Forensic Engineering in Structural Design and Construction

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ABSTRACT

When a structure fails, there is invariably an investigation to find out why it failed. Apart from the legal and professional necessity to determine the cause of failure, there is also the need to learn from it lessons that would enable subsequent designers and builders or fabricators to avoid the pitfalls of the failed structure and develop safer alternatives.

Technological developments in recent decades have introduced new configurations, materials and methods of design and construction that raise new and complex problems. Failures are caused by many unprecedented causes singly or in combination. Paradoxically, in this pursuit of novelty and innovation, even basic principles of sound structural design and good construction practice are often violated, leading to failures.

Author has more than five decades of teaching, research, and consulting experience in structural engineering, computer applications, and recently, in construction safety, failure investigation, and risk management, in USA, Singapore, and India. During his professional service, he has had many opportunities to study structural and construction failures, discuss with other professionals, collaborate with forensic experts, and also report and testify on failure investigations.

This paper will review the scope of forensic engineering in the light of the increased need for increased attention to and proper documentation of the design/construction process; discuss the preparation required for failure investigation; point out critical procedures and protocols in the actual investigation; and illustrate its application by a few classical case studies from around the world, and a few from his own experience.

KEYWORDS

Forensic engineering – structural failure – accident investigation – lessons learned

FORENSIC ENGINEERING BASICS

What is forensic engineering?

“Forensis” means ‘Public’ in Latin; ‘forensic’ has come to refer to legally sustainable documentation, usually applied to accidents, crimes, etc. (Ref. 1.)

In particular, forensic engineering is the application of the art and science of engineering in the jurisprudence (legal) system, requiring the services of qualified experts.

Forensic engineering may include the investigation of the physical causes of accidents and other sources of claims and litigation, preparation of engineering reports, testimony at hearings and trials in administrative or judicial proceedings, and rendition of advisory opinions to assist the resolution of disputes affecting life or property.

Generally the purpose of a forensic engineering investigation is to determine cause or 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.

Who can be a forensic engineer?

Anyone who is an expert in the subject under investigation
- Has the necessary formal education
- Has the necessary experience
- Is licensed, or is otherwise recognised as an expert
- Is active in technical societies

And who is fair, impartial, and ethical
- Is truthful
- Is objective
- Avoids conflict of interest
- Focuses on analysis, design, and technology rather than on fixing blame on persons responsible.

The author believes that a forensic engineer needs further a special mindset to be able to carry out such an assignment. (Ref. 2.) To track beyond the obvious, and find the root cause behind the immediate cause of failure, he (– the male pronoun will cover the female equivalent also, unless gender specific, hereinafter) must:

- "Open his third eye" and not only see more, but also hear more, smell more, taste more, and feel more than the average person.

- Understand more than others about what is going on around him, look under the carpet and behind the screen, and read between the lines.

TYPES OF FAILURE

Failure need not always mean that a structure collapses. It can make a structure deficient or dysfunctional in usage. It may even cause secondary adverse effects.

(a) Safety failure – Injury, death, or even risk to people:
- Collapse of formwork during concrete placement
- Punching shear failure in flat slab concrete floor
- Trench collapse
- Slip and fall on wet floor

(b) Functional failure – Compromise of intended usage:
- Excessive vibration of floor
- Roof leaks

- Inadequate air conditioning
- Poor acoustics

(c) Ancillary failure – Adverse affect on schedules, cost, or use:
- Delayed construction
- Unexpected foundation problems
- Unavailability of materials
- Strikes, natural disasters, etc.

Matousek and Schneider (Ref. 3) cite the figures in Table 1, for sudden failures (a) and unacceptable conditions (b and c above).

SOURCES AND CAUSES OF FAILURE

Errors and stages leading to failures

Matousek and Schneider (Ref. 3) also cite reasons for failure in percentages, as follows:
- Ignorance, carelessness, negligence 35%
- Forgetfulness, errors, mistakes 9%
- Reliance upon others without sufficient control 6%
- Underestimation of influences 13%
- Insufficient knowledge 25%
- Objectively unknown situations (unimagined?) 4%
- Others 8%

Table 2 lists distribution of failure by stages of its occurrence, according to various authors.

