INVESTIGATIVE METHODS IN FORENSIC CIVIL ENGINEERING

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1. INTRODUCTION

The word *forensic* comes from the Latin *forēnsis*, meaning 'of or before the forum.' In Roman times, a criminal charge meant both accuser ('plaintiff') and accused ('defendant') presenting the case before a group of public individuals in the forum. This is the source of the two modern usages of the word *forensic* – as a form of legal evidence, and as a category of public presentation. In modern use, 'forensic' is synonymous with 'legal' or 'court-related'.

Forensic engineering is the application of engineering principles to determine the causes of an accident, failure, or other performance problems. Generally, the purpose of a forensic engineering investigation is to locate causes of failure with a view to improve performance or life of a component, or to assist a court in determining the facts of an accident.

Civil Engineering may be considered to be the broadest of almost all engineering disciplines, covering the welfare and activities of huge masses of people all over the world. It is also the one industry which involves various disparate skills and trades, each having its own agenda and each vying for its rightful space and time. As a consequence, any mishap in civil engineering will generally affect a large number of people, and have far-reaching implications and long-lasting consequences.

Civil engineering often ends up with having the biggest failures in most countries, leading to huge loss of lives and injuries, and massive property damage. Forensic civil engineering is the logical investigation and legal presentation of various aspects of these accidents.

This paper will highlight the common techniques available for forensic engineering, with particular reference to civil engineering. Traditional techniques of failure investigation such as fault-tree and event-tree analyses will not be discussed.

2. QUALIFICATIONS FOR A FORENSIC CIVIL ENGINEER

2.1. Forensic engineer

Who can be a forensic engineer? Columbia University in New York puts it as follows, [1]:

"An engineer's success in the field of forensic engineering is the result of the combination of many components in his or her background:

- First, a good education in engineering and its related subjects;
- Then years of hands-on experience in analysis, design, construction, testing, inspection, condition assessment, and trouble-shooting;
- Understanding of the design-construction process;
- Comprehension of legal implications;
- Good communication skills;
- A knack for problem solving;
- A positive attitude to team work;
- A strong sense of ethics;
- Self-confidence without arrogance;
- Confident and credible disposition; and,
- A high level of intellectual sophistication."

Carper [2] lists some more factors not in the preceding list:

- Detective skills
- Other skills such as familiarity with psychology and sociology, photography etc.

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- Personality characteristics such as flexibility and objectivity, ability to face questioning under stress (as expert witness), and to work effectively with others.

To this I will add, a desire, almost a passion to share one's expertise to benefit a cause he believes in, be it to improve design, to affirm safety, to right a perceived wrong, and so on.

[NOTE: The male pronoun and references there from will include the female counterpart, except when context defines one or the other gender. – NK]

2.2. Forensic Civil Engineer

A career choice source [3] lists the following as job requirements to be a forensic civil engineer:

- ***Education*** – Bachelor's degree in civil engineering. A master's or a doctorate in some aspect of civil engineering – structural, geotechnical, or earthquake engineering – is often an advisable educational qualification in a competitive job marketplace. During these courses, he should become familiar with the way different types of materials behave under stress. The candidate should also have a strong mathematical ability, IT and communication skills. He will need to explain complicated technical matters to lawyers, legislators and the general public as part of his job.
- ***License*** – Candidate must obtain a Professional Engineer license in the state where he is employed. [Where such licensing does not exist, some extra qualification like Membership in national or international professional societies, publications in journals etc. may validate credibility, as happened in my case.]
- ***Site Experience*** – A forensic civil engineer's expertise is gained primarily from site inspection of structural damage, accidents, and disasters. He learns to recognize how and where materials and structures fail, where a building may have been incorrectly located, and the signs of possible criminal negligence or deliberate damage. This site experience provides him with the knowledge to analyze the causes of the damage. Human communication skills and an empathetic personality are also very important as he must interview witnesses on the site who may be very distressed.
- ***Fitness*** – Physical fitness is vital for the forensic civil engineer. He may have to climb on roofs, move or carry heavy loads up to about 50 pounds [18.7kg] at a damage site, and even crawl through confined, damaged spaces such as air conditioning vents. Site inspections have to be conducted in all weathers. Damage sites are dangerous, so he needs quick instincts to move very quickly to escape serious injury from any falling structures.

My journey to my current forensic involvement started in the 1960s in USA when I acted as consultant to accident investigators – not yet known as 'forensic engineers'. It was only by choice that I did not actually appear in court, reluctant to getting involved in legal tangles, especially as I had chosen not to become a citizen. But by proxy, I learnt many of the tricks and traps of the forensic engineering trade. So, when the opportunity arose for accident investigation in Singapore, one might say I was willing, ready, and able.

3. CAUSES AND INVESTIGATIVE METHODS

Accidents are called thus because they are unpredictable, and usually the result of some unexpected combination of unusual circumstances, with generally one or more humans involved in its causation and/or in suffering its consequences.

Accidents must be investigated because the victim (and/or his relatives and friends) and the society at large must know how the accident happened, to apportion responsibility, and to ensure that the triggers and circumstances of the accident be avoided or mitigated.

Most failures are quite straight forward, causing human, property, environment, or other harm or loss, and falling into one or more of a few categories of causes and requiring only a few well-known and simple investigative procedures, as in Table 1.

Table 1. Accident Causes and Investigative Methods

	Cause	***Investigation***
a.	General, for all causes	Review of all existing documents and actions Code conformity Conformity with good practice Accident re-creation, failure simulation Destructive/non-destructive tests Back analysis
b.	Wrong or under design	Design checks and back analysis
c.	Wrong erection or poor workmanship	Check procedures, supervision, etc. Check connections Check temporary supports
d.	Overloading	Recent and long-term history of use
e.	Wrong or bad materials	Material testing (Including physical and chemical properties; high-tech, e.g. gas chromatography, mass spectrography) Strength testing
f.	Vagaries of weather, natural disasters; Acts of God	Historical records versus design briefs and construction/fabrication records

4. DATA COLLECTION

Data is the backbone and lifeblood of any research or investigation. A case stands or falls, the guilty are punished and wrongs are righted, only with adequate quantities of right data. In accidents, data is the rare factor, because accidents happen without warning or control, and much data can get compromised or lost by essential accident response services and well-meaning and curiosity-seeking public – or by carelessness in the chain of custody.

4.1. In a Perfect World

You may be lucky. You may be in a country which has a full-time forensic team on standby to rush to an accident site right behind or along with the ambulance and the police when the first information reaches the authorities. And you are lucky enough to reach the site fast.

Then your job is easy. The paramedics have first shot at the site, trying to save dying victims and patch up the injured to transport them to ICUs and clinics. Police cordon off the area so nobody tramples on accidentally – or modifies intentionally – any of the evidence.

As part of the forensic team you have almost equal powers with the police to approve or deny others access to the site artefacts. Even the police are trained to respect your domain. They wear shoe covers and hand gloves and watch where they walk and what they touch. They sequester potential witnesses for your questioning as soon as they have elicited as much case evidence as they can from them.

You go in with your cameras and specimen kits, special lights and field test equipment, and record everything you are likely to need. Another member of your team handles the witnesses and debriefs them. Or vice versa.

Some specific individual or group is already in charge of the most important immediate tasks after an accident:

- Rescue operations;

- Medical treatment of the injured;
- Prevention of further injuries; and,
- Securing the site to protect the evidence from wilful or unwitting compromise.

You collect the following data, as appropriate:

- Status of the accident site:
  - Documentation of what, where, and how of people and things, by means of photography, videography, and audio recordings;
  - Collection and safeguarding of documents and trace evidence; and,
  - Material Safety Data Sheets (MSDS), equipment manuals, etc.
- Data on personnel present
- Immediate past history:
  - Collection and safeguarding of still and CCTV and other video camera tapes or electronic media;
  - Data on deceased and injured;
  - Temperature, sound, pressure and other records for as long before the event as are available;
  - Eye/ear witness's evidence in recorded interviews; and,
  - Details of personnel and organisations involved.
- Long-term history:
  - Original designs, subsequent modifications;
  - Construction records, safe work procedures (SWPs);
  - Material indents and deliveries, test records;
  - Use histories, and maintenance and repair records;
  - Risk assessment and management records; and,
  - Personnel and organisations in various stages of construction and use.

It may fall to your lot, as a civil engineer, to stabilise the site against repetition of the mishap or further progressive collapse. If you see a beam precariously sagging, you would have to try to prop it up from further sagging – trying to push it up to its original position may neither be possible nor wise, because it may produce further damage.

Advanced countries have strict standard procedures for securing the site for the forensic team. Until this team releases the site, nobody can enter it without specific approval, and even then, only with proper accessories to prevent site contamination, and under strict supervision.

Without such control, forensic engineering would be quite difficult and unreliable.

4. 2. Welcome to the Real World

More often than not, the accident is past history by the time you are in the loop.

Except in rare instances – admittedly increasing due to the ubiquitous CCTVs watching over almost every aspect of our lives – in most countries, the accident is long gone and the site cleaned up before any real investigation gets under way. This puts an extra burden on the forensic engineer, and he needs to have access to a variety of methods and techniques to seek out the truth from the available data after the event.

However, even though the clean-up is over by the time you are called in to investigate, generally it would be worth your while to visit the site to view the lay of the land, the ambient conditions, the scale of operations, etc. There could be exceptions.

In a case concerning a formwork collapse a few years ago, I was called in a few months after the accident, by which time the dead bodies had been removed and the blood had been hosed off, the collapsed formwork had been removed, replaced by a spanking clean and perfect replacement formwork, and the casting of the permanent structure already started.

