Forensic Structural Engineering in education

Terwel, Karel; Hordijk, Dick

Publication date
2016

Document Version
Final published version

Published in
19th IABSE Congress Stockholm

Citation (APA)
Terwel, K., & Hordijk, D. (2016). Forensic Structural Engineering in education. In *19th IABSE Congress Stockholm: Challenges in Design and Construction of an Innovative and Sustainable Built Environment* (pp. 1-9)

Forensic Structural Engineering in education

Karel Terwel
Delft University of Technology, Delft, The Netherlands
Coenraedt, Rotterdam, The Netherlands

Dick Hordijk
Delft University of Technology, Delft, The Netherlands
Adviesbureau ir. J.G. Hageman, Rijswijk, The Netherlands

Contact: k.c.terwel@tudelft.nl

Abstract

Forensic Structural Engineering is the professional practice of determining the cause(s) of a structural failure, often with the aim to lay out a technical basis to identify the responsible parties for a failure.

Although Forensic Structural Engineering is given as course at several universities in USA and UK, at many institutions it is no common practice to include it in the civil engineering curricula. At TU Delft a graduate course has been initiated for building and structural engineering students, starting from September 2015. The course needs to meet a two-fold aim:

1. To understand and explain important structural failure mechanisms in various materials
2. To come up with design measures to avoid these problems

This paper describes how this course was successfully implemented in the civil engineering curriculum.

Keywords: Forensic Structural Engineering, Education, Blended learning, Failures

1 Introduction: international context

Forensic Structural Engineering (FSE) is "the professional practice of determining the cause or causes of failure of a constructed facility and of laying out the technical bases for identifying the parties responsible for that failure" [1].

Dissemination of failure knowledge and more specifically FSE in education has received attention for many years, especially in the USA [2,3]. In this country, failure cases were included by 85% of the civil engineering schools in technical courses, according to a survey in 19 [4]. Bosela [5] identified only 12 courses at different US Universities specifically focusing on failure of engineered facilities. This limited number of forensic engineering courses can be explained by the opinion that the undergraduate curriculum already was crowded [2,6].

However, increased inclusion of forensic case histories in education can serve various aims. According to Kolb [7] learning is a process where knowledge is created by the transformation of experience. In the learning cycle he distinguishes concrete experience, reflective observation, abstract conceptualization and active experimentation.

908 Back to Table of Contents

Some students learn by doing, others by studying more abstract concepts. It is believed that practical parts in a study will increase learning capability of more practical oriented students. Well-developed case studies give the opportunity to gain many of the same benefits of discovery offered by hands-on projects [8]. Furthermore, practical parts in undergrade studies are of importance to foster interest and improve retention in engineering [8]. Moreover, case studies can increase the development of soft-skills [8].

The discussion of forensic case histories can reinforce technical concepts throughout the curriculum. These failure cases can stimulate students to question assumptions regarding loading and boundary conditions, and think of error-tolerant designs [4]. According to Rens et al. [6] students will exercise greater care in investigation, analysis, planning, design and construction of constructed facilities.

Finally, Delatte and Rens argue that learning from failures provides the students with invaluable understanding for improving system-level performance [cited by 9].

Therefore the American Society of Civil Engineers (ASCE) has promoted the use of failures cases in education. From surveys around 1990 it was made clear that universities needed published failure cases, to be able to adequately pay attention to failures and their causes. Examples in the USA are: “Why buildings fall down?” [10] and “Beyond failure” [11]. In Europe Campbell and others wrote “Learning from construction failures” [12] and Van Herwijnen published in the Netherlands “Leren van instortingen” (in English: “Learning from collapses”) [13].

Subsequently, various workshops were organized at different locations in the USA, where college and university professors were provided with adequate knowledge to include failure cases in their curricula [2]. These workshops were also held in various otl countries, like Costa Rica and China [2].

Currently, specific courses on the practice of forensic structural engineering are still scarce [9], although courses are given at for instance Columbia University in New York, USA [14] and University of Warwick, UK [15].

For forensic structural engineering it is believed that professionals need some maturing in design or construction practice, before they will be able to be a successful forensic engineer. Therefore, specialized curricula on master level, solely focusing on forensic structural engineering are not known at this moment (see also: [9]).

