Systematic Prevention of Construction Failures

by
Ilías Ortega
Institute for Technology Management
University of St. Gallen
Switzerland

Abstract
Each construction failure provides information that may be used to prevent similar failures. Therefore, the systematic investigation of construction failures should be encouraged. These investigations identify errors to be avoided, and thus contribute to increase the safety of future designs. Each construction failure points to a gap either in theory or practice and thereby fosters innovations. Besides construction failure analysis, this report discusses other effective methods to prevent construction failures.

Introduction

The Technical Council on Forensic Engineering of the American Society of Civil Engineers defines failure as (Feld and Carper, 1997): "... an unacceptable difference between expected and observed performance". Therefore, construction failures not only include catastrophic events such as bridge collapses, but also damage to building facades, large foundation settlements and the like. Construction failures further comprise deaths and accidents caused by events such as collapsed excavations and roofs.

One of the oldest building regulations known is the Code of Hammurabi (approx. 2000 BC). Its first rule did not promote prevention of failures by learning from mistakes: "If a builder builds a house for a man and does not make its construction firm, and the house which he has built collapses, and causes the death of the owner of the house – that builder shall be put to death." This rule certainly prevented sloppy work and poor craftmanship (Feld and Carper, 1997). While reinforcing established construction practice, it also inhibited innovations.

The development of modern bridge-building technology for example, was characterized by an early phase of trial-and-error. Towards the end of the last century, the United States of America was building its transportation infrastructure, consisting mainly of railroads and railroad bridges. Due to ever increasing bridge spans and trainloads, bridge failures became common and were reported by the hundreds (Feld and Carper, 1997). The lessons learned from these failures led to safer bridges and ultimately to the modern science of bridge design. In addition, they paved the way for modern building codes.

In Münchenstein (Switzerland) in 1891, a railroad train fell down with an iron bridge designed by the famous engineer Gustave Eiffel to the Birs river, thereby killing about 70 persons. The accident's investigation at the Swiss Federal Laboratories for Materials Testing and Research (EMPA, Eidgenössische Materialprüfungsanstalt) led Professor

Ludwig von Tetmajer to the curve describing the unelastic buckling behavior of short beams. Trial and error is not a method that should be promoted; however when errors occur, all possible measures should be taken to prevent similar errors from happening again.

Construction Failures: Causes

Nowadays, despite computer-aided-design technology and sophisticated scientific theories, construction failures have not ceased to occur. In the past, lack of scientific knowledge was a main factor leading to construction failures. Today, however, carelessness and negligence have risen to greater prominence. Also, political and economic trends are increasing the economic pressure on the construction industry, resulting in failures from careless design and inadequate construction practices.

Among the errors frequently occurring during the design phase are the following (Feld and Carper, 1997; Kaminetzky, 1991):

- Mistaken selection of design loads
- Insufficient structural redundancy leading to progressive collapse
- Poor detailing of connections
- Drafting errors
- Misuse of computer programs (Bell and Liepins, 1997)
- Inadequate documentation procedures, e.g. lack of control of design modifications
- Insufficient communication

Errors during the construction phase may include (Feld and Carper, 1997; Kaminetzky, 1991):

- Overloading
- Improper temporary supports
- Inadequate planning and execution of the construction process
- Lack of inspection
- Insufficient safety factors
- Inadequate training of construction workers

Failures also have many other causes such as material defects, poor workmanship, lack of maintenance and so forth.

Construction failures often occur because of lack of attention to the construction phase. Peter Rice, responsible for the engineering design of many architectural milestones such as the Centre Pompidou in Paris has said (Rice, 1994): “We, the designers, must never forget that we do not build our designs ourselves. ... We have only our power of reason to anticipate and avoid any mistakes, but if an error does occur it must be evident from the very beginning that we will be there to take our share of the responsibility and that we will always be available to see our work correctly completed. ... It may be difficult to persuade the client to pay for one’s presence, particularly if the contractor perceives this as unnecessary. But persevere we must because with any other scenario disaster looms.”

Construction projects are complex because of the division of tasks and responsibilities between architects, engineers, and contractors. Building projects requiring the presence of more than forty different specialists at the construction site are not unusual. The various languages that are spoken at Swiss construction sites for example further complicate the matter. Construction projects are interdisciplinary by nature, and the lack of communication between specialists may lead to failures. Efforts to improve communication between the participants of construction projects are therefore important.