While I was testifying as expert witness, the other side lawyer asked me if I had visited the accident site, I simply said *"No."*. When the lawyer wanted to make an issue of it, implying that I had failed in my duty as an investigator, I explained that a visit long after the clean-up would not have been fruitful, and that I had enough certified photographs, videos, and eye-witness accounts to extract all the information I wanted for my forensic analysis.

In most developing and under-developed countries when an accident happens, it is a free show for curiosity seekers (and let us admit it, even to most of us, intelligent, mature adults!) and chaos reigns immediately after the accident. It is a free-for-all, with anybody and everybody standing around busily watching the show, most chipping in with well-intentioned but unhelpful suggestions, and many actually entering the accident site and handling artefacts and people with avowed intention of saving persons in distress or articles liable to damage.

But unfortunately, they are also irrevocably destroying valuable evidence that would have helped find how the accident happened and possibly guide how to prevent future accidents.

Often, it is also the occasion for unscrupulous persons to steal things – even off of the dead and wounded – and for supervisors and managers to modify the scene to protect themselves from litigation. Even in the best of countries, watches, hand-phones and wallets vanish. It is not also unusual for an investigator to find that a safety harness has been placed next to or even <u>on</u> a dead fallen worker, or a brace in a scaffold which had not been in the photograph taken yesterday, to be suddenly in place today!

In such situations forensic engineering is an academic topic for journal publications and conference presentations, but not useful for a practical investigation of the accident.

Also, forensic investigators are not too popular because they probe into tragedies, scratching emotional wounds, and asking inconvenient and embarrassing questions. Not having the authority of the police or the power of medical personnel, forensic investigators are often the last, unwelcome guests in the chain of command.

Still, you do the best you can, and collect whatever data you can in the best way possible. Do keep records of how, when and where you got the data, so that you will not be held responsible for ineffective investigation later on. Once you collect any data, authenticate it, because your word without corroboration will not be worth much in court as evidence.

5. CODE AND GOOD-PRACTICE CHECKS

In any civil engineering investigation, checks on Code compliance or good practice would be the first line of action to take. Many failures happen because the designer or contractor has not strictly or correctly followed the applicable Codes, Standards or good practices, or the contractor has not followed the instructions of the designer.

Such violations are normally sufficient to indict the wrong-doer – although courts may want the plaintiff to prove negligence or intent.

In the infamous Kansas City Hyatt Regency walkway failure (which will be discussed later in another context), the originally designed walkways were barely capable of holding up the expected load, and would not have met the requirements of the Kansas City Building Code, [4]. Further improper modifications simply aggravated the situation into a disaster.

Conversely, findings for which wrong-doers turn out not be punishable under current Codes often trigger changes in Codes. For instance, as a result of the World Trade Center Investigation (2001), a total of 40 code changes consistent with recommendations were adopted in the 2009 and the 2012 editions of International Building and Fire Codes, [5].

There are a large number of cases where Code violation leading to failure has happened. Some of them will be briefly presented.

5.1. Rana Building Plaza, Bangladesh, 2013

On 24 April 2013, an eight-story commercial building, Rana Plaza, housing five garment factories collapsed in a suburb of Dhaka, capital of Bangladesh. More than 1100 workers died and about 2500 were injured, (6)(Figure 1.)

Fig. 1. Rana Plaza Building Collapse

The head of the Bangladesh Fire Service and Civil Defence said that the upper four floors had been built without a permit. Rana Plaza's architect said the building was planned for shops and offices – but not factories. Other architects stressed the risks involved in placing factories inside a building designed only for shops and offices, noting that the structure was potentially not strong enough to bear the weight and vibration of heavy machinery.

More significant than the violations was the discovery that there were not adequate codes and regulations for many of the good practice violations that were encountered. Hopefully, this disaster will pave the way for better standards and more stringent enforcement, not only in Bangladesh but in neighbouring countries where similar conditions of work may exist.

5.2. Fall of Worker from Mobile Tower

I had occasion to investigate the fall of a worker from a mobile scaffold which collapsed with him on top, allegedly while the tower was being moved by another worker, which was against local regulations. The worker received a head injury which necessitated the replacement of part of his scalp with a synthetic shield, depriving him of his livelihood.

The employer offered a token payment. While it would have had a good multiplicative effect due to the exchange rate between the local currency and the worker's home currency, it was very low by local standards, and the worker's lawyers sought my assistance.

What is relevant here were the claims by the employer that:

(a) The employee climbed the side of the scaffold to reach the platform,
(b) He stayed on the top while another worker moved it to a new location, and
(c) He leaned on the guard-rail during his work.

– All three were unsafe acts and the company said it was making the payment more as a donation than as compensation. (Figure 2.)

True, all three acts violated local Codes. If these charges had been proved, the worker would have had not only no compensation, but also to pay a fine and/or undergo a jail term.

After examining the photographs and witness testimonies, I accepted the case because I believed that it was not the worker but the employer who was at fault.

I had an easy time shooting the company arguments down because all three of the charges were traceable to the employer's violation of applicable codes:

(a) Worker climbed the scaffold only because the tower did not have the Code requirement of safe access by ladder or steps, as could be proven by photographs and testimony;

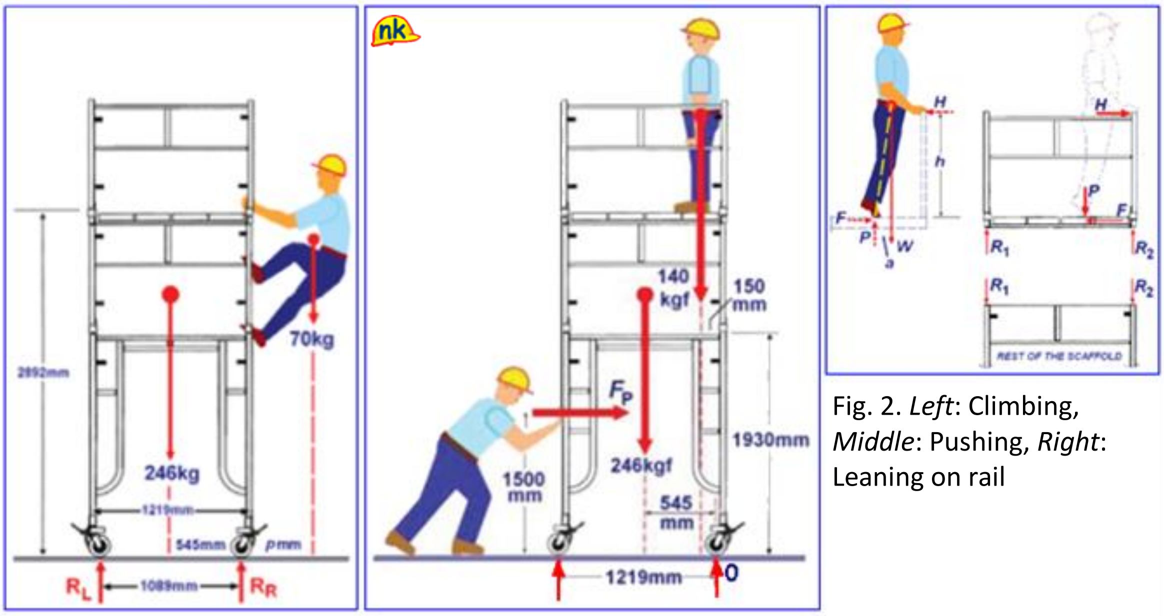

Fig. 2. *Left*: Climbing, *Middle*: Pushing, *Right*: Leaning on rail

(b) Worker stayed on top, only because he did not want to risk injury by climbing up and down the scaffold side (*vide* previous violation); and,

(c) Simply leaning on, or slightly over, the guard-rail in the normal approved course of work, namely painting the ceiling, would not have resulted in his toppling over if the guard-rail had been the Code requirement of 1m minimum height – it was only about 900mm.

To prove the above, my first year engineering Statics was enough – although I was surprised at a similar analysis by the company's expert who had managed to prove quite the opposite, by some convoluted arguments which could not be substantiated.

But the employer would not simply accept my word that if the guard-rail had been the required 1m tall, the worker would not have fallen by simply leaning on it and painting the ceiling. He demanded that I prove any guard-rail shorter than the specified height could result in the worker falling over the rail if he leaned over it in the course of his assigned task. To achieve this, I developed a two segment model of the human body as shown in Fig. 3, left.

After carrying out a large number of parametric studies on this model with various heights and girths of workers for different heights of guard-rail, using anthropometry (measurements of the human body) and biomechanics (static and dynamic behaviour of living systems), I was able to draw a number of general conclusions.

The charts in Fig. 3 clearly show that for a person with girth between about 150 and 200mm, only 1m tall guard-rail would be safe for any angle of leaning over. Specifically for our worker of medium girth (200mm), 950mm would be minimum. The 900mm guard-rail was just not tall enough for him.

