FORENSIC ENGINEERING

Part 1.

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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.

An important task of the structural engineer nowadays is not only to design new structures, but as well to find solutions for existing structures. In a number of cases there is a need for immediate intervention, such as in the case of the damage or even collapse of a structure. Then it is not only important to eliminate the reason for the structural unsafety as quickly as possible, but also to indicate which measures are necessary to restore the structure to such a level that further use is possible, respecting the required structural safety level. An important task for the expert involved is to give an answer to the question who is guilty, because for restoring a structure a financial budget is required. This is not an easy task, since the problem mostly involves more aspects than just a violation of the building code. That means that the forensic experts involved should have considerable experience in structural engineering. Moreover, they should not only have knowledge on the governing building codes, but also on their background. In general, they should be able to well understand the behaviour of a structure under increasing load and/or deformation, and be aware of the fact that not only the material properties of a structure change in time, but often also the magnitude and configuration of the load and the function of the structure.

Why structures fail?

Analyses focusing on the reasons for structural failure have been carried out already for many decades. In a very interesting analysis of 250 structural failures and their causes, Blévot in 1974 concluded that the reasons for structural failure in concrete structures could be subdivided as follows:

- Errors in the structural concept: 3.5%
- Errors in calculation hypotheses: 8.5%
- Errors in reinforcement design or placement 2.5%
- Ignorance of the effect of deformations 20.0%
- Ignorance of time dependent effects 44.0%
- Construction errors 15.5%
- Chemical reactions or frost 4.0%
- Miscellaneous 2.0%

From this classification it is obvious that underestimating and/or not understanding the effect of deformations, in combination with time dependent effects, represent the utmost part of the damage (together 64%). A substantial part of this damage is due to not understanding the effect of imposed deformations: deformations by creep, shrinkage and temperature often cannot freely occur, because the structural element, as a part of the structure, is connected to other parts of the structure.

Fig. 1 shows the floor of an underground parking garage made in reinforced concrete. The floor has been designed for the load of the cars and on the upward pressure of the soil water, which can increase in winter. The floor was cast in summer; the mean temperature in winter is lower and, moreover, the floor is subject to shrinkage. Free shortening, however, is not possible because of the heavy columns, which are connected to foundation blocks in the sand below the floor. Because the design did not take account of shortening of the floor in its plane and its restraint, large cracks in the structure occurred through which the soil water could easily propagate from below.

Another investigation, carried out in Switzerland by Matousek and Schneider in 1978 [2], of 400 cases gave the following classification of the reasons for failure:

- Errors in design, calculation and planning 37%
- Errors in construction 35%
- Errors in design and construction 18%
- Damage during service 5%
- Miscellaneous 5%

Even much more important than this classification was their remarkable conclusion that "about ⅓ of all damage cases and about ½ of all cases with human injuries could have been avoided, without any additional control, by normal attention and adequate reaction of the person who is next in the chain: architect, engineer, contractor and executor". Moreover, they

Fig. 1. Leaking floor in an underground parking house due to ignoring the effect of imposed deformation

Fig. 2. Collapse of a shopping centre under construction due to an unstable scaffolding system

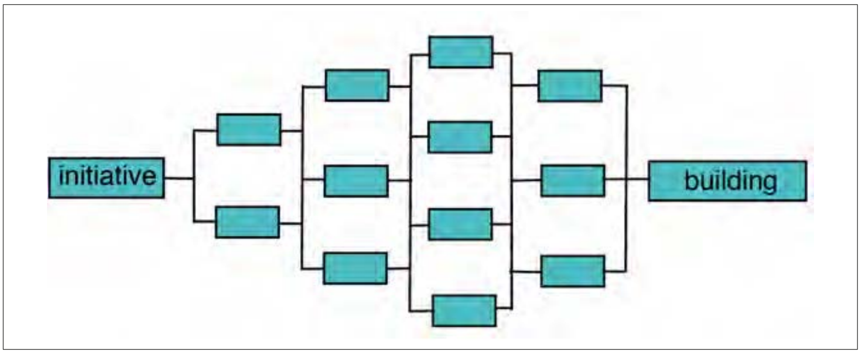

Fig. 3. Chain in design and construction (CUR 2005)

Fig. 4. Progressive collapse of a series of balconies in a high rise building, Maastricht 2003

stated that "by a well-organized control system more than 75% of all errors with material consequences and 90% with human consequences would have been detected in due time".