At the faculty of Civil Engineering and Geosciences in Delft failure cases are included in various design courses, but no specialized course on FSE existed until recently. Because the added value of such a course was acknowledged, it was envisioned to start a course to learn about the investigation process and to learn from failures for new designs. This paper explains the setup of the course, the evaluation of students of this course and success factors for other universities to include such a course. The main research question of this paper is: “How can a master level course on Forensic Structural Engineering successfully be included in a curriculum civil engineering?”

2 Master level course FSE at TU Delft

2.1 Aim of the course

The main aim of the newly developed course is to understand and explain important structural failure mechanisms in various materials and to be able to come up with design measures to avoid these problems. Failures can be collapses due to insufficient strength or stability, cracks, unacceptable deformations or settlements that are caused by inadequacies in design, detailing, unexpected circumstances or construction errors. An extensive explanation of the definition of failures and underlying causes is given in [16]. Furthermore, students have to come familiar with a general investigation proach (See figure 1) and need to know relevant legal aspects after a failure. Finally, students need to be aware of possibly broader consequences of a singular failure case. Especially in case of concrete structures a collapse caused by erroneous detailing of reinforcement or deterioration due to a specific damage mechanism raises questions if similar existing concrete structures within a country might have problems too.

2.2 Content of the course and used educational methods

It was aimed to meet the goal by a case study approach. First a generic way of investigation of failures was introduced, based on figure 1.

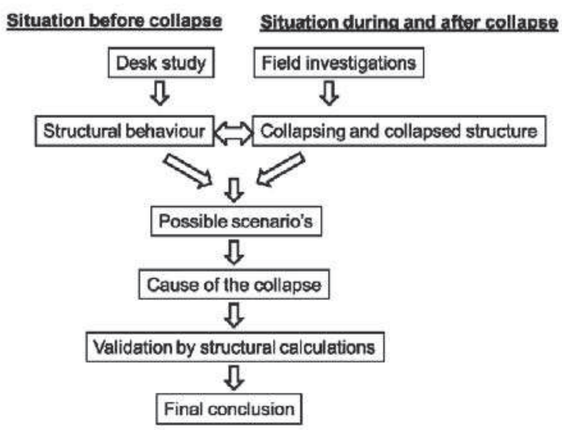

Figure 1: Strategy for investigating structural incidents [17]

This generic way consists of the following steps: providing information on the structure, the damage that occurred, setting possible hypotheses for the damage, testing of the hypotheses and conclusion on the most presumable cause. By following this approach, during the lectures and by applying it in the case study assignment, it is believed that students really got familiar with this generic approach.

The course did not aim to provide a complete overview of all possible failure mechanisms. This would not be possible in the available time and there would be a large overlap with other courses. In addition, when predominantly focusing on technical failure mechanisms, th would be insufficient attention for procedural causes, which we deemed undesirable.

Alternatively, first a list of common failure mechanisms and available cases was drafted. From this list, six suitable structural cases and some failure cases of finishing structures were selected. The various cases had to belong to a common failure type and we deemed it necessary that one of the lecturers had a personal involvement in the cases to make it more personally. In this lecture series all three lecturers had personal experience with failure investigations.

In general, every week one topic was covered with material on blackboard (videos and papers), relevant chapters from the book “Why building fall down” and a two hour lecture covering one case. To stimulate studying the material, weekly knowledge questions were included. The students could answer these questions in a digital environment.

The topics for the lectures were:

- Introduction: CSI for the building industry (forensic engineering process, causes of failures, reporting of failures)
- If anything goes wrong, everything goes wrong (where to start and where to stop the investigation process)
- Construction site is the most dangerous working place (structural failures during construction)
- Sherlock Holmes and the building industry (investigation of reinforcement and detailing errors)
- If you see no damage, it is not always safe (corrosion of post-tensioned tendons in floors)
- Details deserve attention (finishing structures)
- Water finds its way (waterproofing of concrete structures)

During the lectures CSI moments were introduced where the students had to analyze ssible causes in small groups.

To become familiar with the investigation process and with technical and procedural causes of failures, students had to write a scientific paper on a failure case, where they had to address the following issues:

- explanation of the structure and the structural behavior
- description of the damage
- list of hypotheses that were stated, including additional hypotheses that students thought were also reasonable based on first information
- description of the information gathered by the investigation process
- testing of hypotheses and conclusion on the most presumable hypothesis
- consequences of the failure (direct and indirect damage costs, reputation, penalties/ sentences)
- lessons learned for new designs of this specific failure

Students were free to choose an approach for writing this paper. One of the groups for instance deliberately chose to inform one of the group members only of the visible damage and general observations. This group member had to set up a list of hypotheses and with the available information from investigation reports the hypotheses were tested. Other groups stuck more to a description of the listed hypotheses in the investigation reports.

