Safety In Design

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1. Introduction

Designers develop new designs to fulfil various needs: Function, beauty, fame, profit, economy, fun. In recent decades there has been a distinct shift towards safety as a motivating principle.

Newer still is the inclusion of construction safety and worker safety as critical factors in design stage. Thus, “designing for safety” is likely to be the new philosophy, a vital part of new safety culture.

Singapore Minister for Manpower, Dr Ng Eng Hen, speaking on “A New Occupational Safety and Health Framework” in March 2005, said, *“... architects and engineers must ensure that their construction projects are safe to build and maintain.”*

2. Life Cycle Design

A typical project goes through the following phases of its life cycle:

- Concept and planning
- Design and Drafting
- Construction (or manufacture)
- Use and Maintenance
- Decommissioning or demolishing

Until recently, it was thought that a designer’s job was to convert a concept, like an owner’s or architect’s vision of the finished product, into a constructible entity, by computing the dimensions and arrangement of various components, and handing over the detailed scale drawings to the client. Once this was done, the designer’s responsibility was considered to be over.

Recently however, the momentum is gathering to include designers in the chain of root causes for construction and other failures. For instance, from recent surveys in UK, [1] it has been deduced that professionals perceive designers as having a greater impact than designers themselves (and others) had estimated:

- 60% of accidents studied could have been eliminated or reduced with more thought during design
- 50% of general contractors interviewed identified poor design features as affecting safety

It is now accepted that the designer can and must take a role in the safety of those that construct or manufacture his design, of those that use the product, and so on all the way down the life cycle chain, till it is decommissioned or demolished.

Recent failures in Singapore have also pointed the finger towards the designer. Manpower Minister Dr Ng Eng Hen addressing Members of Parliament on Workplace Safety and Health urged industry to *“... reduce and mitigate risks along the whole work process chain from design to maintenance ...”*

3. What Design for Safety is and is Not

Design for safety IS the following:

- Explicit consideration of safety of construction workers in the design
- Awareness and acceptance of worker safety by the designer
- Making design decisions based at least partly on risk assessment of construction, use, etc.
- Inclusion of worker safety in constructability review

But design for safety IS NOT the following:

- Designers taking an active role in construction safety <u>during</u> construction
- Design having to <u>guarantee</u> construction safety
- Designers being <u>automatically</u> made responsible for construction accidents even when the accidents cannot be tied to a design error
- Expecting all designers to be <u>knowledgeable</u> about design for safety, without extra training

4. When Design Intervention is Effective

As to the effectiveness of the participation or intervention of the designer at various stages, it has been confirmed (as illustrated in Fig. 1) that:

(a) Ease of safety implementation is highest in the beginning of the life cycle, falling steeply at first and then flattening out as the project progresses through its various phases.

As a project moves through its life cycle, it becomes harder and harder to introduce and implement safety measures.

(b) Cost of safety implementation is exactly the opposite, being lowest in the beginning, rising gradually at first and then increasing sharply as the project progresses.

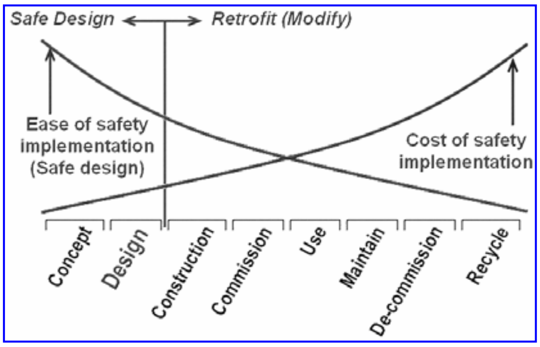

Fig. 1. Ease and cost of safety implementation

It can be shown that in a construction project, if it costs $10 to change a philosophy, it will cost $100 to change a drawing, $10,000 to make a field change, and millions to clear up after an accident.

Thus, safety implementation is most effective in the concept and design phases of a project. It is much easier to recompute a dimension than to redo a scaffolding.

5. Benefits of Designing for Safety

In addition to the well documented advantages of investment in safety, designing for safety has the following benefits:

- Safer workplaces
- Reduced workers' compensation premiums
- Better conformance with health and safety legislation
- Increased productivity
- Improved innovation
- Fewer delays due to accidents during construction
- Continued focus on quality
- Positive response to pro-active clients demanding safer construction and safer designs
- Reduced costs

6. Engineers' Responsibility for Life Cycle Design

In the 18th century before Christ, Hammurabi, ruler of Babylon (1795-1750 BC), had 282 laws engraved on a black stone. Law 229 stated: *"If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death."* (Let us remember that the builder in those days was also the designer.)

In modern times too, the professional obligation for continued functionality of a structure is part of mandatory framework in one form or another.

