FORENSIC ENGINEERING

Part 2.

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In the past, problems with structures were mostly incidental, but nowadays new tendencies are observed, like aging of structures and their consequences, the use of software without understanding its background, and changes of the function of a structure during service life. That means that there is a growing need for another profile in structural engineering: the forensic engineer. The need, and the requirements for such a new professional profile are treated in this paper.

Important capabilities of forensic engineers

4. Being able to deal with the effect of aging of structures on structural safety

For many decades concrete structures have been designed for predominantly two criteria: structural safety and serviceability. There were no considerations about the service life of structures. However the observation of substantial damage to concrete structures developing in time due to deterioration processes became gradually a point of large concern. In the new fib-Model Code for Concrete Structures 2010 design for service life is a central issue. According to this principle, structures are designed to satisfy the demands for safety and serviceability for a specified period of time. Structures serving the infrastructure of a country, like tunnels and bridges, are mostly designed for a low maintenance service life of 100 years. In structures like buildings and offices the functional service life is often the governing criterion, so that a physical service life of 50 years is most often required. Nowadays, we dispose of considerable knowledge with regard to deterioration processes, and we are able to design our new structures for service life by making sure that we use the right materials, that the concrete cover is sufficient and that the cracks are well controlled. We dispose of adequate quality control procedures for the material concrete and its constituents to avoid unforeseen problems like e.g. alkali aggregate reaction.

A problem which is left, however, is that most of the existing structures have not been designed based on service life considerations. The actual structural safety of those structures is a point of concern. If the actual safety turns out to be sufficient, the question is for how long this is guaranteed. This uncertainty is justified, what is often illustrated by unexpected and unwanted surprises, like the collapse of gallery slabs in an apartment building in Leeuwarden, the Netherlands, 2012, Fig. 9.

The collapse turned out to be caused by corroded reinforcement. A remarkable observation was that the structure fulfilled the code criteria of today. There were no cracks and no signs of upcoming problems due to, for instance, spalling of the concrete cover. That illustrates that obviously our knowledge about deterioration processes is not yet complete.

Thousands of concrete structures, especially belonging to the infrastructure, are subject of deterioration due to a variety of detrimental effects. Chloride attack is one of them. After considerable research, there seems to be consensus about the mechanism of chloride intrusion, and the criteria that should be met in order not to lose structural safety due to reinforcement corrosion. Reinforcement corrosion is expected to occur if the chloride concentration at the reinforcement exceeds a certain value. This can be calculated with the equation of the ageing factor giving the decrease over time in the apparent diffusion coefficient. Depending on the time of binder and micro-environmental conditions, the ageing factor is likely to be between 0,2 and 0,8.

$$C(x,t) = C_S - (C_S - C_i)\cdot[erf\,\frac{x}{2\cdot\sqrt{D_{app}(t)\cdot t}}]$$

where:

$C(x,t)$ – is the content of chlorides in the concrete at a depth x (structure surface: $x=0$ m) and time t [wt.-%/binder content]

C_s – is the chloride content at the concrete surface [wt.-%/binder content];

C_i – is the initial chloride content of the concrete [wt.-% binder content]

x – is the depth with a corresponding content of chlorides $C(x,t)$ [mm]

D_{app} – is the apparent coefficient of chloride diffusion through concrete [m^2/sec.] at time t

t – is the time (years) of exposure

erf – error function

$$D_{app}(t) = D_{app}(t_0)(\frac{t_0}{t})^{\alpha}$$

where:

$D_{app}(t_0)$ is the apparent diffusion coefficient measured at a reference time t_0.

It is a remarkable observation that the crack width obviously does not play a role in this respect. On the other hand, design codes give limits to the maximum crack width

Fig. 9. Unannounced collapse of gallery plates in an apartment building in Leeuwarden, The Netherlands, 2003