Historical analyses of failures (Levy and Salvadori, 1994; Petroski, 1994, 1993, and 1992) suggest that unconventional designs may disclose new types of failure, which remain latent in conventional designs. Designs with geometrical dimensions or other characteristics outside the experience envelope may behave unexpectedly and reveal new or surprising failure mechanisms. In many cases, such mechanisms cannot be predicted despite advanced computer programs, because the available computer programs do not simulate the relevant physical phenomena.

Systematic methods of error prevention, from design to construction, were developed by Matousek and Schneider at the Swiss Federal Institute of Technology (ETH) in Zurich (Matousek, 1982; Matousek and Schneider 1983; Schneider, 1997). So-called checkpoints during the design process are now widely used. At these points, the plausibility of the used data is analyzed. Of great importance to design professionals are also organizational measures such as proper project documentation and effective communication procedures. Quality Management techniques are also being used in the construction industry (American Society of Civil Engineers, 1990).

Unfortunately, the groundbreaking research of Matousek and Schneider on the safety of buildings has not been followed by further work in this area. Matousek recently commented that the ETH project “Risk and Safety of Technical Systems” was concluded without further follow-on research (Matousek, 1998).

To appreciate the magnitude of the problem, *Table 1* is provided, which shows the estimates of the annual risk of construction casualties for the U.S. construction industry (Eldukair and Ayyub, 1991). The values were calculated using samples from the years 1975-1986.

These numbers underscore the need for research to increase safety in the construction industry.

Description	**Values**
Annual number of deaths (failures)	456
Annual number of deaths (accidents)	1,569
Annual number of injuries (failures)	2,515
Annual number of injuries (accidents)	968
Total number of deaths	1,985
Total number of injuries	3,483
Annual cost of failures in dollars (direct and indirect costs)	14.4×10^{9}
Annual U.S. construction volume in dollars	300×10^{9}
Annual financial risk of structural failures	48×10^{-3} (approx. 5%)
Size of construction work force in U.S.	6,000,000

Table 1. Estimates of annual risk of construction casualties for the U.S. construction industry (Eldukair and Ayyub, 1991).

Construction Failures: Case Study Analysis

The systematic analysis of construction failures can occur in the form of individual case studies including a description of the failure case and the lessons derived from it (Boutellier and Ortega, 1998; Feld and Carper, 1997; Gnaedinger, 1987; Kaminetzky, 1991; Ortega, 1998; Petroski, 1994, 1993, and 1992). The knowledge gained from such studies should be systematically organized and made available to all interested parties, e.g. in the form of electronic databases or of Internet pages.

Unfortunately, only major failures are reported and therefore broadly discussed. Information from minor, but cumulatively more important, failures is often kept secret, mainly because of legal reasons and of fear for the reputation of the parties involved. Organizations involved in liability suits often do not provide access to information concerning present and past failure cases. The knowledge gained from construction failures is therefore insufficiently organized and at the disposal of a limited number of persons.

Independent, state-run institutions, such as universities, are better suited for the scientific investigation of construction failures. Not only because of their impartial nature, but also because of the social and economical relevance of the built infrastructure and the high costs of these investigations.

The following two case studies are presented with the intention of highlighting the lessons that can be derived from the analysis of construction failures.

The Collapse of the Swimming Pool Ceiling in Uster (Switzerland)

The collapse of the swimming pool ceiling in Uster ranks among the gravest construction failures in Switzerland (Peyer, 1987; TagesAnzeiger, 1985; Theiler, 1985). The indoor swimming pool ceiling was inaugurated in 1972 with a ceiling designed as an eight centimeters thick, reinforced concrete plate. The ceiling was suspended from the roof by 10-mm thick, chrome-nickel V2A steel bars. In order to avoid the costs of providing conventional, sheet metal ventilation ducts, the suspended ceiling served for ventilation purposes. The 166-tons heavy ceiling was suspended from 207 bars. According to the responsible civil engineer, the ceiling's safety factor was 2.5. However, the ceiling was built thicker than originally designed and therefore 20% heavier than intended. This reduced the safety factor correspondingly. Because of aesthetic and acoustic considerations, in 1981 a wooden ceiling was suspended from the reinforced concrete plate.