For instance, BS 5950-1:2000 [2] states:

2.1.1.1 Aims of structural design

> Should facilitate safe fabrication, transport, handling and erection
>
> Should also take into account needs of future maintenance, final demolition, recycling and reuse of materials.

2.1.1.2 Overall stability

> Designer should ensure compatibility of structural design and detailing between all structural parts required for overall stability, even if some or all structural design and detailing of those structural parts is carried out by another designer.

However, specific assignment of construction and worker safety to designers is relatively recent.

In 1995, Construction Design and Management (CDM) Regulations of UK [3] stated that designers shall *"ensure that any design…includes adequate regard to the need to avoid foreseeable risks to the health and safety of any person at work carrying out construction work….".*

Yet, as late as 2003, authorities found that a significant number of designers had failed to consider the practical details of how the structure they had designed could be safely constructed, maintained and cleaned.

In 2003, the American Society of Civil Engineers, Occupational Safety and Health Administration, and the Construction Institute formed the ASCE-OSHA-CI Alliance, *"to use* *their collective expertise and share information and technical knowledge to promote safe and healthful working conditions for construction employees".* [4]

In Singapore, the Report of the Commission of Inquiry (COI) into the Nicoll Highway collapse [5] said:

- The potential for major accidents whether due to the construction process or deficiencies in design ... must be recognised and expeditiously controlled.
- Overall safety must be integrated into design phase.
- All in all, the Safety Management System (SMS) must be made more effective. One way to achieve this is to integrate the SMS into the design, construction trials, execution of works and maintenance phases.

In 2005, following up on this report, the Singapore government announced a new initiative towards improved safety culture. The Ministry of Manpower has been reorganised, and modified policies have been announced. There is a strong shift of safety responsibility towards the designer.

Beyond rules, beyond codes, beyond legal niceties and financial inducements, lies the "duty of care" that designers owe to their clients, to their co-citizens, on this matter of safety in design.

Designers may not have the time or the resources to do more than what they have agreed to do, but they have a professional obligation, a moral duty to at the least:

(a) Clearly define boundaries of their commitment, so that no one may innocently or wilfully extend them

(b) Document the assumptions they make and the details of computer models they create in their work

(c) Point out real risks and potential hazards within the scope of their work, and in the tasks that may be related to their design

(d) Review all aspects of their design and rework it as necessary if and when the contractor has difficulty implementing the design, or the owner insists on some sudden change

7. Barriers to Designing for Safety

Against the many benefits of designing for safety, there are hindrances to their routine or wide application, from the point of view of the designers:

- Fear of liability
- Lack of safety expertise
- Lack of understanding of construction processes
- Professional fees
- Contract terms (– presently forbidding designer intervention, in some codes!)

Additional responsibilities and tasks will mean that designers would have to put in more time and effort into ensuring safety further down the activity chain, and then appropriate reimbursement will become a problem.

All these barriers would of course have to be overcome.

8. Assumptions for Realistic Design

Often, large structures are designed with assumed ideal support and connection conditions, and without sufficient attention paid to constructability.

Experienced designers usually make proper assumptions in their designs, assumptions which can be realised in practice, meaning those which can be implemented during the construction process. Even so, often critical assumptions must be double checked whether they correspond to the ground realities. Some thought given to fabrication or erection may avoid dangerous traps.

(a) Support conditions:

A very common source of problems is in the assumption of support conditions. Designers often assume in their computations, and detail in their drawings, fixed supports.

Most of the time, the assumptions do get implemented. However, the integrity of fixed supports must not be taken for granted, and method statements for their fabrication or erection, and proper supervision during every stage until final handover must be provided.

On a drawing, it is easy to mark a support as fixed. But a lot of planning, design, and construction know-how must go into achieving the desired fixity. A simple example is the often overlooked large tension forces on the top bolt(s) and anchor(s) of a simple bracket connection.

Just because a column's reinforcement is embedded into a certain amount of concrete at its base, it cannot be taken to be fixed to its support. Sound embedment into cut rock, or continuity with a buried pile would be a pre-requisite to the base being treated as fixed.

In the same fashion, a bolted or welded base may not always be a fixed base. Its integrity would depend on the configuration of the elements jointed, number and size of bolts or shape and size of weld, and other factors.

An opposite problem arises when a support is assumed to be pinned at one end and “on rollers” at the other end as presumed in a simply supported structure, but no provision is made for safe relative movement of the two supports.

In a recent failure of trusses during erection in a school building in Singapore, a main cause of the problem was found to be the fact that the truss was supposed to be able to slide on at least one of the supports, but was unable to do so. (Fig. 2.)