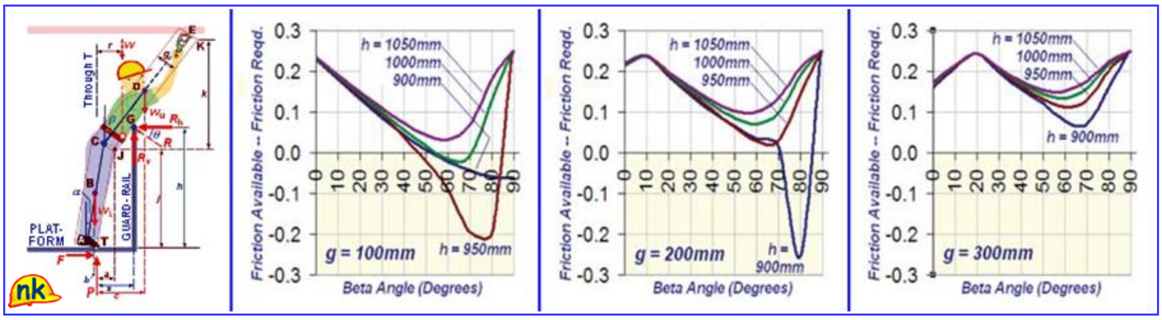

Fig. 3. Painter fall from scaffold – Angle, girth and guard-rail height effects

Faced with my report listing these (and a few other) Code violations and technical findings, the employer settled out of court for a much higher compensation, with which the worker was able to return home, assured of a reasonable livelihood for the rest of his life.

If the case had gone to court, for the unsafe conditions which violated the Code and resulted in the worker's fall, the employer would surely have been heavily penalised. At the same time, the worker would also have been punished for his unsafe acts, because in theory, a worker is not supposed to commit an unsafe act but refuse to carry out instructions under those conditions – courts may not accept excuses of nervousness and language problems of the worker in this regard which prevented him from refusing to work.

This research into falling behaviour was a bonus to me. The entire investigation including my research on the fall behaviour has been published in a journal, [7].

Similar case with a different outcome:

Forensic engineers must remember that each case is unique and must be analysed in the context of circumstances prevailing at the place and at the time the accident happened, and under the regulations governing the design, construction, and use in that situation.

For instance, in a situation by Zallen [8] very similar to the one I have described above, two workers were working on a mobile scaffold, and one of them was severely injured when the scaffold fell while he was exiting.

The two workers usually climbed up a step ladder to reach the scaffold, and normally exited the same way. However when one of them swung his body around a guard-rail post and exited under the end frame rail, the scaffold toppled.

The differences between our two cases were two-fold:

(1) Unlike in my case where the scaffold was of steel, this scaffold was of Aluminium, and hence much lighter than the worker's weight.

(2) In my case the law forbade climbing the side of a scaffold, but in USA there is often no law against such climbing.

Figure 4 shows two scenarios of the fall. The left figure shows the worker exiting from the front ('end') and swinging around the left post, thus imposing a horizontal dynamic force on it, which toppled the scaffold.

The right figure shows the case of his ducking under the side rail and simply climbing down; even this was unsafe because the overturning moment by the worker was more than the stabilising moment from the much lighter Aluminium frame.

Both these acts were shown to cause overturning moments in excess of the stabilising moments. As in the USA scaffolds are required to be designed for any and all such acts by workers, the employer was found culpable – he should have provided out-riggers extending the base to allow for the overturning moments.

6. WRONG DESIGN

One would think that in this day and age of advanced technology designers would not make a mistake in engineering basics. While most designs pass through more than one set of hands and eyes, occasionally, either the complexity of the problem throws an engineer or even a team off track, or at the other extreme the problem appears so simple that nobody pays much attention to the solution. A borderline situation is when something wrong has been working without problems for long, and you get so used to it, you do not see the mistake staring at you, until something bad happens and a fresh set of eyes catches the mistake instantly.

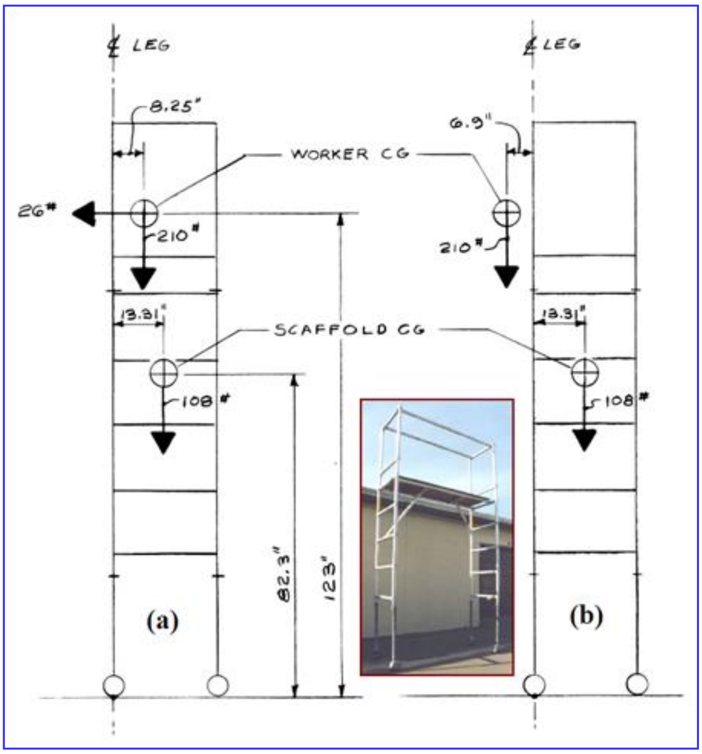

Fig. 4. Unsafe acts on mobile scaffold

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6.1. Hotel New World, Singapore, 1986

On March 15, 1986, the six-story Hotel New World in Little India, Singapore, collapsed due to a design error. [9] (Figure 5.)

Fig. 5. Hotel New World, before and after collapse

The structural engineer had forgotten to add the dead load of the reinforced concrete building to his calculations when determining how strong he needed to make the support pillars that held up the building during construction in 1971. On top of it, the owner added quite heavy water tanks and air-conditioning units on the roof, and a bank tenant added a heavy vault, both the actions done without checking or approval, [10].

Thirty-three people were killed and 17 others were injured.

In regard to the bank's liability, the Court of Appeals held that: *"[T]he collapse of Hotel New*

World in 1986 must be looked at with a 1986 pair of spectacles. Having found that until 1986 there was no instance of a collapse of a building such as the hotel which stood for more than 10 years, the bank could not be imputed with knowledge of the various unusual dangers that were raised in that case, such as tremors, vibrations and cracks in the building."

Following this disaster, many lessons were learnt. Buildings built in the 1970s were checked for structural faults, and some of them were declared structurally unsound and had to be evacuated. The government also introduced tighter regulations on building construction; since 1989, all structural designs are required to be counter-checked by Accredited Checkers.

6.2. Nicoll Highway Collapse, 2004

The 20 April 2004 Nicoll Highway collapse in the C824 project for the cut-and-cover underground MRT Circle Line in Singapore had two critical design errors according to the International Committee of Enquiry, [11] as follows, (Figure 6):

(a) Under-design of the diaphragm wall using an inappropriate method in the computer program; and,
(b) Under-design of strut-waler connection in the strutting system, (Arrows, Fig. 6.)

These design errors resulted in the failure of the 9th level strut-waler connections together with the inability of the overall temporary retaining wall system to resist the redistributed loads as the 9th level

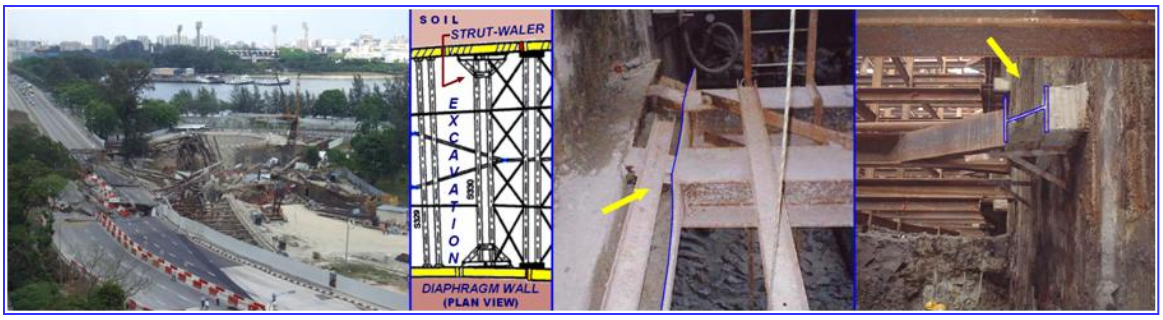

Fig. 6. Nicoll Highway Collapse, *Left* – General View, part plan, *Right* – Buckled walers

strutting failed. Catastrophic collapse then ensued. Three workers and one official died and three others were injured.

The sad fact was that the high deflections of the diaphragm walls had given ample warnings of impending disaster for weeks, which were ignored.

The Executive Summary of the report also charged the designers with *"Abuse of the back analyses in Type M3 where the collapse took place."* Back analysis is a reverse procedure, to solve external load or partial material parameters, based on known deformation and stresses at limited points and partially known material parameters. It is often used in geo-technical engineering. With sufficient redundant data it has also been also applied to structures.

The company was fined S$200,000, and three senior executives were fined S$120,000, S$160,000 and S$160,000. Government officials who were also found guilty of negligence in their duties were not fined, but were warned and/or counselled.

A legal criterion which could greatly impact criminal liability to such negligence has been articulated many times: We should judge the conduct of designers by the standards prevailing and accepted at the time when it was designed (in this case the Factories Act), and not by any later standards. So, perhaps the penalties were not as severe as they would be today.

But out of this disaster came the development and implementation of the Workplace Safety and Health Act of Singapore in 2006.

7. CONSTRUCTION AND ERECTION DEFICIENCIES

Often, the design is fine, but the contractor finds he cannot implement parts of it. Technically, the contractor should bounce the ball back to the designer explaining his difficulty so that the designer can either revise his design or advise a practical method of achieving his ends.