The tragedy began on Thursday, May 9th 1985, at around 20:00 when a bang was heard coming from the ceiling. At that time, approximately 40 persons were in the indoor swimming pool. Seconds later, a second bang followed. A quarter of an hour later, the ceiling fell down suddenly with a rubbing noise. Due to the falling ceiling twelve persons died either directly hit by the falling structure or drowned, caught in the pool. The rescue work, carried out by approximately 350 persons, lasted until the following morning. It was only good luck there were no more casualties since the disaster could have occurred on the previous weekend when an event with more than 400 visitors took place.

The Swiss Federal Laboratories for Materials Testing and Research (EMPA, Eidgenössische Materialprüfungsanstalt), in cooperation with the Scientific Department of the City Police Zurich, carried through the accident's investigation. EMPA's calculations determined a safety factor of 1.3 for the ceiling structure prior to the suspension of the wooden ceiling and a safety factor of 1.2 when the wooden ceiling was considered. The safety factor of 2.5, indicated by the civil engineer, could not be ratified. Although a safety factor of 1.2 is small, it was rejected as the exclusive cause of the accident. Already at the beginning of the accident's investigation it was suspected that the chrome nickel steel bars were damaged by the chlorine vapors coming from the swimming pool. In 1979, after the ceiling had suddenly bent strongly, the steel bars were inspected for the first time. In the corresponding inspection report, the ceiling's deflection was judged harmless. In 1984, during the repair of rusty window frames, a second, coincidental inspection was performed. A broken chrome-nickel steel bar was found. Assuming that it was damaged during construction, it was repaired by welding a second bar to it. In the inspection report to the City of Uster, in which the repair was not mentioned, the condition of the ceiling was described as flawless.

Two major effects triggered the final collapse of the swimming pool ceiling: Corrosion and simultaneous mechanical stress. On steel with at least 12% chrome, a protective passive surface layer forms. It consists of oxidized chrome, with oxygen from the air or from the water. Unfortunately, a passive layer can be very easily damaged. The damage can result chemically, e.g. from chlorine in the air, or mechanically. Under tension loads, the chemically or mechanically caused injury to the passive layer can - like a notch - become the starting point of a crack. Due to the combined chemical and mechanical effects, the crack grows, and thus can lead to the fracture of a bar. Probably at the beginning of the collapse of the ceiling in Uster, some chrome nickel steel bars were so strongly damaged by stress corrosion, that they broke. The loads to be carried by the broken bars were then transferred to the neighboring bars. Some of them were already weakened by stress corrosion, and they promptly broke. Further bars tore due to overloading. This process repeated itself, until all bars had torn like a collapsing house of cards, and the ceiling fell down. The final mechanism that led to the collapse of the ceiling of the Swimming Pool Uster was lack of structural redundancy.

In the course of the investigation it became evident that both the engineers and architects lacked experience in the design of suspended ceilings. Furthermore, they held chrome-nickel steel for a "stainless" steel, even though stress corrosion had been known for more than twenty years before the accident happened. Even though the ceiling's designers chose an unconventional steel alloy, they did not engage a specialist in material sciences, who could have referred them to the risks of the selected material. Alone the large, sudden deflection of the ceiling - as with each construction, which deforms strongly very fast - should have prompted the evacuation of the building and led to a thorough investigation. Still graver is the fact that no inspections at all were intended for this - for the responsible designers - unconventional structure. The only inspections that were carried through took place coincidentally.

The collapse of the ceiling of the Swimming Pool Uster cannot be pinpointed to a single cause.

Figure 1 shows the different events contributing to its failure while using the damage level classification scheme proposed by Brauner (1990).