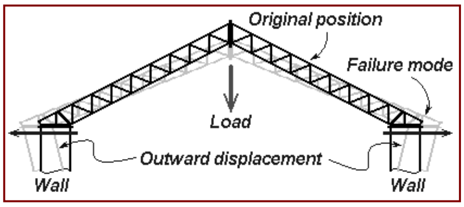

Fig. 2. Wall and truss collapse

Instead, the outward thrust at the support simply pushed the wall away and the wall crashed, bringing down the other trusses that had already been erected.

End fixities are all the more important in the case of slender columns, because the capacity of a “fixed ended” column can drop to one-fourth of the computed value if the anticipated rotational restraints cannot be developed in the finished structure.

Codes provide slenderness ratio (*k*) factors for various positional and rotational restraint situations; it is very important to correctly evaluate the positional restraint status on the merits of each case.

Related issues, which also require equally realistic planning and execution, are:

(i) intermediate supports for long columns to reduce the effective length of a column; and,

(ii) anchors and bracings to prevent sway, both during construction, and subsequently.

Many real supports lie between the extremes of pinned and fixed supports. This is particularly true in bolted column bases where depending on the arrangement of the connected parts and the bolt arrangements, the connection could range from very low rigidity (almost pinned) to very high rigidity (almost fixed), with wide variations in between of “semi-rigidity”.

While hand calculations to include semi-rigidity could be tedious, computer programs are available which incorporate this facility. Still the two-fold problem remains, of estimating the accurate value of semi-rigidity and of the user properly inputting it.

Actual end conditions in temporary structures are particularly critical, because unlike for permanent structures, foundations for temporary structures are also temporary, with little or no base preparation or anchorage. They must invariably be assumed pinned.

Further, in temporary structures, foundation strength and stability cannot be relied upon. Rain can jeopardise the safety of an entire formwork.

(b) Connection Integrity:

Just as in the case of supports, connections between members must also be designed realistically, with an aim of constructability, spanning the entire range from pinned to fixed.

Again in temporary structures, joints between members cannot be assumed to be continuous or rigid, because components of temporary structures are dismantled and reused a number of times, depending on material and type of component.

Figure 3 shows two situations where a designer’s assumptions vary drastically from actual conditions. The clamping force in the first depends mainly on workers.

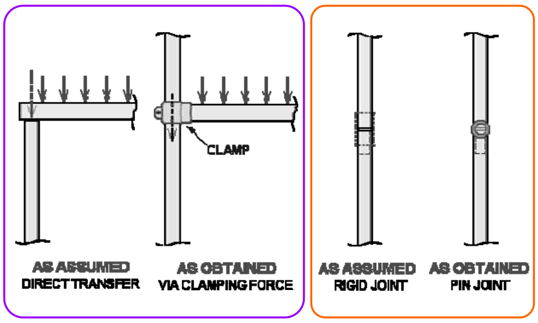

Fig. 3. Assumed and actual connections

The joint fixity in the second case, often advertised by the manufacturer as a selling point, is reduced or completely negated after a few efforts of a worker who shakes the upper rod from side to side to facilitate its removal from the lower rod.

It is imperative to check if a designer’s intentions have been incorporated in the fabrication. Occasionally, non-destructive testing (NDT) shows up embedded in large welds, some strange metal pieces or other “fillers” which reduce the design strength of the connection.

9. Realistic Structural Modelling for Design

Most truss and frame designs are carried out on stick models of the member assemblages. Most designers assume members to be straight lines in their manual or computer analyses. Various anomalies may occur in such line idealisation, as follows:

(a) Variations in centre-lines:

Modelling of eccentricity, step, and haunch in structures with large-size members may cause problems in design.

Left part of Fig. 4 shows the conventional assumption of centre lines in beam-column assemblies, while the right part shows the more realistic variation of the centre lines.

It is presumed that in both cases, the analyst incorporates varying section properties for different segments along the length of beams and columns.

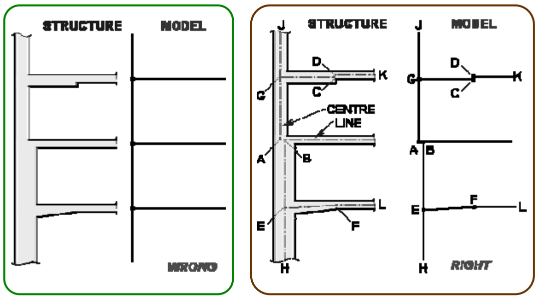

Fig. 4. Centre-line assumptions

However, a comparison would clearly indicate that in the more realistic idealisation, moments and inclined forces are introduced at junctions of segments. These discrepencies may in most cases be minor but can get significantly adverse when they accumulate.

(b) Non-intersecting truss members:

One common example where practice is often forced to deviate from design is in truss member joints. Analysis and design would have conventionally assumed that all members met at a single point.

However, in practice, the varying sizes of the individual members and the need to arrange them suitably on the gusset plate would often result in eccentricities of member forces not meeting a point. If the calculated moments caused by eccentric forces are large, they must be fed back into the member and gusset plate designs.

