FORENSIC CIVIL ENGINEERING AND RISK MANAGEMENT

Dr. N. Krishnamurthy

B.Sc. & B.E.(Civil)(Mysore U.), M.S.(CE) & Ph.D. (Univ. of Colorado at Boulder, USA)
Workplace Safety and Risk Management Consultant, Singapore
E-mail: safety@profkrishna.com

ABSTRACT

Forensic engineering is considered to be a lagging indicator aimed at investigating accidents after they happen, while risk management is usually a leading indicator aimed at predicting mishaps before they occur so as to prevent accidents. In this paper, author attempts to bring together the two apparently opposing concerns and procedures into a single integrated and synergistic whole. Using a number of case studies to illustrate his points, author demonstrates that by a judicial combination of the two specialties, improvements to existing planning procedures may be made to avoid accidents or at least minimize their impact.

1. Introduction

Which came first, the hen or the egg? Do we suffer accidents and regret our ignorance or do we assess risks on the basis of past accidents so we can avoid future accidents? This is a cyclical procedure and which comes first is irrelevant.

What is true today is that we have enough information and knowledge on almost all possible mishaps that can happen to engineering artifacts and their users that we can identify the hazards (i.e. potential dangers) in any activity, and eliminate them or mitigate their effects by risk management (RM).

For good risk management, experience with mishaps and their consequences, that is experience with accidents, is essential. This experience is usually gained from exposure to and analysis of past accidents and their aftermath, in short from forensic analysis of the accidents.

From another point of view, risk management is a leading indicator (meaning that it helps to predict the outcomes of an activity so we can avoid them or reduce their impact) rather than a lagging indicator (meaning that it helps analyse what happened in a mishap after it happened).

Forensic engineering is generally thought of as an accident investigation procedure while RM is an accident prevention device. Although by usage 'forensic engineering' is restricted to accident investigation procedures to satisfy legal requirements, one accepted basic definition [Ref. 1] of the term is as follows:

- Forensic (adj.) *"pertaining to or suitable for courts of law,"* 1650s, with *-ic* stem of Latin *forensis "of a forum, place of assembly,"* related to *forum* "public place". Later used especially in sense of *"pertaining to legal trials."*

Author would prefer the even broader definition below [Ref. 2]:

- *"Forensic Engineering is the art and science of professional practice of those qualified to serve as engineering experts in matters before courts of law or in arbitration proceedings."*

These definitions do not preclude the application of the term 'forensic engineering' to pre-accident analyses or in particular to accident prevention exercises. The rest of the paper will deal with the interaction of risk management and forensic engineering with particular reference to civil engineering.

2. RISK MANAGEMENT

The basic steps in risk management [Ref. 3] are as follows:

- Identify the hazard in a workplace activity.
- Assess the likelihood of its occurrence and the severity of its consequences.
- Combine their effect by a risk matrix to determine the risk from the hazard.
    - The preceding three steps constitute 'Risk assessment' (RA).
- Depending on the magnitude of the risk, check if the existing controls are adequate or what additional controls would be necessary to reduce the adverse consequences of the risk to within acceptable or at least tolerable limits.
- Implement the additional controls.

In general, most accidents occur because the person(s) involved did not identify the hazard, or if they did, did not assess its likelihood and/or severity properly.

Whether all accidents can be avoided by risk management or not, proper risk assessment will direct attention to weak links in an engineering activity and lead to an estimate of the consequences and recommendations on how to control the worst of them.

3. Legal Requirements Of Risk Management

Most advanced countries have stringent requirements for risk management for activities at hazardous workplaces. Singapore has the Workplace Safety and Health Act [Ref. 4] which includes the Risk Management Regulations [Ref. 5] and Code of Practice for Risk Management [Ref. 6].

When the Regulations were promulgated in September 2006, only the three most hazardous industries in Singapore, namely construction, ship building and repair, and manufacturing were covered. In subsequent years, all the other workplaces were covered so that today, even offices, banks, and barker shops are included in the requirement.

If an employer (or more precisely, an 'occupier' of a workplace) does not carry out risk assessment they will be fined S$10,000 in the first instance, and if repeated, fined S$20,000 and/or jailed for six months.

The 3×3 risk matrix shown in Fig. 1 (Left) is the minimum size. The 5×5 numerical risk matrix of Fig. 1 (Right) is recommended, but any size 3×3 or larger is acceptable.

Severity \ Likelihood	Remote	Occasional	Frequent
Major	Medium Risk	High Risk	High Risk
Moderate	Low Risk	Medium Risk	High Risk
Minor	Low Risk	Low Risk	Medium Risk

Severity \ Likelihood	Rare (1)	Remote (2)	Occasional (3)	Frequent (4)	Almost Certain (5)
Catastrophic (5)	5	10	15	20	25
Major (4)	4	8	12	16	20
Moderate (3)	3	6	9	12	15
Minor (2)	2	4	6	8	10
Negligible (1)	1	2	3	4	5

Fig. 1. (Top) 3×3 Qualitative Risk Matrix (Right) 5×5 Numerical Risk Matrix

Definitions of the levels of likelihood and severity are given to enable the assessment of their level by the risk assessment team. From these levels, the category of risk is chosen either from the qualitative matrix as shown in Fig. 1 (Left), or by multiplying the likelihood and severity level numbers and determining their risk index as shown in Fig. 1(Right).

For all the apparent logic and rigour of the assessment procedure, the estimates of likelihood and severity levels are quite subjective. In particular, the likelihood of the mishap occurring is mainly a function of local circumstances and human factors, and its assessment is generally done on the basis of relevant statistics to the particular industry, site, and job.

4. Interaction of Risk Management with Forensic Engineering

As already mentioned risk management, being a leading indicator, is the antithesis of accident investigation which is a lagging indicator. The former aims to prevent accidents and the latter focuses on analyzing accidents. Both must meet legal requirements.

However, we may use both of them synergistically, supporting and reinforcing each other, to accomplish two objectives:

(i) To analyse an accident by risk management principles so as to learn lessons from it – as is conventional practice; and,

(ii) To prevent accidents by conducting a risk assessment before starting a project and implementing required additional risk controls.