By the mandatory attendance of the lectures, studying the relevant chapters from the book and additional study material and by writing the paper, it was believed that the various learning goals would be met.

2.3 Assessment of learning objectives

During an oral exam of 45 minutes by two lecturers with three students each time, the learning objectives were assessed. First, the paper of the case study was discussed, and it was checked if every individual really understood the core points of the relevant case.

As an indication of the marks for the case study we used a list set up for a forensic course on the University of Warwick. An example description for grade 8-9:

"The team has demonstrated a substantial knowledge through the use of relevant sources and has written a proficient article. Key primary sources have been used appropriately. Work is mostly self-directed and reveals team effort and commitment, but the article lacks breadth, depth and fluency. There are some misunderstandings based on lack of experience. Writing is generally clear, organised, appropriately illustrated and nearly of the correct length. All specified aspects in the brief are covered adequately. Referencing contains minor mistakes only."

In the second part of the oral exam, the students were tested on theoretical knowledge. The questions were a random selection of a prepared list of possible questions.

The grade was based on the oral exam and the paper. Marks could vary within a group.

2.4 Evaluation of the course

At TU Delft courses are evaluated with a digital system called Evasys. To stimulate participation in the evaluation, at the end of the course a video message was recorded and posted on blackboard. Finally, 11 out of 46 students cooperated in the evaluation.

Evasys evaluates contents of the course, education methods, lecturers, assessment and organization on a 1-5 Likert-scale (Strongly disagree-strongly agree). Figure 2 provides the results.

For every category one score was extremely low; authors assume that a single student was very negative about the course decreasing the average scores.

The course was well received with an overall score of 4.0 out of 5.0, which is a very good result for a course that is given for the first time. One student expressed it in this way: "Amazing new course and learning about these failures was fascinating!" The study load of the course compared to the number of ECTS was just right, according to the students.