Type of errors in design/planning

In 295 cases of damaged structures, the types of errors in design and planning were as follows:
- Conceptual errors 34%
- Structural analysis 34%
- Drawings and specifications 19%
- Work planning and preparation 9%
- Combinations 4%

Primary causes of failure and how handled

Walker (1981) has summarised findings by numerous authors as shown in Table 3.
In 723 cases of damaged structures, the damage-initiating influence was taken into account in the building process as follows:
- No consideration 26%
- Incorrect consideration 26%
- Insufficient consideration 16%
- Considered but risk accepted 22%
- Consideration unknown 10%

Risk probabilities

Table 4 lists the risk probabilities for various common activities, based on American data. The death rate in number of deaths per hour times the exposure of the person performing the activity in number of hours per year, gives the death risk in number of deaths per year.

The table clearly shows that (permanent) structural failures are certainly not the disastrous killer that many may consider them to be. On the other hand, construction work involving temporary structures is 1500 to 4400 times as risky, and demands considerable attention from forensic engineers.

PRACTICE OF FORENSIC ENGINEERING

Forensic engineer's kit

The kit should contain some or all of the following items, depending on the size and complexity of the accident:

- The LENS, of course
- Graph & Lined Paper
- Pencils/Pens
- Warning Signs
- Camera and Film *
- Sample Containers
- Safety helmet, gloves, shoes
- Flashlight w/batteries
- Small Blackboard w/chalk
- Ruler and Tape Measure
- Cassette Recorder w/tape
- Data Collection Forms
- High Visibility Marking Tape
- Calculator

* – Many courts do not admit digital photos as evidence, but today's forensic engineer must carry a digital camera as well as a video camera to record for later analysis. His skill set should include familiarity with computers, spreadsheets, and computer graphics.

When to start

The investigation should begin as soon as possible after the accident happens, as otherwise:

- ***Operations may be disrupted.*** The more serious an accident is, the more time and effort it takes to bring work back to normal. The sooner an investigation begins, the sooner normal operations can resume.

- ***Memories may fade.*** As time passes, what a person remembers can change. Interviewing witnesses as soon as possible after the accident helps assure a more accurate account of what happened.

- ***Employees may be put to risk.*** There is a good chance a similar accident can happen again unless the causes are identified and corrected. The earlier an investigator can determine the causes, the earlier corrective action can be taken to prevent a recurrence.

Sources of information

Gathering information from variety of sources helps to avoid overlooking possibly important information. To be thorough, an accident analysis should include information from all available and existing records including:

- Documents
- Police reports and records
- Testimony of officials and affected worker(s)
- Physical evidence at the scene
- Newspaper reports
- Medial reports and records
- Photographs, videos
- Statements of witnesses*

* – Note that statement of witnesses must be carefully evaluated for consistency, credibility, bias, etc. It may also change at any stage of the proceedings!

Physical evidence

Physical evidence includes, but is not limited to, the following:

- Condition of site
- Condition of work environment
- Condition of machinery and equipment
- Condition of materials
- Permits to Work, Safe Work Procedures
- Supervisors' and signalmen's' forms

Permission in writing (or tape) must be obtained to:

- enter site,
- take photographs,
- talk to personnel,
- view records at site,
- conduct tests at site, and
- take away samples from site

Chain of custody of evidence

To stand up in court, every bit of evidence collected from the site or other sources must be tracked and documented in detail from beginning to end. Hence, attention must be paid to:

- Location, witnesses present, weather conditions if relevant, number, dimensions, etc.;
- Each sheet of paper and each item of physical artefact to be uniquely identified, tagged, and listed;
- Written (signed) and/or photographic documentation of giver and receiver of evidence, with third party witness if possible;
- Facts as distinct from opinions and conjectures.

Boundaries and constraints

The investigator must:

- Limit himself to the field of his expertise;
- Support his conclusions with computations or other established precedents;
- Support his opinions with citations from published literature, or from universally accepted practice;
- Use only facts or corroborated opinions in conducting analyses and drawing conclusions;
- Develop all possible and credible failure scenarios;

- Analyse outcomes under various plausible situations, e.g. Different support or loading conditions for structure;
- Strictly avoid pre-conceived notions and prejudices, even when working for a private paying client;
- Document his credentials and references for all to see;
- Ensure that his theoretical and experimental analyses follow standard procedures and are reproducible;
- Think "out of the box", think laterally, remembering that most accidents are unique even though they may appear to fit a pattern;
- Accept that he too can be wrong in some part of his submissions;
- Be ready for twists and turns in the investigation as it progresses, as further expert evidence or new testimony is adduced; and,
- Be prepared to lose an argument (or the case itself!), and not take it as a matter of prestige to win all the time.

