structure isn’t uncertain anymore since it’s already built. However, the uncertainty of use is still latent so that their partial safety factors must be used.

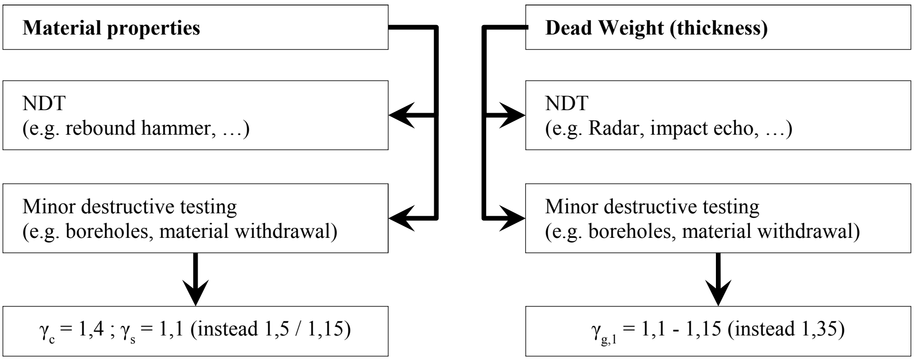

Fig. 2. Reduction of partial safety factors after NDT (recalculation)

Thus a recalculation based on non-destructive investigations of material properies and of geometry can lead to a increase of load carrying capacity up to 19% (dependent of the dead weight portion of the entire capacity).

3. Experiments

3.1. Non-destructive Material Testing

As stated before non-destructive or minor-destructive material testing is one of the basic tools to assess existing structures. Several techniques were developed, extensively tested and are today established. In this contribution we leave it listing methods, which are the most important in structural engineering:

- Opening (→ concrete covering, reinforcement diameter, depth of carbonation)
- Rebound Hammer (→ concrete strength evaluation)

- Detection / Scan of reinforcement (e.g. magnetic inductive)
- Ultra Sonic, Impact-Echo (→ thickness of layers / structure)
- Boreholes / core drilling (→ thickness of layers / structure)
- X-Ray / radiography (Gamma rays) (→ 3-D-Scan of reinforcement)

The detailed advantages and disadvantages, their limitations and more techniques are discussed in many publications, i.e. [2-4].

3.2. Monitoring / Long-Term Measurements

During the last decades, the technology of measurement techniques has been significantly improved and extensively tested. Thus it seems technically possible to monitor the actual state of a structure if the equipment works electronically and a data logger is recording simultaneously. Some systems allow to watch the results via internet and to maintain the system from afar. However, the challenge is to measure the right reaction at the right location and to know the decisive limit criteria in advance. We are noticing censoriously some approaches to sell systems with an integrated traffic light: green means everything is all right, yellow lead to maintenance and red means immediate action. The term *monitoring* suggests sometimes that an interpretation and evaluation is done automatically by the system. Few structures and tasks are suitable for this procedure why we suggest using the term *long-term measurements* instead. In the majority of cases the measurement results have to be interpreted and analysed by an engineer to draw the right conclusions based on his experience.

Fig. 3. Long-term cable vibration measurement

Fig. 4. Long-term deflection measurement

Experience of long-term measurements we gained in practise has been, e.g.:

- Vibration measurement of cables to investigate if rain and wind may cause any extreme amplitudes (12 months, Fig. 3)
- Deflection measurement of a road bridge ($l = 80$ m) to assess the source of occasional measured amplitudes of $\Delta f = \pm 35$ mm by topographical survey (Fig. 4)
- Deformation measurement of a hall roof if external loads (e.g. snow) and temperature difference may damage structural integrity

Both monitoring and long-term measurements have one disadvantage: they are measuring during operation maximal at live load level. The observed reactions are only a short range of the whole load-reaction-curve (Fig. 5).

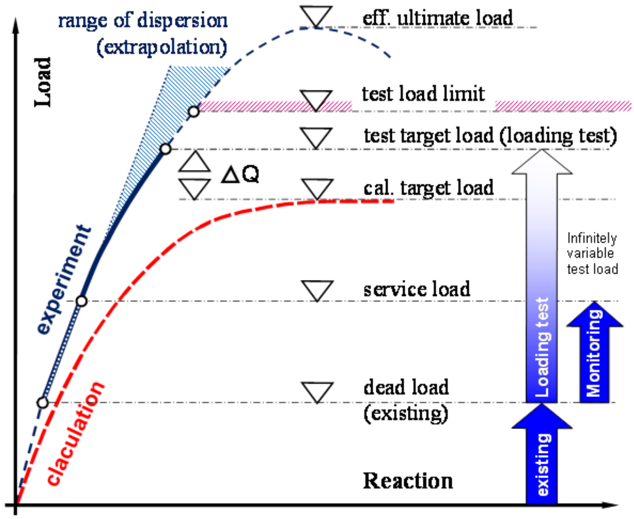

Fig. 5. Extrapolated load-reaction curve of a structure

3.3. Hybrid Static

Test loading of structures by gravitational forces, e.g. vehicle crossing, is a technically easier alternative, but it is not considered to be acceptable in any case. For safety reasons the load level reached in this way should not exceed the service load. Consequently, by using gravitational loads only, a self-securing experimental safety evaluation (incl. partial safety factors) is impossible.