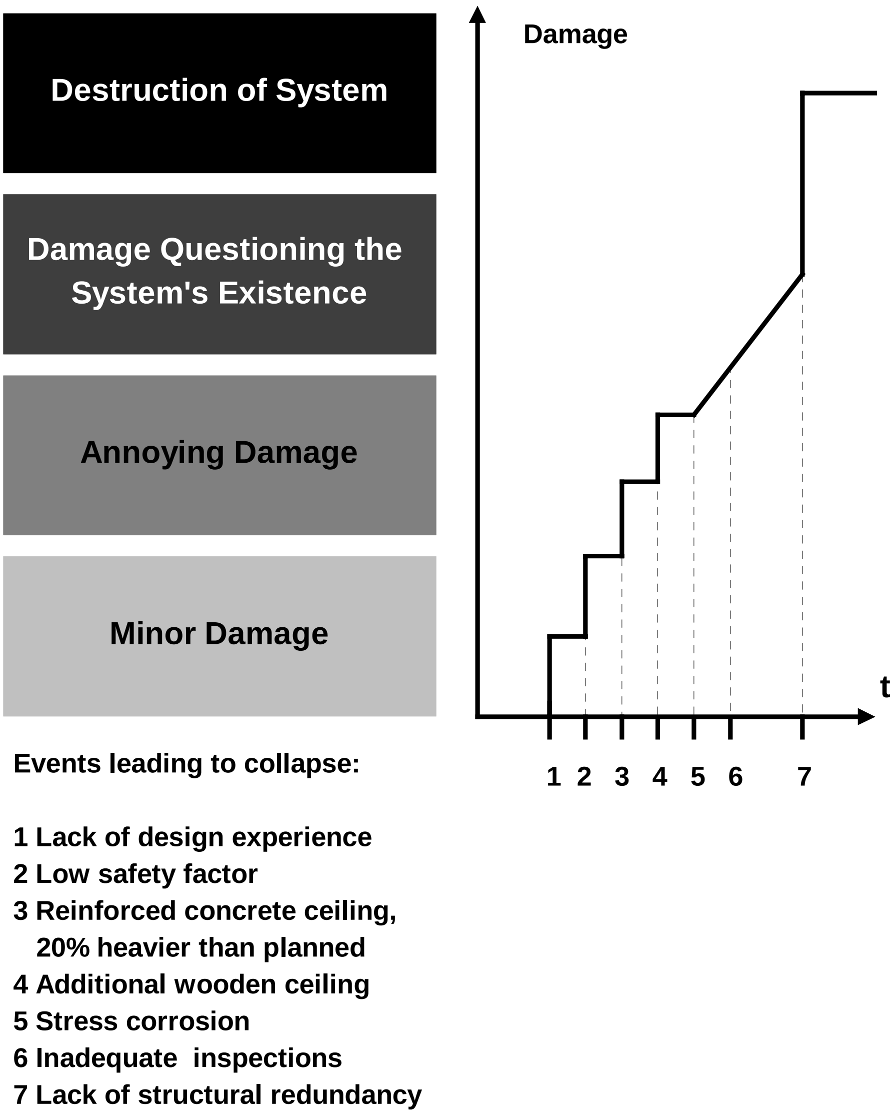

Figure 1. Events leading to the failure of the ceiling of the Uster indoor swimming pool using the damage level classification scheme proposed by Brauner (1990).

The collapse of the ceiling of the Uster indoor swimming pool was not caused solely by “material failure”, “selection of the wrong material” or “steel corrosion” but was caused by at least seven different factors. None of them by itself would have been sufficient to cause the accident. It was the unfortunate combination of all factors that precipitated the tragedy. The Uster ceiling collapse vividly illustrates the fact that, in many cases, the cause of failure cannot be attributed precisely to a single fact or individual, but is caused by an unfortunate chain of events. Because the fatal combination of events leading to failure is random, it cannot be predicted. However, the managerial environment of carelessness and negligence which leads to accidents can be improved. However, this implies major changes at the management level of the architecture and engineering office.

The events leading to the collapse are recapitulated in the table below:

Event	**Category**
The architect and engineer lacked experience in the design of suspended ceilings	Managerial
The concrete ceiling was designed with an insufficient safety factor	Technical and managerial
The concrete ceiling was built 20% heavier than planned	Technical and managerial
An additional wooden ceiling was suspended from the concrete ceiling	Technical and managerial
The steel bars were damaged by stress corrosion	Technical
The engineers did not specify an inspection plan	Managerial
The coincidental inspections were not done adequately	Managerial

Table 2. Events and their corresponding categories leading to the failure of the Uster indoor swimming pool.