Back analysis, Re-building, Simulation, and Re-enactment

Back analysis is a common technique of forensic investigation, involving the repetition of earlier computations, tests etc. with data extracted from later developments at site. This must not be used to justify an earlier conclusion, particularly if assumptions are involved; instead, the assumptions, and even the processes must be re-examined.

Re-building of a collapsed structure may be possible in certain situations, but it may be undertaken (even when economically and practically feasible) only if there are detailed original designs and plans from which it was built the first time, and not from memory.

Simulation is generally accomplished via the virtual world of the computer. In this, extreme care is necessary to reflect the actual conditions obtaining at the time and place of the failure.

Re-enactment of an accident is a very risky and high-profile activity, not to be undertaken lightly, and should <u>only be used</u> under the following conditions:

- When it can supply information that cannot be obtained in any other way.
- When it will aid in determining preventive action.
- When it is necessary to verify facts given by a witness or the injured employee.

If investigator decides to re-build or re-enact a process or scenario, he must make certain that the re-enactment <u>does not</u> result in a repetition of the injury or damage. Well-trained professionals (like certified stuntmen) may need to be employed with extra safeguards, to take the place of workers, injured or otherwise.

Report of investigation

The investigator's report normally includes the following items:

1. His qualifications/credentials as they pertain to the accident;
2. Terms of reference of assignment by the individual or organisation commissioning it;
3. Facts and brief review of the accident;
4. Summaries or reviews of existing analyses and reports by officials and witnesses;

5. Review and rebuttal of reports by opposing investigators and experts, etc. including points of concurrence;
6. Analyses of situations and events leading to the accident;
7. Possible credible scenarios for the accident;
8. Conclusions, prioritising the scenarios;
9. Recommendations for avoidance of similar accidents;
10. Statement of his contribution and disclaimers, if any.

Recommendations

Win or lose, and whether root causes for the accident can be found or not, the investigator should come up with improvements to the safety management system. Recommendations for deficiencies may be addressed under the following heads:

(a) Hazardous (unsafe) acts that occur because employees are:

- Unaware of the hazards they face and consequently do not know the special precautions that are necessary; or,
- Unable to perform in a safe and healthy manner because they are not properly trained, or they are not physically capable of performing the job; or because some aspect of the operation or work site prevents them from being able to work safely; or,
- Unmotivated to consider working safely as an important part of their job.

(b) Hazardous conditions that occur because they are either:

- Unnoticed: hazardous conditions that have not been identified during scheduled or informal inspections; or,
- Uncorrected***:*** hazardous conditions that have been identified, but have not been eliminated or controlled.

CASE STUDY 1 : DESIGN THEORY ERROR

Hyatt Regency Walkway Collapse

On July 17, 1981 in Kansas City, Missouri, USA, the walkway of Hyatt Regency Hotel opened the year before, on which hundreds of spectators were standing watching and enjoying the music and dance in the atrium area, collapsed, killing 114 people and injuring more than 200 others. (Ref. 4, 5, 6.) At the time it was the deadliest structural collapse in U.S. history. (*See* Fig. 1 for before and after pictures of the collapse.)

The cause of the failure was traced to the failure of the flanges of two toe-to-toe welded channels at the suspension rod nut at the upper walkway, as shown by bold red arrows in the overall view and enlarged detail of Fig. 1. To simplify fabrication and erection, the contractor had replaced the original design of a single rod supporting both the suspended walkways, with two separate rods, one for each suspended walkway, the lower one being hung from the upper.

After all the exotic forensic theories and scenarios had been exhausted, it turned out that the disaster was caused by an overlooked fact of simple high school level statics: That the substitution of two rods in place of one in the particular fashion it was done doubled the load at the nut, as illustrated in Fig. 1.

While this turned out to be a one-line trivial solution by hand, a computer package would not have automatically caught it, unless the modelling had included the particular connection, modelled in considerable detail by finite elements – which is generally unduly expensive.

Apparently the original design was at least marginally safe. It was the fabrication change that halved the factor of safety. It appeared that the contractor had referred the change to the designer, but one of his assistants approved it after a cursory glance.