The chain of actions may be designed to learn from past accidents to prevent future accidents through risk assessment and control, as follows:

- Determine the immediate and root causes of the accident.
- Check if these causes had been identified earlier in the risk assessment.
  - If not, ensure that the fresh knowledge is utilised in future risk assessments.
- Check if the actual time frame or frequency of the accident fits within the likelihood assessed for the accident.
  - If not, update the criteria for deciding the likelihood to include the fresh knowledge.
  - For example if as in Fig. 2, forklift accident frequency of 1 per year from 1999 to 2002 has led to a 'Low' likelihood, when in 2003 there were 6 accidents, it would be prudent to raise the likelihood level to at least 'Medium' as a predictor for subsequent years.
  - In particular, it may be noted that to reduce the likelihood to 'Low' again in 2005 because there were no accidents in 2004 would be unwise as the three-year average for 2003 and 2004 are still high.

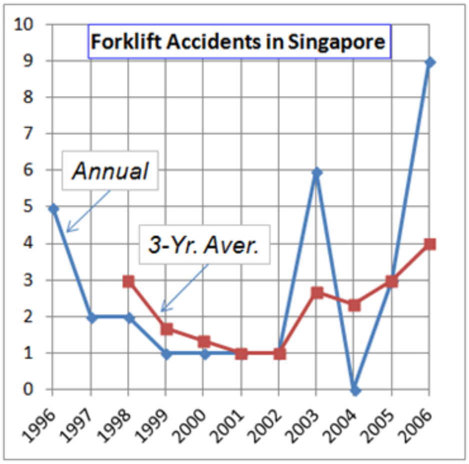

Fig. 2. Lessons from Accidents

- Check if the actual impact of the accident fits within the severity assessed for the accident.
  - If not, update the criteria for deciding the severity to include the fresh knowledge.

- If in the example of Fig. 2, the worst severity of the increased number of accidents happened to be simple fractures ('Medium') rather than death ('High'), then there would be no need to increase the severity level despite the increased number.
- If all of them happened to be just bruises, then it may also be acceptable to reduce the severity from 'High' to 'Low'.

The usefulness of forensic engineering to risk management is well established and widely utilised. It will not be an exaggeration to say that if it were not for forensic engineering, risk assessment will be almost impossible. It is the investigation of accidents, documentation of details of their severity and frequency, and identification of root causes and contributory factors that build up the database and statistics from which the likelihood and severity of hazards can be assessed with any degree of certainty for future use.

Thus, an industry which has high volume and good quality data on workplace accidents can provide sufficient information to risk assessors to estimate accurately the likelihood and severity of various mishaps that may happen in any workplace activity in that industry.

5. Importance of Risk Assessment to Forensic Engineering

Out of the more than hundred Singapore accident reports in public domain recently studied by the author, about three-quarters had the citation *"Lack of or inadequate risk assessment"* as the first item in the list of possible causes, and/or *"Conduct proper risk assessment"* as the first recommendation to be followed, signifying a weakness in that regard in the occupier company for that accident.

It is also a fact that a cause of most of the accidents can be traced back to the omission of the particular hazard during the risk assessment even when it has been done.

So it is clear that risk assessment can be a very powerful tool to anticipate and prevent or mitigate the effect of accidents.

This approach is gaining more and more importance in forensic engineering because in Singapore and many other countries one of the leading questions asked by the prosecution or plaintiff in cases involving workplace accidents is if the risk assessment had included the item found to have been a root or contributory cause for the mishap.

6. Role of Risk Management Codes in Forensic Engineering

As outlined earlier, risk management code of practice normally prescribes:

(a) The procedure to be adopted to arrive at an assessment of the risk of a particular hazardous activity; and,

(b) The sequence of consideration and implementation of control measures to be adopted to eliminate or mitigate the consequences of the risk.

These are legal requirements, and violation of any of the mandated terms attracts definite and significant penalties such as suspension or revocation of licenses, fines, and jail terms. Whether a party in an accident followed these procedures for risk assessment and control hierarchy will therefore become critical in any court proceedings on the accident.

The author, like most expert witnesses, has faced this question on behalf of his client or has put this question (through the attorney) to a witness from the opposite party.

A court hearing on an accident may include the following line of questioning:

- *Did you conduct a risk assessment (RA) of this activity?*
- *If yes, did your list of activities in the RA cover this particular trigger or contributory event?*
  - Eg. Reaching beyond the worker's grasp (beyond 2 m) while working at height on a safe base, such as for fixing a light bulb at a 6 m high ceiling from a 3 m high mobile scaffold.
- *If yes, did you have a Safe Work Procedure (SWP) for this activity written out and distributed to the personnel concerned?*
  - Eg. Provide some means of reaching higher from the work platform, say by means of a 2 m ladder.
- *If yes, did you identify the hazards (potential dangers) in this SWP?*
  - Eg. Once the worker climbs on the ladder, he will no more be protected by the 1 m high guard-rail specified in the Work at Height code. So further SWP must be specified to prevent or protect the worker from the falling risk.
  - The SWP requirements may open up another series of questions and answers, which may point to culpability in not providing safe conditions for working!
- *If yes, how did you assess the likelihood of occurrence and severity of consequence?*
  - Why did you assess the likelihood as 'Low'? [Witness must explain the logic or statistics behind the entry. Assessors usually get trapped here because many (if not most) simply follow previous years' entries, or use their personal or company's experience for the assessment. – They should use the industry's current statistics.]
  - Why did you assess the severity as 'High'? [Witness must remember to include the controls that reduce severity but not those that do not reduce severity. For instance, a guard-rail reduces only the likelihood of falling to very low, but does not affect the severity of injury once the person falls for one reason or another.]
- *In recommending controls for this fresh risk, did you follow the hierarchy of controls?* (Fig. 3.)
  - Many sincerely believe that giving the worker Personal Protective Equipment (PPE) will safeguard him* from all harm.

    [In this paper, use of male pronoun will automatically cover the female counterpart, except where the context is gender-specific. – NK]*
  - But experiment and experience have shown the wisdom of following the hierarchy (order of decreasing effectiveness) to reduce injury.