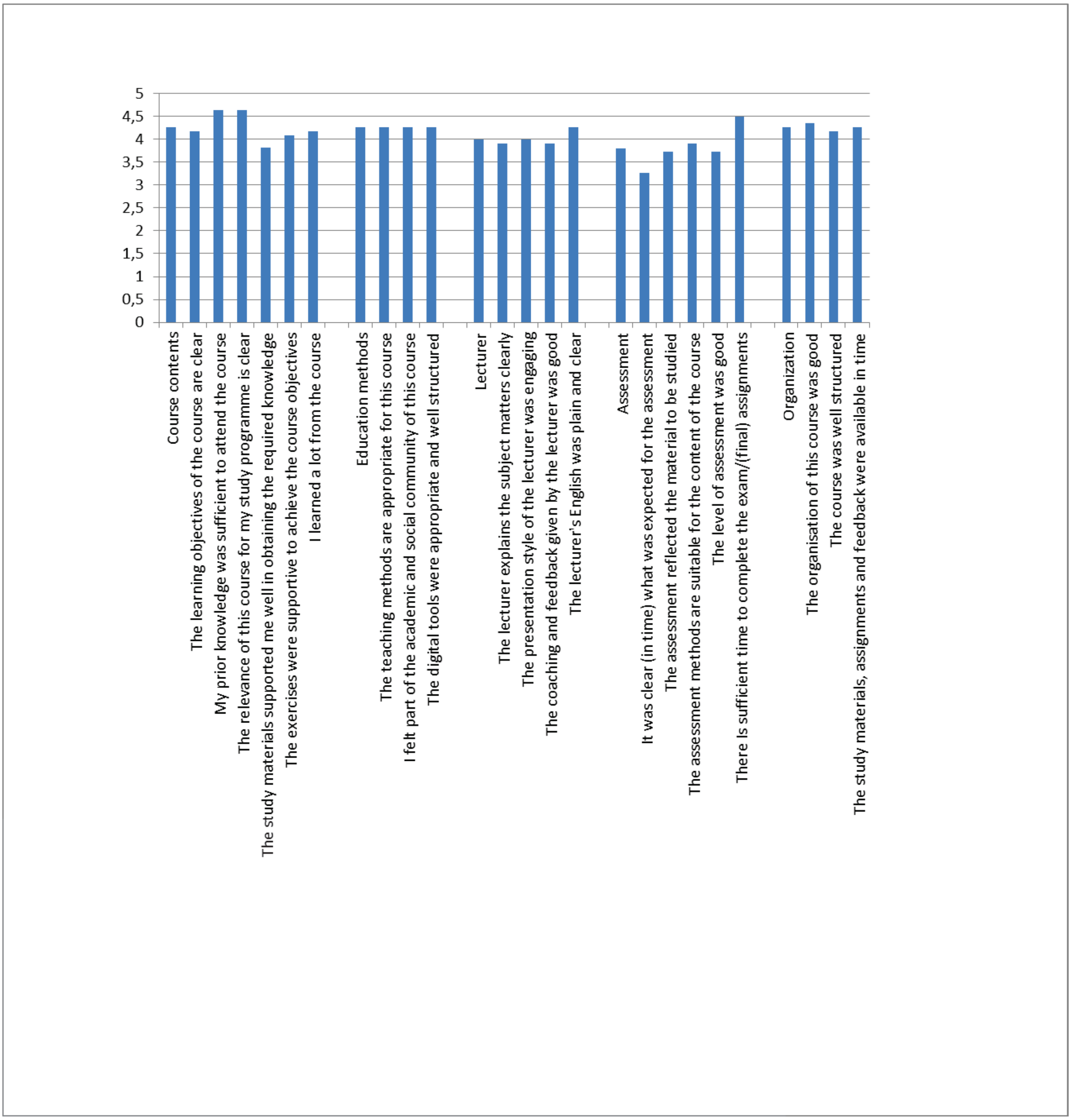

Figure 2: Evaluation results (from Evasys, n=11, 1=strongly disagree, 5=strongly agree)

The detailed results in figure 2 reflect the overall positive evaluation of the course.

Regarding the content and objectives of the course it appeared that the learning goals were very clear (4.6 out of 5.0) and the relevance of the course for the study was also without doubt (4.6 out of 5.0). The assignment was supportive to meet the course objectives (4.09 out of 5.0). The assignment showed that almost all students used the standard approach of investigation in their cases and students showed understanding of various failure mechanisms.

Although the teaching methods in general were quite 'old-fashioned', with a focus on mandatory lectures, students assessed these methods appropriate (4.27 out of 5.0). During the lectures sometimes CSI moments were introduced, were students had to give their own opinions of probable causes. In the evaluation students asked if this could be included more often.

Students appreciated enthusiasm and sharing of personal experience from lecturers. Or, to quote a student: "The lectures were engaging and many interesting stories were told. I really wanted to go to these lectures, not just because I had to do. Which is a big deal considering my view on other courses."

Because the course was new, for students it was not always clear what to be expected from the assessment (3.27 out of 5.0). Students suggested for next year to provide an example of the assignment of this year. The method of assessment was regarded as very suitable (3.91 out of 5.0), although some students pointed out that during an oral exam just a little part of the study material can be tested.

The lectures were supported by an actively managed digital supporting system (blackboard), where for every week it was made clear what should be read from the study material and done on the assignment, supported by interesting videos and weekly voluntary knowledge questions. This support system was assessed as very appropriate (4 out of 5.0), and it added to the valuation of the structuring of the course (4.18 out of 5.0).

3 Discussion and Learning points

For successful development of a FSE course authors believe that it is necessary to develop clear learning objectives. In the Netherlands FSE is hardly a profession in itself, so it is important that such a course is relevant for structural engineers in general. A FSE course can be relevant for general structural engineers, when they internalize an approach where design choices are systematically evaluated on possible failure mechanisms. The toolbox of every practicing structural engineer should be filled with profound knowledge of important failure cases and mechanisms.

The search for relevant study materials will remain. Although the book "Why buildings fall down" provides very interesting material, it does not follow the basic schema of investigation we would like to teach (figure 1).

For giving the course, it is recommended to have scientific staff members involved with educational experience to safeguard quality and coherence of the course, together with practitioners who can flavor the course and provide relevant content.

New educational methods, like the CSI moments (or "flipping" the class room) should be encouraged, because they involve students in the course. Digital tools, like blackboard, can give a structure to the course and can provide interesting side material, like videos.

However, new methods and digital tools cannot replace the live experience of a well told personal experience about a failure investigation, with the possibility to real time adjustments to meet the needs of the audience.

In the lectures many points of attention for new designs were mentioned. It is not always clear if students will remember all these points, but

Back to Table of Contents

an interesting lecture will increase the probability of remembrance.