The tendency of contractors though is to substitute the impossible design with a feasible alternative, with or without a rigorous analysis by their own competent person, particularly on how the substitute design component fits into the overall design which the original designer had submitted. Many accidents are on record due to this non- or mis-communication between designer and contractor.

Things are changing. The high costs of accidents have forced formerly separate entities to share mutual concerns, before tragedy hits. Many standards have adopted the 'Design for Safety' and 'Life Cycle Design' approaches whereby the designer is expected at least to highlight hazards and difficulties in the implementation of the design details.

7.1. Skyline Plaza Apartments, USA, 1973

Around 2.30pm on March 2, 1973, the Skyline Plaza 26-story apartment building in Bailey's Crossroads, Virginia collapsed while under construction, at the rate of one floor per week, except that recently, the pace had been accelerated, so that when the concrete was being placed for the 24th floor, the 23rd floor slab was only four days old instead of seven days, [12]. This was against the local Code. (Figure 7.)

Fig. 7. Skyline Plaza

The collapse killed fourteen workers and injured 34. It was found that while full shoring remained on the 23rd and 24th stories, it had been removed from 22nd story in about three-fourths of the area. Thus relieved of its previous loads, slab deflection of the 22nd story would have decreased, causing its re-shores underneath on the 21st floor also to fall out.

Construction did not adhere to the engineer's stated requirements: *"Slab being poured to be shored for two floors and back-propped at center of span each way and at center of bay on next floor down,"* or the architect's specifications requiring *"in all cases, two floors shall be fully shored".*

Probable cause of the collapse was a punching shear failure of the 23rd floor, caused by the premature removal of forms supporting the 23rd story slab, resulting in the shear stresses exceeding the concrete capacity at the time of the incident. The accumulation and impact of falling debris from the collapsing 23rd and 24th floors overloaded the 22nd floor slab and induced the progressive collapse of successive floors down to the ground.

Average air temperature was 6-7°C, at which, concrete takes twice as long as in a laboratory to gain strength. Field-cured concrete cylinders should have been used rather than laboratory cured cylinders to ensure that the concrete had achieved sufficient strength before removing shores and forms.

The concrete subcontractor paid less than $20,000 in fines, despite the fact that the collapse had caused $8 to $10 million in damages, in addition to the deaths and injuries. The architect and engineer, sued by one injured worker, were held responsible for the collapse, even though their explicit specifications for required shoring were not implemented at the site, and they had to pay his claim of $250,000 – ironically, this last was because it violated the requirement at the time that the designers had a responsibility to inspect the work and warn those involved of any unsafe conditions.

7.2. The Chicago City Post Office

On November 3, 1993, a portion of Chicago's new main post office under erection, collapsed, killing two ironworkers and injuring five others. At the time, workers were laying beams in place before fastening them. One of the insecure beams caused the collapse by creating a chain reaction and pulling down 60 to 70 other already erected steel members. The beams that collapsed were 32 ft (9.75m) long and weighed four and a half tons (45kN), [13].

Root cause was traced to the changes made by the fabricator in the erection procedure, solely for ease of erection, resulting in the beams being placed 1/4 inch (6mm) farther away from columns than required. (Figure 8.)

This change made the use of the 1 inch diameter bolts impossible. Instead, workers had to use 3/4-inch bolts to secure the beams. This change in hardware led to a series of weak connections, some without nuts to secure bolts. Unsurprisingly, the location where collapse began was a connection where a nut was not used.

All this havoc for just a 1/4-inch shift of a temporary support, and a 1/4-inch thinner bolt!

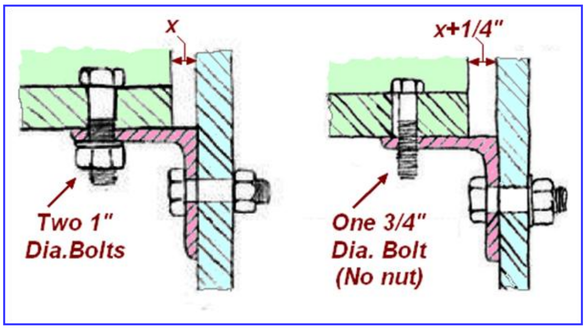

Fig. 8. *Left* – As designed, and *Right* –

7.3. Hartford Civic Centre Arena Roof Collapse

Another classical case where the erector modified the designer's connection and caused structural collapse was the Civic Center Arena in Hartford, Connecticut, USA, completed in January 1973,

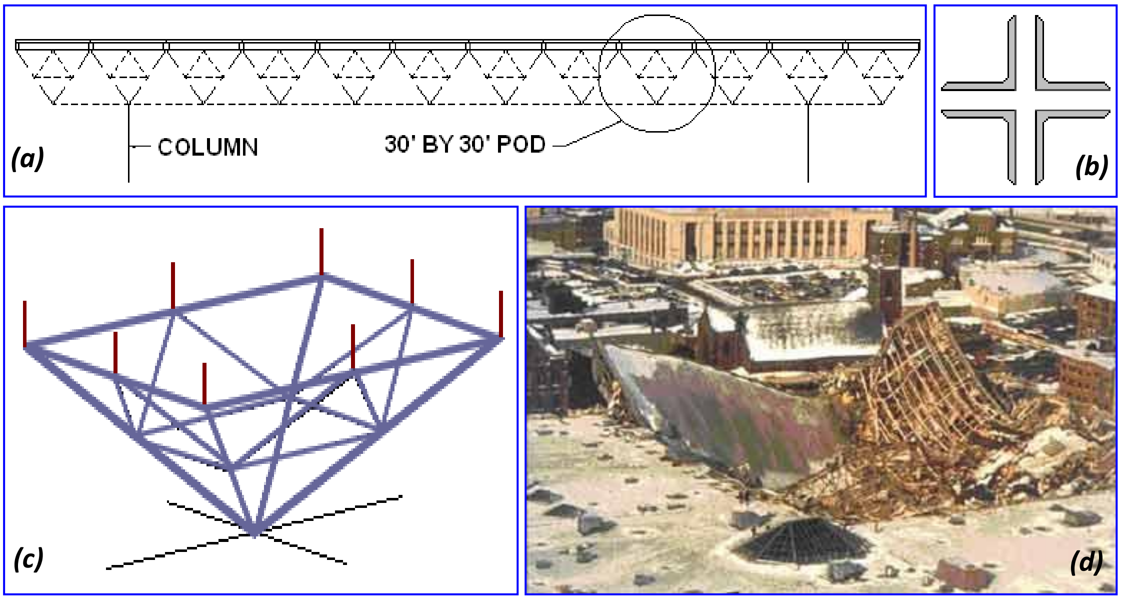

Fig. 9. Hartford Civic Center Arena, Sections and Collapse

designed for first time by a 3D truss analysis computer programme, [14].

As shown in Fig. 9, the 300 ft. by 360 ft. (91m by 110m) roof space frame consisted of pods in 30 ft. by 30 ft. (9.1m by 9.1m) grids, 21 ft. (6.4m) apart, made from members in the shape of a cross – which unfortunately is a most inefficient shape for bending and buckling.

On January 18, 1978, the largest snowstorm of its five-year life hit the arena. Early morning, the centre of the arena's roof crashed down 83 feet to the floor of the arena, throwing the corners up into the air. Luckily the arena was empty.

Table 2 Comparison of (a) As designed, and (b) As-built connections

	Connection A	Connection B	Connection C	Connection D
(a) Original	Allowable moment: 0 Allowable force: 160,000-lb	Allowable force: 185,000-lb	Allowable force: 625,000-lb	Allowable force: 565,000-lb
(b) As-built	Allowable moment: 9,490 lb-ft Allowable force: 15,440-lb	Allowable force: 59,000-lb	Allowable force: 363,000- lb	Allowable force: 565,000-lb

Cause of the collapse was traced to relatively minor changes in the connections between steel components, with the fabrication deviating from design. The most frightening result of the changes was in a particular connection in which a few centimetres shift of the fabricated connection cut down axial force capacity to less than a tenth of the design value. (Table 2.)

The designers should have checked whether their proposals could be translated into practice. Alternatively, the fabricator should have had the designers check and approve the changes he was proposing for practical reasons.

As in many other cases, the structure itself gave ample warnings of impending failure by excessive deflection, which were ignored.

The designers too were over-confident about the computer programme which at that time had not considered all buckling modes, and ignored the large deflections during erection.

The collapse triggered a complete nation-wide review of similar structures and of computer applications, and resulted in upgrading the safety aspects in design.

8. COMBINED DESIGN AND CONSTRUCTION DEFICIENCIES

Often in accidents it is found that design flaws and construction compromises combine to result in collapse although separately they might not have been that much of a problem.

8.1. Hyatt-Regency Walkway Collapse

A classical example of a combination of design and construction error is the Hyatt Regency Walkway failure at Kansas City, Missouri, USA, on 17 July 1981, [15].

On that fateful evening, during a 'tea dance', at 7.05 pm, the fourth floor walkway of the 4-storey high atrium in the 40-storey Hotel collapsed with excited foot-tapping couples, on to the second floor walkway, dragging it and its occupants to the bottom dance floors, leaving 114 dead and more than 200 injured. (Figure 10, left two parts.)

