NON-DESTRUCTIVE TESTING AND MONITORING AS ELEMENTS OF BUILDING INSPECTION

ZERSTÖRUNGSFREIE PRÜFUNG UND BAUWERKSÜBERWACHUNG ALS ELEMENTE DER BAUWERKSPRÜFUNG

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SUMMARY

Periodic building inspection is the main pillar for ensuring structural safety, traffic safety and durability of civil engineering structures. Its primary focus is rightly set on the close visual inspection, as this allows the detection of the vast majority of defects or indications for such, if carried out by an expert with knowledge of the materials, specific vulnerabilities and construction types. Yet, when it comes to the determination of causes for some detected damage or the precautionary early detection of still invisible weaknesses, the instruments of non-destructive testing (NDT) and building monitoring techniques come into play. This article provides an overview of the requirements for the use NDT and building monitoring with reference to the primary legal documents for building inspection.

ZUSAMMENFASSUNG

Die regelmäßige Bauwerksprüfung ist das wichtigste Standbein zur Gewährleistung der Standsicherheit, Verkehrssicherheit und Dauerhaftigkeit von Ingenieurbauwerken. Das Hauptaugenmerk wird dabei zu Recht auf die handnahe Sichtprüfung gelegt, denn diese ermöglicht es, die weitaus meisten Mängel oder Hinweise auf diese zu erkennen, wenn sie von einem fachkundigen Experten mit Kenntnis der Materialien, der möglichen Schwachstellen und der Konstruktionsarten durchgeführt wird. Wenn es jedoch um die Ursachenermittlung für erkannte Schäden oder die vorsorgliche Früherkennung noch unsichtbarer Schwachstellen geht, kommen die Werkzeuge der zerstörungsfreien Prüfung und Bauwerksüberwachung ins Spiel. Dieser Artikel gibt einen Überblick über die Anforderungen an den Einsatz zerstörungsfreier Prüfmethoden und der Bauwerksüberwachung

mit Verweisen auf die grundlegenden offiziellen Dokumente für die Bauwerks-prüfung.

1. PERIODIC BUILDING INSPECTION

The German model building code [1] reads in § 3 that "Installations shall be arranged, constructed, modified and maintained in such a way that public safety and order, in particular life, health and the natural bases of life, are not endangered". The EU construction products regulation [2], which is similar in wording with regard to this, applies likewise. It states that "The structures must be suitable for their intended use throughout their life cycle, both as a whole and in their components, taking particular account of the health and safety of the persons involved". According to § 823 and § 836 ff. civil code [3], the responsibility for any necessary measures to meet the legal duty to maintain safety is held by the building owner or authorized party. Yet, despite being required by law, an adequate structural maintenance is in most cases also in the owner's own interest, both financially and regarding availability.

Against the background of an aging volume of buildings owned and operated by the public sector, especially in the field of traffic infrastructure, but also generally of wide-span civil engineering structures, periodic inspections have become increasingly important for sustaining their usability and structural safety. For the majority of all relevant types of defects, these permit an early detection of signs for incipient damage and thus allow a timely initiation of measures to prevent further deterioration.

The legal requirements can be translated in detail by ensuring proper preventive maintenance in the three categories structural stability, traffic safety and continuing durability. This is commonly recognized that this can largely be achieved through regular, i.e. periodic inspections. The legal responsibility is implemented in various documents, the application of which depends on the type of structure and the relevant building authority.

- The binding approach in Germany for the implementation of periodic inspections regarding road infrastructure is agreed on in the standard DIN 1076 [4], and the thereof based guidelines and regulations for the practical application, especially [6], [7] and [8]. The standard mainly embraces bridges and tunnels, but also traffic sign gantries, noise protection walls, support structures, etc. The documents are supplemented by instructions for the special challenge of stress corrosion cracking [9] and the recalculation guideline [10] with [11].

- Bridges in the course of the railroad infrastructure must be inspected according to module 8002 of the DB guideline 804 [15], [16]. All other buildings and structures within the area of responsibility of the German railroad has to be inspected in compliance with the other modules of the guideline [17], [18].
- The remaining large part of other civil engineering buildings, such as assembly or lecture halls, indoor pools, gymnasiums or warehouses, has to be inspected according to the recommendations of the construction ministers' conference [12]. Compared to the previous directives, which mainly deal with buildings in the reals of the public traffic infrastructure, this document has a stronger emphasis on cities, municipalities, companies and private individuals owning or responsible for wide-span buildings. The specifics of the necessary inspections are further elaborated in guidelines [13] and [14].