Currently no full curriculum on FSE will be developed in Delft, because authors believe that engineers should first mature in practice at a contractor or at a structural engineering company before going into forensic investigations. Furthermore, in the Netherlands the demand for forensic engineers is currently low, although this might change in future [9]. Probably a “forensic annotation” will be set up, with a combination of other linked courses like forensic building materials and repair and maintenance of construction materials.

4 Conclusion

This paper shows that successfully implementing a new course on FSE in an existing master level curriculum of a faculty civil engineering is possible. For successful implementation it is important that clear learning objectives are stated and that relevant study material related to the learning objectives is available. Furthermore, appreciation of the course is increased when lectures are engaging. To develop skills and test the learning objectives it is necessary that a relevant assignment is designed. Well structuring of a course and being clear about what is expected adds to positive evaluation of a course.

References

[1] Ratay RT. Forensic structural engineering practice in the USA. *Proceedings of the Institution of Civil Engineers - Civil Engineering* 2009;162(5):52-56

[2] Ratay R. Education to prepare for the practice of forensic engineering. *Forensic engineering* 2012;165(FE3):111-13

[3] Carper KL. Failure information: dissemination strategies. *Journal of performance of constructed facilities* 1987;1(1)

[4] Rendon-Herrero O. Including failure c studies in civil engineering courses. *Journal of performance of constructed facilities* 1993;7(3):181-85

[5] Bosela PA. Failure of engineered facilities: academia responds to the challenge. *Journal of performance of constructed facilities* 1993;7(2):140-44

[6] Rens KL, Rendon-Herrero O, Clark MJ. Failure of constructed facilities in civil engineering curricula. *Journal of performance of constructed facilities* 2000;14(1):27-37

[7] Kolb DA. *Experiential learning: experience is the source of learning and development* Prentice-Hall, 1984.

[8] Lewis JE, Ralston PA, Delatte NJ, et al. Implementation and assessment of case studies in a freshman engineering program. 118th Anual conference and exposition. Vancouver: ASEE, 2011.

[9] Chen S-E, Janardhanam R. Forensic engineering education reform. *Forensic engineering* 2013;166(FE1):9-16

[10] Salvadori MG, Levy MP. *Why buildings fall down?* New York: W.W. Norton & Company, 1992.

[11] Delatte NJ. *Beyond failure: forensic case studies for civil engineers*: ASCE, 2009.

[12] Campbell et al. P. *Learning from construction failures-applied forensic engineering*. Caithness, Scotland, UK: Whittles Publishing, 2001.

[13] Van Herwijnen F. *Leren van instortingen*. Zoetermeer: Bouwen met staal, 2009.

[14] Carper KL, Delatte NJ, Bosela PA. Status of forensic engineering education in the United States. Forensic engineering: From failure to understanding. London: ICE, 2008:575-84.

[15] Mottram JT. Undergraduate lessons from historical failures. *Management Procurement and Law* 2007(MP3):129-33

[16] Terwel KC. Structural safety: study into critical factors in the design and construction process. Delft University of Technology, 2014.

[17] Borsje H, Renier B, Burggraaf H. Collapse of roof of a football stadium. In: Pulido MDG, ed. h IABSE symposium. Madrid: IABSE, 2014.

Back to Table of Contents

Forensic investigation of early age Alkali-Aggregate Reaction damaged concrete elements: causes and lessons

Eugen Brühwiler

BridgIng Consultant and Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland

Contact: eugen.bruehwiler@epfl.ch

Abstract

Precast L-shaped reinforced concrete of the platforms of a railway station showed excessive damage after only 8 years of service. Damage led to important deformation (outward bending towards the railway clearance outline) of these elements to such an extent that they had to be urgently replaced because of safety reasons. Forensic investigation revealed Alkali-Aggregate Reaction (AAR) to be the cause for the damage.
In view of establishing the responsibilities in this costly case, a major question was whether the contractor mandated for the fabrication of the elements could have been sufficiently knowledgeable of the AAR phenomenon at the time of execution of the construction works. Also, the role of standards and in general the notion of "state-of-knowledge" of the profession were important issues.

Keywords: Alkali Aggregate Reaction in concrete, advanced numerical simulation, precast concrete elements, fabrication process, state-of-knowledge.