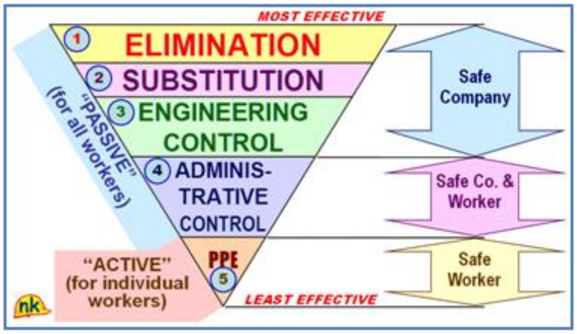

Fig. 3. Hierarchy of Controls

  - In the hierarchy, elimination of risk is considered first, followed by substitution with a less hazardous material, process, tool etc., engineering controls, and administrative controls, before providing PPE.

Obviously, a 'No', wrong or inadequate response to any of the above questions confirms a violation of legal norms and leaves the door open for penalties.

It therefore behooves a forensic engineer to be thorough in the Code of Practice for risk management

[Ref. 6], and related regulations. Author will present a few case studies to demonstrate the interaction between forensic engineering and risk management.

7. Resonance of Suspension Bridges

The Tacoma Narrows bridge in the State of Washington, USA, failed on 7 November 1940. The Millennium Bridge in London had to be closed on opening day, 10 June 2000.

7.1. Case Study 1 : Tacoma Narrows Bridge Collapse

In the case of collapse of Tacoma Narrows Bridge, called *"Galloping Gertie"* because of the way it failed, [Ref. 7] the reason for the failure was a design flaw due to lack of knowledge on response of structures to aero-elastic flutter and vortex shedding, basically torsional oscillation, (Fig. 4).

Fig. 4. Tacoma Narrows Bridge Collapse

Although it was well known that soldiers marching over a flexible bridge caused high amplitude vertical oscillations due to resonance, the phenomenon of vortex shedding was not known at the time.

At that time also, the art and science of risk assessment as a strategy for elimination or mitigation of consequences of accidents was not sufficiently developed to have been of any use in anticipating or forestalling this disaster.

7.2. Case Study 2: Millennium Bridge Sway Problem

But the Millennium bridge [Ref. 8], called the *"Wobbly Bridge"* because of the sideways pendulum-like motion, was designed and built by world-renowned designers and constructors (Fig. 5).

Fig. 5. Millennium Bridge

Yet, on opening day, when the people walked on to the just-opened bridge, the oscillations escalated to literally dizzying proportions to the extent it had to be closed.

Subsequent analysis showed that the cause was 'positive feedback' phenomenon, known also as 'synchronous lateral excitation'. It took nearly two years and 5 million pounds to fix the problem.

But this problem was not unknown! While vertical resonance was known more than a century earlier, horizontal resonance had also been documented from the early 1970s for bridges with lateral frequency modes of less than 1.3 Hz, and sufficiently low mass.

A careful risk assessment would have identified the risk of such lateral motion on pedestrian bridges and appropriate pro-active controls could have been implemented to avert the subsequent embarrassment and expense.

8. NASA Shuttle Disasters

Can a world-famous best-endowed government agency be involved in two catastrophes of similar kind? Yes, the National Aeronautics and Space Administration of USA (NASA) had two similar problems in two of their space shuttles, one named *Challenger* [Ref. 9] on 28 January 1986, and the other named *Columbia* [Ref. 10] almost exactly 17 years later, on 1 February 2003, in each of which all seven of the crew died.

The circumstances under which the two shuttles were destroyed were quite different, as shown in Table 1, but there were certain common deficiencies in risk management. Ethical issues involved in these cases have been discussed by author elsewhere [Ref. 11.]

Table 1. Comparison of Challenger and Columbia Disasters

Item	***(a) Challenger***	***(b) Columbia***
Date of disaster	28/1/1986	1/2/2003
No. of crew members dead	7	7
Main cause of failure	Freezing of 'O' rings	Impact of foam piece on wing
Time frame of failure	73 seconds after launch	During re-entry to earth
Role of Engineers	Warned about consequences of cold weather launch	Had warned about foam tile breaks; sought more information for rescue
Role of Management	Over-rode engineers recommendation and launched in cold weather	Ignored engineers' warnings and denied information sought

8.1. Case Study 3 : Challenger Disaster

Data on failure probabilities at various low temperatures for the freezing of the 'O' ring sealing the connection for burning gases was available, as shown in Fig. 6, all predicting high probabilities of failure at temperatures below about 65°F.

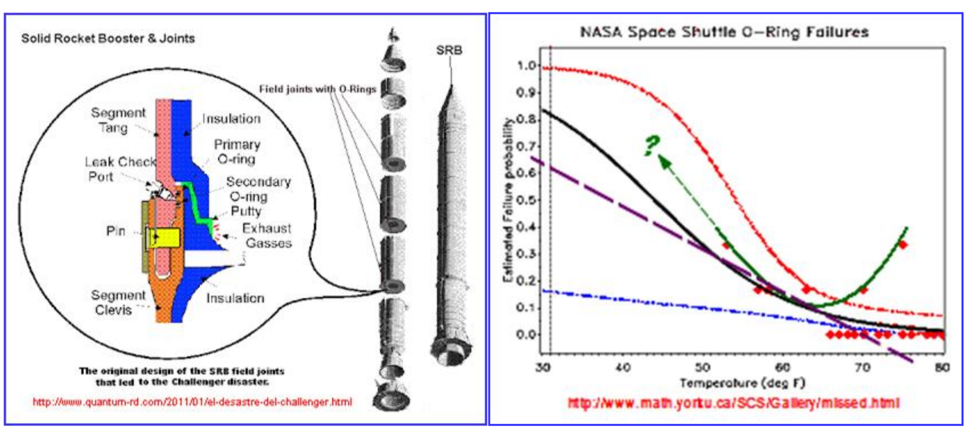

Fig. 6. (Left) The 'O' ring that froze; (Right) Various curve fits to failure

Engineers had done a certain kind of risk assessment and concluded that with the overnight temperature of 18°F (–8°C) and even at the launch morning temperature of 28°F (–2.2°C) it was too risky to launch.

But the management out-talked and out-maneuvered the engineers to the extent that key personnel changed their mind and approved the launch, with the disastrous results that followed.