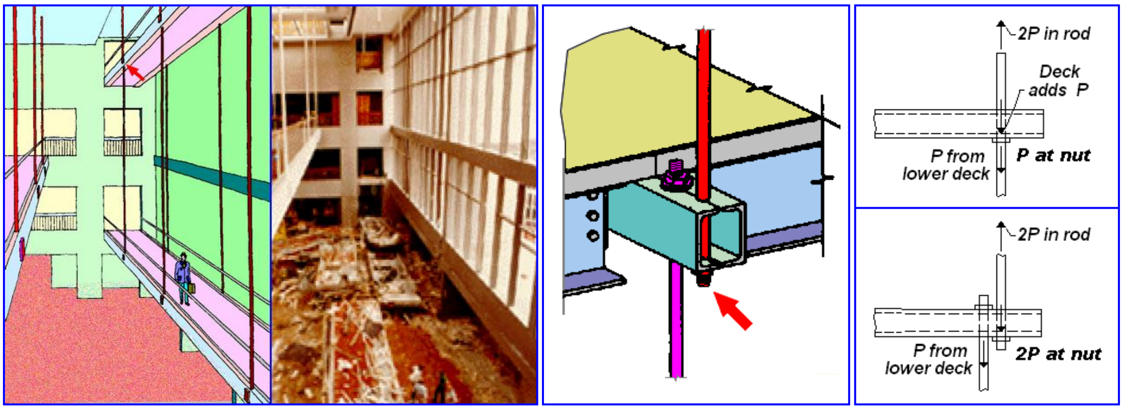

Fig. 10. *Left pair* – Hyatt Regency Walkway, before and after collapse; *Middle* – Nut at upper walkway; *Right* – Static analysis of single vs. double hanger rods

The hotel was opened in July 1980, with three walkways suspended from the ceiling by hanger rods, one set of rods on one side of the atrium for floors 2 and 4, and a second set on the other side for floor 3, as shown in Fig. 10 (Left). Both floors 2 and 4 were to hang from a single rod, with each floor load being supported by a washer and nut under the respective floor, as indicated by the arrows in the first and third parts of Fig. 10.

But the contractors felt that to place a nut in the middle of the single rod to support the fourth floor was too much trouble, and proposed two rods, one going from the ceiling to the fourth floor and the other going from the fourth to the second floor, as shown in the third part of the figure. Whether the contractors got approval for the change from the designers was not quite clear, but the contractors went ahead and implemented their change.

The problem was that while the single rod, inconvenient to erect though it was, would have been loaded with only a single floor load at each of the second and fourth levels, the two-rod solution, while simpler, transferred the second floor load also on to the same washer and nut holding up the fourth floor, thus in effect doubling the design load on it, which became the direct cause of the collapse during the dance.

Although this could be referred to as a design flaw in that nobody checked the design capacity of the revised design, it was triggered more by the contractors wanting (and rushing) to change the design without proper re-analysis.

The error that killed 114 people would not have occurred if the two-rod problem had been given to a first-year engineering statics student as a home assignment – so simple that veteran engineers did not think to check! Moral of the story: Nothing is too simple to avoid checking!

8.2. Rebar-cage Collapse

I was invited by the authorities to investigate for the prosecution, the collapse of a rebar-cage used for 3m and 5m R.C. base slabs, which killed two workers and injured 29 others. I investigated the accident and discovered a number of design and erection deficiencies, [16].

Bar-Chairs:
The main bone of contention were the supports for the upper layer of slab reinforcement by means of 'bar-chairs' made from 32mm steel rebar bent into a hat shape. (Figure 11, left.)

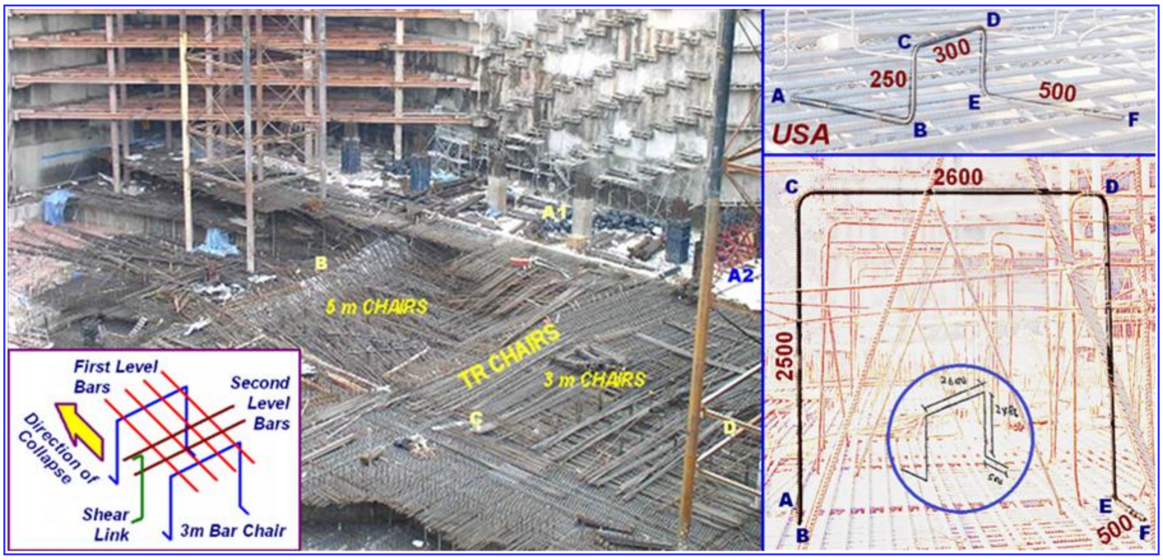

Fig. 11. Left – Rebar cage collapse (Inset: Bar-chair and rebars); Right – Bar-chairs

Bar-chairs are in common use in many parts of the world, but they are generally less than half a metre tall, with legs that are longer than the height (Fig. 11, right, top), so that there is no problem with stability.

However, the bar-chair system that collapsed was for 3m and 5m thick slabs with 2.49m and 4.35m chair heights, and their foot projections were only 500mm, much smaller than the heights, as shown in Fig. 11, right bottom. The stand-alone stability of both chairs was greatly in question.

Erection drawing consisted of free-hand sketches as in right bottom inset of the figure. Another design consultant had suggested bracings to ensure stability, but these suggestions were not carried through as complete designs, did not have Safe Work Procedures, and were not implemented consistently throughout the system.

I analysed the chairs from fundamental structural analyses principles. As there were only six joints and five members, simple moment distribution would have given the answers. Computer analysis with the stiffness method was used only for speed and convenience.

Asymmetry Problems:

The asymmetry in the bar feet led to asymmetrical stress and deformation behaviour.

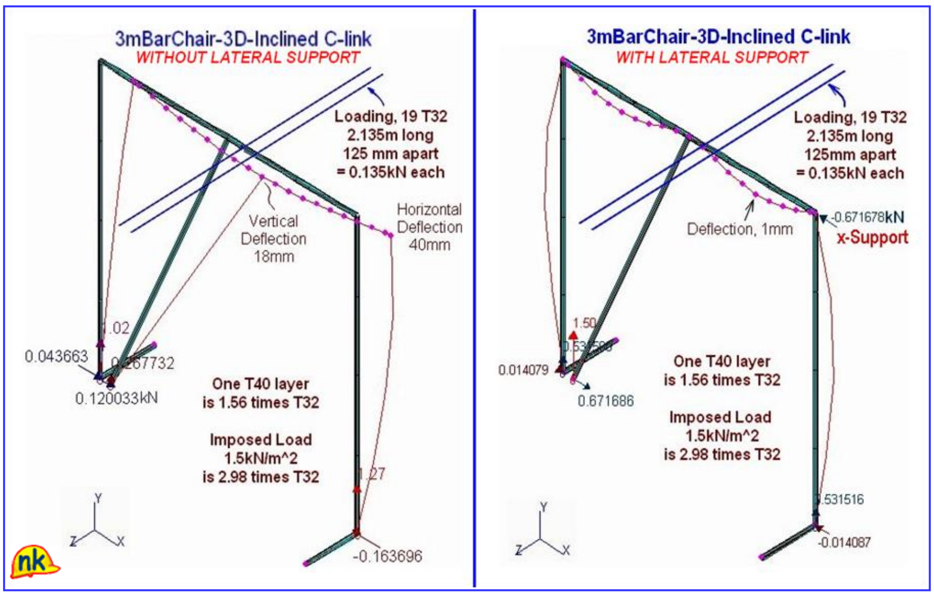

Fig. 12. Effect of the inclined leg of the bar-chair

Moreover, the 3m bar chair had a mid-span support which was not vertical but inclined because the contractor used longer props he already had but did not want to cut up. This led to further asymmetry, and tendency to move in the direction of the slope, or alternatively, if such longitudinal displacement was restrained, a reaction force at the restraint. (Figure 12.)

Design Error:

Another of my main concerns was the buckling capacity of the bar-chair legs used to support the upper rebar layer in the cage.

The following formula was found used in the original design for the critical column load:

$$P_{cr} = 2\pi^2 EI/L^2$$

which is the well-known Euler Formula, with an extra '2' attached, doubling the result. (*E* is Young's modulus, *I* and *L* are the moment of inertia of the bar and its unbraced length.)

For '2' to reflect increased capacity, it would imply end-restraint factor *k* of √(1/2), i.e. 0.707, which would correspond to Code case of both ends 'fixed', and theoretical case of one end pinned and other fixed in position and direction, as marked by asterisk in Fig. 13.

If it was indeed the designer's intent to provide supports at the two ends which would enable this doubling of capacity, it was not mentioned in the design, and there was no method statement (SWP) or recommendation of any special device for this purpose.

