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Loading tests involving historic structures, opportunity or risk?

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SPECIAL FEATURES OF BUILDINGS AS HISTORIC TESTIMONIES

Buildings are built for a special purpose. The designated use dominates the structure and its design. Not many master builders lay claim to eternity. An awareness of transience of the material and changes in the requirements is omnipresent. Nevertheless, the value of a building for people far exceeds the actual intended use. After all, it is an objective part of the environment they experience and reflects everyday life, production and culture of the time of its construction more clearly than written or visual sources. Therefore, buildings are an important part of our cultural heritage.

Unlike musical and literary works of art, buildings are subject to destructive influences from wind and weather, damaging substances and organisms and intense utilisation. However, the, most significant damaging factor is a different one, as already observed by Dehio in a presentation he gave in 1905 in Strasbourg, which set a trend for the preservation of historic monuments in Germany: «And the people themselves contribute more to their destruction than the forces of nature. Architecture destroys architecture. This is how it has always been, and people just accepted it like an objective necessity». (Dehio 1905). Therefore, the superficial interest in a building is not based on a beautiful façade, an historic event or a new technology, but in its utilisation. If it is no longer relevant, people decide on its future destiny: demolition or preservation and conversion. In the most favourable case, an old building can become a mirror image of changing ideas about life, production and culture over a prolonged period. For this to happen, new uses keep having to be found for the structure that make it worth preserving for clients and preservers of historic monuments. Only then is the building prepared for the new utilisation requirements through the work of architects and engineers.

Due to the rapid development of structural engineering and the predominant orientation of training towards innovations, less and less practical experience and know-how about the management of historic structures and materials are available. How often do planners use forceful allegations that the old structure is no longer viable and therefore has to be replaced to disguise their uncertainty, lack of knowledge and ability to empathise with? An eloquent example is common practice of replacing of old timber joist floors with new reinforced concrete slabs. A different route has been used for more than 40 years in former Czechoslovakia, where the load carrying capacity of such ceilings is increased by a factor of 4 or 5 through the creation of a composite effect with concrete (Postulka 1997). This is the result of an examination of the old design, and the detection and compensation of weak points. Even from an economic point of view, this solution is very advantageous. Significant parts of the historic design are thus preserved for future generations, and any reinforcement is clearly attributable.

There can be no doubt that historic designs and structures do not meet all of today's binding standards, which have emerged from the know-how of generations. But does this mean that they should a priori be classified as unsuitable for the new utilisation requirements? Using calculations alone, it is often not possible to achieve compliance, notwithstanding the use of state of the art calculation techniques, because the calculations cannot be better than the model assumptions we make for old structures. Far more promising are experimental methods for determining the condition of the structure that are not based on models, but on reality. Loading tests can therefore help to explain the structural behaviour of old structures and utilise it for the new requirements.

EXTRA —A TECHNIQUE FOR EXPERIMENTAL STRUCTURAL SAFETY ANALYSIS

Development of the technique and state of standardisation

Loading tests are as old as construction history. The development has always been based on trying out and observing. The loading tests for new bridges that decided the fate of the master builders are almost proverbial. As early as 1925, normative regulations for loading tests existed as part of DIN 1045 for reinforced concrete buildings.

In the early 70s, the passages about loading tests were removed from the German standard. Calculation was therefore the only method available for the verification of adequate load carrying capacity. Only railway bridges continued to be subjected to a loading test using heavy load vehicles prior to commissioning. A different development occurred in the GDR, where experimental testing of buildings and components had the same normative status as calculations (1986: TGL 33407/04).

Figure 1
Loading test of the newly developed Möller girder; the inventor can be seen in the foreground (source: Quade, Reuschel 1994)

However, modern methods go far beyond the approaches mentioned. Experimental structural safety analysis is a very young branch of science that only emerged since the mid 80s. The German research project «EXTRA —in situ experimental structural safety assessment of buildings for the purpose of preserving the substance or alternative utilisation» carried out at the universities of Bremen, Dresden, Leipzig and Weimar plays a significant role. As part of the project, the methodical, scientific and technical preconditions for experimental structural safety verification for ductile building construction components were created and tested in many pilot objects. In subsequent years, this method was successfully used for a variety of structural designs and for bridge structures.

The «Guidelines for loading tests for concrete structures» of the German reinforced concrete committee have been in force since 2000. They specify the steps required for preparing and carrying out loading tests (assessment of the structural condition, test programme, implementation including maximum load criteria, evaluation taking account of the safety concept and test report), as well as the requirements for the test centre carrying out the tests. Internationally, there is also increasing interest in experimental structural safety assessments. Lewicki and Opitz provide a good overview.