Roger Boisjoly, an engineer who vehemently opposed the launch in the face of heavy criticism was given an award for his 'whistle-blowing' on the violation of safety norms.

This is one glaring example where even with risk assessment pointing to high risk, managers could take action that might lead to disaster.

8.2. Case Study 4: Columbia Disaster

Columbia's history was even more colourful. During the launch on 16 January 2001, a piece of foam broke off the space shuttle's external tank and struck the left wing, (Fig. 7).

A few previous shuttle launches had seen minor damage from foam shedding with no significant consequences, and so nobody thought any more about it.

But when *Columbia* re-entered the earth's atmosphere on 1 February after completing its 16-day mission, the hole caused by the foam hit (travelling at Mach 2.46, i.e. 1,870 miles per hour or 840 meters per second) allowed hot atmospheric gases to penetrate and destroy the internal wing structure.

This caused the spacecraft to become unstable and slowly break apart, burning itself and the crew on re-entry.

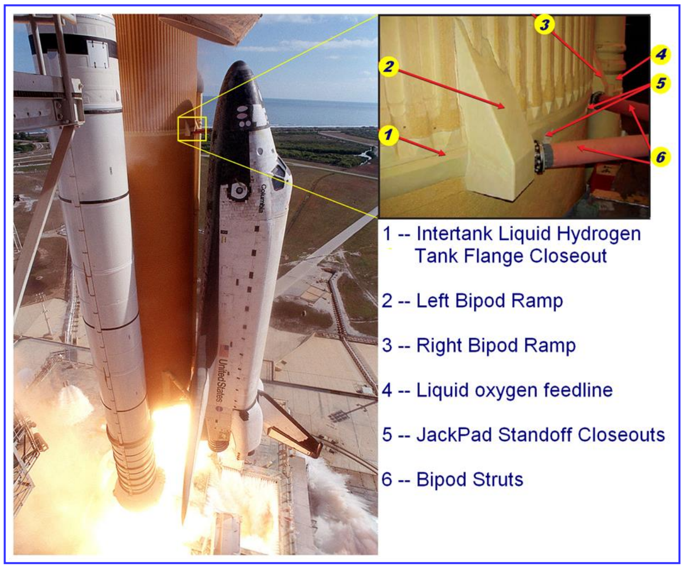

Fig. 7. Broken Foam Location

Here again, engineers were on the right track, wanting higher resolution images of the wing to assess the extent of the damage and work out some rectification control. But the managers refused, influenced by the apparent futility of any such information.

As with the O-ring erosion problems of *Challenger*, NASA management became accustomed to the foam shedding phenomena in *Columbia* when no serious consequences resulted from these earlier episodes. Earlier warnings by engineers had also been ignored.

Apparently, the lessons from *Challenger* had not been learnt well enough, or the lessons learnt had been forgotten over the preceding 17 years. Risk assessment had pointed in the right directions, but the likelihood of disaster had been downgraded.

9. Design Changes

Changes to design to enable fabrication or construction to take place are often carried out by the fabricators or constructors without the knowledge of the designers.

Such changes can cause catastrophic repercussions, as will be illustrated by two classical cases, which the author had also presented at an earlier conference in a different context [Ref. 12.]

9.1. Case Study 5 : Hartford Civic Center Collapse

Built in 1975 in Hartford, Connecticut, USA, the roof of the Hartford Civil Center, known as 'XL Center', collapsed early morning on 17 January 1978 due to a heavy snowstorm [Ref. 13]. Only six hours earlier, 5000 had attended a basketball game. Luckily as the stadium was empty at the time of collapse, no one was injured.

The roof was 300 ft. by 360 ft.(90 m by 110 m), supported by a three-dimensional steel truss system assembled from pods 30 ft. by 30 ft. (Fig. 8).

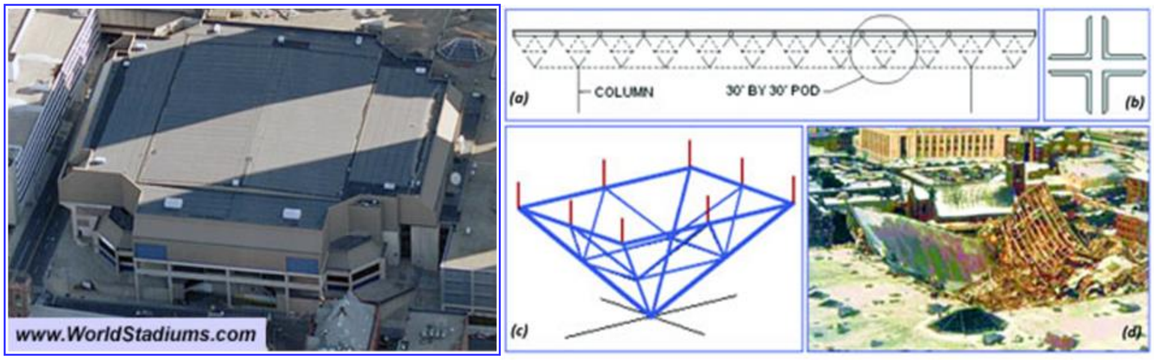

Fig.8. (Left) XL Center, (Right) (a) 3D Truss Section, (b) Member Cross-section, (c) Typical Pod, (d) Collapsed view.

There were many reasons for the collapse, main ones among which were the following:

(1) Long compressions members were not braced in the middle as should have been.

(2) The computer analysis, being the first 3D truss analysis, was flawed.

(3) The contractor moved the connections a few centimeters (marked 'S' in Fig. 9) below the designed level for convenience of fabrication, resulting in reductions in capacity by as much as 90%.

(4) Warnings of excessive deflections from the site personnel during the erection process went unheeded by the designers.

The sad fact about the whole mess was that nobody bothered to assess the consequence of the changes made to the design and the possible reasons for the excessive deflections.

In other words, there was a complete lack of risk assessment and lack of risk control!

