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FAILURE LITERACY IN STRUCTURAL ENGINEERING

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The history of the development of practice in many engineering disciplines is, in large part, the story of failures, both imminent and actual, and of the changes to designs, standards and procedures made as the result of timely interventions or forensic analyses. All engineers, and more particularly structural engineers, should be failure literate. Failure literacy means knowing about the critical historical failure cases that have shaped the profession, not merely the surface technical details, but the environment, the communications difficulties and the procedural issues. In the U.S., an intensive effort has been under way for nearly a decade to promote failure literacy in engineering education and practice. A number of educational resources have been developed by the Education Committee of the American Society of Civil Engineers Forensic Engineering Division (ASCE FED) to make it easier for engineering students and practicing engineers to learn from failures. Some landmark failures include the Tacoma Narrows bridge collapse, 1940, the Point Pleasant/ Silver Bridge collapse, 1967, the Ronan Point building collapse, 1968 (U.K.), the 2000 Commonwealth avenue building collapse, 1971, the Bailey's Crossroads building collapse, 1973, the Hartford Civic Center building collapse, 1978, and others. This list, unfortunately, is a living document that will expand as more failures occur. Thorough forensic investigations are vital to capture the lessons from the unfortunate occurrences.

Keywords: Collapse, Forensic engineering, Steel structures, Concrete structures, Buildings, Bridges.

1 INTRODUCTION

Learning from failures is an essential element of structural engineering, as well as many other engineering professions. The author coined the term "failure literacy" for the concept that engineering students and practicing engineers must possess a working knowledge of landmark failures and of how failures have informed and changed the practice of engineering (Delatte 2006, 2009, 2010). "This literacy entails knowing about the critical historical failure cases that have shaped the profession, not merely the surface technical details, but the environment, the communications difficulties and the procedural issues." (Delatte 2006). Learning from failures is an essential element of structural engineering, as well as many other engineering professions. All engineers, and more particularly structural engineers, should be failure literate. This paper expands on an earlier journal manuscript (Delatte 2010) and updates the previous work.

In some engineering disciplines, such as mechanical, aerospace, and electrical engineering, it is possible to build and thoroughly test prototypes before putting a design into production. That is not practical for structures. It is difficult and expensive even to test a small part of a building or bridge.

Therefore, since it is not possible to thoroughly test a structural design in advance, it is important to know what failure modes are likely to apply through knowledge of past failures of similar designs and systems. It is important to consider history and failure analysis in the context of design. Design can be viewed very simply as a two-step process:

1. Figure out everything that can possibly go wrong.
2. Make sure that everything that can possibly go wrong does not happen.

The first step of the two is the more difficult. It is hard to know, in advance, what all the potential modes of failure are, and, more importantly, what the governing mode of failure is likely to be. However, this knowledge is necessary for a successful design. Thus, engineers must be knowledgeable and "literate" about past failures and patterns of failure. This includes a working knowledge of landmark structural failures.

2 LANDMARK STRUCTURAL FAILURES

Earlier papers (Delatte 2006, 2010) listed a series of landmark structural failures, mostly from a U.S. perspective. The structural failures occurred in the U.S., unless otherwise noted below, and have often been well documented in investigation reports and technical papers. These are shown in Table 1, in chronological order, with some references:

Table 1. Some landmark structural failures.

Year	Case	References
1907	Quebec Bridge (Canada)	Holgate *et al*. 1908, Middleton 2001, Pearson and Delate 2006
1940	Tacoma Narrows Bridge	Delatte 2009
1967	Point Pleasant/ Silver Bridge	Lichtenstein 1993
1968	Ronan Point	Griffiths *et al*. 1968, Pearson and Delatte 2005
1971	2000 Commonwealth Avenue	King and Delatte 2004
1973	Skyline Plaza/ Bailey's Crossroads	Delatte 2009, Schellhammer *et al*. 2013
1978	Hartford Civic Center	Martin and Delatte 2001
1978	Willow Island power plant cooling tower	Delatte 2009
1981	Harbour Cay Condominium	Delatte 2009
1981	Hyatt Regency walkways	Luth 2000
1983	Mianus River Bridge	Delatte 2009
1987	L'Ambiance Plaza	Martin and Delatte 2000

In addition to technical issues, concepts such as professional and ethical responsibility may be analyzed through the cases. There are also a number of recent international cases of interest. These include the Sampoong Super Store collapse in Seoul, Republic of Korea (Gardner *et al.* 2002), and the Laval, Quebec, Canada bridge overpass collapse (Commission of Inquiry 2007).

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3 DEVELOPING FAILURE LITERACY WORLDWIDE

In the United States, the National Science Foundation (NSF) and the American Society of Civil Engineers Technical Council on Forensic Engineering (ASCE TCFE) have been providing funding and support for promoting failure literacy in engineering education through various projects for over a decade. Some early efforts were documented in a 2002 state-of-the-art paper (Delatte and Rens 2002).

Starting in 2003, a series of half and one-day workshops on integrating failure case studies in engineering education has been held annually at a number of different locations in the U.S. [17]. These workshops were geared toward university faculty in civil engineering and related disciplines, with a total of over 100 participants over the years. As part of each workshop, the participants were provided with computer disks with presentation files about the case studies suitable for classroom use.