(c) Size effects:

A similar situation is created when massive reinforced concrete or steel frame members are idealised by straight lines, as shown in the left and middle figures of Fig. 5.

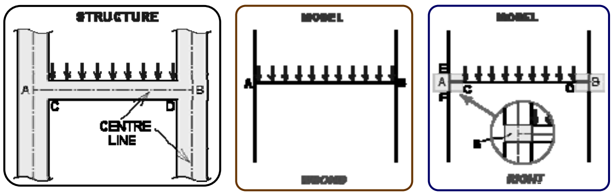

Fig. 5. Idealisation of large size members

Not only do the spans of beams and the unbraced lengths of columns increase, but the total load on these spans and lengths also increase, resulting in overdesign. While this situation may be overlooked as conservative, the cumulative effect of many such compromises may lead to uneconomic design.

With modern computer software, there is an elegant way out of this dilemma, representing the real joint by means of “rigid zones” with very high stiffness as shown in the rightmost part of Fig. 5, so that the spans, lengths, and loaded lengths are correctly represented. However, many casual users, even if they know about this feature, may not use them due to the extra effort and difficulty of input – or just by oversight.

10. Overlooked Loadings on Permanent Structures

While all possible loadings and their worst combinations are routinely estimated and introduced into the design process, unusual loadings for normal use of permanent structures may be often overlooked.

(a) Unusual Loads:

In the case of complex structures developed for the first time, it could prove useful to look for unusual and abnormal loads that may develop during normal use.

- As most loadings will be downwards, wind uplift on sloping roofs may be overlooked. (Walls of most American homes in hurricane-prone areas are anchored to foundations, and roofs anchored in turn to the walls, by steel straps of sufficient size, to prevent roofs being torn loose and blown away.)
- The increase in the reactions of penultimate supports of continuous beams.
- With multi-span continuous beams, loading of all but one span can lead to greater moments than loading of all the spans.

(b) Modifications of Usage:

An interesting example of a routine modification of office space causing vibration problems is described in the paper by

Lichtenstein [6]. Removal of cubicles and converting to an open-office concept, changed the loading and staff traffic pattern, resulting in low frequency floor vibrations which resonated through the entire floor, disturbing work and inconveniencing staff. An active vibration control system had to be put in to mitigate the effects of this change.

The moral to this story is that configurations and loadings different from the original planning but equally plausible over a period of time, or under a different management, must also be examined at the planning and design stage itself, to avoid expensive surprises later.

(c) Terrorism, a New Criterion:

A recent development contributing to design criteria is the increasing terrorist activity around the world.

The New York World Trade Center designers had considered airplane impact during their design. Yet, the twin towers failed, because while the design impact was by nearly fuel-empty planes at low landing speed, the actual impacts of September 11, 2001 were by fully laden planes at maximum speed, planned by terrorists.

From then on, many metropolitan high-rise buildings have to take into account terrorist activity in some fashion or other. Experts advised as follows for future:

1. Include terrorist activity into the hazard analysis and risk assessment.
2. Continue the good practice of redundancy.
3. Increase egress size and protection.
4. Improve fire protection and inspection.
5. Tighten up and expand emergency preparedness.

Significantly, nothing more was said on the structural design itself. There is no way to design any structure against wilful destruction wrought by evil minds.

11. Design for Constructability

Designers must check if any of their proposals will be difficult to implement, or likely to create unusual problems during construction

A novice or careless designer may come up with a flawless design on paper, parts of which may not be capable of being implemented in practice. Common examples are in support and connection details, as already discussed.

One situation that occurs frequently in welding is when a designer specifies "weld inside and outside" a pipe, as in Fig 6(a), or marks with a simple circle and an arrow, the symbol for "weld all around", around pipes (or column bases) in awkward arrangements, as in Fig. 6 (b, and c).

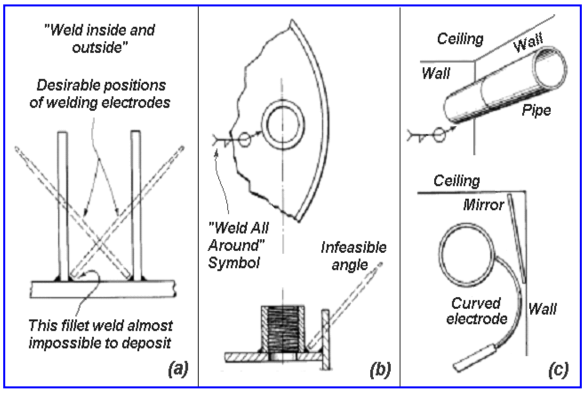

Fig. 6. Infeasible or awkward welding

While heroic measures such as the curved electrode applied with the aid of a mirror as shown in Fig. 6(c) may be required in unavoidable cases, they are not conducive to safe or economical fabrication.