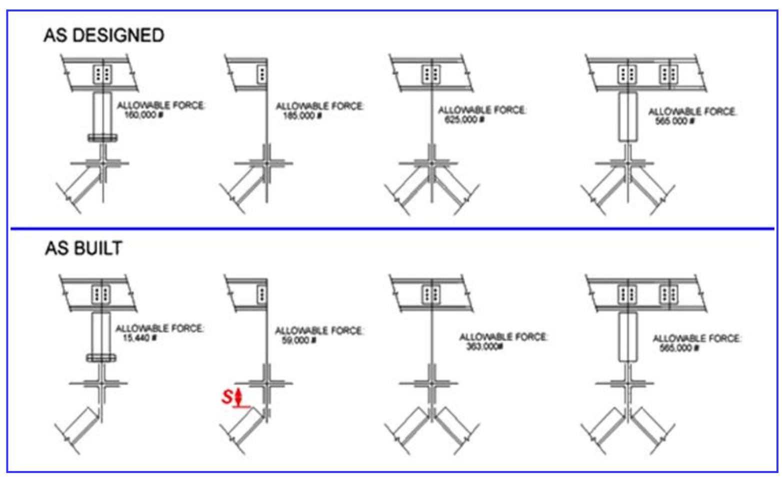

Fig. 9. Hartford Civic Center Roof Connection

9.2. Case Study 6 : Hyatt Regency Walkway Collapse

Built in 1978, the second and fourth floor walkways of the Hyatt Regency Hotel in Kansas City, Missouri, USA failed catastrophically on the evening of 17 July 1981, killing 114 and injuring 216 more (Fig. 10).

Although it had other shortcomings, the main reason for the collapse was the fact the fabricator changed the single rod design supporting both floors (as at top right in Fig. 10) to a double rod design each supporting one floor (as at bottom right in Fig. 10), [Ref. 14].

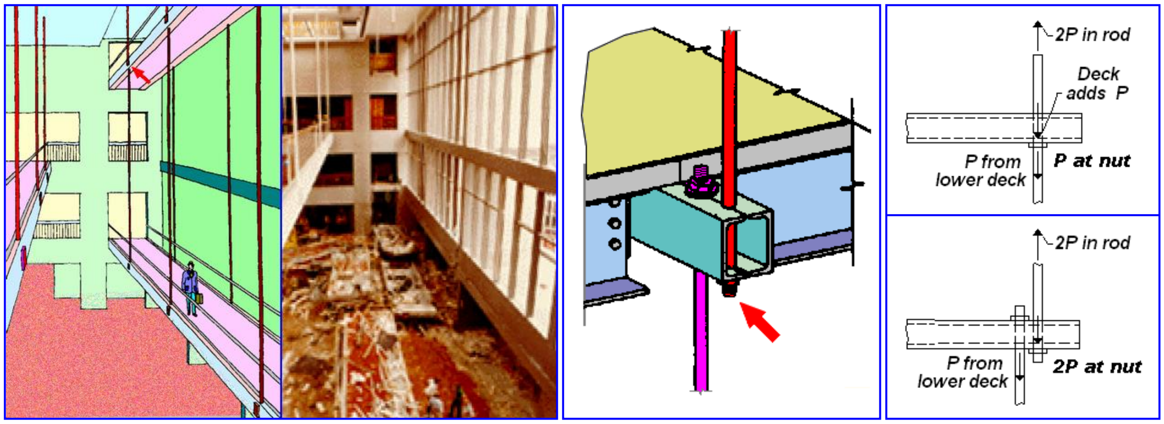

Fig. 10. Left pair – Hyatt Regency Walkway, before and after collapse; Middle – Nut at upper walkway; Right – Static analysis of single vs. double hanger rods

Apparently, approval was obtained for the change over a long-distance phone call. The exact nature of the approval was under hot debate and court battle for a long time.

But what was not at all done was analysis of the actual effect of the change on the force distribution – in short, there was no risk assessment to check the result of the change. A static free-body analysis of the junction of the two rods at the third floor level would have shown that the nut there would be subjected to twice the load of the original design.

This situation addresses squarely the need for risk assessment and management in any task that requires re-design.

Singapore has launched a thrust for integrating the safety in the design and construction phases, and in fact throughout the life cycle of the structure, by the newly mandated Design for Safety, to come into force from 1 August 2016.

10. Case Study 7 : Hurricane Katrina Levee Failures

On 29 August 2005 Hurricane Katrina hit New Orleans, Louisiana, in Mississippi, USA, destroying more than 50 levees (i.e. embankments) and flood walls protecting the city and its suburbs (Fig. 11). [Ref. 15.]

Fig. 11. New Orleans Ground Elevations

The levee and flood wall failures caused flooding in 80% of New Orleans and many townships in the vicinity. Tens of billions of gallons of water spilled into vast areas of New Orleans, flooding over 100,000 homes and businesses (Fig. 12).

More than 1200 people died in the hurricane and the subsequent floods, making it the deadliest USA hurricane since 1928. Total property damage was estimated at $108 billion (in 2005 USD).

Although the engineering failures were caused by a natural disaster beyond human control, forensic engineering highlighted many flaws in the emergency preparedness and crisis response system, as well as certain design and construction deficiencies in the levee system.

Fig. 12. New Orleans, during Katrina and a decade later

The main civil engineering deficiencies were:

- The project was incomplete even after 40 years of construction;
- Possibility of overtopping of levees and floodwalls;
- Designed pile depth below sea level was only 17 ft. (5.1 m), about half of what was required, due to a misinterpretation of pile test results in a cost-cutting exercise;
- Over-estimation of soil strength and hence under-design of levees leading to foundation failures;
- Inadequate pumping system and emergency power for it; and,
- Low factor of safety (1.3) in design, ignoring water gaps from older channels.

What is relevant to this paper is the inadequacy of the risk management system in the project. [Ref. 16.] The risks of levee failure were never quantified before Hurricane Katrina.

Dam failure scenario was adopted for levee failure, which grossly underestimated the risk. Likelihood of dam failure was set at once in 1 million years of operation, but likelihood of 1000 deaths from failure of hurricane protection system could be once in 40 years.

Further the severity was also underestimated, as downstream evacuation after dam failure would have been relatively easy, while rescue from levee failure would be almost impossible.

As a result of this underestimation of risk, emergency preparedness was terribly flawed. A risk assessment of areas that would be submerged would have indicated many vulnerabilities that were overlooked, such as escape routes, venues for emergency shelter, transportation facilities for evacuating people, etc.

The Superdome was the only place available to the displaced masses, and at one time 30,000 homeless people crowded in it without the basic amenities, for five days.