Short description of the experimental structural safety analysis approach

Experimenting means influencing a test object in a controlled way and observing the response. Loading equipment is used for subjecting the structures to controlled influences. Metrology deals with the observation of the response of the structure. Figure 2 shows a diagram of the computer-aided procedure. What is new?

The loading equipment makes the effect of the load

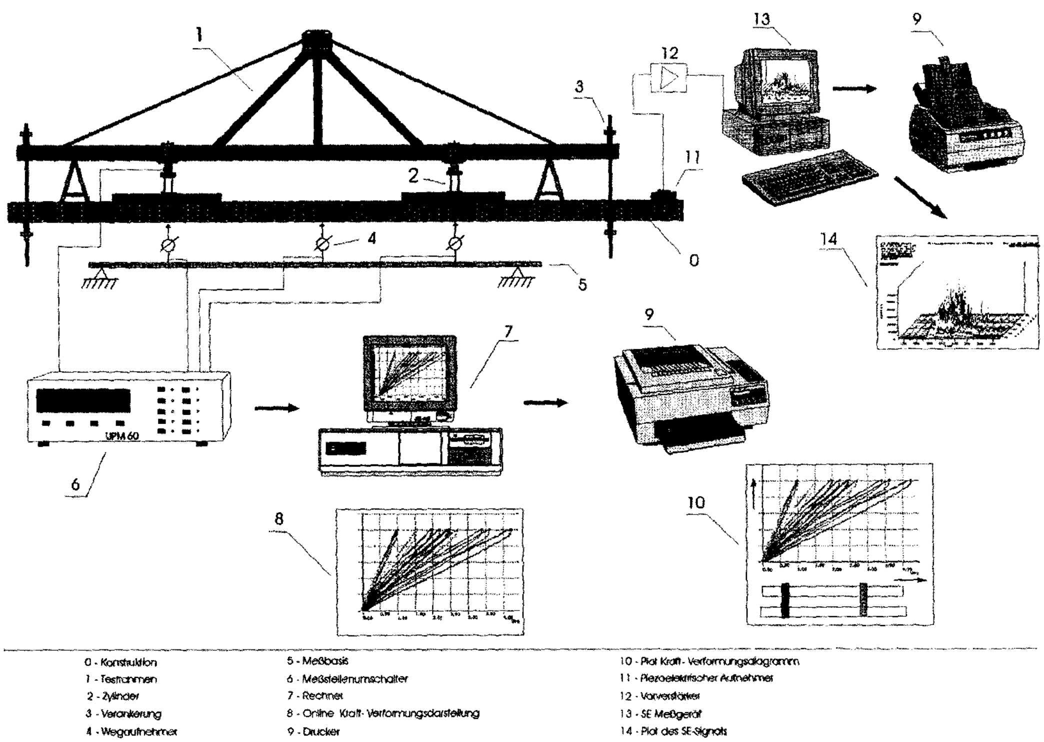

Figure 2
Overview of experimental load carrying capacity tests (source: Reuschel, Fiedler 2000)

reproducible in terms of magnitude, direction and change over time. It consists of force generation, force measurement and force transmission into the test object. For experiments with floors, the active load is generated via mobile hydraulic cylinders through oil pumps according to Figure 2, measured via load cells and distributed across the required load model via a load device. The reaction forces of the cylinders are absorbed by a steel load transmission structure (lattice frame, girder) and transferred into the existing structure. In this way, a closed force loop is created that can be adjusted according to the test requirements. This is done, for example, through anchoring of console profiles in the load-bearing masonry walls or via tie rods and cross bars below cross beams.

Of even greater significance is the question of load protection during experimental structural safety analyses, i.e. rapid relief in case of critical shape change conditions must be possible. So-called self-securing loading systems have to be provided. For bridges, a newly developed load vehicle has been available since 2001, which meets all requirements for a self-securing loading device.

The structural responses generated depending on the load are measured using suitable sensors, and stored and displayed on a monitor using a computer-aided measuring system. All measuring points are monitored simultaneously and in real-time. Load/distortion diagrams are generated that are similar to those of a stress/strain line of the relevant building materials. The formation of the load/distortion diagrams must be monitored thoroughly. Deviations from a straight line, i.e. changes in slope, indicate structural changes (e.g. crack formation, crack enlargement, local plastification) or system changes (e.g. lifting of a support, breaking of a bond). Whether these changes are of a stable or unstable nature can be determined by a load stop and brief load holding. In order to avoid damage, deformation limits should be specified for the fitness for purpose test, depending on the building material used. Misjudgement of the monitor displays can thus be avoided. The procedure can be made more sensitive by accompanying measurements of the sound emission during the loading process, which can provide information about structural changes. To this end, sound sensors are placed in appropriate locations on the floors.