The general lessons learned from the failure of the ceiling of the Swimming Pool Uster are the following:

1. Inexperienced architects and engineers designing unconventional structures should seek the advice of an experienced, independent architect and engineer. A peer-review of the project design should also be considered.

2. Unconventional structures require a monitoring plan (e.g. of deformations) for the construction and operational stage. Thus damage to the structure can be noticed before it is too late. In particular, deformation discontinuities in certain parts of a structure may indicate failure of a structural component. Continually growing deformations may indicate necessary remedial measures.

3. The use of unconventional materials without a thorough understanding of their behavior in the intended environment should not be attempted. It is recommended to consult an independent expert on the material in question.

4. The effect of design changes (heavier loads, different load-

carrying mechanisms, modifications to connection details, etc.) on design assumptions should be carefully analyzed. Design changes should be systematically documented, so that their effect on the original design can be easily determined.

5. It is recommended that structural redundancy studies be undertaken to reduce the danger of progressive collapse of long-span or high-rise structures. These studies may become the departure point for measures to increase the redundancy of the structures in question.

The Axle Failure of the Riederalp-Mossfluh Funicular (Switzerland)

On December 14th 1996 approx. 35 persons were aboard the funicular that goes from Riederalp to Mossfluh (Neue Zürcher Zeitung, 1996a; Neue Zürcher Zeitung, 1996b; Neue Zürcher Zeitung, 1996c). At approximately ten o'clock in the morning, the 280-mm thick axle of the lower wheel guiding the cable broke. The several tons heavy wheel was later found more than 20 m away from the accident place. Due to the axle break, the cable became slack and the cabs were swung so strongly that some passengers were thrown out of the cabs. A 36-year-old ski teacher, who was thrown out of a cab, was later hit by it, thereby losing his life. Eighteen persons were seriously injured. Experts who examined the accident suspected material fatigue as the cause of the failure of the one-year-old installation. The co-operation of the manufacturer of the funicular contributed to the quick discovery of the accident's cause: The manufacturer soon announced that during the calculations for the design of the axle a "methodical error" had occurred.

Calculations performed by the manufacturer of the funicular, the Federal Office of Transportation and an expert came to the same results. The manufacturer announced later, that the "prescribed safety margin" was not kept. After the accident, a review was done to review the safety of more than one hundred funiculars. On recommendation of the manufacturer of the funiculars, six funiculars were immediately closed. The funiculars were put into operation only after they had been reinforced. The final conclusions of the forensic investigation concerning this failure have not yet been disclosed. However, it can be said with certainty, as this case implies, that the uncritical, repeated use of design formulas may lead to design errors with serious consequences.

The Rieder-Mossfluh accident led to the following lessons:

1. The use of design principles or formulas, whose theoretical or empirical context and limits are not understood, should be avoided. Otherwise, unpredictable risks may be incurred.

2. The failure of a particular structure may indicate that other, similar structures are at risk. It will therefore be necessary to review the safety of those structures and to eventually reinforce them.

3. The close cooperation of the designers or builders of a failed structure will help determine early, accurately and economically the failure's cause.

Construction Failures: Systematic Prevention

Although failures will probably not cease to happen, certain strategies can be implemented in order to reduce their frequency. The following steps to prevent failures could be undertaken:

1. *Education.* Besides presenting successful design examples, education at universities should also point to errors to be avoided. Individual case studies are ideal for this purpose (Gnaedinger, 1987).

2. *Research.* Failures refer to gaps in scientific knowledge and therefore, are useful for identifying main points of emphasis for scientific research. Scientific investigations of construction failures should be carried through by independent state-run institutions such as universities and laboratories for materials testing. The lessons learned from failures should be disseminated as quickly as possible.

3. *Failures database.* The data extracted from failure analyses should be systematically organized in electronic databases and made available to all interested persons.

4. *Building codes.* Failures also point to gaps in building practice. Building codes need to be updated to take account of the conclusions reached from failure analyses. A failures database could support this endeavor.

5. *Journals.* Failures should be published and openly discussed in professional journals. The Journal of Performance of Constructed Facilities of the American Society of Civil Engineers and Technology, Law and Insurance of the International Society for Technology, Law and Insurance are two examples.