There are two well-known alternatives if the experimental investigation shall exceed the proof of serviceability:

- Computational extrapolation of the experimental results
- Use of special loading technology (see the following chapter)

A parallel application of computational and experimental methods allows the extrapolation of experimental results to higher load levels. Analyses purely based on computational methods might fail to predict realistically the structural behaviour resulting in underestimated load-carrying capacity. For that reason, it is of advantage to combine computational and experimental investigations (hybrid static). On the basis of the experimental observation, the input parameters required for the analysis are obtained (Fig. 6 and 7). The advantage of the subsequent extrapolating analysis is its totally non-destructive character. However, the disadvantage is the remaining uncertainty concerning the correctness of the extrapolation (Fig. 5, range of dispersion). Parametric studies or the consideration of large safety margins are means for handling these uncertainties.

Fig. 6. Measurements during operation

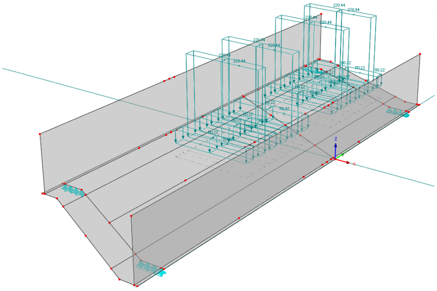

Fig. 7. Calibrated FE-Model

3.4. Load Tests

If one needs information about the structural behaviour above the service load level or wants to proof directly adequate safety by experiments, special measures have to be prepared.

The research team EXTRA of the University of Applied Sciences Bremen, the Technical University Dresden, the Leipzig University of Applied Sciences and the Bauhaus-University Weimar dealt with the experimental safety evaluation from 1992 through 2001 [3]. Furthermore, the team contributed into the formulation of a technical guideline for loading tests which has been issued in 2000 [1]. The guideline contains the safety concept and technical rules for loading tests as well as criteria for critical load levels, for example. Today many international recommendations contain references to experimental methods, e.g. Eurocode 2, chapter 2.5 (01.2011): „Design assisted by experiments".

The basic idea is to apply external loads up to a target, which is the result of preliminary calculations and is approximately twice as much as the service load. It includes remaining uncertainties, considered by partial safety factors. To avoid any structural damage during the test a concerted measurement concept has to be worked out. The choice of the applied devices results from a static pre-calculation, which has to identify the critical structural parts and where the reactions get maximal [5]. Symmetries should be used for control of measurement redundancy and the repeatable resolution of the sensors must ensure a safe interpretation.

Load tests have limitations:

- High effort without guaranty of success
- Not suitable / economical for every structural problem
- No statement possible about the remaining lifetime
- Restoration still necessary

Fig. 8. Load tests using loading frameworks

Fig. 9. Load tests using the special loading vehicle *BELFA* [5] www.belfa.eu

However, over 300 projects carried out by our Institute have shown that it is possible to prove much higher live loads than calculated. Load tests identify and exploit latent bearing reserves, the actual structural behaviour and boundary conditions. In our opinion the experimental results are staying valid as long as the conditions and the state aren't changing. This is in fact the same approach as any new built construction. Periodic inspections may take care that any changing state is monitored. In Germany the DIN 1076 recommends for bridges a small inspection every 3 years and an intensive inspection with a 6 years cycle.

4. Strengthening

4.1. Temporary strengthening

Temporary strengthening isn't a suitable alternative in most cases (e.g. bracing). They lead only solution without remedying any deficiencies and constrain often serviceability (e.g. clear cross section).

4.2. Durable strengthening

Durable strengthening is in many cases an economical approach. The measures may be planned and conducted not only to reach the previous load carrying capacity, e.g. in case of damages, but also to increase the capacity. They lead additionally to a higher quality of serviceability since deflection and crack width are reduced as well. However some strengthening methods as guniting or applying of carbon fibre layers have limitations as

- Gain restriction (bearing gain $\eta_B \leq 2.0$)
- To strengthen shear areas needs time and (economical) effort
- Temperature sensitivity ($24 \leq \max T \leq 40°C$)
- Moisture and / or sunlight sensitivity
- Inappropriate for dynamic loading

5. Conclusions

The projected service life of solid structures is about 80 years. Due to the damaging effects of the environment and increased traffic loads, it is in reality reduced to about 50 years. The ensuing need for reinvestment can only be covered taking into account financial resources and environmental concerns if the service lives of existing structures are significantly extended. Experiments can make an important contribution here.

If computational verification does not give realistic results due to inadequate or missing building documentation, complex load-bearing behaviour or obvious or hidden defects, then, after appropriate preliminary investigations, experimental assessments of load-bearing capacity can supply information about the real structural behaviour with the inclusion of all existing conditions. In these cases the experimental investigations usually produce more favourable results than the static computation, as has clearly been shown analysing over 300 examples. Combinations of several experimental approaches lead often to the best results. Some procedures need a minimum of experience.

International trends indicate that experimental methods become more important in the last decade, especially the German efforts in this field show promise. Concepts have been developed and improved to asses existing buildings and to extend their lifetime avoiding extensive building measures.

Acknowledgements

At this place we want to send special thanks to the University of Applied Sciences Bremen, which gives permanent support and enables us to have done more than 300 successful investigations in the field of analyzing the load carrying safety of existing building structures.

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