Even the National Guard headquarters were flooded. Figure 13 shows the hundreds of school buses which were expected to have been utilized for evacuation purposes, themselves stranded in the flood due to inadequate risk assessment and control.

Risk management also failed in the communication of risks and controls to the main stakeholders who faced the risk, namely the public. Due to lack of information and organization, there was complete chaos for a few days before the floods subsided, people were evacuated out of the Superdome, and some kind of order was restored.

It took five to ten years for the city to return to normalcy, with increased vibrancy.

Fig. 13. Rescue Buses Stranded in Flood

11. Pro-Active Forensic Civil Engineering

As has been proposed, deviating from the conventional definition of forensic engineering as confined to accident investigation, we may expand the term to cover the heuristic sense of engineering analysis carried out to eliminate accidents in proposed civil constructions and modifications, in such a way as to stand legal scrutiny.

Author would like to call this approach "Pro-active Forensic Engineering".

Actually, such a definition would bring us squarely back to the sole aim of good design, namely to develop a procedure for developing a needed facility in such a way that it can serve with full functionality for a specified period of time without systemic or functional failure – in other words, satisfying the "Duty of Care".

Whether one is obligated to test a design under various failure scenarios may be a matter of debate, but as already mentioned, Singapore Government will require designers to check and 'design-out' potential risks in their designs from August 2016. To address this and avoid accidents, risk assessment will become a pre-requisite.

The author would like to share two experiences involving his going beyond the call of duty:

(i) To explore what might happen if and when certain alterations were made to proposed procedures, and in that process some new risks were identified, leading to pro-actively preventing adverse consequences and failures from previously unidentified hazards; and,

(ii) To identify existing risks in a built structure and get them rectified.

11.1. Case Study 8 : Procedure to Install an Additional Sewer Line

Some time in the early 1970s while the author was in USA, his advice was sought in regard to the installation procedure for an additional steel sewer pipe as the existing brick-lined R.C. tunnel had reached its capacity.

Figure 14 illustrates the whole story, which author had also presented at an earlier conference in a different context [Ref. 17.]

This was the era when the finite element method (FEM) of structural analysis was getting into full swing, finding new applications every day.

Author was among the first to use the method to analyse all kinds of artifacts from a filling in a tooth to a pre-tensioned steel bolted connection in his consultancy and research.

So he grabbed this opportunity to use FEM and in the next couple of days analysed a finite element model of the existing R.C. sewer.

He was able to confirm that the extra load from the crane installing the new sewer in the excavation was safe, as long as the pipe-laying job was done slow and steady and steel plates were used to distribute the wheel loads.

As author had already developed the habit (or game?) of playing around with changing scenarios within the computer, he casually did a check on what would happen if the sheet pile tie-back slackened by 1/2 inch as at 'p' in Fig. 14(d), before the crane came on the soil bank.

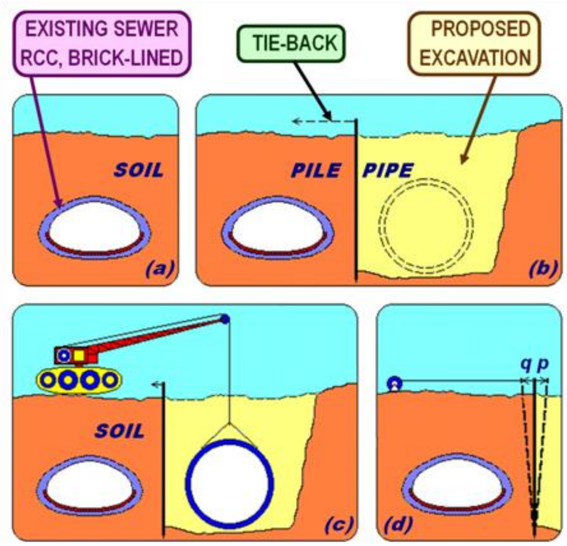

Fig. 14. Sewer Installation Risk Assessment

There was no big problem with it and so sent off his recommendation on Sunday evening that with due care they could install the new pipe as planned, on Monday morning.

During the night, he got the doubt what, if instead of slackening, an over-zealous operator tightened the tie-back 1/2 inch, as at 'q' in Fig. 14(d). He called his client and asked him not to start, and early next morning ran the computer analysis with displacement 'q' instead of 'p'.

He found that the crown of the old sewer would crack up under the lateral compression! Immediately he called back and advised the client not to install the new pipe from the old sewer (left) side, but somehow find a way to install it from the other (right) side of the excavation.

Author believes that it is this *"What if …?"* approach to design, amounting to risk assessment and conforming to the new paradigm of 'Design for Safety', that would eliminate potential dangers in unusual structures and untested processes.

11.2. Case Study 9 : Risk Assessment of Handrail in Children's Park

This was one of the author's small contributions to safety in the township where he lived.

A few years ago, just having moved to his new address, he happened to notice that in the adjacent children's park, steps leading from the park down to the next level had inadequate edge protection.

He was able to get the problem rectified through the authorities. Author had presented this at an earlier conference [Ref. 12] in a different context.

As he was teaching a course on risk management, he later turned the situation into a tutorial on risk assessment and management. He presented the problem as an architect's proposal (Fig. 15), together with an engineer's drawing (Fig. 16) and carried out a risk assessment on it.

Two hazards could immediately be identified during use of the steps, particularly by the children to whom the steps were intended, and by pregnant mothers and old grandparents accompanying them, as shown in Table 2.

For both the hazards, the risk, predictably, came up to 'High'. This meant that the task cannot legally be carried out without reducing the high risk to at least 'Medium'.