CASE STUDY 2 : PRE-FAB CONNECTION DESIGN FAILURE

Ronan Point Collapse, East London, UK, 16 May 1968

Ronan Point was a 23 storey apartment block in East London, assembled from pre-cast wall panels around floor slabs. Building started in 1966, and construction was completed on 11 March 1968. (Ref. 7, 8.) On 16 May 1968, a gas leak explosion on Floor 18 blew out kitchenette and living room walls. Same areas of higher Floors 19 to 22 collapsed, and the entire weight fell on the floor slab of Floor 18. Floors 17, 16, ... collapsed one by one, down up to the ground floor. 4 died and 17 were injured. (*See* Fig. 2.)

Findings

- Found no violation of any applicable building standard, nor defect in workmanship
- Building standards gave detailed requirements for design of elements, but little guidance on stability of entire structural system.
- Joint forces were resisted solely by bond, friction, and gravity.
- Upon removal of the walls, connection above could not redistribute loads since they were designed only for compression.
- Many connections were shoddily done.
- Existing building standards and codes of practice having general warnings and guidance on design of large panel structures to mitigate some of the problems were not consulted.

Root Causes and Response

Root causes were found to be:

- No structural redundancy
- Weak connection design
- Bad workmanship

The following actions were taken:

- All new buildings constructed after November 1968 and over 5 storeys were required to be able to resist an explosive force of 5 lbs per square inch.
- Existing buildings were allowed to resist an explosive force of 2.5 psi, provided that the gas supply was removed and flats were refitted for electric cooking and heating.
- In 1984, all nine blocks on the estate were demolished.

Most of the authoritative papers on progressive collapse were published within a few years of the event. Interest in progressive collapse was immediately created in the United Kingdom and other nations, leading to changes to UK Building Regulations

- November 1968 – "Standards to Avoid Progressive Collapse – Large Panel Construction" – Had Alternate Load Path, Continuity, and Accidental Load
- April 1970 – Standards became mandatory
- 1974 – Provision of structural ties in British Standards

Ronan Point generated research and discussion in several countries. In the United States:

- 1972 – ANSI A58.1 addressed the issue
- 1976 – PCI included ties for pre-cast concrete walls
- Later events of 1970s influenced U.S. developments.

CASE STUDY 3 : DESIGN CHANGE FAILURE

Hartford Civic Center Arena Roof Collapse, 18 January 1978

A 300' by 360' space frame for a stadium roof in Hartford, Connecticut, USA, completed on 16 Jan. 1973, collapsed on 18 Jan. 1978 under heavy water-ponding from a storm. (Ref. 4, 5, 6.) Luckily there were no spectators or other personnel in the stadium at the time. (*See* Fig. 3a for a sectional view, and Fig. 3d for a collapse scene.) The space frame was an assembly of modular pyramidal pods, each 30' by 30', as shown in Fig. 3c.

Lapses in design and construction

Built in 1972-1973, the roof was an early example of a space truss, and of the use of computer-aided design. It was considered at the leading edge of design. But certain code specifications were violated. Its use of the cruciform shape shown in Fig. 3b – a very inefficient form for compression loads – was itself a wrong start.

Warning signs were ignored during the erection process: The deflections at initiation of jacking up the roof were quite high, but overconfidence on the computer analysis made the designers ignore them, and instead urge the contractors to make ad-hoc arrangements to complete the erection without delay. Large deflections during normal use were also ignored.

Findings

Investigation showed that three design deficiencies responsible for collapse:

1. The top layer's exterior compression members on the east and the west faces were overloaded by 852%.
2. The top layer's exterior compression members on the north and the south faces were overloaded by 213%.
3. The top layer's interior compression members in the east-west direction were overloaded by 72%.

In addition to these design errors, there were bracing deficiencies as follows:

1. Midpoint braces for rods in the top layer were omitted.

2. The exterior rods were only braced every 30-feet, rather than the 15-feet intervals specified.
3. The interior rods were only partially and insufficiently braced at their midpoints.

Root Causes and Response

Major reasons for the reduction in design capacity were the changes in the connection configuration, as shown in Table 5. The key difference is that as-built diagonal members were attached some distance (only a few centimetres) below the horizontal members, thus unable to brace the horizontals against buckling.

The engineers for Hartford Arena depended on computer analysis to assess the safety of their design. The roof design was extremely susceptible to buckling which mode of failure was not considered in that particular computer analysis and thus left undiscovered. Incorporated into the computer model were some fundamental assumptions about end conditions on 30-ft. long members of the frame, grossly oversimplified. Connection details were difficult to incorporate in computer model. As a combination of these factors, and over-reliance on computer analysis with an imperfect model, the seriousness of the change in the connection was not revealed.