Use of modular assemblies and prefabricated segments may overcome inherent risks of on-site fabrication or installation of individual components. Pre-cast concrete units eliminate concrete formwork and casting problems.

12. Overlooked Construction Loadings

Loadings developed during construction stages and erection procedures on the temporary structures erected to build or repair/maintain the permanent structure are overlooked, or casually assumed to be non-critical.

(a) Partially Completed Structures:

It is only in recent versions of computer structural design packages that the capability to automatically analyse the effects of deformations due to the construction process itself has been included.

Incomplete foundation anchorages, connections, bracings, etc. may often result in structural elements not having developed the full strength or stiffness.

A very interesting example was the failure of the steel frame dome of an auditorium, in which during erection, the radial struts between the compression ring at top and the tension ring at bottom of a circular roof angled laterally within the top connection and slid sideways, rotating the compression ring, and leading to collapse of the roof, as shown in Fig. 7.

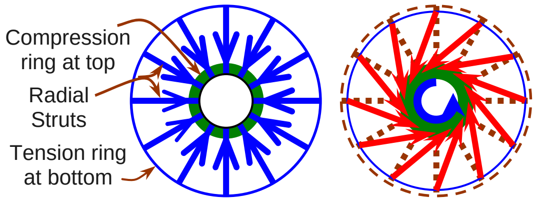

Fig. 7. (Left) As designed, (Right) As deformed, causing collapse

In the figure, the broken lines in the collapsed configuration at right are the original position of the tension ring and radial struts.

With roof cladding in place and attached to the struts, such twisting of struts would have been impossible. Hence this failure mode was not included in the design. The strut-ring connection was designed for the compression, but not for the twisting moment on the incomplete dome which had not been anticipated.

Similar failures have happened when a deep pre-stressed concrete beam was accidentally tilted during transport or erection. This would reduce the vertical gravity compensating force for the tendon, resulting in a net upward force, leading to explosive break-up of the beam.

(b) Loadings during Delivery:

Imposition of heavy concentrated loads many times normal design loads from stacking up of delivered materials with their removal lagging behind can cause havoc. Example: Placement of reinforcement bar bundles on a formwork by a crane, for spreading over an area.

(c) Good Intentions Gone Bad:

Sometimes, a well-intentioned “improvement” of a structural element can lead to a worsening of the overall strength or stability.

With tall masts or scaffold posts during erection, guying may become necessary for maintaining verticality. If in the process, the guys are over-tightened, the axial compressive component in the post due to the tension in the guys may exceed its reserve buckling capacity, as suggested in Fig. 8.

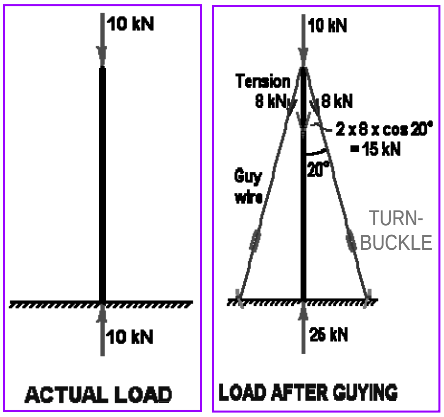

Fig. 8. Well-intentioned buckling

With pre-stressed concrete, more pre-stressing is not always better, often worse in fact.

13. Design for Abnormal Loadings

Many structures are accidentally, by oversight, or by over-confidence, subjected to overloads and unplanned loadings. Although it is not possible to accommodate all overloads, some extra measure of failure protection must be provided where human life and health are concerned.

(a) Redundancy in Design:

Redundancy is the incorporation of more strength and safety features than are strictly necessary to take the design loads, such extras being provided with the sole aim of protecting human lives, environmental damage, etc. from unexpected risks.

Redundancy in the form of repeated or extra members can be quite useful, particularly for temporary structures.

In roof truss erection part of FedEx Forum building construction in Memphis, Tennessee in USA, the site engineer added an extra set of guy cables for redundancy, as indicated in Fig. 9, one out of each of the five pairs shown being the redundant. [7]

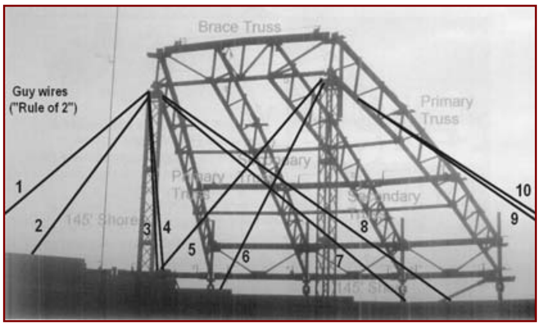

Fig. 9. Redundancy in temporary structure

Overnight a wind storm developed, raising winds of more than twice the design wind load. While cranes toppled and other temporary structures crashed, the roof panel withstood the extra wind loads.