In fact, the similarity of the materials, constructions and partly the loads and challenges in general allow, even suggest, consideration of the directives of the respective other disciplines.

The main source of information of the structures' condition is the hands-on examination, where the term "hands-on" literally describes a no-distance visual and physical inspection by an engineer with (certified) particular expertise. The results must be recorded in detail in a building logbook to make slow changes over time, such as crack growth or settlements, recognizable.

If the engineer discovers severe or complex damage, or a deviation from the normal condition, e.g. a distinct new crack, which cannot be explained by simple means (such as local corrosion of the surface-near reinforcement) and may point towards a more serious issue, an object-related damage analysis must be performed. The goal is to determine the extent and identify the cause of the damage and subsequently to initiate appropriate repair, rehabilitation, retrofitting, restraining or removal measures. This analysis usually includes some kind of extended material or structural testing. Of particular importance for the analysis are non-destructive testing methods and, in the long term, building monitoring.

2. NON-DESTRUCTIVE TESTING

The major issue for all aged structures alike is the natural non-consideration of at that time unknown weaknesses that have since been proven important for the maintaining their usability and safety. A good summary of such issues in the case of concrete bridges may be found in [19], where many of them also apply to other wide-span structures. Some examples are the lack of specifications for minimum shear reinforcement, the neglect of the temperature load case ΔT (differential heating on the top and bottom), the design and construction with hollow bodies and the use of prestressing steels susceptible to stress corrosion cracking. Yet, it is often not the resistance side, but the load side, that requires a review of the structure. In the case of bridges, this especially refers to the traffic loads, which have significantly increased in frequency and amplitude, far more than predicted at the time of construction. For other buildings, it may be changes in use, constructional modifications, or new requirements from the standards regarding loads, e.g. from earthquake or snow, that have to be considered.

Experience has shown that, even for buildings of recent construction, essential planning and execution documents, containing information that is indispensable for structural assessment and recalculation, often deviate from what has been built in the end (an alternative statical analysis and execution design by the respective construction company was permitted for a long time), or have entirely disappeared without trace. Strong efforts are made trying to counteract this troublesome problem of data loss with approaches of digital data storage and cloud-based document distribution and accessibility. However, they will never be able to revive information that has been lost or unknown from the beginning.

In all of the above cases, i.e. a deficit of the structure, a change in the loading conditions or the need for structural data, NDT can help to assess the current state of the building, complementary to (but not substituting) conventional inspections and providing deep insights into the structures beyond the possibilities of visual testing and other regularly performed, surface-bound techniques. The benefits of NDT methods lie in the volumetric retrieval of information and in the visualization of features invisible to the naked eye, such as corrosion (potential field measurement), concrete cover, reinforcement arrangement and diameter (e.g. inductive measurements and radar), voids, unwanted inclusions and unknown geometries (e.g. ultrasonic testing and radar), concrete compressive strength (rebound hammer), ruptures of prestressing wires (magnetic stray field measurement), moist areas (e.g. infrared thermography), and many more.

It must be honestly noted and strongly emphasized in this context, that the applied methods of NDT do not directly paint a perfectly accurate picture of reality, but are only used to acquire data, which then requires an engineering interpretation in the context of the visual inspection and the available information on the tested structure. This is also true for seemingly straightforward, easy-to-use, commercial measurement devices. Although most of them allow an on-site interpretation of the data, their representation of reality is often, without malicious intent, taken at face value, or, at least, suggest a confidence that may lead to wrong conclusions. Against this background, the different societies for non-destructive testing (e.g. DGZfP[1] in Germany) and other boards (e.g. DBV[2] or RILEM[3]) are continuously working on developing and updating guidelines on how to apply NDT methods in civil engineering.

From the list of non-destructive test methods, the magnetic stray field measurement (MSM), used for the detection and on-site localization of broken tension wires, has gained particular importance, both for prestressed concrete bridges within the transport infrastructure and other wide-span concrete structures. The reasons for this are found in the special topic of stress corrosion cracking, which is considered to be highly critical in connection with the buildings' ever increasing age and simultaneously risen loads, and the near non-inspectibility of these load-bearing components, inaccessibly embedded in the concrete, with often little potential for load redistribution. The now as before only possibility for a non-destructive examination of prestressing wires for fractures is the magnetic stray field measurement. It was originally developed and deployed in the 1980s for the examination of prestressing steel in high alumina cement after the collapse of such structures, and its use was in the further course formally recommended by the authorities [20]. It is meanwhile well established for the inspection of all prestressed concrete members, especially if susceptible to hydrogen- or chloride-induced stress corrosion cracking, but also in case of careless drilling, suspected overloading, etc. Its theory, application and limits are described in the relevant position paper [21].