The collapse shook public confidence in space truss roofs. President Ford ordered water load testing for a similar roof over a museum in Michigan. The failure tempered the tendency of engineers and architects to rely on computer models to cut down the structure to bare minimum, leaving no redundancy or margin for error.

Lessons learnt

1. Ensure that computer analysis/design covers ALL modes of failure. If it cannot, check out by conventional methods, those modes that cannot be (or would be too difficult to be) investigated by computers.

2. When any change is made to the design, reanalyse the as-proposed-to-be-built, with the eccentricities and changed support and joint conditions that actually would exist.

3. Heed warning signs during erection and construction. When deflections exceed computed values, stop the work, and evaluate the basic assumptions on which the computer analysis was performed. Do not start until the excessive deflection can be explained, and the problem corrected.

CASE STUDY 4 : BROAD REACH OF FORENSIC ENGINEERING

Northridge earthquake - 1994

At 4:31 a.m. PST on Monday, Jan. 17, 1994, the ground shook for approximately 20 seconds in the Northridge section of the San Fernando Valley in Los Angeles, California. (Ref. 9, 10.) The earthquake had Richter magnitude of 6.7, with the same epicentral region that had been rocked during the 1971 San Fernando earthquake. Fifty-seven people lost their lives in this disaster.

Adverse Observations

(a) Reinforced Concrete Bridges

- Older bridges with unusual geometries and large skews respond to earthquakes in complex ways that were not accounted for when designed.
- Retrofitting improves earthquake resistance.
- The significance of high vertical accelerations needs further investigation. (Fig. 4a.)

(b) Steel Bridges

- Practice of only a few bays resisting lateral load risky.
- Standard detail of beam-column connections leads to severe inelasticity and stress concentrations.
- Welding practices leads to brittle failures.
- Yield zones under seismic action need considerable further investigation.

Recommendations and actions

The following list for this case study illustrates how forensic engineering can lead to better structural design and construction and to improved safety:

- More forensic engineering
- Further analytical and experimental study
- Consideration of combined horizontal and vertical loadings
- Changes and improvements to maintenance regimen
- Revisions of formulas and coefficients, and changes to codes of practice
- Improvements to detailing practice
- Modifications to construction practice
- New construction methodologies
- Avoidance of expansion joints
- Development of new designs (Fig. 4b.)

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TABLES

Table 1 Sudden Failures and Unacceptable Conditions

	Type of failure/damage	***%***
Sudden failures Subtotal = 63%	Loss of equilibrium	13
	Failure with collapse	29
	Failure without collapse	11
	Other types of failures	10
Unacceptable conditions Subtotal = 37%	Excessive cracks	16
	Deflections and change of shape	7
	Errors in dimensions and support conditions	8
	Other unacceptable conditions	6
	Total	***100***

Table 2 Distribution of Failures over Various Stages

P&D = Planning and Design, C = Construction, U&M = Use and Maintenance, OMF = Others and Multiple Factors, T = Total					
Reference	***P&D***	***C***	***U&M***	***OMF***	***T***
Matousek	37	35	5	25	100
Brand & Glatz	40	40	-	20	100
Yamamoto & Ang	36	43	21	-	100
Grunau	40	29	*31	-	100
Reygaertz	49	22	*29	-	100
Melchers, et al	55	24	21	-	100
Fraczek	55	53	-	-	^108
Allen	55	49	-	-	^104
Hadipriono	19	27	33	20	99
Average	***43***	***36***	***16***	***7***	***^102***
All numbers percentages. * = Includes materials, environment, and service conditions. ^ = Multiple effects for single cause, >100					