1 Introduction

Precast L-shaped reinforced concrete elements of the platforms of a railway station showed excessive damage after only 8 years of service. This damage led to important deformation (outward bending towards the railway clearance outline) of these elements to such an extent that they had to be urgently replaced because of safety reasons. Intersection of the bent elements with the clearance outline of the railway vehicles was imminent. Replacement of the elements led to significant costs.

A team of three experts led by the author of this paper was formed in May 2010 and officially appointed in September 2010 by the related Magistrate, to establish an expertise concerning the disorders observed of the prefabricated concrete elements of the platforms of the railway station.

In the following, the disorders are described, and major technical topics and issues of liability handled within the framework of this expertise are outlined. They have been established as a report being part of the questionnaire to be answered on request by the Magistrate.

No names of involved persons, companies or locations are given as this is of no relevance to the technical facts and the lessons to be learnt from this forensic case.

2 Course of actions

In May 2010, the experts visited the railway station in presence of representatives of the owner, contractor and consulting engineering firm, responsible for the design and construction works of the platforms. Disorders of the prefabricated concrete elements of the platforms were identified, and a general overview was obtained.

In June 2010, the main expert also visited at night the works of replacement of the elements in order to get familiar with the construction procedure. In the same period, the co-experts also visited the construction site.

In July 2010, the team of experts met on site to analyse the situation, discuss the content of the studies and the already available expert reports established by the contractor and the owner. The team of experts identified the needs for follow-up studies and established a working program including a cost estimation for the expertise. The follow-up studies made or ordered by the team of experts concerned five particular aspects with results reported in this paper.

In November 2010, the leader of the expert team heard each party. A series of questions prepared by the team of experts was treated. The results were documented in the minutes reports that were submitted to the parties for comments before finalisation.

The team of experts met by the end of November 2010 to synthesize the results of analyses and formulate the answers to the questionnaire initially formulated by the Magistrate.

3 Description and analyses of disorders

3.1 Dimensions and construction of the platforms

At the railway station, three new platforms with a length of 330m were built to replace and extend existing platforms. The platforms consist of L-shaped prefabricated reinforced concrete elements creating a heightened platform allowing for easy access to the trains (Fig. 1).

The building works of the platforms were awarded to the Contractor on July 12th 2002. In November 2002, the Contractor appointed a specialized Company for the manufacturing of the prefabricated RC elements.

These elements were fabricated, delivered and built-in between December 2002 and December 2003. The construction works related to the elements were conducted according to the indications of the Contractor. The works were performed without difficulty and were received by the Owner on July 8th 2004.

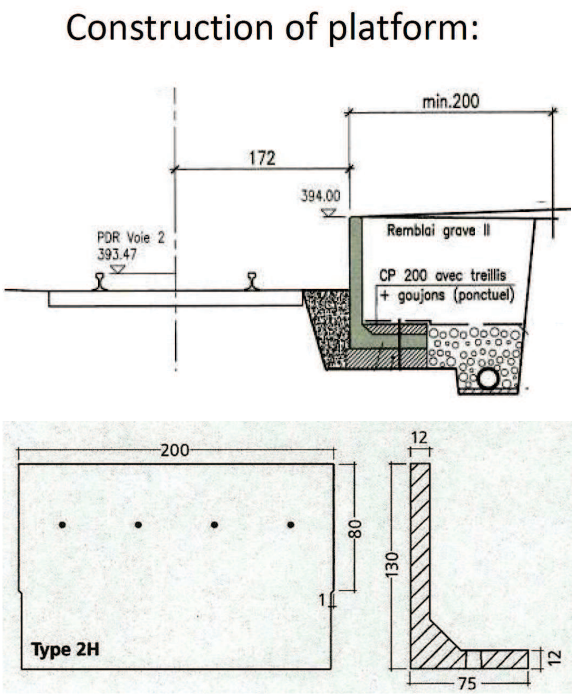

Figure 1. Principle of construction of the platform (typical cross section); dimensions of the L-shaped prefabricated RC elements.

3.2 Detection and description of disorders

Disorders were identified by the Owner and described in a report dated January 21st 2009. During their visits, the team of experts made visual inspections and noticed same disorders as described by the Owner.

These disorders were described as follows (Figs. 2 and 3):

– Several concrete elements showed large displacements of the head of the vertical part of the L-shaped elements towards the railway. The largest displacements entered into the clearance outline of the railway thus creating a safety problem. A contact or impact of railway vehicles with these elements could have caused a derailment or other dangerous events.