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[1] German Society for Non-Destructive Testing

[2] Germany Society for Concrete and Construction Technology

[3] International Union of Laboratories and Experts in Construction Materials, Systems and Structures

Non-destructive measurements are often accompanied by some destructive testing. Depending on the task, this can for example be required for calibration purposes or for verification of the suggested data interpretation. Similarly, NDT may be used to minimize destructive intervention in quantity or size when used for large-area testing to locate specific structural elements, particularly conspicuous spots or weak points. Both destructive and non-destructive testing perfectly complement each other, especially if large structures have to be inspected.

Out of these considerations and with the given progress in NDT technology, non-destructive testing has become well accepted and appreciated in the building inspection community. Many of the documents mentioned in section 1 thus advice the use of NDT:

- In addition to the bridge inspection standard [4], the directive for the maintenance of civil engineering structures [6] recommends that, “if necessary, non-destructive testing methods [...] shall be used”. It also considers the employment of NDT methods by requiring that detailed specifications for their use are to be included in the inspection manual. This is further discussed in the documentation for building inspection according to standard [5].
- The guide to object-related damage analysis [7] repeatedly recognizes the “special importance” of NDT in the damage evaluation.
- The instructions for stress corrosion cracking [9] recommends “further investigations on the condition of the prestressing steel” if necessary, yet without directly referring to NDT, i.e. magnetic leakage field testing (but destructive sampling).
- The guideline for the recalculation of road bridges [10], [11] notes, that “properties of concrete bridges and their components can be determined by investigations and measurements on the structures [...]”.
- A detailed paragraph on the use of non-destructive testing methods may be found in the VDI guideline on the structural safety of buildings [13], in which various possibilities are listed for quantitatively recording changes in the properties of construction materials.
- The railroad’s directive for the inspection of engineering structures [16] notes that “the detection of material defects” can also be carried out using NDT equipment.

3. MONITORING

Both periodic visual inspection and case-specific non-destructive testing are limited in their informational value when it comes to the quantification of damage progress. This might at first seem contradictory to the previous arguments and therefore requires further explanation. Viewed in itself, any inspection carried out by an expert, both with and without help out of the non-destructive toolbox, can provide correct results, if performed according to the state of the art and if the data is decently interpreted. These investigations thus undoubtedly form an irreplaceable basis for evaluating the as-is state of buildings and structures. However, they must fail regarding any defect evolution that either is too fast to be caught by the effective periodic testing interval or causes changes within the range of the apparent noise.

Two exemplary, non-exclusive cases with sudden failure scenarios are bridges with X10Cr13 stainless steel roller bearings or any prestressed concrete structure with high-tempered prestressing steel that is prone to stress corrosion cracking (St 145/160 and St 140/160, especially in connection with steel superstrengths) and shows unfavourable announcement behaviour [19]. Once such hazards become evident on a building, at a minimum, traffic compensation measures (restrictions of use with regard to load level and/or frequency) are unavoidable, but also detailed investigations of the condition and, if deemed necessary, interim emergency safety measures for case of failure. However, despite these actions, the structures do not become “safe” again, necessitating a significant reduction of the inspection intervals. This can pose a serious challenge, particularly for parts that are difficult to access, or where an inspection entails a slew of disruptive, if not completely undiscussable consequences, such as a persistent or the frequent closure of a motorway, railroad line or waterway.

The above-mentioned second limitation regarding the magnitude of the change in relation to the “noise level” refers in particular to the considerable influence of temperature on the structures under analysis. Inspections carried out at different times of the year can lead to completely different results, depending on the particular examination. This is quite obvious, for example, in the case of the movement of a roller bearing, which depends on the thermal expansion of the superstructure. Its position can be easily verified through an approximate calculation and can be reasonably well documented in connection with the mandatory recording of the weather conditions (yet, as a side remark, not with regard to the weather history, which actually determines the thermal expansion of a massive building component). It quickly becomes a lot more complex for other values, starting already with the calculation of a true deflection (in contrast to the design calculation for the deflection under load, which is governed by the serviceability limit and underestimates the deflection on the safe side). Data from repeated measurements therefore may appear to be subject to a large variation, which could be falsely attributed to either poor testing and inaccurate equipment, or even damage formation or damage evolution. The consequences would be to label the measurement entire series uninterpretable, despite the effort, or lead to subsequent precautionary actions with all economic, structural and disposability consequences. Strongly reduced measurement intervals that reflect seasonal, daily or even shorter fluctuations, significantly improve the apparent signal-to-noise ratio and allow a much deeper insight into the state of the buildings structural health.