Safety considerations

A significant difference between experimental structural safety analysis and traditional loading tests lies is in the magnitude of the test load. Späthe provides the following concise description: «From a safety theory point of view, a loading test can be useful, pointless or even harmful. It is useful, if the information gained means that the safety index after a successful test is noticeably higher than before. The effort is pointless, if there is no noticeable increase in safety, because the chosen load level was too small or the load arrangement was inappropriate. And a lot of damage can obviously be done if the load level for a loading test is excessive». (Späthe 1994)

Conventional loading tests use the dead load of concrete slabs or steel plates, sand bags, heavy vehicles or similar, which are usually only part of the live load to be applied for the object being examined (see also Figure 1). They are suitable for checking mathematical models or for system identification, but they do not enable statements to be made about the safety of the structure and undoubtedly bear a higher risk in the event of concealed damage. The test load for experimental structural safety assessments should therefore be as high as possible, so that, in the event of a positive test result, the safety margin gained for increased load can be used for example, for changes in the floor structure or for higher live loads (Figure 3). On the other hand, it should not be too high, because the loading tests should not cause any damage that would reduce the load carrying capacity and fitness for purpose. Experiments therefore approach limits without precise prior knowledge about where these limits are. Important limit criteria are deformations such as elongation, changes in crack width or deflections that must not be exceeded. Such limits are specified for concrete structures (2001 guidelines). Structures using other materials should be treated correspondingly. In this case, close co-operation with test engineers and building and construction authorities is required.

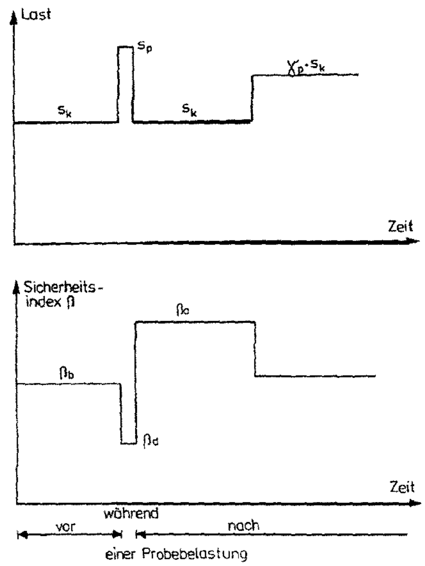

Figure 3
Basic curve for load S and safety index β during a loading test (source: Späthe 1994)

In order for experiments to become an opportunity for historic structures, rather than a risk, in addition to the measuring and loading equipment, detailed preliminary examination of the weak points of the construction, advance calculation of the expected measurement readings, and of course experienced and responsible test personnel is required, because the decision about a further load increase or the abortion of a test can never be made by following a certain recipe. The target load for the trial is specified based on the boundary state technique, using the same partial safety factors and combination coefficients as for mathematical verification.

Potential applications

Due to the specifications in the relevant standards, in Germany experimental structural safety analysis are only carried out in cases where mathematical techniques reach their limits. For example, meaningful and reliable structural documents are often not available for old buildings. As a result, a sophisticated building survey is required that covers not only the geometry of the structure, but also the technical details such as type and condition of the reinforcement, the building materials used etc. Particularly for the critical points of a building, this information is often difficult to obtain in a non-destructive or low-damage way, e.g. only in a very cost-intense way via radiographic examination, or not at all.

Properties of building materials can be determined, for example, via drill cores. However, if the results are scattered, the load-carrying capacity determined via calculation can easily be corrupted, because drill cores with high strength may be located at points with higher load and drill cores with lower strength at points with lower load —or vice versa. Furthermore, the direction of the core does often not correspond to the load in the building. Uncertainties in the assumptions for the material properties can also result from fire, corrosion or overload etc.

Loading tests are highly recommended, if there is uncertainty about the modelling of the structural behaviour of a structure, e.g. due to the contribution of components that are not part of the load-bearing section. Often, the modelling of damaged structures or components is also difficult. Experimental verification is also appropriate in cases where historic structures do not meet modern standards for the constructive design of the components.

