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What Goes up, Shouldn't Come down: Learning from Construction and Engineering Failures

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Abstract

Design errors can severely jeopardize safety and contribute to failures in construction and engineering projects. Such failures can have devastating economic, environmental and social consequences. Significant efforts have been made to reduce the incidence of failures through learning from previous disasters and events by modifying building and engineering codes and standards accordingly. Design errors, however, remain an innate feature of construction and engineering projects. Most errors are identified during construction and require rework, but there is always a potential for some to remain undetected and contribute to failure, and as a result potentially contribute to accidents and loss of life. This paper examines the circumstances and issues that contributed to a series of construction and engineering failures, to enable development of a systemic learning framework to contain and reduce design errors and potential failures and accidents.

Keywords: Construction, engineering, error, failure, learning

1. INTRODUCTION

The prevalence of design errors and their resultant cumulative negative impact upon the structural integrity of buildings and the financial performance of organizations and projects is a recurrent problem within the construction and engineering sectors (e.g., Wantanakorn *et al.*, 1999; Wardhana and Hadipriono, 2003). The collapse or distress contained within a structural element can be a result of an

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error. Design errors are a major cause of accidents and research has revealed that gross errors can cause 80 to 90% of the failures occurring on buildings, bridges and other civil engineering structures (Matousek and Schneider, 1976). Despite the considerable amount of research that has addressed failures in construction and engineering facilities, design errors remain a constant threat. From structural and geo-technical engineering perspectives, lessons have been learnt from several prominent failures such as the New World Hotel, Highland Towers, Sampoong Department Store, the World Trade Centre towers. Building and engineering standards have been modified and improved in many countries such as Australia, United Kingdom (UK), United States (US) and Singapore. Despite such modifications and improvements, inappropriate organizational and managerial decisions, practices and procedures prevail within many design and construction firms, which can adversely impact an individual's cognition. As a result of cognitive impairment, the propensity for an individual to commit errors considerably increases, especially when time and cost constraints are being imposed on design tasks and processes (Manavazhi, 2004).

Errors contained within design documentation have been identified as a major problem during the construction of projects (Manavazhi, 2004). The nature and severity of errors made varies significantly between projects. In particular, as projects increase in size there is a proclivity for errors to increase. Most errors that are made in design documentation are identified by the contractor, subcontractor or manufacturers prior to or during construction. If they are not identified then the ramifications may be colossal if a failure occurs. Errors contained within contract documentation alone can contribute to a 5% increase in a project's contract value (Cusack, 1992). Such costs would be significantly higher in the event of an engineering failure and consequent loss of life. The concept of failure has been espoused as a unifying principle for successful design, but according to Petroski (1989) there is a danger of designing by emulating success as designers may overlook critical structural, economic, political and aesthetic issues that require greater consideration. Replication without an understanding of context and constraints can invariably lead to errors and failure. Significant failures that have occurred in construction and engineering facilities due to errors are examined. A systemic learning framework for reducing design errors and potential failures is then propagated. Considering the degree of knowledge and the advancements that have been made in areas such as structural analysis and design, structural reliability, material science, and technology, construction and engineering facilities should not be failing once they have been constructed as risks are known or can be predicted 'a priori'. Issues for terrorism and other malicious acts however pose on-going problems for structural engineers.

2. ERRORS AND FAILURES

Errors have become an innate feature of the design process in construction and engineering (Love et al., 2009). Errors occur due to physiological and psychological limitations of humans. It is a matter of contention whether individuals can justifiably be blamed for all errors, as making mistakes is an innate characteristic of human nature (Reason, 1990). Human errors occur for various reasons and therefore different actions are needed to prevent or avoid the different sorts of error experienced in construction and engineering facilities. Regardless of the skill level, experience or training that individuals possess, errors and omissions may be made at any time. According to Reason and Hobbs (2003) errors involve a deviation of some kind, whether a departure from an intended course of action, departure from a path of actions planned toward a desired goal or a deviation from the appropriate behavior at work. An error can arise due a *mistake*, *non-compliance*, *slips* or *lapses*. Even the most qualified and highly competent individual can make a mistake or mishap. Indeed, Reason (2000) contends that it is often the best individuals that commit mistakes with the worst consequences. The general understanding, however, of the adverse effects of errors is better understood than the potential benefits that can be acquired through

learning to prevent their occurrence (van Dyck et al., 2005). Lessons that can be learnt from accidents, crises or events, have been identified as an integral component of an organization's ability to learn (Choularton, 2001).