This “Rule of Two”, meaning, when in doubt, double the safeguards, is a wise rule to adopt. A good example is a rigger’s lanyard attachment to a frame, as against to a lifeline. To move along further than his lanyard would allow, he has to unclamp the lanyard from one frame member and attach it to another member.

During this switch, he is unconnected to any safe anchor and is exposed to high risk. To eliminate this hazard, he may have a double lanyard, as is common in shipyard work.

The Nicoll Highway Collapse COI also noted in its report, *"The design should also have sufficient redundancy to prevent a catastrophic collapse in the event of a failure of any particular element."*

Certainly redundancy will involve additional expense, but like insurance, the benefits in risks avoided may well be worth the extra expense.

(b) Unaccounted Alternate Load Path:

Occasionally, the design may happen (or be revised) to have features that may provide an alternate path for loads and if their contribution to total capacity is not factored in, they may prevent immediate or progressive collapse.

It was this kind of redundancy (Fig. 10) that enabled the New York World Trade Center twin towers to withstand the impact of planes (on 11 September 2001) which took down numerous perimeter columns and core columns, still standing up for 103 minutes in the case of North Tower and 53 minutes in the case of South Tower, allowing thousands to escape.

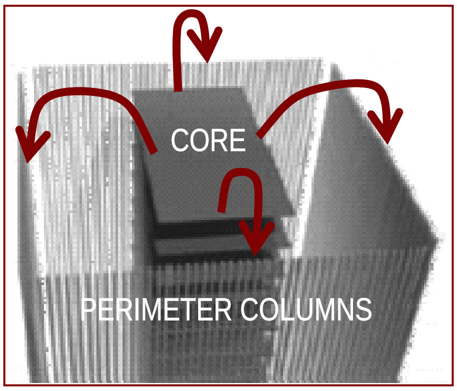

Fig. 10. Load transfer in WTC

The redundancy for alternate load path was provided (along arrows shown in Fig, 10) by the steel mullions of the windows around the perimeter.

The external mullion tubes of the windows shared and redistributed the loads with the inner core columns through the medium of the floor slabs and trusses.

(c) Back-Ups:

Back-ups are alternate ancillary mechanisms that can facilitate or take over the function of a load-bearing component in an emergency, especially when the intended component fails. E.g. The hand-brake in a car.

In the construction industry, such back-ups are not common. But it would be worthwhile to review the active first lines of defence against the impacts of failures, and examine if inexpensive back-ups can be provided which could offer warnings and safeguards to users, in case a main member fails.

One important back-up system in a tall building is the staircase for use in case the lift fails or is endangered by fire. Design of the staircase evacuation system received considerable attention during investigation of the New York World Trade Center collapse, and certain design improvements were recommended, such as reinforced concrete walls instead of plaster boards on frames.

14. Unauthorised Changes from Design

By far the largest number of failures of structures during erection or in the early stages of their life is because of the changes to the design made by the builder/contractor, for possibly very legitimate reasons such as:

- To avoid delay, to make up for lost time
- To use available materials or equipment
- To overcome site constraints

After this, if the contractor fails to inform designer of the changes, or does not send sufficient detail, or he informs the designer but the designer fails to appreciate or evaluate the impact of these changes on the integrity and safety of his design, then failure is very likely to happen.

Two case studies [8] illustrate the points made.

(a) Hyatt Regency Walkway Collapse:

Built in July 1980, the 40-storey tower Hyatt Regency Hotel in Kansas City, Missouri, USA, was holding a special party on July 17th, 1981. The upper walkway across the atrium failed, and fell on the lower walkway, both walkways crashing onto the floor three storeys below, killing 114 people and injuring 200.

The cause? Just one simple deviation from the design. The design had specified one long vertical suspension rod running from upper support through both walkways, never mind how the intermediate support would be fixed.

But the contractor replaced it with two shorter rods, one from the upper support to the first walkway, and the second from the bottom beam of the first walkway down to the second walkway.

Although the change seems innocuous and even reasonable, basic statics can show that the washer under the upper rod was subjected to double the design load, and that was precisely what tore off and led to disaster.

(b) Hartford Civic Center Arena Roof Collapse:

The Civic Center Arena in Hartford, Connecticut, USA, had been completed in January 1973. The 300 ft. by 360 ft. roof space frame consisted of pods in 30 ft. by 30 ft. grids, 21 ft. apart, and constructed 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, with a loud crack the center 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.

The cause of the collapse was traced to relatively minor changes in the connections between steel components, the fabrication deviating from the 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 the axial force capacity to less than a tenth of the design value.