All these preconditions often apply to protected objects. Some application examples were described in (Quade, Reuschel 1994; Steffens, Wolters 1997; Steffens 2001). Studies carried out on historic ribbed floors are presented below.

Examples for experimental structural safety assessments

The problem of historic ribbed floors in Germany

After the take-over of the property of the East German «National People's Army» by the Federal Armed Forces and the withdrawal of the Red Army troops based in (East) Germany, the desperate need for refurbishment of most of the barracks, some of which had been built before World War I, became apparent. Both the continued utilisation for military purposes and the search for new civilian utilisation options required statements about the existing load carrying capacity of the floor structures to be made.

In addition to the frequently poor structural state of preservation, missing or incomplete building documents hindered structural recalculations, so that initially comprehensive diagnostic structural studies for determining the floor constructions, the materials used, the placement of reinforcements and the damage characteristics had to be carried out. In order to keep the diagnostic effort within reasonable limits, usually —conservative— structural assumptions based on the knowledge level at the time when the buildings constructed had to be made. The permissible floor loads calculated on this basis did often not match the designed utilisation requirements or contained large uncertainties, so that the refurbishment concepts provided for cost-intensive reinforcement or replacement measures for ceilings and beams. The only alternative to this approach was experimental structural safety assessment of these components.

Construction, calculation and load carrying capacity of reinforced concrete ribbed floors

Reinforced concrete ribbed floors are slab-and-beam floors with a maximum clear distance of 70 cm between the ribs. The thickness of the pressure plate should be 1/10 of the rib distance, but no less than 5 cm. The minimum width of the ribs should also be 5 cm. The ribs may be visible, although for achieving a level ceiling, the voids between the ribs may be filled with light-weight, non-load-bearing hollow blocks made of gypsum, breeze concrete, brick or similar. The only load-bearing components are the concrete pressure plate, the narrow concrete ribs and the flexural tensile reinforcement within the ribs.

This active static principle is the main difference to reinforced block floors, whose load-bearing effect is a result of the synergy of brick, steel and cement mortar, i.e. the stones are used for absorbing the compressive stresses. Standardisation efforts for level ceilings with brick and iron reinforcements go back to the year 1905. In 1913, a distinction was made for the first time between rib and block slabs and reinforced block floors (Berlin police headquarters, 1913), but the final definition in the above sense did not appear until 1925 (German reinforced concrete committee, 1925).

During the first few decades of the 20th century, a large number of, sometimes very different, floor types were developed, based the on the ribbed floor principle. More frequently used floor types were, for example, the Koenen slab (Figure 4a), the Rella slab with rib distances of 50 cm and infill blocks made of gypsum, slag or cement concrete (Figure 4b) and the Ackermann slab with hollow blocks of 30 cm width (Figure 4c). After World War 2, DIN F slabs with prefabricated beams and infill blocks that played a role in the compression zone became very significant. Structural requirements in terms of transverse reinforcement, the shear reinforcement and the arrangement of transverse ribs were developed during this time for ribbed floors.

Due to

- the assumptions that had to be made about the material strengths for the reinforcement steels used at the time and for the concrete,

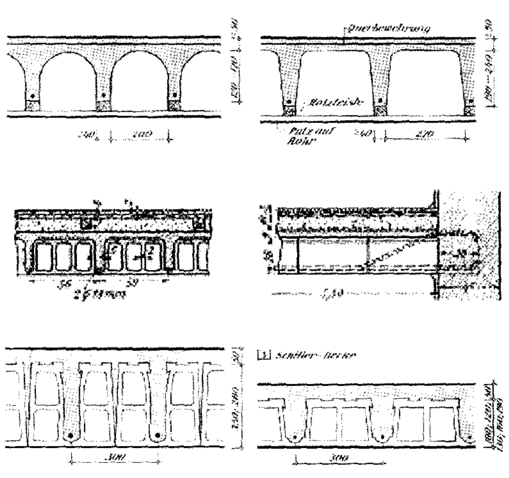

Figure 4
Examples for ribbed floors constructed before World War 2
a) Koenen slab, (source: Ahnert, Krause 1991)
b) Rella slab, (source: Bargmann 1993)
c) Ackermann slab, (source: Ahnert, Krause 1991)

- the predominantly longitudinal load transfer due to the small amount of transverse reinforcement and the arrangement of transverse ribs, and
- partly inadequate shear reinforcement

even the recalculation of the floor constructions with the aid of techniques commonly used today only provided little options for mathematical verification of increased live loads due to new requirements and/or increased dead weight of the ceilings through modified floor construction (protection from structure-borne sound, thermal insulation and fire protection).