Wardhana and Hadipriono (2003) define failure "as the incapacity of a constructed facility or its components to perform as specified in the design and construction requirements" (p.152). More specifically, a structural failure refers to loss of the load-carrying capacity of a component or member within a structure or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit. This causes a fracture or excessive deformations. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure such as that experienced in 1968 at Ronan Point in the UK, which killed four people (Ellingwood, 2006).

Failures arise because of deficiencies in design and detailing, or the inappropriate specification of substandard materials. Deficiencies that manifest themselves as errors and result in a failure may occur because of lapses, slips, mistakes, and omissions during the design process, or downstream in the construction and/or maintenance phases of a constructed facility's life cycle. Design errors can be significantly reduced when design checks are undertaken prior to construction commencing. Schneider (1997) has revealed that through rigorous design checks 32% of errors can be detected. In addition, if an independent third party is used then as much as 55% of design errors could be accounted for. While design checks and verifications are useful for identifying errors their usefulness is somewhat limited if lessons are not learnt from previous projects and appropriate training and skill development is put in place for individuals and teams.

3. EXAMPLES OF CONSTRUCTION AND ENGINEERING FAILURE

Common factors that contribute to failures to occur include inadequate structural redundancy; lack of consideration for loadings; defective connection detailing; calculation errors; misusing computer software; detail constructability problems; and unclearly communicated design intent. In addressing these causes a number of significant construction and engineering failures that have occurred are examined.

The collapse of the hanging walkway at the Hyatt Regency Hotel in Kansas City in 1981, which killed 113 people and injured more than 200 others, was attributable to an erroneous connection detail. A detailed chronology of events contributing to this cataclysmic disaster has been widely documented (e.g., Pfatteicher, 2000). A defining feature of the hotel was its lobby. It featured a multistory atrium crossed with suspended concrete walkways on the second, third, and fourth levels. The fourth floor bridge was suspended directly over the second floor bridge, with the third floor walkway set off to the side several meters away from the other two. Difficulties during construction led to a subtle but flawed design change that doubled the load on the connection between the fourth floor and walkway support beams and the tie rods carrying the weight of both walkways. The engineers failed to review the initial design thoroughly, and accepted the contractors proposed plan without performing basic calculations that would have revealed its serious intrinsic flaws — in particular, the doubling of the load on the fourth-floor beams. The new design could not handle the dead load weight of the structure and the spectators standing on it. The connection failed and both walkways crashed one on top of the other and then into the lobby below. The two walkways were suspended from a set of steel tie rods, with the second floor walkway hanging directly underneath the fourth floor walkway. The walkway platform was supported on three cross-beams suspended by steel rods retained by nuts. The cross-beams were box beams made from C-channels welded toe-to-toe. The original design called for three pairs of rods running from the second floor all the way to the ceiling. Investigators determined that this design supported only 60% of the minimum load required by the building codes (Moncraz and Taylor, 2000).

In a prominent case that occurred on the premises of Charles de Gaulle International Airport in France, a portion of the terminal roof collapsed and four people were killed and three injured in 2004. The results from an administrative inquiry revealed that an array of procedural and structural issues were to be blame for the collapse. It was found the concrete vaulted roof was vulnerable to exterior temperature swings. Sources close to the enquiry also disclosed that the whole building chain had worked as close to the limits as possible, so as to reduce costs. In particular, it was pointed out that there margin for safety was also minimal. Upon further investigation, structural surveyors concluded that the roof was beyond repair and so the entire vault of Terminal 2E had to be demolished and re-built at a significant expense; €130 million or US\$205 million. Subsequent legal proceedings failed to apportion sole responsibility for the event because of uncertainty and interdependency of events that led to the failure occurring.