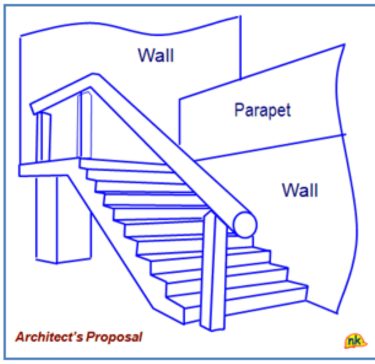

Fig. 15. Architect's rendering

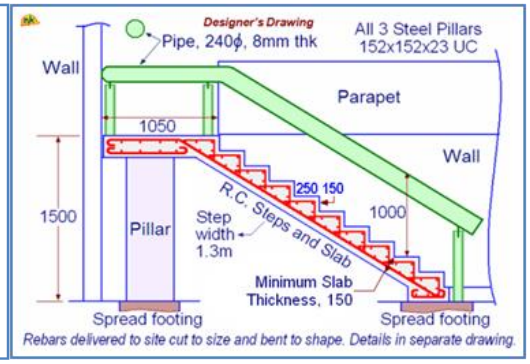

Fig. 16. Designer's Drawing

Table 2. Risk Assessment for Steps in a Children's Park

1. Sl. No.	2. Design Item	3. Hazards Identified	4. Risk – Consequences	5. Risk Assessment		
				Severity	Likelihood	Risk
1.	Handrail in use	Too large gap below handrail	Falling off the steps, injury	H	M	*H*
2.	Handrail in use	Top rail too big	No grip when needed, injury	H	M	*H*

Proposed control measures were a redesign with mid-rail and verticals, and reduction of hand-rail diameter to about 30-40 mm, as per the schematic shown in Table 3 and Fig. 17.

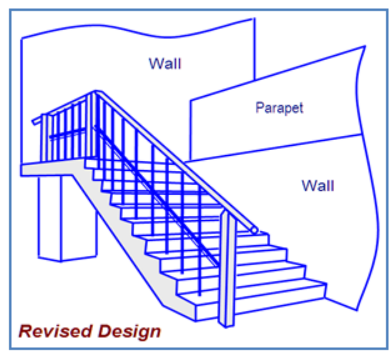

Fig.17. Revised Proposal

Both risks would be reduced to medium.

Note that the severity remains unchanged at 'H', as the guard-rails reduce only the likelihood from 'Medium' to 'Low'. But the combination now reduced the risk to 'M'.

While this is a very simple, almost trivial, example, the impact of risk assessment on accident prevention is fully brought out through it.

Hopefully, it also demonstrates how one individual can improve safety in a community.

Table 3. Recommended Redesign for Steps in Children's Park

1. Sl. No.	6. Can hazards be designed out?	7. Proposed Control Measures	8. Residual Risk			9. Further Review Required?	10. Staff & Date
			Severity	Likelihood	Risk		
1.	Yes	Redesign with mid-rail and verticals	H	L	M	Yes, to confirm	AB/+1M
2.	Yes	Reduce size of rails to about 30-40 mm	H	L	M	Yes, to confirm	AB/+1M

12. Case Study 10 : Fall from Height Investigation

Author wishes to close with a recent accident investigation by authorities, findings and recommendations which might summarise the relationship between risk management and forensic engineering.

In a recent seminar on fall from height accidents, it was reported that a worker tasked to install telecommunication equipment on a monopole (Fig. 18-a), fell off the ladder and died.

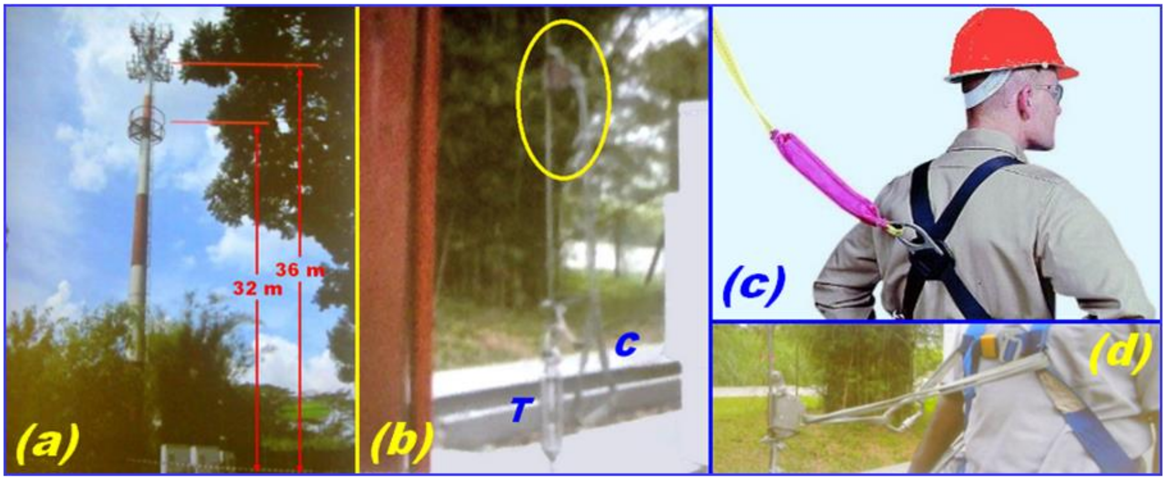

Fig. 18. Investigation of Fall from Height involving Risk Assessment

What follows is a review of the report by the enforcement and investigating authority. It was determined that the company had provided the requisite fall prevention device in the form of a 'rope-grab', a sliding handle which would allow the user to move along as long as the handle was kept pressed, but which would hold him up in case the user slips and loses his grip on the handle.

In Fig. 18-b, the rope-grab is shown enclosed in an oval, 'T' is the turnbuckle to maintain tension in the rope, and 'C' is the metal loop to which the worker must attach his safety harness.

The main reason the worker fell and died was that he had not attached his safety harness to the rope grab. This showed a lack of detail in the SWP and/or insufficient site supervision to ensure that the worker was using his PPE correctly and at all times.

Beyond this, the investigators discovered a violation which would have been adverse to the user even if he had been properly attached to the rope-grab. Normally the 'D' ring to which the harness lanyard should be attached for fall arrest is at the back, between the shoulder blades, as in Fig. 18-c.

However in the subject case, the user had attached the lanyard around the straps in front as in Fig. 18-d, which was a violation of the regulation, because if he had been attached to the rope-grab during the fall, he might have been strangled by the straps around his chest choking him at the neck.

1. Official findings by the authorities were reported as follows:
   - (1.1) Risk assessment was not adequate for the installation work; and
   - (1.2) Fall arrest system was not appropriate
2. Lessons learnt were reported as follows:
   - (2.1) Risk was foreseeable;
   - (2.2) Risk assessment was not conducted based on site conditions;
   - (2.3) Established risk controls were not relevant.