Studies in former barracks in Saxony

In a barracks complex in Saxony, a building constructed before or during World War 1 was to be used as an accommodation block. However, no structural documents were available that would allow conclusions about the load carrying capacity of the existing ceilings to be drawn. The organisation managing the project had already commissioned an expert report based on a diagnosis of the building and static recalculation. However, even with a reduction of the requirements based on P.3 of the «civilian» DIN 1055, this did not produce permissible live loads, so that complex and cost-intensive structural measures appeared unavoidable.

A large proportion of the total ceiling area of approximately 3,600 m^2 was diagnosed as a reinforced concrete ribbed floor construction with a rib distance of 50 cm (probably type Rella), the remainder was identified as massive reinforced concrete slabs (partly designed as continuous systems). The clear spans of the ribs had been adjusted to the spatial requirements, with a maximum of 4.6 m. Consequently, the cross section of the reinforcement inserted between the ribs also varied, between 2.36 and 3.92 cm^2. No transverse reinforcement was present, and there were clear cracks along the direction of the effective span. At all levels, the hollow blocks had a height of 17 cm, the thickness of the compression concrete fluctuated between 3 and 5.5 cm, the concrete strength determined from drill core tests was between B10 and B15 in different areas.

At the suggestion of the consultants, the client decided to have the actual load capacity of the ceilings determined via an experimental analysis of the load carrying capacity. The aim of the studies was the verification of the maximum distributed loads the ceilings could accommodate, taking account of the required future live load level according to DIN 1055 (accommodation block), in order to have a certain amount of design flexibility. The tests were to be carried out for the existing state of construction of the ceilings, without causing damage that would impair the load carrying capacity and fitness for purpose during the intended period of future utilisation.

In the current building, five reinforced concrete ribbed floors, which had shown unfavourable diagnostic results in terms of reinforcement, span, compression concrete slab and damage, were specified for the loading tests. The loading equipment was installed on or below the ceilings to be tested, see Figures 5 and 6. The test loads were determined based on the safety concept of the relevant guideline (German reinforced concrete committee 2000), with factors added, for example, for the existing dead weight due to the diagnosed thickness variations of the floor layers, for the scatter in material properties, for variable loads and for the transfer of the test results to similar areas that had not been investigated. As a result, the live loads to be applied at this site were realised in the test with a global safety factor of $\gamma \geq 1.82$.

Due to the limited space available, the measuring instrument, the computer and the monitor as well as the hydraulic pump were installed in the corridor outside the spaces included in the examination. For recording the ceiling deflections, inductive displacement transducer were installed in a transverse and longitudinal grid on the underside of the ceilings examined.

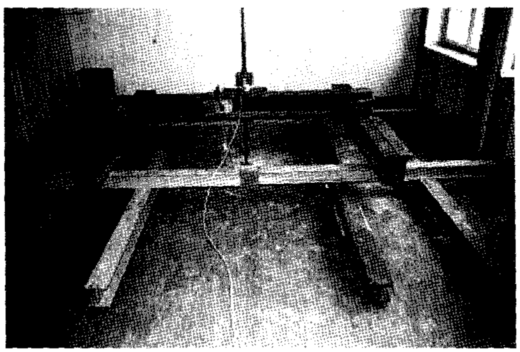

Figure 5
Load distribution on 16 individual load transfer areas of the reinforced concrete ribbed floor to be examined

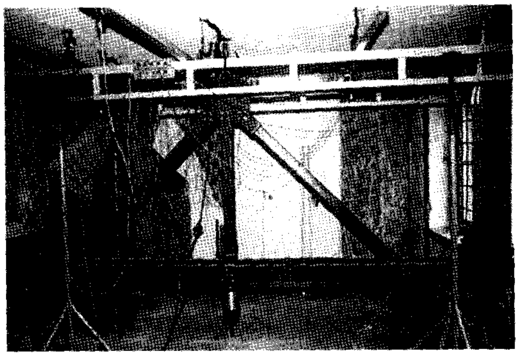

Figure 6
Transfer of the force generated by the hydraulic cylinder into the load-bearing walls with the aid of a steel frame construction; below the ceiling being examined, the measuring base with displacement transducers arranged in a grid can be seen

The loading test according to (German reinforced concrete committee 2000) was carried for each ceiling live load to be verified in a loading/unloading cycle, for which the behaviour of the structure was observed and analysed online. This also included a creep test for each target live load to verify reliable load transfer via the ceiling. Figure 7 shows examples of load/distortion diagrams for a ribbed floor subjected to a load increase test, Figure 8 shows a creep test.