The collapse of Melbourne's West Gate Bridge in 1970, which killed 35 people and injured many others, was primarily due to a culmination of minor 'errors upon errors' that were committed in the design of box-girder bridge (Public Record Office Victoria, 2005). Two years into construction of the bridge, a 112 meter span between two piers collapsed. Many of those who perished were on lunch break beneath the structure in site huts, which were crushed by the falling span. Others were working on and inside the girder when it fell. On the day of the collapse there was a difference in camber of 11.4 cm between two half girders at the west end of the span that needed to be joined. It was proposed that the higher one be weighted down with 10 concrete blocks, each 8 tons, which were located on site. The weight of these blocks caused the span to buckle; a sign of structural failure. The longitudinal joining of the half girders was partially complete when orders came through to remove the buckle. As the bolts were removed the bridge snapped back and the span collapsed. Despite the significance of this accident, omissions, errors of judgement, inefficiencies and communication failures remain prevalent within the construction industry (Love et al., 2008; Love et al., 2009). Additionally, mistakes form an integral part of the design documentation that is produced by both architects and engineers primarily due to schedule pressure imposed by clients.

The Hotel New World in Singapore collapsed in 1986. Thirty three people were killed. An inquiry investigating the cause of the accident tested for many potential causes such as concrete composition (Thean et al., 1987). Sections of concrete were tested to ensure they were to proper construction standards, and it was revealed that they were. Construction work of the underground railway tunnel workers who had assisted in the rescue were also investigated, even though the excavations were more than 100 yards from the collapsed building. The inquiry revealed the derivative source of the collapse retrospectively was due to "when the structural design was still on the drawing board" placing responsibility on the structural engineer. In addition, the following causal factors were also attributed as determinants:

- the unsatisfactory quality of construction;
- substantial loads that were inadequately provided for the structural design but were added to the building and caused overloaded and poorly constructed structure to burdened; and
- lack of proper maintenance

Fundamentally, the structural engineer had made a serious error in calculating the building's dead load. The structural engineer had calculated the building's live load, the weight of the building's potential inhabitants, furniture, fixtures and fittings. However the building's dead load was completely omitted from the calculation. This meant that the building constructed could not support its own weight. Collapse was therefore imamate.

Lawsuits taken against the engineering consultants United Research Services (URS) and Progressive Contracting (PCI) over the fatal collapse of the I-35w bridge collapse in Minneapolis have been filed (Brown, 2009). URS were responsible for checking the bridge and maintenance work undertaken by PCI. The investigation undertaken by the US National Transportation Safety Board (NTSB) revealed the bridge designer to be at fault as the gusset plates used to connect load-bearing columns and trusses had an

inadequate load bearing capacity. The NTSB found that 24 gusset plates had been woefully under designed on the I-35w being only half the thickness required. In addition to oversights that occurred during the original design review, subsequent design reviews completed (most notably during the bridge's modification) failed to adequately cater for increased traffic volumes. This case has forced dramatic changes to work practices, and bridge design and maintenance procedures to be undertaken in the US.

4. SYSTEMIC LEARNING FRAMEWORK

Many of the examples of engineering failure cited above could have been avoided. It would appear that time and cost constraints, in many instances, led to omission errors. An absence of design checks and reviews juxtaposed with cost cutting procedures, such as in the case of the Westgate Bridge, and I-35w Minneapolis Bridge appear to be the main contributors to failures. With this in mind, error reduction and prevention should be viewed as a continuous process, rather than a product of certain activities or behaviors, as it involves an exploration of people, organizations and project systems. In doing so, this process enables the mapping of dependencies and interfaces that influence the error prevention process. Furthermore, viewing error prevention as a continuous process implies that learning from errors is a collective capacity that can produce the knowledge needed for individual, organizational and project-related error prevention practices. Given the complexity of the project environment within which designers work, the production of a collective capacity would involve the learning processes of not only design organizations but the entire project team. Based upon the above examples cited, a systemic r learning framework for design error and failure reduction is propagated in Figure 1.