Then, pinned ends being the most basic and most realistic assumption for temporary structures at site, the '2' was in error, which over-estimated column capacity by 100%.

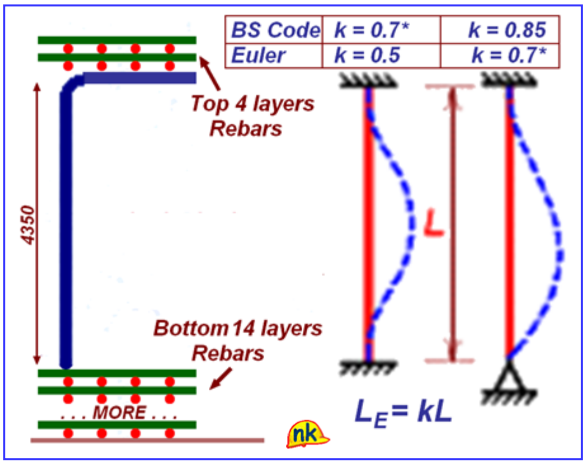

Fig. 13. Buckling of bar-chair

As the design load factor was 1.5 (at that time, since then revised to 2.0) obviously, the column was under-designed by 25%.

When the testifying designer was pressed to explain what the significance of the '2' was, he admitted it was an "oversight". It was thus a design error, and by itself, might also have contributed to the collapse.

Apart from all these, as part of my forensic investigation, I had conducted numerous finite element analyses of the entire grillage and come up with a lot of interesting leads pointing to other design flaws, with many factors of safety in the design working out to less than 1.5.

Additional Analyses requested by the judge:

After my first day's expert witness testimony in this case, the judge wanted me to come up with information on the effects of the loss of one or more such support struts, particularly whether and how such losses would result in complete collapse.

Needless to say, I worked most of the night with the computer, and came up with sufficient results to demonstrate that loss of one or a few of the supports would not have resulted in collapse – provided the system was suitably anchored in the lateral direction.

My presentation in court next day included (of course in colour PowerPoint) of a fairly exhaustive

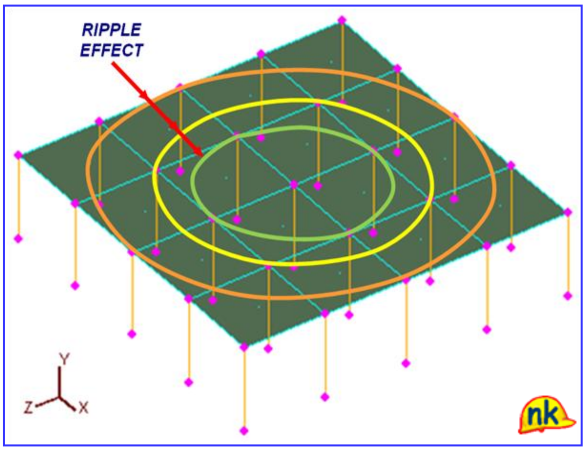

Fig. 14. Local failure and ripple effect

analysis of loss of the central 1, 5 and 9 legs (Fig. 14), and (alternatively) the corner 1, 3, and 6 legs. The reactions simply re-distributed themselves at the still active legs – in what I called the 'ripple effect', surviving at least for the first two rounds of losses.

The spans for horizontal rebars would have increased corresponding to the support losses, but the rebars simply sagged more without failing, although any other spanning material might have failed under the increased span.

Again the following day, after this presentation and some further testimony, the judge asked me to explain (next morning) the effects of in-line supports versus staggered supports.

Staggered versus in-line bar-chairs

12mm plate

	In-Line	*Staggered*	*InL/Stag*
			Stag. Better
Other Str.	23.1	8.6	2.69
Rot.x	2.6	1.7	1.53
Myy	1.9	1.4	1.36
Syy	77.8	58.5	1.33
Max. Str.	72.2	56.1	1.29
Vyy	1.0	0.8	1.25
Vxx	2.0	1.7	1.18
			InLineBetter
Ver. Defl.	0.25	0.26	0.96
Mxx	0.43	0.6	0.72
Sxx	18.0	26.7	0.67
Rot.z	0.14	0.3	0.47

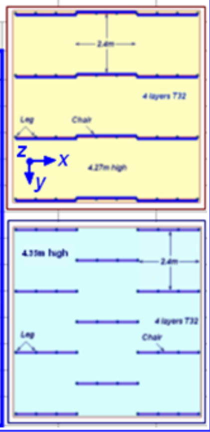

Fig. 15. Collinear vs. staggered supports

Again, I went to work with my computer software, to get usable results, as in Fig. 15. The judge recorded appreciation of my contributions both times.

But it would be wrong (and unwise) to think that such extra requests (more like commands when coming from a judge) are an indication of your high professional stature or that you are doing a favour to the court. Far from it. It may simply mean that while examining an expert the Court is claiming its right for more information – or even that you were not clear enough or complete enough in the first place.

In fact, the more you say, the deeper you may be getting into trouble! So, it was no feather in my cap that I was able to come up with useful results at short order. It would have been egg on my face and a real tragedy if I had <u>not</u> come up with the answers.

Disposition of Case:

As expert witness, I testified to all the above and other deficiencies in design and construction. However, there were other erection considerations such as placement of heavy loads on the cage, on which there was no definitive information, but which also might have led to the collapse. In the first portion of the case, the main contractor pleaded guilty to *"failing to ensure that the worksite was properly built and safely maintained"*, and was fined S$160,000.

None of my preceding technical testimony was contradicted. However, some of my recommendations were for future improvement, and violation of those norms could not be held against the management personnel on the convention that a case must be judged according to the laws and practice prevailing at the time and place the accident happened. The rest of the charges were dismissed on certain legal inconsistencies, and hence the details of design and construction deficiencies never became a cause for individual penalties.

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9. ACCIDENT RE-CREATION

It would be wonderful if we can simply rewind life's tape a few minutes and review how exactly an accident happened. Actually, the chances of having a record of accidents are increasing because more and more CCTV cameras are being deployed. Also, with the ever-increasing versatility and power of hand-phones, some might record the accident 'accidentally' while they were shooting something else, or purposely because they just happened to be there with a camera on stand-by mode.

In the West, there is money to be made from such records, by selling them to the media, or to one side or the other (or both!), in the subsequent investigation – East may not be slow to catch up!

Barring such direct records, the next best thing is a re-creation (surely not 'recreation'!) of the accident – also called ‘re-enactment’ or ‘reconstruction’. This can get pretty complicated.

For one thing, things are never the same at a microscopic or instantaneous level. Most materials may be reproducible, but the exact sequence and intensity of actions may not be. For another, some acts are not feasible to reproduce, such as a live person falling off from height. A cardinal rule in re-creation is that no human, and nowadays, no animals either, may be harmed, and no irreplaceable or expensive damage occur in the process of re-creation.

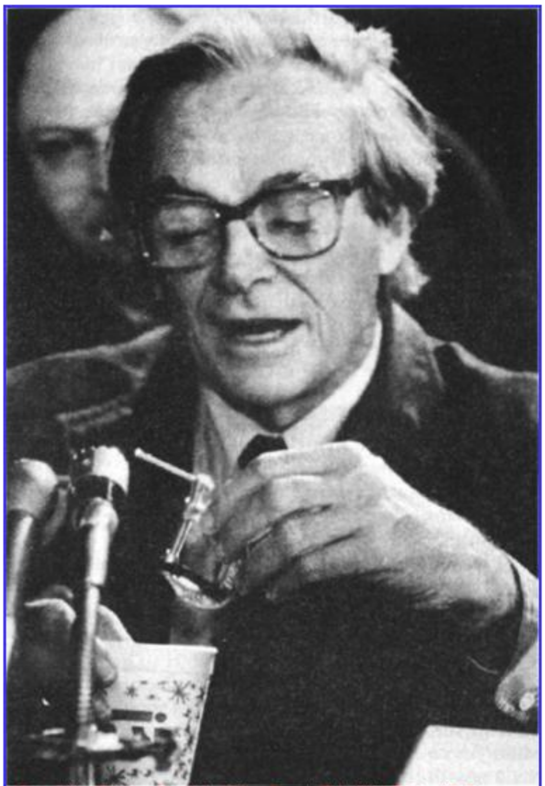
Still, a lot of information can be gleaned from an intelligent re-enactment of the accident.

Here, scale becomes a problem. For instance, cell-phone and auto makers, even aircraft manufacturers, will be happy to sacrifice one or more of their products to undergo various destructive tests. But a civil engineer, involved with huge projects, generally does not have the luxury. He can only put a small segment of the structure through the accident scenario.

In citing examples of this, I would like to start with a non-civil engineering example of how sometimes the simplest and the cheapest of tests can prove a major truth.

9.1. NASA Challenger Disaster

During the heyday of American space supremacy, sending crews into space orbit for various lengths of time to carry out experiments and bringing them back to earth became a routine chore like sending kids to school and receiving them back in the evening. The Space Shuttle program became a bus ride.



From "What Do You Care What Other People Think?" by Richard P. Feynman
FIGURE 15A. The O-ring ice-water demonstration. (© MARILYNN K. YEE, NYT PICTURES.)

Fig. 16. The Challenger Disaster. *Left* – Launch, crew of 7, and blow-up. *Top* – Richard Feynman shows cold effect on gasket

It was during the tenth mission on 28 January 1986, launched in very cold weather against the warnings of some of the engineers involved, at about 73 seconds after launch, the shuttle blew up, and the pieces fell into the ocean, killing all the seven crew members, (Figure 16.)