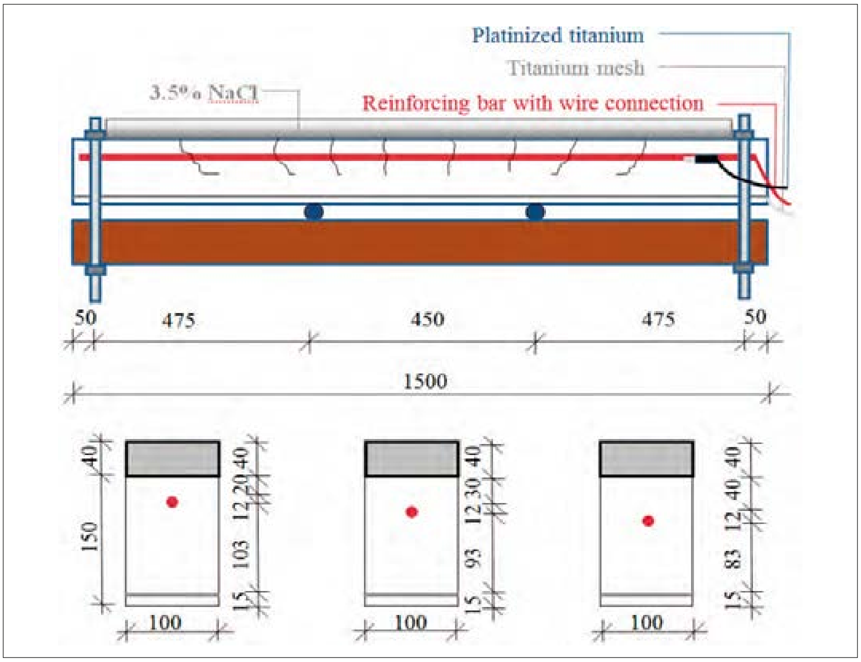

Fig. 10. Test specimens for the determination of the role of crack width on durability (Blagojevic, 2016)

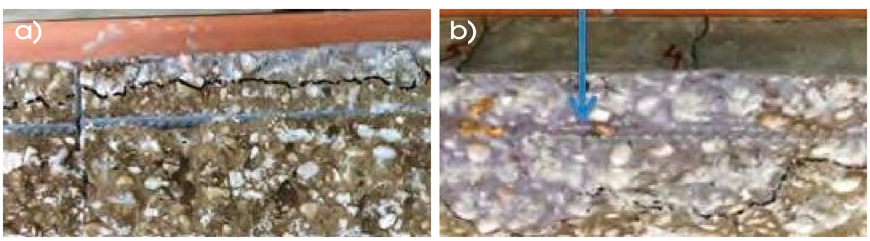

Fig. 11. a) Chloride intruded area in a beam without bending cracks (light grey area), b) Chloride intruded area in a beam with bending cracks (light grey area) (Blagojevic, 2016)

not to be exceeded. This looks controversial. In order to get a better understanding of the role of crack width for the service life of reinforced concrete structures, a series of tests concentrating on the role of crack width in the development of corrosion at TU Delft was carried out. Altogether 32 concrete beams (1500x100x150 mm) were tested, see Fig. 10.

Parameters were: the main crack width, the number of cracks, the concrete cover and the type of loading (static versus variable). The cracked concrete beams were exposed to alternately wetting and drying cycles once a week - to 2-day ponding using a 3.6% NaCl solution and a 5-day drying phase to simulate an aggressive environment. After 2 years, the beams were sawn open and the areas into which chlorides had protruded were highlighted. Fig. 11. shows that the chloride intrusion is substantially influenced by the presence of cracks. The bending cracks facilitate the ingress of chlorides over a large area, because the crack faces function as areas in direct contact with the environment. The areas where corrosion was observed are related to the crack pattern. In a number of cases, the corrosion occurred at the reinforcing bar at the location where the bar intersects the crack, but in other cases at some distance from the crack, showing that chlorides, oxygen and water can infiltrate the concrete to a more remote location from the crack along the bar across the area adjacent to the crack, damaged by micro- and meso-cracking. These observations show that theoretical models, used for the probabilistic determination of service life, based on the assumption that serious damage only occurs after the end of the initiation time, and that cracks do not play a role, should be reconsidered.

The research has shown that the maximum stress in the reinforcing steel, occurring in the service life, is a better indicator for the start of reinforcement corrosion than the maximum crack width. Nevertheless, in an existing structure without analytical data, the maximum crack width is certainly an indication for the location, where the reinforcement should be investigated for corrosion.

5. Determining the residual bearing capacity of structures

Due to the increase in the traffic load on many infrastructural systems, like bridges, the accurate determination of the bearing capacity of those structures is necessary in order to avoid unnecessary investments in strengthening. It should be noted that design equations found in codes are not the best option to decide whether a structure is strong enough or not. Design equations are developed for the realization of new structures. If simplification of rules leads to conservatism in the design of new structures this is not a disadvantage. The additional safety margin obtained might proof to be very useful in future, when some residual capacity may pay off. However, in order to be able to determine the residual capacity and use it to demonstrate that a structure has sufficient bearing capacity for loads larger than adopted in the original design, it is necessary to dispose of more accurate means in order to reliably determine the real bearing capacity. The fib Model Code 2010 introduced the concept of various "Levels of Approximation". The lowest level can be used when high accuracy is not required, e.g. in a preliminary design. The highest Level of Approximation should be used if decisions have to be taken about investing money in upgrading or strengthening of a structure, with considerable financial consequences.