The ideal approach to error reduction is to view errors as symptoms of underlying problems so they become sources of information to understand how systems work (Love et al., 2009). Design errors and the resultant rework and failures should be viewed as tools that can be used to define margins of risk and safety so that learning how to prevent them can occur. This approach is based on the premise that humans are fallible, errors must be expected and individuals' poor performance is a non-issue. Instead the focus should be on the failure in procedures, processes, teams and the organization. Emphasis is on feedback and knowledge acquisition from work processes, information, reflection discussion between colleagues and other project team members. The use of reviews at each stage of a project's life cycle also provides the impetus for 'real-time' learning to take place. Learning about error causation through interaction and participation with others is deemed an effective learning milieu for their prevention (Love et al., 2009). A 'community of practice' can be used to formalize situating knowledge and learning, though the extent to which it learns internally or imports new knowledge is in part a function of the nature practices it undertakes (Love, 2009). The situated dimensions of learning are concerned with its practical and social aspects within a context. Most designers learn on the job in culturally embedded ways. This learning evolves through participation and interaction of people and their collective sense-making activities as they develop their competencies and construct their identities to function effectively. Interaction is a prerequisite for learning how to prevent errors, as it enables the sharing of experiences to be acquired. This situated perspective may encourage designers to understand the necessity for project learning and interaction so as to make 'sense' of their activities.

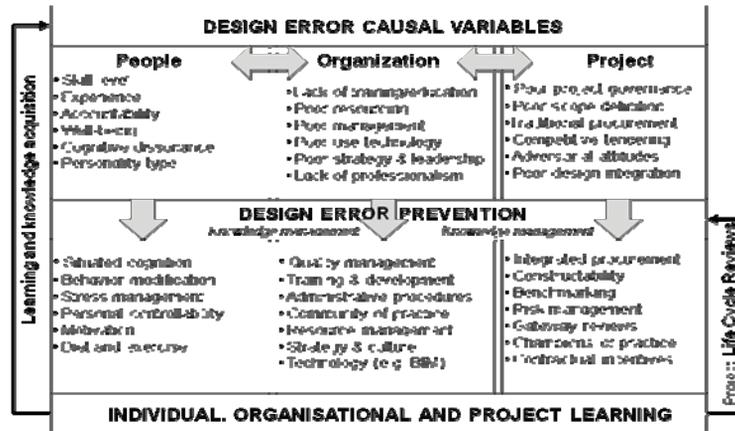


Figure 1. Systemic learning framework for error and failure reduction

While situated learning is effective for error prevention, an individual’s capacity to learn can be adversely influenced by the conditions they are subjected to (Reason, 2000). Design organizations need to foster a leadership enriched culture and structure that engenders groups and teams to develop error free work practices, as their prevention can only be achieved to a limited extent by interventions at an organizational level. Fundamentally, people need to take responsibility for their actions and take the necessary precautions to not succumb to slips and lapses. In overcoming issues pertaining to memory and lapses in consciousness, personal aids such as post-it notes and tie-on labels have been found to be effective reminders (Reason, 2002). In addition, if incentives (e.g. remuneration and additional leave) are used to motivate people to improve process quality, then an individual’s ability to learn and reduce errors can increase. Providing designers with adequate time to produce documentation, implementing audits, reviews and verifications, and using computer-aided design applications will go some way to containing errors, but not mitigating them. Similarly, at the project level, the implementation of constructability analysis, building information modeling, benchmarking, champions of practice, quality management, risk management, alliancing and integrated procurement methods can also be used to contain errors, but there is a limit to the extent to which they can be eliminated using these strategies. Furthermore, such strategies are rarely, if at all, implemented simultaneously during the delivery of construction and engineering projects. If they were, then many of the problems that arise in projects due to safety, rework, claims and disputes could be prevented.

5. CONCLUSION

Design errors are a symptom of dysfunctional organizational and managerial practices that prevail within the construction industry. They significantly contribute to cost and schedule growth, and rework. Furthermore, they jeopardize safety and are major contributors to accidents that occur during and post construction. Significant failures were drawn upon to highlight the adverse role that errors and failures can have upon the safety of workers and the general public. Many of the failures that have occurred could have been prevented if design checks and reviews had been undertaken and appropriate managerial and project management practices had been implemented. Instead cost and time pressures appear to be prevailing nemeses contributing to errors and failures. A systemic learning framework is propagated to reduce errors and failures. It is suggested that an array of strategies should be implemented incongruence at a project, organizational, and people level. If such strategies are not adopted, then it will only be a

matter of time before the next major construction and engineering failure occurs. Learning from the past is the first step toward attaining improvement. Taking action is an even bigger step, as it requires major cultural and behavioral change, which is urgently needed within the construction industry.

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