As a result of the loading tests, a live load of 5.0 kN/m^2 could be recommended for the reinforced concrete ribbed floors of this barracks building. The deflections under this working load were less than 1/2600 of the span. Since the loading tests carried out at the reinforced concrete slabs were also successful, the building could be designated for the new utilisation without fundamental ceiling reinforcement measures, thus providing significant savings in building costs. The supporting structure as a testimony of a certain era-defining barracks architecture could thus be preserved.

Studies in a Spanish embassy building in Berlin

Following the decision of the German parliament to reinstate Berlin as the capital of Germany, numerous ministries, public authorities, embassies, associations

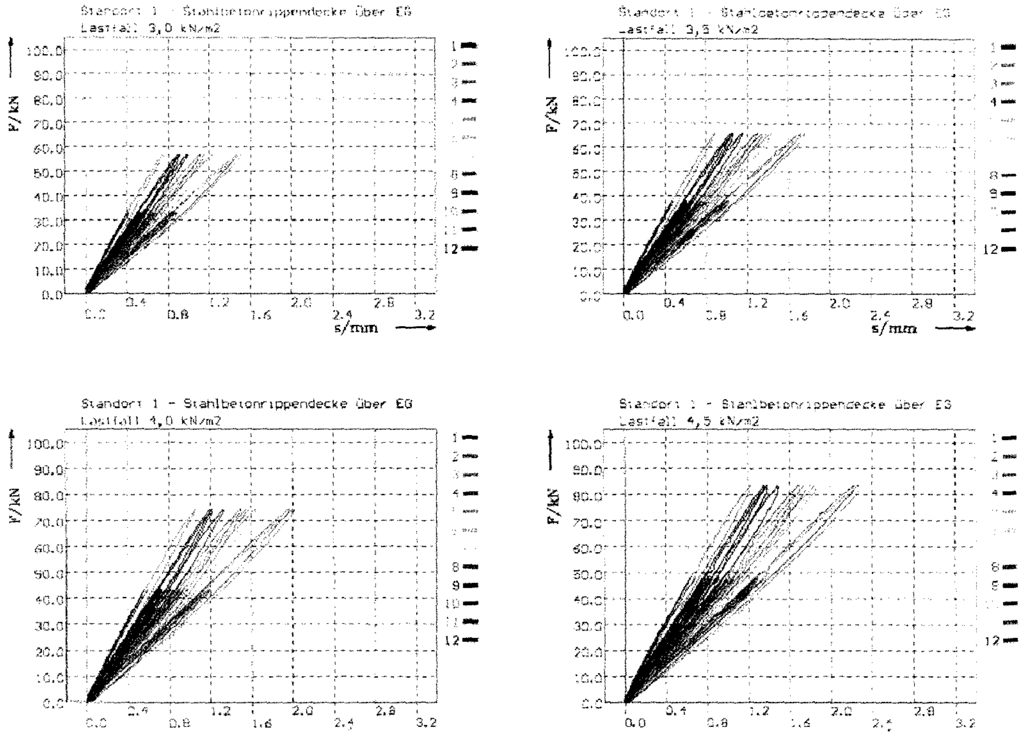

Figure 7
Load/distortion diagrams with several loading/unloading cycles for a reinforced concrete ribbed floor subjected to a load increase test for live loads of 3.0 / 3.5 / 4.0 and 4.5 kN/m^2

etc. moved to Berlin. In many cases, existing buildings were repaired or modified and adapted to current requirements. In a number of cases, this also required experimental verification of their structural safety, which was usually carried out based on the guideline for loading tests (German reinforced concrete committee 2000).

As part of the refurbishment of an embassy building, reinforced concrete slabs made from semi-prefabricated components with in-situ concrete layer were installed. Inadequate support during the placing of the concrete led to significant deformations that were corrected after a few hours through intermediate supports. The hardening state of the ceiling was not checked at the time when the supports were installed, and it was feared that the ceiling may have been damaged due to the late installation of the intermediate supports, particularly in terms of the bond between prefabricated and in-situ concrete. At the request of the client, a test programme for the experimental verification of the structural stability was developed.