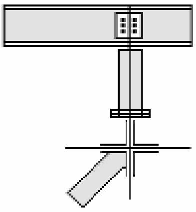
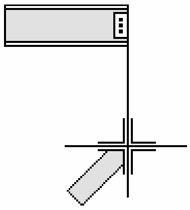
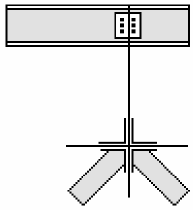
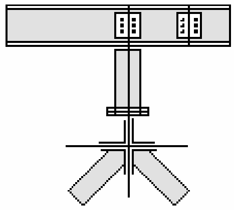
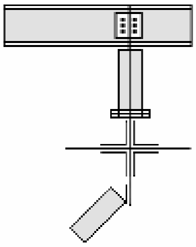
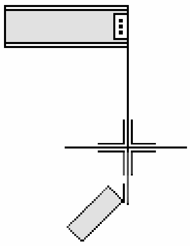
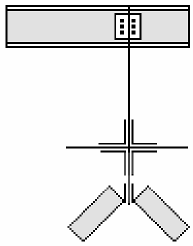
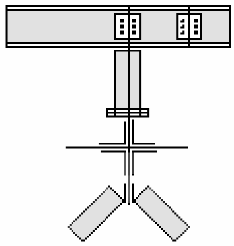
Table 3 Primary Causes of Failure

(a) Can be remedied by increased safety factors in structural design; unfavourable random effects lead to failure [%]		
Inadequate appreciation of loading conditions or real behaviour of structure	36	
Inadequate appreciation of loadings or real behaviour of connections	7	
Excessive reliance on construction accuracy	2	
Serious mistakes in calculations and drawings	7	
Inadequate information in contract documents and instruction	4	
Contravention of requirements in contract documents and instruction	9	
Inadequate execution of erection procedure	13	
Unforeseen misuse, abuse and/or sabotage, natural catastrophe, deterioration	7	
Others	5	
Sub-total for (a)		***90***
(b) Cannot be counteracted or avoided by increased safety factors in structural design; gross human errors reducible by checking and supervision. [%]		
Unfavourable load variation or combination (related to partial factors for loads), present but small	0	
Inaccuracies in design assumptions of support conditions, hinges etc, (related to model uncertainties)	3	
Material and workmanship deficiencies (related to partial resistance factors)	4	
Foreseeable deterioration	3	
Sub-total for (b)		***10***
Total		***100***

Table 4 Risk Probabilities for Various Activities

Activity *[* Estimated average per person]*	***Death rate, No. per hr. of exposure (10^{-9})***	***Exposure, No. of hrs. per year***	***Death risk, No. per year (10^{-6})***
Alpine climbing	30,000 to 40,000	50	1500 to 2000
Cigarette smoking	2500	400	1000
Coal mining (UK)	210	1500	300
Construction work	70 to 200	2200	150 to 440
Car travel	700	300	200
Swimming	3500	50	170
Boating	1500	80	120
Manufacturing*	20	2000	40
Air travel	1200	20	24
Building fires*	1 to 3	8000	8 to 24
Train travel	80	200	15
Structural failures	0.02	6000	0.1

Table 5 Comparison of (a) as designed, and (b) as-built connections

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

FIGURES

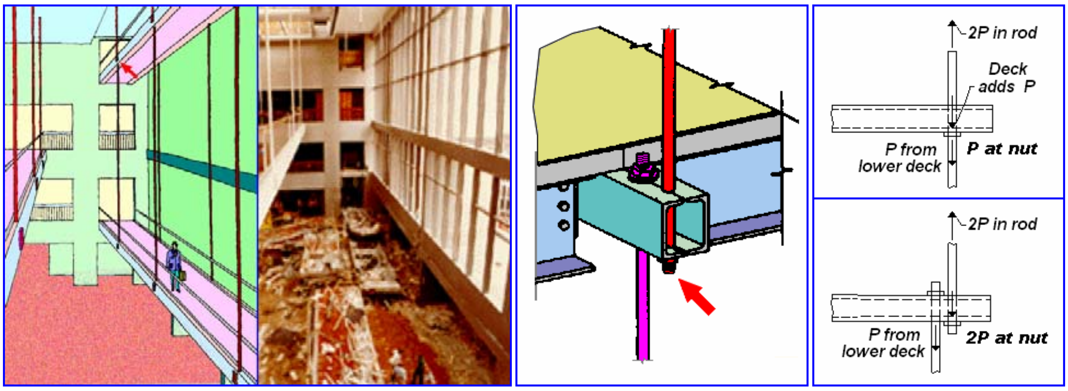


Fig. 1 (Left pair) Hyatt Regency Walkway, Before and After the Collapse; (Middle) Nut at Upper Walkway; (Right) Static Analysis of Single versus Double Hanger Rods.