The culprit was a gasket called the ‘O-ring’, which lost its elasticity in the extreme cold and failed to seal the hot combustion gases from cabin crew and instrumentation. The web is replete with details of the disaster, starting with a brief account from Wikipedia, [17].

The anecdote I wish to relate here is the way the gasket’s dangerous behaviour in cold temperature was demonstrated by Nobel Prize winner Richard Feynman, while giving expert evidence on NASA's Challenger failure, [18] (Fig. 16, Right.).

To prove how easy it was to understand this, Feynman asked for a glass of ice-water while waiting for his testimony for the Presidential Commission, and soaked a sample of the material of the 'O-ring' compressed in a ‘C-clamp’ which he had picked up on the way from a hardware store. When his turn came to speak, he simply pulled the sample out of the water, and showed that when he removed the clamp, the specimen did not spring back to its original shape, having lost its elasticity temporarily, destroying the integrity of the ‘O-ring’ seal, [19]!

If this sounds like something out of the American show CSI or Perry Mason stories by Erle Stanley Gardner, I can confirm that such is possible in the USA. Even in other countries, as long as you understand and abide by the local culture, you can present your re-enactment results with telling effect.

9.2. Field Test for Support Rotational Capacity

It may be sacrilege to speak about my Mickey Mouse experiment in the same breath as Feynman’s demo above, but it will illustrate the point that sometimes a simple field test may prove an important valid point.

In the bar-chair system collapse case described earlier, one of my contentions to explain the collapse was that the vertical supports had very little lateral resistance. The defence had conducted lab tests to document its tension, compression, and shear tests, but had overlooked the rotational capacity. I did not have the time (or the means!) to conduct a similar lab test for rotation, so I chose to set up my own ‘quick-and-dirty’ field test.

I had my lawyers arrange with a local contractor to set up a single bar of the same size as the leg

Fig. 17. Author’s field test for rotational capacity

of the collapsed bar-chair with same end conditions. I got a worker pull gradually at top with a rope, with the pull force being measured by a simple spring balance, (Figure 17.)

When I presented this in court, the defence lawyers argued at my conducting such an unprofessional test which would prove nothing of value in the case. Briefed by their expert, they asked if I had calibrated the spring balance, which was a common 25kg capacity household item bought from a local store. I explained that I had not wanted to conduct a high-tech lab test to fractions of a kg force, and was willing to accept the usual precision of say plus or minus 1kg for the household spring, which would be sufficient for my purpose.

After all, the bar fell at about 15kg pull, which was a small fraction of what would have been necessary to prevent collapse of rebar cage under lateral force. What difference would it have made if it had been 16kg, or even 18kg? It confirmed my argument that rotational mode of failure was much easier than any other mode, and that was the way the cage had failed.

The defence had also conducted a re-creation of the accident in a university lab taking a sizable segment of the bar-chair and top rebar system, at considerably greater time and expense. On that, I presented my own arguments as to how a too-well organised and planned lab test might not explain the collapse due to site deficiencies – but that is another story.

None of the arguments from both sides was really conclusive, because there were various other factors at work contributing to the accident.

But I had my two-cents' worth at much less expense than the other side!

9.3. Re-creation of Ladder Accident

When someone gets hurt while using a commercial product, quite often (particularly in the West), product liability claims can run into the millions, and then, experts would have an awesome job to prove 'beyond reasonable doubt', the culpability of the manufacturer or facilitator of the product.

A case which illustrates such a re-creation is the forensic analysis of a fall from a ladder in UK in the 1990s. The 73kg owner of a house cleaning the second floor window from his recently bought extensible ladder fell while climbing. He approached the Legal Aid Board for an opinion on whether

Fig. 18. Re-creation of ladder fall (Far ladder is for control.)

he can sue the ladder company for a faulty product.

One of the methods the Board's expert used was to re-create the fall using a weight suspended from different rungs of the ladder corresponding to different positions of the user, and also for different angles of the ladder with the horizontal, (Figure 18.)

It was established from the owner's description of how he had set up the ladder that the owner had started with an angle of ladder about 56° with the horizontal as against the approximately 75° (corresponding to 1 horizontal to 4 vertical slope) recommended for safe use by the manufacturer – and by most others the world over.

Tests with the dummy weight demonstrated that when the weight was hung near the top, as the owner was positioned when he fell, at the 56° angle of the ladder, it became unstable and the foot slipped away from the wall, the top sliding down the wall. In the right portion of Fig. 18, the ladder is static only because the top has been stopped by a ledge on the wall.

As the owner had not followed the manufacturer's instructions for slope, he would not be able to sue them, according to the Legal Aid Board. Had it been otherwise, in such product liability cases, the payout tends to be huge (often in the millions!) in Western countries.

Rest of the Forensic Analysis:

A side-note to this example is worth adding. The Board investigation conducted so many other analyses and tests as follows, with reference to Fig. 19:

1. Ladder draw-down marks on the wall;
2. Impact damage to the sill above patio door;
3. (a),(b) – Ladder tip fracture surfaces, (c) – Failed ladder tip, abrasion from brick;
4. Infrared spectrum of ladder tip material;
5. Uncontrolled side slip marks on wall (on white board tacked for that purpose);
6. Melting curve of Differential Scanning Calorimetry (DSC) for tip material;
7. Coefficient of Friction vs. Load, for ladder tip material;
8. Foot-prints of ladder feet at 75° and 60°; and,
9. (a), (b) – Various statics analyses of ladder friction on surfaces of different slopes.

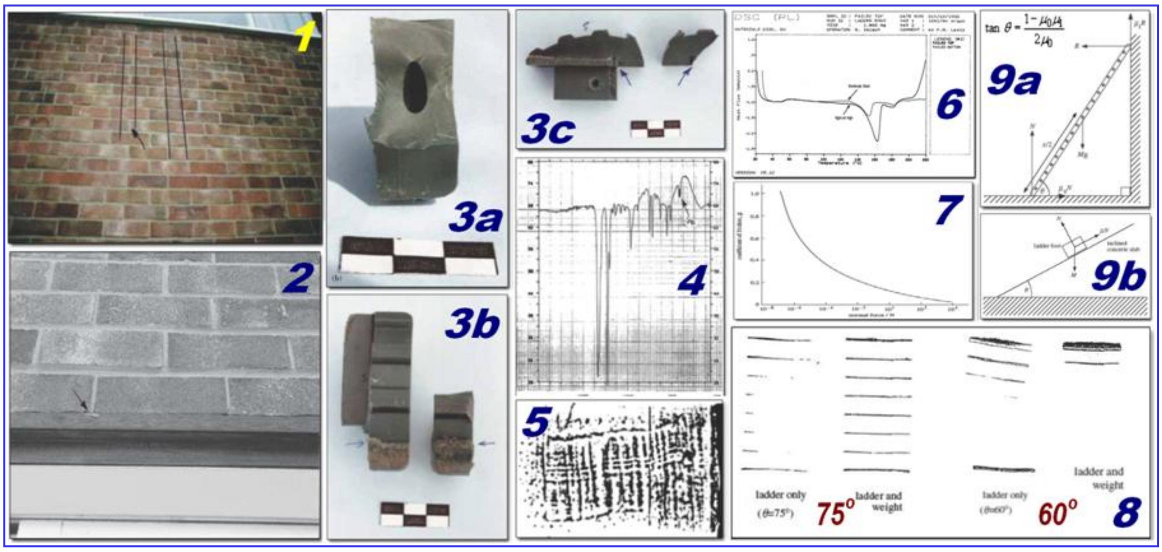


Fig. 19. Various tests and analyses run in ladder investigation

This is an unusually comprehensive list of forensic investigations for a ladder accident – but it shows how much a serious investigation would involve!

10. ACCIDENT SIMULATION

While accident re-creation is on a physical prototype of model of the accident artefacts and events, accident simulation is a virtual reconstruction of the accident with a computer model or a physical small-scale model (or occasionally a large-scale version when the object itself is very small and you cannot see much in an actual scale re-creation).

This is also a godsend where physical re-creation would be too large, too expensive, too time-consuming, and/or too dangerous to people or property or environment.

10.1. Computer simulation of accidents

Today, most major accidents are simulated with computer models. The computer is used not only for very highly complicated mathematical analysis of accident parameters, but through computer graphics and animation, also for quite realistic visuals in still and video format.

Apart from impressing all viewers, the computer formulation also allows the analyst to 'play around' with the objects and their movements with very little effort beyond the first modelling, so that by repeated trials, one or a few scenarios which would have led to the accident can be quite reliably determined.

The computer applications will be discussed in detail in another paper, [20].

10.2. Model Analysis of Complex Structures

Another alternative is some kind of model analysis in which a scaled version of the situation is subjected to the same event as in the accident.

Before computers became so common, so powerful and yet so inexpensive, model analysis flourished both as a science and as a practical procedure to solve complex engineering problems. Even now, except that people would not know or care for the power of model analysis, it can serve as an effective alternative to complex computer analysis, which even today depends much on the proper use of good software.

While doing my PhD in the USA, a Professor took our class to visit the well-known structural designer Ken R. White's office in Denver. Mr. White showed us some small-scale models of innovative structures he had built out of tooth-picks and drinking straws, and then loaded them and pushed them around until they failed, to get an idea of their failure modes and loadings.