With this background in mind, it seems only logical to automate on-site data collection as far as possible and sensible; an approach that is known as (building) monitoring.

Although not as common in civil engineering (compared to mechanical engineering), monitoring is considered important and permitted by the aforementioned documents, similarly to NDT, as a tool for ensuring structural safety and usability.

- The documentation for building inspection according to standard [5] recognizes monitoring as “useful for certain aspects, e.g. deflections, warping or temperatures”.
- The directive for the maintenance of civil engineering structures [6] requires that detailed specifications for the use of monitoring are to be included in the inspection manual.
- The guide to object-related damage analysis [7] allows, in the case of high risk potentials, the supplementary use of monitoring for the long-term surveillance of critical structural conditions that were determined by the building inspection.
- Special attention is given to monitoring in the instructions for stress corrosion cracking [9], which reads: “Suitable monitoring systems must be provided at inaccessible cross-sections in order to be able to detect crack formations with sufficient warning time”. And further: “In spite of a given analytical proof of sufficient announcement behaviour at a cross-section, it can only be assumed, if the considered cross-sectional areas can be visually inspected or, alternatively, are continuously checked for crack formation by

monitoring". The same applies for the utilisation of possibilities for load redistribution in longitudinal and transverse direction. Fibre-optic monitoring systems are especially referenced for this task. If monitoring is used for crack detection, the service conditions must be specified in detail in the inspection specifications.

- The guideline for the recalculation of road bridges [10], [11] defines that "Compensatory measures [ensuring the continued traffic use of a structure with a given bearing capacity] include the establishment of permanent control mechanisms or [...] reduced test intervals according to DIN 1076".
- The recommendations of the construction ministers' conference [12] notes, that "Wired and wireless, permanently active monitoring systems may be considered suitable as an early warning system for the prevention of damage, especially in the case of structural systems with large spans". It advises to in any case, consult an engineer with special experience and knowledge of the state of the art in this field.
- Another focus for monitoring is set in the VDI guideline on the structural safety of buildings [13]. It states, that "Building monitoring serves to synchronise the current bearing structure behaviour with that of the computer model." However, it also describes monitoring systems as "safety management systems" with the aim of "the determination of the current safety and usability".

The bridge inspection standard [4] also mandates building monitoring, but uses the term in the outdated designation for merely repeated measurements and not, as used in the context of this paper, for instrumented monitoring.

Two amongst many challenges of an automated monitoring lie in the selection of a suitable instrumentation in terms of sensor type, amount and position, and the inevitable necessity of automated data evaluation, which should only trigger notification of the operator or owner if data has been collected that indicates relevant events at the building. This "relevance" is in general difficult to determine, since, as explained above, buildings move and deform surprisingly vigorously in the static case and can behave completely unexpected during component failure, beyond conventional engineering expectations. The definition of admissible limit values is therefore often difficult and is usually only possible as relative change, based on a fairly long series of measurements in an assumed undamaged or, at least, stable state. The provisional continuation of periodic building inspections with reduced intervals is therefore initially indispensable in complement to monitoring.

Regarding the selection of reasonable instrumentation, fibre optic measurement technology has proven to be very valuable in recent years, as mentioned in [9], due to the possibility of an almost 100 % - monitoring, even for large structures. It still comes at relatively high costs compared to conventional electric measurements (yet far below financial benefits it generates), but clearly outperforms them in terms of accuracy, coverage and reliability. The topic has been treated in detail in last year's article in this series and the citations therein [22].

A first guideline that gives advice on how an effective monitoring system can be designed is now available from the DBV [23]. A further guideline with a stronger focus on technical specifications is currently being prepared by the DGZfP [23].

4. CONCLUSIONS

Both NDT and building monitoring are tools that can – sometimes must legally be – used to complement periodic visual inspection of civil engineering structures. The basis for a profitable information gain is their correct application, which is in details still often disputed, even by experts. However, it is without doubt commonly appreciated that those technologies are valuable in understanding the actual state of structures. Consequently, in recognition of their benefits, their employment is recommended or requested by most of the binding documents for building inspection, which has been assembled in this article.

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