A good example is the punching shear resistance of thin bridge decks, supported by prestressed beams, Fig.12. The deck is provided with transversal beams, by virtue of which the thin upper slab, subjected to a high wheel load, takes profit of compressive membrane (confining) action. This action substantially adds to the punching shear capacity of the deck. However, the code rules for the punching shear capacity have been derived on the basis of tests (circular or rectangular slabs with free edges) which did not allow compressive membrane action to develop. Therefore, they underestimate

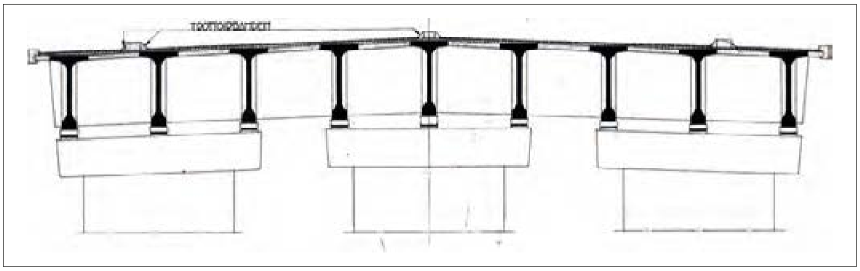

Fig. 12. Slender bridge deck with unexpected residual capacity against punching shear (Amir, 2014)

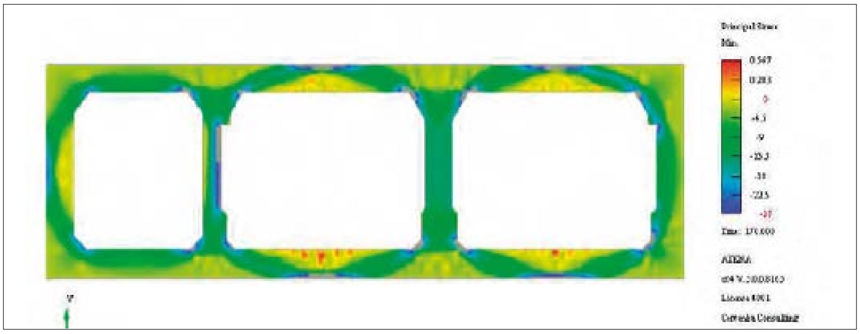

Fig. 13. Numerical FE Analysis of a submerged tunnel with corroded reinforcement in the bottom slabs

Fig. 14. Shaking table test on a typical Dutch house in Pavia, Italy, 2015

the real bearing capacity which is in reality significantly larger than the design capacity. This demonstrates that new code rules to be developed should move away from the empirical approach that has been often used so far, and be developed as much as possible on the real physical behavior. In the fib Model Code 2010 this was a leading principle. An example is the calculation model for the punching capacity. Based on the research program quoted before (Amir, 2014), it turned out that the fib approach could be extended, introducing the effect of compressive membrane action. By using this modified model it could be demonstrated that the bearing capacity of 70 large span bridges in The Netherlands was enough, contrary to earlier expectations. This demonstrates that forensic engineers should base their expertise on a solid understanding of the real physical behavior of concrete structures, and not rely on superseded code rules.

If the determination of the real bearing resistance is getting high priority, it is logical that numerical FE-simulations will be applied more frequently. It should be realized, however, that the reliability of FEM calculations depends on the choices made when developing the FEM schedule, the appropriateness of the constitutive relations and the reliability of the input values. An interesting example is shown in Fig. 13.

The figure shows a cross-section over the Maas Tunnel, already mentioned before. Fig. 13 shows the results of the additional analysis carried out with ATENA program. The picture shows that during the increase in the water load the tunnel cross-sections start to act like a set of circular pipes, after crack formation and local crushing of the concrete. It turned out that even in the hypothetical case when all reinforcement had become inactive due to corrosion, the ultimate water load on the tunnel at failure would have been equal to 4.3 times the maximum service water load on the structure. The ATENA program gave realistic results because of the advanced formulation of the behavior of the concrete under multiaxial loading: a 3D combined plastic fracturing model was used according to Cervenka (2008). Moreover, the analysis confirmed that the initial "quick-check" on the basis of a concrete arch model had been a reasonable approach as well. With this model, a ratio of 3.2 between ultimate load and maximum service load was calculated. This shows that the forensic engineer should not only be able to simplify the behaviour to such a level that a first provisional decision can be taken (closing the tunnel for traffic or not), but should additionally be able to use the tool of NLFEM analysis in an optimum way in order to determine the reliability as accurately as possible (and to decide on upgrading or not) and to verify the results of the "quick check".