The test was based on the Spanish concrete standard EHE 2000, with the load specifications based on the Euro codes. In contrast to many other guidelines, this standard not only includes the option of experimental verification, but also detailed information about the experimental procedure and the criteria that have to be met. These include the following:

- Application of the maximum load in 4 stages
- Measurement of the distortion directly after reaching each load level and after 30 minutes
- Creep test after reaching the maximum load over 24 hours; Distortion measurement every 8 hours

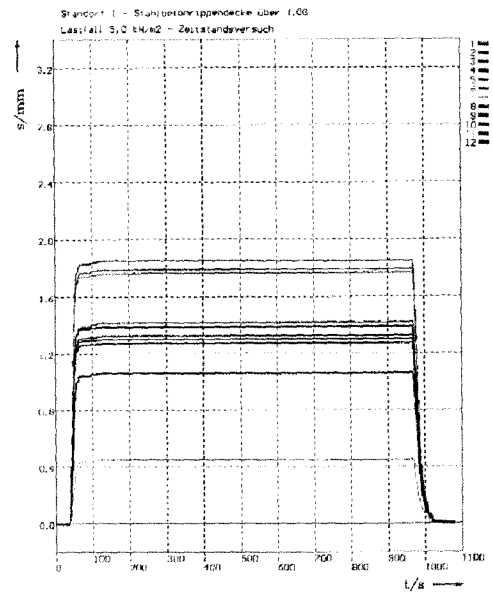

Figure 8
Creep test at 5.0 kN/m² for a reinforced concrete ribbed floor

— Unloading in four stages with a 15 minute dwell period at each stage
— Creep test without load over 24 hours; Distortion measurements every 8 hours

The limit criteria are:

— The test is considered to have been passed, if the maximum distortion is less than $L^2/(20000\ h)$.
— If this value is exceeded, the permanent deformation after removal of the load must not be greater than 25% of the maximum distortion.
— If this is not the case, the loading test should be repeated. The permanent maximum distortion must now be less than 20% of the maximum distortion under load.
— The formation of cracks that could affect the durability is not permissible.

Such specifications provide the engineer with a tool that defines at least the main data. They go far beyond the data commonly provided in most other European standards. Within RILEM working group TC 125, attempts to find a uniform regulation had been made in the past. This has not yet been possible, since the national boundary conditions are too varied. On the other hand it became clear that, even without such rules, «design by testing» is not an invention of recent years, but common practice for a limited number of testing institutes, who use the tool very responsibly.

In deviation from the original concept of using water as the load (this would have required the creation of a 95 cm high water basin; in the event of failure, more than 40 m³ of water would have poured across the building site; furthermore, due to the limited water supply, this would have required a very long test duration), four frames were constructed on site, which were back-anchored to the supports via tie rods. The load was generated via small hydraulic cylinders that created a load in the «fifth-points» via load distribution girders.

The distortions were measured in longitudinal and transverse direction in the centre of the span measuring approximately 4.50 × 9.00 m², also the support distortions, the temperature and the temperature-related distortion of the measuring frame below the ceiling. Figures 9 and 10 show the experimental set-up.

Figures 11 and 12 show the results of the distortion measurements. Figure 12 corresponds to Figure 11, but includes a temperature compensation of the deformations of the measuring frame.

In conclusion it can be noted that only one load cycle was required for verifying adequate structural safety and fitness for purpose and for stopping the endless discussion about potential damage and its significance. This would not have been possible without the willingness of the client and the engineers, both on the Spanish and on the German side.

Summary evaluation of the studies

Reinforced concrete ribbed floors developed during the first decades of the 20th century make up a large part of the building substance of that time. With the diverse demand for conversion of this building substance since the early 1990s —not least with regard to former barracks buildings— the problem of

Figure 9
Experimental set-up with test frame and load distribution girders on the ceiling