3. Summary of recommendations was as follows:
   - (3.1) Hazards are often obvious;
   - (3.2) Risk controls are usually common knowledge and practicable;
   - (3.3) Risk assessment must be conducted on the site to ensure risk controls are relevant and effective.

Here, risk assessment should have been used to identify potential and credible dangers in the job, and then appropriate risk controls should have been documented in the SWP. Otherwise, violations of these and collateral controls (such as direct continuous supervision) will become the arguments for the prosecuting attorney to prove culpability of the accused.

This kind of interaction between risk management and forensic engineering is becoming an essential factor in meeting the requirements of the law.

13. Conclusion

Whether a forensic engineer chooses to become an expert witness or not, he is better off knowing the details of legal requirements concerning the accident he is investigating, particularly in regard to workplace risk management.

Explanations and examples provided in this paper should have conclusively confirmed the close relationship between risk management and forensic engineering.

An organization or a country that does not emphasise risk management at the workplace will not be able to extract the maximum information from its accident investigations, and by extrapolation, will not be able to reduce its accidents.

While many lessons may be learned separately from the twin topics of risk management and forensic engineering, their combined potential for knowledge on accident prevention and mitigation is greater than the sum of the individual contributions.

Forensic engineering is absolutely essential for risk management. It is now being realized that good risk management can not only cut down accidents but also serve as a powerful tool in forensic engineering.

A recent article in the *Forensic Engineering Newsletter* [Ref. 19] states:

> *"Professional understanding among risk managers and forensic engineers has practical benefits. The two fields, ultimately, have similar professional focuses, function, purpose and work products. Recognizing this fact can only serve to help both professions."*

The author can add that in his own experience, he has found risk management an indispensible ingredient for forensic civil engineering, whether to analyse an accident or to prevent an accident, particularly where legal implications may govern the outcomes.

In another paper [Ref. 18] author has explained the various uses of the risk matrix for risk management, many of which also may apply to forensic engineering.

14. References

1. _____, *On-line Etymology Dictionary*. Retrieved on 21 Nov. 2015 from: http://www.etymonline.com/index.php?term=forensic

2. Specter, M.M., 1987, National Academy of Forensic Engineers, *Journal of Performance of Constructed Facilities*, ASCE, 1, No. 3.
3. Krishnamurthy, N., *Introduction to Risk Management,* (Self-Published), Singapore, May 2007, 88p, ISBN: 978-981-05-7924-1.
4. _____, *Workplace Safety and Health Act,* Govt. of Singapore. Retrieved on 21 Nov. 2015 from: http://statutes.agc.gov.sg/aol/search/display/view.w3p;query=DocId%3Aa7b4b808-d195-44ec-aa3d-dd5b1fa938f3%20Depth%3A0%20Status%3Ainforce;rec=0;whole=yes
5. _____, *Risk Management Regulations,* Govt. of Singapore. Retrieved on 21 Nov. 2015 from: http://statutes.agc.gov.sg/aol/search/display/view.w3p;orderBy=numUp;page=0;query=DocId%3Acd9437b7-419b-40de-99a3-09f2e7b8c90a%20Depth%3A0%20Status%3Ainforce;rec=0;whole=yes
6. _____, *Code of Practice for Risk Management*, Workplace Safety and Health Council and Ministry of Manpower, Singapore, 2011 (2nd Revision 2015). Retrieved on 21 Nov. 2015 from: https://wshc.sg/files/wshc/upload/cms/file/CodeOfPractice_RiskManagement_SecondRevision.pdf
7. _____, *Tacoma Narrows Bridge (1940).* Retrieved on 24 Nov. 2015 from: https://en.wikipedia.org/wiki/Tacoma_Narrows_Bridge_(1940)
8. _____, *Millennium Bridge – London.* Retrieved on 24 Nov. 2015 from: https://en.wikipedia.org/wiki/Millennium_Bridge,_London
9. _____, *Space Shuttle Challenger Disaster.* Retrieved on 24 Nov. 2015 from: https://en.wikipedia.org/wiki/Space_Shuttle_Challenger_disaster
10. _____, *Space Shuttle Columbia Disaster.* Retrieved on 24 Nov. 2015 from: https://en.wikipedia.org/wiki/Space_Shuttle_Columbia_disaster
11. Krishnamurthy, N., "Forensic Engineering and Professional Ethics", *Proceedings of the Second International Conf. and Exhibition on Forensic Civil Engineering*, Nagpur, India, 21-23 January 2016.
12. Krishnamurthy, N., "Investigative Methods in Forensic Civil Engineering", *Proceedings of the (First) International Conf. and Exhibition on Forensic Civil Engineering*, Bangalore, India, 23-24 August 2013.
13. _____, *Building Collapse Cases/Hartford Civic Center*, Wiki. Retrieved on 24 Nov. 2015 from: http://matdl.org/failurecases/Building_Collapse_Cases/Hartford_Civic_Center.html
14. _____, *Hyatt Regency Walkway Collapse*, Wikipedia. Retrieved on 24 Nov. 2015 from: https://en.wikipedia.org/wiki/Hyatt_Regency_walkway_collapse
15. _____, *Hurricane Katrina*, Wikipedia. Retrieved on 1 Dec. 2015 from: https://en.wikipedia.org/wiki/Hurricane_Katrina
16. Delatte Jr., N.J, (Ed.), "New Orleans Hurricane Katrina Levee Failures", *Beyond Failure – Forensic Case Studies for Civil Engineers*, ASCE Press, 2009, pp. 287-299.
17. Krishnamurthy, N., "Use of Computers in Forensic Engineering", *Proceedings of the (First) International Conf. and Exhibition on Forensic Civil Engineering*, Bangalore, India, 23-24 August 2013.
18. Krishnamurthy, N., "Construction productivity and risk management in Singapore", published in *'The Singapore Engineer' - The Magazine of the Institution of Engineers, Singapore*, Feb. 2015, p. 22-29.
19. _____, "Risk Management from the Forensic Engineering Perspective – Part 2 of 2", *Forensic Engineering Newsletter*, Vol.2, Issue III, June 2007, Plick and Associates, Forensic Engineers, USA.