It turned out in a study focusing on structural safety by CUR (2005) that this important conclusion was still valid. Fig. 3 shows the chain of participants in the process from initiative to the final structure. Many parties are involved: an architect, a design office, consultants, a contractor and subcontractors. The information has to be transmitted from partner to partner. If, say, there are 12 activities and 21 communications, and all of them have a reliability of 99%, the probability of a good result is only 110-12-21 = 67%.

Fig. 2 shows the collapse of a part of a shopping centre under construction (Rotterdam, 2010). When casting the third floor, the scaffolding system failed. It turned out that this was due to the absence of a significant part of the bracings in this system that should ensure stability. According to Terwel (2014), an advisor of the supplier noticed this and warned, but no amendments were introduced. The main contractor asked for a final check, but this was not carried out. According to Terwel ,"the underlying factors of this case are a lack of technical competencies of the assembly team, unclear responsibilities regarding structures, insufficient risk management for the temporary structure and inadequate checking. No party felt responsible for the quality of the supporting structures".

The following new classification of causes for structural failure was presented by CUR (2005). Three main levels are distinguished, all including a number of causes for errors:

1. Micro-level:
- Errors caused by insufficient skill

2. Meso-level:
- Errors caused by inadequate organization, like:
  - Unclear commitment of tasks and responsibilities
  - Insufficient interface management
  - Inappropriate communication
  - Inadequate quality of the control procedures

3. Macro-level:
- Increasing specialization
- Pressure to work faster and cheaper
- Increasing fragmentation by increasing delegation of tasks
- Deficiency or reduction of general knowledge
- Complexity of building codes
- Lowest bid system (focus on cost instead of quality)

Fig. 4 shows the example of a series of balconies which failed through progressive collapse (Maastricht 2003). The balconies were supported only at one side by a steel column (Fig. 4 top right). The forces were all transmitted to the lower column at the 1th floor, which was supported by a corbel with inappropriate reinforcement detailing. This corbel failed in shear, resulting in the progressive collapse of the whole series of balconies. The first obvious cause of the failure was the inappropriate detailing of the corbel and the risky support of balconies on a single corbel. Those can be regarded as errors on a micro-level, but a further consideration reveals that also on the meso- and macro levels errors have been made. The full survey is:

1. Micro-level:
- Errors in detailing of the corbel
- Insufficient robustness of the structure

2. Meso-level:
- Insufficient communication between the designer, construction team and the producers of the precast balcony slabs
- Insufficient steering of the process (too many independent partners)
- Inadequate reaction to warning signs of the structure during construction
- Responsibilities not clearly defined

3. Macro-level:
- Too small capacity of control authorities
- Insufficient skill
- Too many subcontractors

Important capabilities of forensic engineers

1. Understanding the behavior of structures under loads and imposed deformations

Structures are in general designed on the basis of codes of practice. Very often the codes are not fully transparent since they are a product of a compromise at