Under the auspices of ASCE TCFE, a half day workshop was held in London, U.K. in December 2008 and a two-day extended workshop was held in Cartago, Costa Rica in July 2009. The London workshop was also sponsored by the U.K. Institution of Civil Engineers (ICE). Each of these two international workshops had about thirty to forty participants, and had some practicing engineers as well as university faculty. Interest in failures is keen, therefore, not only in the U.S. but throughout the world. In December 2007, information from the workshop series was also presented at an international conference in Mumbai, India. Subsequently workshops have been held in Costa Rica, Ecuador, Guatemala, and in various locations in the U.S. (Delatte *et al.* 2012).

4 RESOURCES

One of the major references for failure literacy is Delatte (2009). Other sources include, of course, the other references cited in this paper. Newson and Delatte (2011) address ways to integrate cases into engineering education. Some other short case studies have been published (Bosela *et al.* 2012) and others are currently under development. Another useful resource focusing on teaching applications has been published by Cavalline and Delatte (2015).

The ASCE formed the Technical Council on Forensic Engineering (TCFE) in the 1980s to collect and disseminate failure information. The TCFE was recently renamed the Forensic Engineering Division (FED). TCFE/FED sponsors the ASCE Journal of Performance of Constructed Facilities (JPCF), which started as a quarterly journal in 1987 and is currently bimonthly (http://ascelibrary.org/journal/jpcfev).

TCFE also sponsored international Forensics Congresses in Minneapolis (1997), Puerto Rico (2000), San Diego (2003), Cleveland (2006), Washington, D.C. (2009), and San Francisco (2012), and recently, Miami (2015). For each of these conferences, a Proceedings publication volume is prepared and available for purchase at ASCE Publications.

Both the JPCF and the Congress Proceedings provide a venue for publishing the results of investigations from all sources. In many cases, investigations that support litigation are documented through these papers.

A useful web site is the Failures Wiki, Pennsylvania Building, Architectural and Civil Engineering Failures and Forensic Practices (http://failures.wikispaces.com/) developed by Professor K. Parfitt at Pennsylvania State University, USA. Much of the material for this site is developed by Professor Parfitt’s students as part of a class AE 537 – Building Performance Failures and Forensic Techniques. This project also has a link to a building failures forum blog (http://buildingfailures.com/).

Although these resources were developed for educators and students, they are also of considerable interest and value for practicing engineers. The resources are suitable for use by engineering firms for their own internal training, or for continuing education. In many U.S. licensing jurisdictions, registered professional engineers are required to attend a minimum of 15 hours per year of continuing education to maintain licensure. This provides a means to embed failure literacy into the engineering profession.

In the United Kingdom, a Structural-Safety system has been set up. This system has two components, Confidential Reporting on Structural Safety (CROSS) and a Standing Committee on Structural Safety (SCOSS). The effort is a joint collaboration of the Institution of Structural Engineers, the Institution of Civil Engineers, and the Health and Safety Executive (http://www.structural-safety.org/).

The ability to keep a report confidential makes it more likely that persons with direct knowledge of incidents can report without fear of reprisal from their employers. Reports may be made through a form which is available online but must be sub-mitted through the mail if there are concerns about leaving an audit trail. If leaving an electronic trail is not a concern, then the report may be submitted online (http://www.structural-safety.org/confidential-reporting/how-to-report/).

To date, 37 CROSS newsletters have been published. Other publication categories include Alerts and Topic Papers. An example four page topic paper addressed the collapse in June 2012 of part of the roof of a thirty two year old Mall in Ontario, Canada which killed two people and injured nineteen (Elliott Mall Inquiry 2014). The topic paper provides web links to the original; reports from Ontario, Canada, which total over 1,500 pages, with the executive summary alone 76 pages long http://www.attorneygeneral.jus.gov.on.ca/inquiries/elliotlake/report/index.html). This inquiry was carried out by the Province of Ontario, and it seems that the Canadian provincial failure inquiries are generally thorough and well done. Although CROSS and SCOSS are in the UK, their topic papers are often based on cases from other countries, such as Canada and Holland.

The Structural-Safety system provides an excellent model that other nations should consider. It combines the resources of the UK professional societies the Institution of Structural Engineers and the Institution of Civil Engineers, with the government efforts of the Health and Safety Executive. This structure is permanent in the UK, but is unfortunately used only on an ad hoc basis in the U.S., such as with the combined efforts of ASCE and NIST with the building performance studies of the World Trade Center towers and the Pentagon.

5 SUMMARY AND CONCLUSIONS

The history of the development of practice in many engineering disciplines is, in large part, the story of failures, both imminent and actual, and of the changes to designs, standards and procedures made as the result of timely interventions or forensic analyses. In addition to technical issues, concepts such as professional and ethical responsibility are highlighted by the cases. A number of educational resources have been developed to make it easier for engineering students and practicing engineers to learn from failures.

Although engineering is typically regarded as technical work, in reality, it is a form of communication. Engineers communicate their vision of a structure and how it should perform through drawings and specifications. Thus, expanding failure literacy also includes understanding how errors in communication and management can be as dangerous as technical errors.

Failure literacy builds a broad awareness of all of the things that can go wrong on a construction project. Awareness brings care, and hopefully that care and caution will enable the engineer and the project team to avoid future failures. This is necessary not only for design, but also for the construction and maintenance phases of projects.

All engineers, and more particularly structural engineers, should be failure literate. It is somewhat frightening to think that for many engineering undergraduates, the Hyatt Regency walkway collapse of 1981 occurred before they were born. Therefore, it is unrealistic to expect them to know about it. It is important for engineering educators to know and understand these stories, and to pass them on.

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