6. *Associations.* Further organizations such as the Forensic Engineering Division of the American Society of Civil Engineers and the International Society for Technology, Law and Insurance should be established to spread the lessons learned from failures.

7. *Events.* Congresses, conferences and conventions are needed to disseminate the lessons learned from failures. Examples are the upcoming Second Forensic Engineering Congress held by the American Society of Civil Engineers (San Juan - Puerto Rico, 2000) and the 7th International Conference on Structural Failure, Product Liability and Technical Insurance – SPT-7 held by the International Society for Technology, Law and Insur-

ance (Vienna - Austria, 2001).

8. *Collaborative design.* Architecture and engineering projects should be carried out in a collaborative manner. In most cases, architecture and engineering projects are completed sequentially, with the architectural design, the engineering design and the actual construction undertaken by the architect, the engineer and the contractor, respectively. The sequential design process has severe disadvantages. Besides holding back creativity, it is detrimental to construction projects because engineering and constructability concerns are not addressed early, when project changes are most economically carried out. Collaborative designs should be carried through by architects, engineers and contractors working together from the beginning until the end of the construction project (Lin and Stotesbury, 1988).

9. *Design-construction reviews.* Several review meetings should be held starting from the design phase until the actual construction phase (Goodden, 1996). These meetings have the purpose of reviewing the technical aspects of the architecture and engineering project. Architects, engineers and contractors should participate in these meetings. These reviews should be thoroughly documented. All relevant problems should be discussed as early as possible. It is well known that the cost of carrying out modifications increases as the project progresses.

10. *Particular attention to construction phase.* The loading cases relevant to each step comprising the construction phase should be carefully analyzed. The adequacy of the selected temporary structures and the value of the chosen safety factors should be justified (Carper, 1987).

11. *Inspection of construction site by designers.* Architects and engineers should carry out inspections of the construction process to ensure that structures are built safely and according to plan (Carper, 1987).

12. *Peer reviews.* Complex, unconventional or large architecture and engineering projects should be reviewed by an independent professional or organization (Bell, 1989; Zallen, 1990).

13. *Monitoring.* Exceptional or unconventional structures should be monitored not only during the construction process but also during the operative phase. A monitoring strategy should be developed during the design stage, before construction has started. In this manner, the behavior of structures can be studied

and conclusions for future designs can be drawn.

14. *Unified risk insurance.* A unified insurance offered by insurance companies should cover all members of a project team (Vince, 1989). This will help reinforce cooperation between participants in construction projects.

15. *Incident Reporting Systems.* Incidents are defined as "any deviation from the expected course, with a strong potential for an adverse outcome" (Staender et al., 1997). Instead of investigating accidents, Incident Reporting Systems (IRS) analyze incidents. Because incidents happen more often than accidents, larger databases can be obtained by collecting incident reports. Incident reports can be used to gain insight into the factors leading to failures. IRS have been successfully used in the aviation industry (Air Data Acquisition System, ADAS; Swissair) and in anesthesiology (Anesthesia Critical Reporting System, ACIR; University Hospital Basel, Switzerland). The author is currently studying the application of Incident Reporting Systems to the construction industry.

16. *Safety management methods from other sectors.* Industrial sectors with highly developed risk-consciousness, such as the aeronautical industry, use advanced methods to ensure the safety of their technical systems. In comparison to the methods used in these sectors, the methods used by the construction industry can be considered to be rudimentary. The transfer of these methods to the construction industry deserves further study.

Conclusion

Even though each construction failure is to be regretted, each failure provides information that may be used to prevent similar failures. The systematic investigation of construction failures helps advance the science of construction and building regulations. The results of such investigations identify errors to be avoided, and contribute to increase the safety of future designs. Each construction failure points to a gap either in theory or practice and thereby fosters innovations. In this report, several effective methods to prevent construction failures were discussed. Among them are: Case study analysis, collaborative design, design-construction reviews, peer-reviews, monitoring and Incident Reporting Systems.

Acknowledgment

I would like to thank Professor Søren Bisgaard for helpful comments on this report. The work on this report was supported by the Basic Research Commission and the Institute for Technology Management, University of St. Gallen, Switzerland.

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