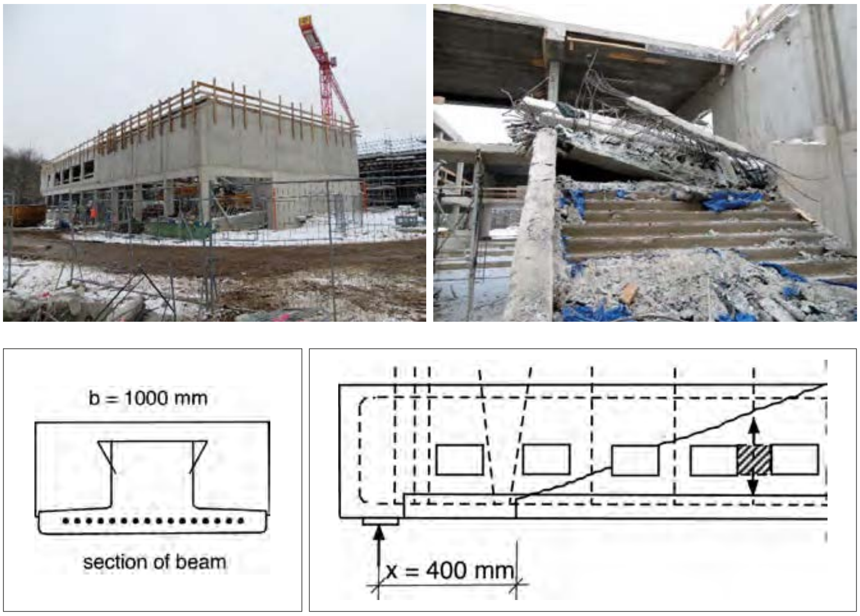

Fig. 5.a) School building under construction, b) Collapse of roof for auditorium, c) Cross section of prestressed beam, d) Side view on prestressed beam with web openings

Fig. 6. Building to be investigated, Curacao 2014

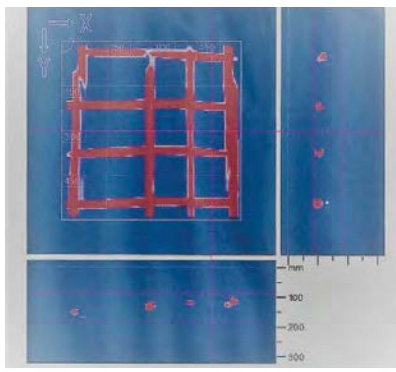

Fig. 7. Reinforcement in column determined by Ferroscan

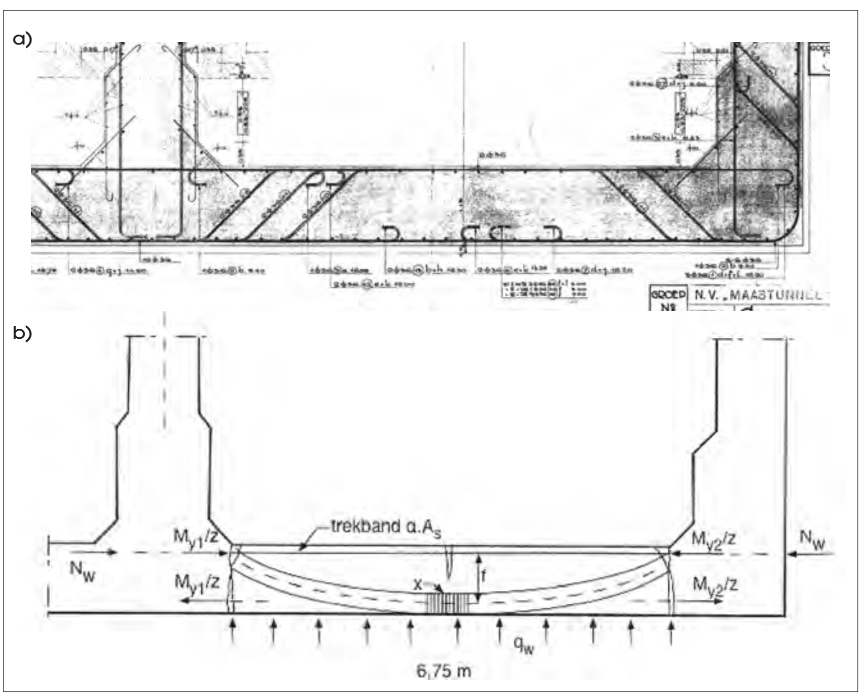

Fig. 8. a) Original design drawing of bottom slab of Maas Tunnel Rotterdam b) Simplified representation of bearing mode based on arch-action