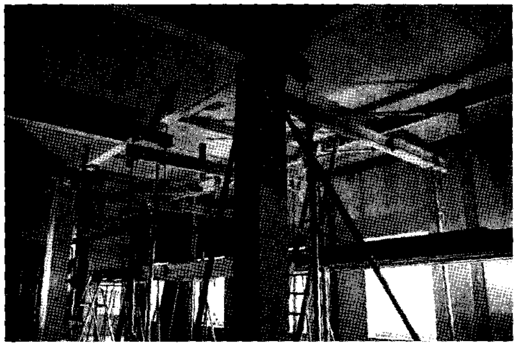

Figure 10
Experimental set-up and measuring frame below the ceiling

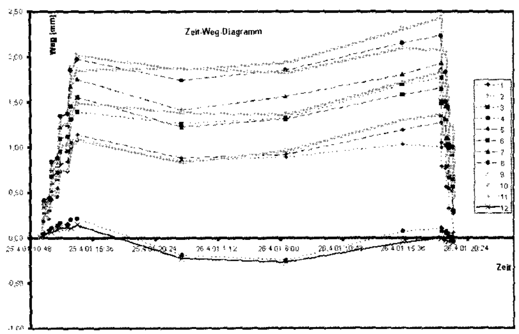

Figure 11
Deflection during the loading phase without temperature compensation

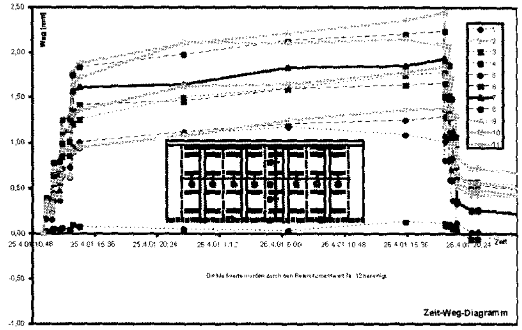

Figure 12
Deflection during the loading phase with temperature compensation; maximum distortion under maximum load over 24 hours: 2.5 mm

determining the structural safety of these floor constructions became more topical, since conventional approaches do not provide satisfactory answers. The load carrying capacity of ribbed floors established via experimental structural safety verification according to (German reinforced concrete committee 2000) could be used without a reduction in safety levels, not only for the example presented, but also for other cases. For theses floor types, working loads of up to 2.5 kN/m^2 higher than those identified by calculation were shown to be safe.

The reserves ascertainable in loading tests are based on the actual monitoring of the load-bearing effect including the support conditions, and on the existing material strengths. For the ribbed floors, in practice the first factor means: the end sections are often structurally obstructed or distorted, thereby enabling the utilisation of the vault effect of the compression concrete. On the other hand, the transverse distribution of the loads through the compression concrete layer, the contribution of the infill blocks in areas with good bond, the partly load-carrying floor layers etc. are taken into account.

These influences can also be demonstrated in experiments on other historic floor support structures such as reinforced block floors, timber joist floors or massive reinforced concrete slabs. In many cases, the magnitude of the ascertainable load reserves justifies the use of this undoubtedly costly verification procedure, if it enables expensive reinforcement, demolition and reconstruction work to be avoided and if enables continued utilisation of the existing spaces. Based on the diverse experience in the application of experimental structural safety assessments for historic floor structures —both in protected and other buildings— the risk during the loading tests can be minimised through a thorough diagnosis of the structure, preliminary calculations and experienced testing staff. The chances of preservation of the historic structure, either in unchanged or only slightly modified form, are good. In each case, the recommended load capacity of the ceilings resulting from the structural safety assessment justified the experimental effort.

In the second example, the technique was used for a new design, whose structural behaviour had been assessed differently by different experts. Considerations comparable with those for the assessment of the structural safety of historic structures were able to provide valuable clues about the actual behaviour. Considerations and calculations based on theoretical considerations alone would have been fruitless.

Summary

Unlike testimonies of cultural history from the areas of music or literature, buildings are subjected to strictly objective utilisation and to harmful influences and permanent changes. Buildings are usually only designed for a limited service life and for a certain purpose. As a logical consequence, the replacement of buildings through new buildings is the rule. Only few buildings are preserved as testimonies of the history of technology due to their aesthetic and cultural significance and are treated as historic monuments. If such exemplary significance is not apparent, it is often merely the usability, closely related to structural stability, which decides the further destiny of a building.

The method of experimental structural safety assessment, methodologically and technologically developed at the end of the 1990s, can, in principle, be used both for protected buildings and for other historic structures. As a largely non-destructive loading test, it can make a significant contribution to the stability analysis of historic structures, if original computational or currently available techniques fail to provide satisfactory answers due to inappropriate or missing data or due to changes in utilisation requirements. Detailed analysis of the behaviour of a construction under controlled loads can provide valuable insight into the interaction of different structural elements, into any damage that may exist or into material ageing. This in turn can be used to minimise or avoid irrevocable interventions into the building substance. Preservationists and interested building owners therefore have the opportunity to critically question the argument of «lack of load-bearing capacity» often used by planners and to come up with new solutions. Significant cost and time savings are often an important side effect of an experimental structural safety assessment.

This paper uses selected examples of the application of loading investigations on historic structures to introduce and discuss preconditions, technology, methodology, safety and cost effectiveness of the technique.

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