An important task to increase the reliability of NLFE analysis is to reduce the model- and user factor. A reduction of the model factor is achievable by developing "tailor-made" NLFE Models, which are especially suitable for certain well-defined applications, see e.g. Belletti 2013. In The Netherlands, NLFEM programs with preselected element type and size, constitutive equations, crack models and multi-axial stress states have been developed and calibrated against tests results focusing on the same aspect of the analysis to be carried out. Within this scope, for instance, guidelines were produced for the determination of the shear capacity of large prestressed T- and I-beams. It was demonstrated that such an analysis, as a level IV approach, gave more accurate results than the best analytical models.

The next challenge is to determine the bearing capacity of structures against seismic loads with non-linear finite element time history analysis. Calibration of programs for certain types of houses is costly, since it requires shaking table tests on a sufficient number of prototypes, Fig. 14.

In the northern part of the Netherlands, the buildings have to be verified for seismic resistance since gas extraction from deeper layers in the soil has turned out to result in seismic agitation, which is governing for the structural safety. At this moment about 180,000 buildings are concerned. Some of them can be classified as prototypes with similar properties, but they are not identical. Analyzing any house with a nonlinear time history analysis would not be a viable option. Therefore, expert systems are under development in order to provide a "simple approach" based on the insight gained from testing, inspection and nonlinear time history analyses of representative buildings. If the structural reliability is insufficient, upgrading is required. An appropriate choice has to be made between options like base isolation, window frames, façade replacement, etc. This project asks for a solid theoretical base, experience and creativity of the engineers in charge.

Conclusions

1. Forensic engineers able to judge upon deficiencies in structures, their cause and the treatment for upgrading are more and more needed.
2. In order to carry out their task of finding the cause of deficiencies, damage or even partial or full collapse, the forensic engineers should dispose of profound knowledge about the real behavior of structures.
3. It is important to realize that the cause of failures should not only be explained from a technical point of view, but can also be found in bad communication and lack of quality control.
4. The ageing of concrete structures asks for a lot of additional expertise in order to be able to assess the structural reliability, at the moment of investigation and during the remaining service life.
5. Large scale evaluations of structural safety are necessary due to changes in the magnitude of loads, like related to increased vehicle loads, or unforeseen influences like seismic loads.
6. Building codes should offer different levels of approximation to satisfy not only the need to design new structures but also to assess existing structures.
7. Education of students should be more directed to understanding structural behavior, stimulating the ability for adequate assessment of buildings. ■

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ABSTRACT

For decades structural engineers have been educated to design new buildings. This is certainly a good start of a career as a structural engineer since it is an appealing perspective to use creativity and to support society with structures that are safe and serviceable during a long service life. However, structures are often not built as they should be, which may result in malfunctioning, insufficient structural safety or even collapse. In such a case the cause of the problem has to be determined as quickly as possible in order to eliminate the risk or inconvenience for the users. To this aim experienced engineers are required, who are able to come to a quick assessment based on a reliable judgement. In the past, problems with structures were mostly incidental, but nowadays new tendencies are observed, like ageing of structures and their consequences, the use of software without understanding its background, and changes in the function of a structure during service life. That means that there is a growing need for another profile in structural engineering: the forensic engineer. The need and the requirements for such a new professional profile have been discussed in this paper.

Keywords: forensic engineering, damage, collapse, assessment, structural failure, diagnosis, concrete structures.

Abstrakt: Od dziesięcioleci inżynierowie budowlani kształceni są w zakresie projektowania nowych budynków. Jest to z pewnością dobry początek kariery inżyniera konstrukcji, ponieważ stanowi realną możliwość wykorzystywania swojej kreatywności i wspierania społeczeństwa poprzez tworzenie obiektów bezpiecznych i trwałych w długim okresie użytkowania. Jednak konstrukcje często nie są budowane tak, jak być powinny, co może skutkować ich nieprawidłowym funkcjonowaniem, niewystarczającym bezpieczeństwem, a nawet zawaleniem się. W takim przypadku przyczynę problemu należy ustalić możliwie szybko, aby wyeliminować ryzyko lub niedogodności dla użytkowników. Do tego potrzebni są doświadczeni inżynierowie, którzy są w stanie dokonać szybkiej oceny w oparciu o wiarygodny osąd. W przeszłości problemy z konstrukcjami budowlanymi zdarzały się sporadycznie, ale obecnie obserwuje się nowe tendencje, takie jak starzenie się struktur ze wszelkimi tego konsekwencjami, stosowanie oprogramowania bez znajomości kontekstu i zmiany funkcji budynów w okresie ich użytkowania. Oznacza to, że istnieje rosnące zapotrzebowanie na inny profil w inżynierii budowlanej: inżyniera diagnosty. O potrzebach i wymaganiach dla takiego nowego profilu zawodowego traktuje ten artykuł.

Słowa kluczowe: inżynieria diagnostyczna, uszkodzenie, zawalenie się, ocena, awaria konstrukcji, diagnoza, konstrukcje betonowe.