In both cases, the designer should have checked whether his proposals could be translated into practice. Alternatively, the fabricator should have had the designer check and approve the changes he was proposing for practical reasons.

Another danger in temporary structures is that some components such as bracings or ties may be temporarily removed for expediency of movement of workers or materials, but are not replaced after passage. While this violation is not directly within the province of the designer, it still is within his responsibility to emphasise the need to retain – or replace after a transient removal – bracings, or alternatively, to suggest redundant components to allow for these variations.

15. Ignoring Warning Signs

Compounding the problem of inadequate design is the frequent habit of turning a blind eye to warning signs.

In the case of the Hartford Civic Center collapse, the structure had kept throwing out warnings of its impending failure. To quote one of the reporters: *"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.

This is reminiscent of what transpired in Singapore's own Nicoll Highway collapse. Chapter 5 of the Commission of Inquiry's Report [5], titled "Causes of the Collapse and Findings", says: *"Warnings of the approaching collapse were present from an early stage but these were not recognized."*

16. Prevention of Progressive Collapse

It is often noticed in accidents that what starts as a minor localised failure, escalates in domino fashion into a complete system collapse. It is the duty of the designer to prevent such an eventuality, whether it is a permanent or a temporary structure. Codes usually highlight this need.

Usually such domino effects occur because if the failing member is critical to the stability of the entire structure, then system collapse is inevitable. The designer should analyse scenarios with different critical members omitted, to track down their effects on the system.

Although it may not be possible to protect the entire structure from overall collapse due to failure of any of the critical members, reasonable protective means must be provided to contain the damage, so that occupants may exit and valuable property may be removed from the structure as soon as one or a few members failed.

A common scenario is for one of a set of columns to fail by accidental impact, localised explosion, isolated foundation failure etc. The entire building must not collapse as a result.

In temporary structures, it is quite common for one bay or one member to fail, and it drags down the entire scaffold or formwork. The cause can often be traced to omission or deficiency of bracings or anchors against sidesway. A design must include detailed instructions for the provision of not only bracing against buckling of individual members, but also sway bracing against system collapse.

Redundancies and alternative load paths are the normal safeguards to avoid this situation.

17. Design for Maintenance

A simple feature of design for safety is to eliminate construction and maintenance hazards with a minimum of temporary additional safety measures. Examples are:

1. Appendix C to Subpart M (Fall Protection) of OSHA Standards for Construction [9] recommends: *"Anchorage points can be incorporated during construction, for use then and later for window cleaning or other*

building maintenance."

Accordingly, floor perimeter beams and beams above floor openings are designed with rings and other anchors to support lanyards, with their details being marked on the contract drawings.

2. Sloping or curved roofs (E.g. Esplanade, in Singapore) to have embedded lanyard anchors at convenient locations for servicing.
3. Ceilings in interstitial space designed to be walkable and allow worker access.
4. Floor finishes underneath raised metal floors designed to be smooth and easy to crawl across.
5. Permanent guardrails designed to be installed around skylights.
6. Skylights designed domed, rather than flat, with shatterproof glass or strengthening wires; skylight to be installed on a raised curb.
7. Upper story windows designed to be 1.1m above the floor level, so that the window sills may act as guardrails during construction.
8. Parapets for roofs to be accessed for maintenance (E.g. water tank cleaning) to be 1.1 m high to eliminate the need for additional safeguards.
9. Air-conditioners on cantilevers outside high-rise apartments are particularly hazardous for maintenance. One solution is to gather all A-C units in a ventilated enclosure at basement level, or at intermediate floors for convenient servicing.

18. Risk Analysis and Control

Most designers, especially in structural engineering and construction, have not often been faced with the need for risk analysis and control, because conventional thinking relegated that responsibility to contractors.

As more and more accidents are traced to wrong or inadequate design, the role of designers in preventing accidents by eliminating or mitigating risks, came under scrutiny. Now, it is established policy that designers should review their designs for potential hazards and:

(a) try to eliminate or reduce the risks at design level; or,

(b) leave adequate documentation and guidelines for follow up by subsequent stakeholders in the supply chain, such as contractors, supervisors, etc.

It is fully recognised and accepted that designers cannot be responsible for all the hazards in the workplace. We are talking here about hazards in the design itself, hazards that arise due to certain features of the design, and may escalate into risks further on during erection, use, maintenance, decommissioning, etc.

The Singapore Ministry of Manpower has recently come out with guidelines and simple templates for risk assessment and management.

Designers will be urged, even required, to check their designs for potential hazards and list safeguards and other risk management measures. It is in their own interest, apart from the larger interest of saving lives and other losses in the construction industry.

19. Over-dependence on Computers

Most engineers of the current generation think of computers as God's own gift to mankind, which it indeed is, in many ways. But it is also a double-edged sword, with the benefits being accompanied by responsibilities, hidden problems, and increased risks.