the table of a code committee. Especially when compromises have to be made between different countries, like in the case of the Eurocodes, the resulting rules do not fully reflect a rational model of the physical behavior. Furthermore, the rules are simplified so that the designer only has to make a number of checks. An example is the design in shear, where shear forces are represented by shear stresses in cross-sections, which hide the real behavior. So, the designer knows the rules but not the truth behind them. An illustrative example is given in Fig. 5, showing the collapse of a roof of a school under construction. Fig. 5a shows a part of the building under construction. Fig. 5b shows the collapse of the auditorium roof during construction. Fig. 5c shows a cross section of the prestressed beam that should carry the auditorium roof and Fig. 5d shows a side view of the same prestressed beam, with large web openings. In the construction stage the beams are placed in parallel so that the lower flanges form a closed plane on which in-situ concrete is cast. Through the web openings transverse reinforcement connects the beams. After hardening of the in-situ concrete, a composite roof with a large bearing capacity is obtained. The problem, however, is the situation just after casting the in-situ concrete. In this situation the beams have to carry the fresh concrete, which only contributes to the load and not yet to the strength. The shear capacity of the beam is decisive here. However, the large web openings prohibit the formation of truss action, because the inclined compressive struts cannot develop.

2. Being able to determine the actual condition of a building by adequate measuring the material properties

When the structural reliability of a building is under discussion, it is of importance to be aware of the most advanced measuring techniques in order to be able to judge upon the bearing resistance of the structure. A special case is shown in Fig. 6a. The picture shows a new building on a Caribian island just before finalization. However, the developer went bankrupt, and the building became the property of the bank. When the bank investigated the state of the building, it turned out that during the construction the builders had decided to build one story more than initially planned. Moreover, it turned out that there were no drawings of the cross-sections of the columns so that the reinforcement in the columns was unknown. Finally, there were no data on the strength of the concrete.

In the first stage of the investigation concrete cores were drilled from a number of columns and beams. Those cores were used to determine the strength, but also to calibrate a rebound hammer so that this device could be used to collect more information elsewhere in the building. The position and the diameter of the reinforcing bars in the columns were measured by a so-called Ferroscan (Fig. 6b). The results could be verified using pictures made during the construction, showing the reinforcement of some columns. Finally, it turned out that the structural safety was sufficient. A favourable condition was that the building had been designed for a seismic load assuming a too high seismic class (the design calculations had been made in another country where the local seismic design requirements were more severe).

3. Being able to make quick and reliable decisions in the cases of potential danger

In situations in which suspect details or damage in a structure are detected, the consequences should be investigated as soon as possible and decisions have to be made with regard to further use of the structure and even evacuation. An example of such a situation was the la Concorde Overpass in Laval Canada in 2006. On a Saturday afternoon it was reported to the authorities that pieces of concrete had fallen down from the viaduct onto the road below. The authorities decided to send inspectors on Monday morning, but this was too late. The bridge collapsed in the weekend.

A situation in which a quick decision had to be taken as well was the discovery that the reinforcement in the concrete bottom of the Maas Tunnel in Rotterdam was heavily corroded. In some places the reinforcement cross section was reduced to about 50%.

The tunnel, which was at the moment of the discovery of the corrosion about 75 years old has an important role in the city traffic system. It connects the northern part of the city of Rotterdam with the southern part and immediate closure would lead to an enormous traffic collapse. A quick evaluation of the bearing capacity is shown in Fig. 7b. It shows the representation of the bearing system by an arch model carrying the upward load at the bottom of the slab due to water pressure to the walls. This quick check showed that, even when all reinforcement in the top of the slab had disappeared due to corrosion, the bearing mechanism would still have had considerable residual bearing capacity. A favorable circumstance is that when the water level of the river Maas increases, not only the upward load at the bottom increases, but as well the lateral support of the arch, by the increased lateral water pressure at the walls of the tunnel (force NW in Fig. 7b). Therefore, it was decided that there was sufficient residual bearing capacity to drop the option of immediate closure and take some more time to investigate the structural safety more in detail. Afterwards, two independent nonlinear finite element analyses confirmed that this decision was right.

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