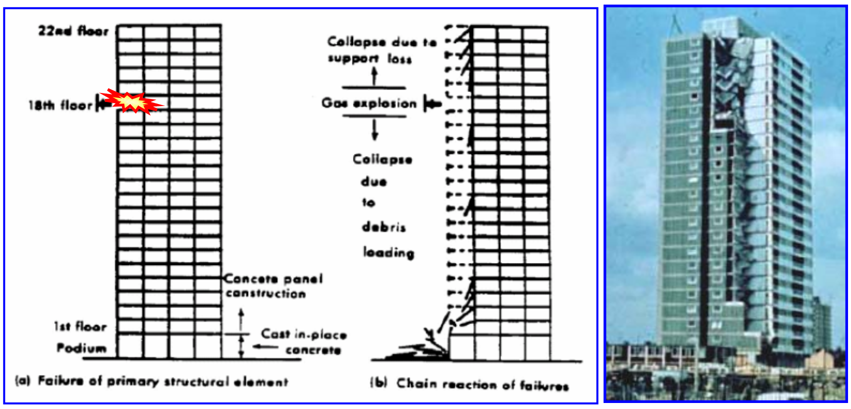


Fig. 2 Ronan Point: Schematic of Collapse, and Photograph.

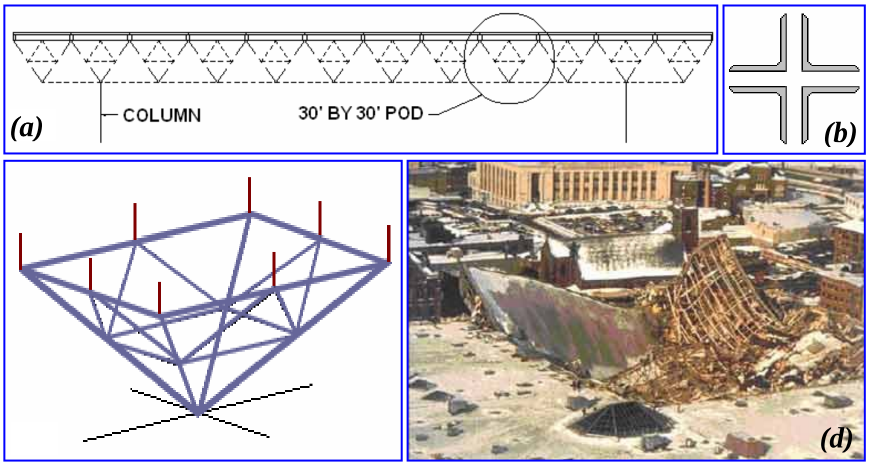


Fig. 3 Hartford Civic Center Arena: (a) Schematic Section; (b) Cruciform Section Used; (c) 30' by 30' pod; (d) Collapse Scene.

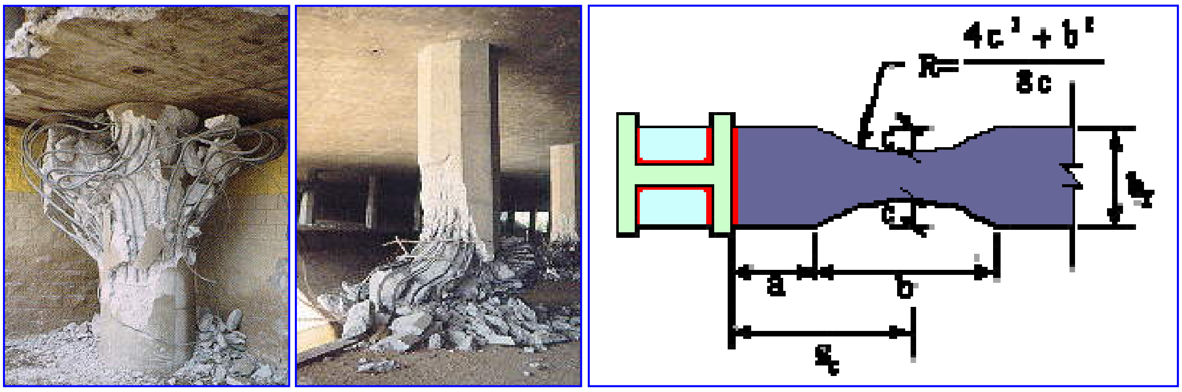


Fig. 4 (Left pair) 'Bird-caging' of top and bottom of R.C. columns; (Right) Reduced beam section in steel 'I' beams.

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