(a) Computational Risks:

Advantages of computers are too numerous and well-known to list. While most of them may be right and effective, we must also remember the following:

- The computer does not analyse a structure, it only manipulates the numbers from a model of the structure we give it, based on standard formulas and built-in logic.
- Modelling of complex structures is as much an art as a science, depending on many varied factors. It has to be done with great care, and by experienced personnel.
- Results will depend to a large extent on the modelling.
- Interpretation of results is also likely to be complex and subjective in many situations.

As we use more and more computers, we tend to forget the basic principles and assumptions on which structural analysis depends. As computer packages become more and more automated, we tend to lose sight – and the "feel" – of the significance of the data that we put into it, with the gaps in data being filled in by the computer program itself.

That is when the computer analysis takes on a life of its own, and slips away from the engineer's grasp.

Many forensic engineers and code authorities who have tracked back failures to their root causes have identified the computer – or, since computers are dumb machines – to those who use computers, as the prime culprits who were responsible for the failures.

Sometimes, a simple shift from manual calculation to computer analyses by modern packages can land us in trouble. The simplifying assumptions we used to make in the pre-computer era, if fed into the sophisticated theoretical integrated analysis of the computer programs, may conflict with each other and produce some alarming results.

Dr. Leroy Z. Emkin, Professor at School of Civil and Environmental Engineering, and Founder of the Computer Aided Structural Engineering (CASE) Center of Georgia Institute of Technology, U.S.A., wrote a landmark paper [10] comparing the results of a high-rise building by various methods with conventional assumptions and methodologies.

He found that the results from analyses by experienced engineers using well-known computer packages differed by as much as five orders of magnitude. The question is: *“Which one is right?”*

On the Nicoll Highway collapse, The Straits Times newspaper of May 14, 2005, said: *“Wrong [computer] model [was] used to simulate strength of soft marine clay at site. And how much the support walls would move was underestimated by about 50 percent.”* It added, *“mistakes in design caused the collapse of temporary support structures ...”*

(b) Computer Graphics:

Computer graphics is another pretty trap. Modern software and hardware for computer graphics produce such sleek multi-colour drawings that the eye and the mind often skip over flaws which would have been obvious to a pre-computer generation.

Today’s drawings, no doubt with clarity and legal commitment as the aim, are filled with a lot of text material relating to design: parameters and assumptions; materials and loadings; erection, fabrication, and concrete casting instructions; legal disclaimers; etc. Both designer and contractor should seriously ensure that the drawings reflect the intentions of the former and the feasibility of the latter.

As nowadays drawings are usually sub-contracted out, the designer is one-step removed from the completion of his obligations.

Further, as the input to the drafting equipment may not be prepared by an engineer familiar with the designed product, but by a computer data entry operator, any accidental mistake at source or wrong input at the machine level (such as switched numbers) may not catch the eye of any one.

It is not also unusual for drawings to contain dimensions different from the designed values. Horror stories abound, even in space shot disasters, where the wrong location of a number on a computer plot, or misinterpretation of a computer plot was the cause.

(c) General Cautions on Computer Usage:

Computers are here to stay. The more “automatic” and sophisticated that hardware and software get, engineers in general and designers in particular must become more careful. To this end, designers must not accept computer results of complex and critical problems at face value – especially where human life and health are involved. They must:

(i) Always insist that the analyst submit details of the computer model along with the results; and,

(ii) Have a rough manual check on crucial results, which should confirm the computer result at least to the same order of magnitude (i.e. to within ±25 to 50%, yes, even to 50%!).

(iii) Designer should make a thorough check of the drawings for correctness and completeness, and should insist that he initial the approved drawings before fabrication or construction

20. Basic Recommendations

1. Assumptions and steps in manual design, and, assumptions and models in computer analysis, must be fully and clearly documented. They must be accompanied by complete and consistent drawings (even if freehand), with all the dimensions marked, for interpretation of the various hand calculations, and of the computer output.
2. Special and particular attention must be paid to design for unique features, unusual predictable loadings, erection and construction loadings, etc.
3. Design documents must include erection requirements and guidelines, particularly for bracing against buckling, for horizontal sway resistance, and to prevent any local failure due to overload or other trigger leading to total collapse.
4. Design should include, to the extent possible and under proper professional contract and compensation, features to

facilitate maintenance and demolition.

5. Design reports should include specific exclusions of what designer is <u>not</u> responsible for, so that he may not be held legally accountable for omitted items.

21. Acknowledgements

The author acknowledges with gratitude material from various developers of resources in hardcopy and electronic resources on the web, some of which have been cited under References. Any omission of citation or infringement of copyright is unintentional and accidental; upon intimation of such lapses, the author will be happy to make appropriate acknowledgment.

22. References

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