This was before the days of finite elements and 3D computer graphics, but the idea was the same: You have no record of the accident itself. You develop a model, and experiment with various scenarios, until the outcome is closely similar to the actual accident. Even today this is the most common procedure. In many cases however, the creation and testing of the model, physical or digital, can get quite expensive.

For physical models in pre-computer days, scaling effects and material properties were handled by a science now relatively uncommon called 'Similitude'. I developed a lab-oriented course on 'Similitude in Engineering' during my tenure at Auburn University in Alabama, USA (1967-1975), and employed the method to good effect in my research and to guide student theses.

After the advent of computers, by the 1980s, we got the power to model huge structures in great detail and analyse them by computers, and then model analysis became less popular.

11. SUMMARY OF AN ACCIDENT INVESTIGATION AND REPORT

One of the first accident investigations I took up was that of a construction worker who fell seven storeys while working at a demolition of a multi-storey building. The worker was paralysed, and the company was directed to get their safety management system checked.

Many causes for accidents may be classified as unsafe conditions by the management and unsafe acts by the workers. The managements of the scaffolding and demolition contractor involved were very experienced, so experienced in fact that they began taking certain short cuts and worker behaviour for granted, leading to both unsafe conditions and unsafe acts.

The injured worker had been with them for many years, and he had chosen to ignore rules, and his supervisor had relaxed site discipline*"because he was such a good worker"*.

He had been given a double lanyard (Fig. 20) which consisted of two short leashes from his waist-belt to clamps at least one of which had to be attached to a dependable anchor while he was working. This was considered “100% tie-off”, a requirement for good fall prevention.

On that fateful day, allegedly he had used only one of the lanyards, and while changing location from one work platform to another, he had missed his step and fallen.

The company approached me five days after the accident to produce a report of their Safety Management System as required by the Government.

Fig.20. Double lanyard

I visited the site three times, reviewed their scaffold design, erection and safety procedures, interviewed their supervisors and workers, and exhaustively analysed their plans and actions. I submitted a report with my findings and recommendations, which they had to implement before their stop-work order could be lifted.

My report was 23 pages long, with the following contents and page numbers:

1. Introduction 3
2. Risk Assessment Techniques Adopted 4
3. Risk Assessment of Violations Noticed 5
4. Scaffold Frame Design 12
5. Accident Scenario 13
6. Safety Management System 13
7. Recommendations 14
8. Photographs 15

A typical page of risk assessment violations noticed is presented as Fig. 21 as a sample.

3.1. Violations of Factories Act (Chapter 104)

FACTORIES (BUILDING OPERATIONS AND WORKS OF ENGINEERING CONSTRUCTION) REGULATIONS

PART II : GENERAL PROVISIONS

Vio. No.	Cl. No.	Particulars of violation	Lkl.	Sev.	Risk	Control	Remarks
1	9.	*Tripping and cutting hazards:* (1) and (2) both violated in stairways and corridors. (Debris removal may not be contractual obligation of sub-contractor.) Sub-contractor's workers and supervisors habitually use the debris-choked stairways and corridors of the demolished building to reach the scaffold platforms and frames to carry out scaffold erection and dismantling, or inspection duties. This practice is extremely hazardous, especially where the stair handrails are missing or buried under debris.	3	2	6	Workers not to use debris-cluttered stairs or corridors, unless special lifelines are previously provided along the staircase walls at every floor, before demolition work commences.	Photos 1 to 5
2	10.	*Access to workplace:* Ladders or other means of access to scaffolding not provided. Workers now climb on to the platform from the ends or outside frames. They also use the stairs, in spite of the demolition debris, as explained for Violation No. 1.	2	3	6	Provide proper access: Ladders attached to scaffold frames, movable as necessary from level to level.	Photos 6 and 7

Fig. 21. Sample extract from Table of Violations

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Also is shown the 3 by 3 risk matrix, (Fig. 22) used to evaluate the risk for various activities from their likelihood and severity levels in the Table of Fig. 21.

Likelihood ↓	*Severity*		
	Minor (=1)	*Moderate (=2)*	*Major (=3)*
Frequent (=3)	3 (= Medium Risk)	6 (= High Risk)	9 (= High Risk)
Occasional (=2)	2 (= Low Risk)	4 (= Medium Risk)	6 (= High Risk)
Remote (=1)	1 (= Low Risk)	2 (= Low Risk)	3 (= Medium Risk)
Risk Index = Likelihood Score × Severity Score			
1-2 = Low Risk, 3-4 = Medium Risk, 6-9 = High Risk			

Fig. 22. 3 by 3 risk matrix used to assess risk

I also attached 17 pictures such as the two in Fig. 23, on each of which I pointed out various deficiencies.

Fig.23. Specimen photos from author's investigation or worker fall

This is one situation where you are paid to find fault! In fact, there is a strong third-party audit practice in Singapore, by which companies can find out their deficiencies and correct them before Government inspectors visit them and find them with much worse consequences.

My task ended with submitting the report with my findings and recommendations, because the case had already been heard, and penalties meted out.

It must be mentioned that this accident occurred before the Workplace Safety and Health Act was introduced in 2006, and many workplace practices were tightened up for greater safety, gradually replacing the Factories Act.

12. FORENSICS IN VARIOUS ENGINEERING DISCIPLINES

12.1. Forensics in Structural Engineering

Columbia University describes structural forensic engineering in the following terms, [21]: *"Engineering investigation and determination of the causes of structural failures of buildings, bridges and other constructed facilities, as well as rendering opinions and giving testimony in judicial proceedings, often referred to as Forensic Structural Engineering, has become a field of professional practice of its own in the US.*

"With rapid economic development, increased design sophistication, more-and-more daring construction technology and accelerated project delivery came the proliferation of structural failures throughout the world. Several countries are reviewing and/or streamlining technical, business, and legal procedures modeled on US practices – with both their advantages and faults – which require expert consultants/witnesses in both the forensic investigation and in the ensuing dispute resolution."

Structures are the most common civil engineering products which fail in accidents.

Mechanics and structural engineering, and more recently biomechanics, are my forte, and I try to accept assignments primarily in that area, computer graphics running a close second. I have found that tools of the trade here should include:

- Strength and properties of materials, and structural testing;
- Mechanics and structures analysis tools, both classical and digital;
- Fair degree of familiarity with biomechanics analysis;
- Strong fundamentals of various factors that make structures and components stand up or fall down – not ignoring very basic statics and dynamics; and,
- Associated skills like computer spreadsheets and graphics.

Carper [22] lists the common causes of structural failures, as follows:

- Site selection and site development errors;
- Planning deficiencies – high client expectations;

- Design and/or construction errors;
- Material deficiencies; and,
- Operational errors, such as alterations, use change, inadequate maintenance, etc.

Non-destructive testing (NDT) at the site and destructive testing in the lab are the common investigative test methods in structures.

In particular, concrete is quite amenable to NDT [23], as shown in Table 3.

Table 3. Non-destructive testing methods

SR NO.	Information required (to determine)	Method / instrument available
01	Strength	A) Rebound hammer. B) Ultrasonic pulse velocity meter. C) Penetration probe. D) Pull-out method.
02	Concrete quality	A) Ultrasonic pulse velocity meter B) Penetration probe C) Gamma radiography
03	Concrete density	A) Ultrasonic pulse velocity meter B) Gamma radiography
04	Bar size and location	A) Cover meter B) Gamma radiography
05	Cover to reinforcement	A) Cover meter
06	Bar corrosion	A) Electro potential meter. B) Concrete resistivity

12.2. Forensics in Transportation Engineering

On this, Hochstein [24] states, *"Forensic engineering in transportation matters requires the application of basic Traffic and Transportation Engineering principles in investigating, analyzing, reporting and testifying with regard to an incident on, or the design, operation, and maintenance of, a transportation facility, a building, commercial, residential and other public sites, pedestrian areas, etc. It may require services such as accident reconstruction, right-of-way appropriation, pedestrian fall down, driver behaviour, design defects, signing, seat belts, code reinforcement, vehicle mechanics, maintenance practices, etc."*

As traffic injuries and fatalities are the most common around the world, forensic analysis of traffic accidents is a very essential professional service, and many companies and experts thrive from it. Re-creation and simulation constitute a very large part of the investigation.

12.3. Forensics in Geotechnical Engineering

Saxena [25] opines: *"Forensics in the geo-domain encompasses an extensive array of topics with general emphasis in civil engineering and specific emphasis in geotechnical and related fields having geological, geophysical, geo-environmental, and structural applications. Mostly, it applies to failures after they occur when their application has prevented and/or identified failures prior to their occurrence. Furthermore, cases of analyses and evaluation of selected remedial measures, along with their effectiveness and economy, are normally subjected to judicial scrutiny."*

As geo-technical engineering deals with properties of soil and other natural materials of which we can find only limited data from which we must extrapolate to the rest of the domain, and as these natural materials are susceptible to wide variations with complicated interactions with structures built in and on them, any accident which involves natural earth can get highly complex in its investigation. Experts here should be really experienced in their work and be willing to face a lot of argument in their testimony. Singapore, induced by the Nicoll Highway collapse discussed earlier, has in recent years highlighted the importance of sound geo-technical analysis and design, and emphasised its role in accident prevention.

13. CONCLUSION

What has been presented here is the tip of the iceberg. Forensic engineering is essential to bring justice to the losers in an accident; but it is vital to prevent or reduce future accidents.

It needs special knowledge and skill, but more important, it needs a special attitude to convince a court with that talent. It is not a game to win or lose; it is a professional service to share for the good of the community – and it can be very fulfilling, beyond financial rewards.

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