# BUILDING FAILURES

-CAUSES & CASE STUDIES

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## INTRODUCTION

In today's fast rising era where the thing of the future boils down to a country's ability to establish world class infrastructures and magnificent skyscrapers- construction builders, engineers and architects consider the most important aspect of the project itself, the structural stability.

Recently if we notice present problems facing by civil engineers, first and foremost thing is building failures and its collapse.

Before considering failures let me ask

- From where the concept of factor of safety came?
- Why we are particular about fire safety in buildings?
- Can any anyone tell me why every civil engineer has to follow certain code for design?

Since humans first started construction, there have been numerous occasions when the structures failed. From those failures they searched for solutions. And those solutions are the codes we follow to prevent further such failures.

**"Bad times have a scientific value. These are occasions a good learner would not miss."**
**-Ralph Waldo Emerson**

According to him there will be some scientific cause for every failure to happen. A good learner in the sense a good civil engineer always finds a way to overcome that failure.

Every civil engineer should accept the concept of failure as study from failures is essential to appreciate engineering, with its objective to obviate failure. Every designed structure is still a man-made endeavor thus, it is subject to error. Owed to this, some designs are predestined to fall short.

All efforts are essential to prevent structural failure as it involves dangers to human life and property. There are numerous causes for a structural failure, and there is a requirement for a proper analysis of all the factors before construction.

***What to learn from this:***

- Discuss ways to improve designs and design process to prevent structural failure.
- Discuss common causes of construction failures, and their prevention.

## GENERAL CAUSES OF FAILURE:-

The causes of building collapse can be classified under certain heads as:

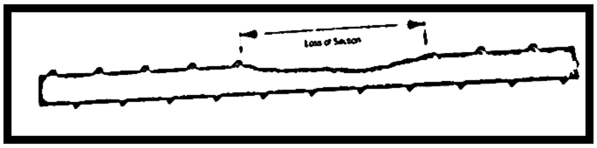
- Cracks and corrosion
- Thermal changes
- Bad Design
- Faulty Construction
- Foundation Failure
- Fire accidents
- Extraordinary Loads and many more..

### Cracks and corrosion

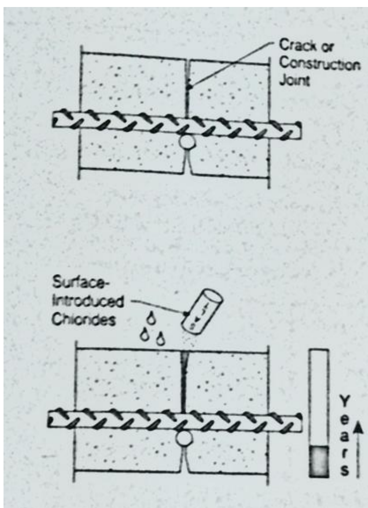
- ✓ A properly designed and constructed concrete is initially water-tight and the reinforcement steel within it is well protected by a physical barrier of concrete cover which has low permeability and high density.
- ✓ Concrete also gives steel within it a chemical protection.
- ✓ Steel will not corrode as long as concrete around it is impervious and does not allow moisture or chlorides to penetrate within the cover area.
- ✓ Steel corrosion will also not occur as long as concrete surrounding it is alkaline in nature having a high pH value.
- ✓ Due to wetting and drying cycles, heating and cooling cycles, loading and unloading cycles, cyclic loading, leaching of lime and most importantly additions and alterations

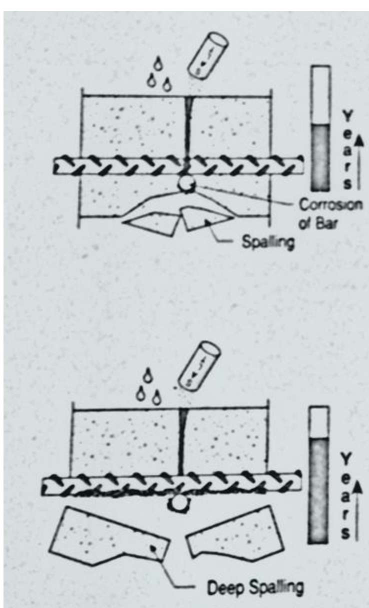
done on the structures, isolated cracks, voids, entrapped air and large capillary pores get interconnected and external moisture and chlorides find their way to reinforcement steel and corrosion starts.

- ✓ Main causes –
  - i. Sulphate attack
  - ii. carbonation

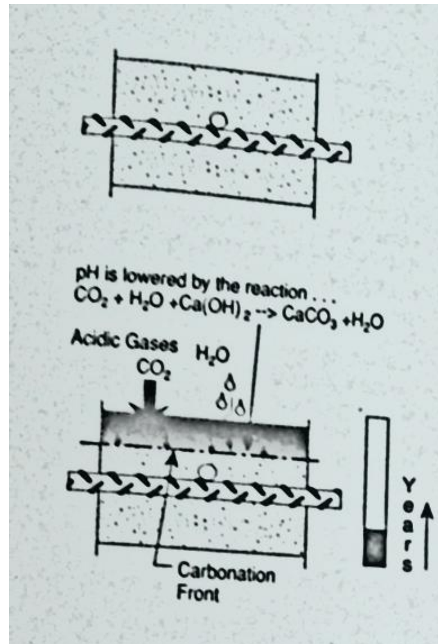


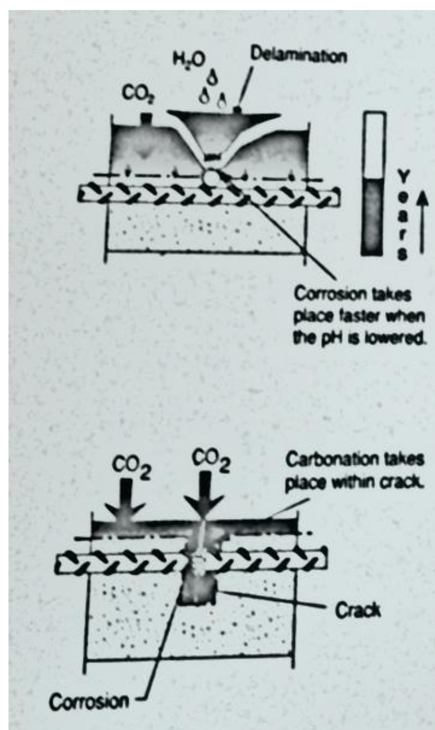
**SULPHATE ATTACK**



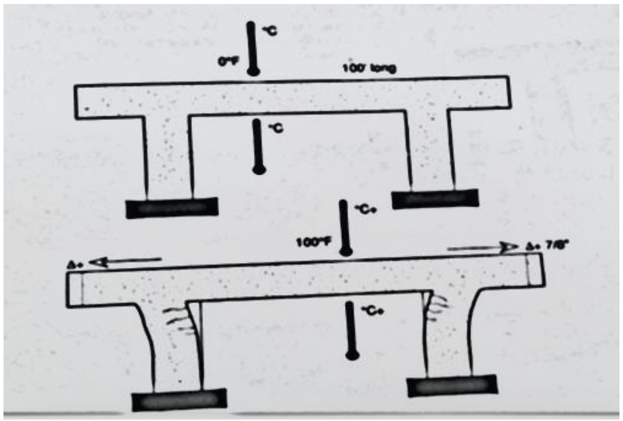

**CARBONATION**



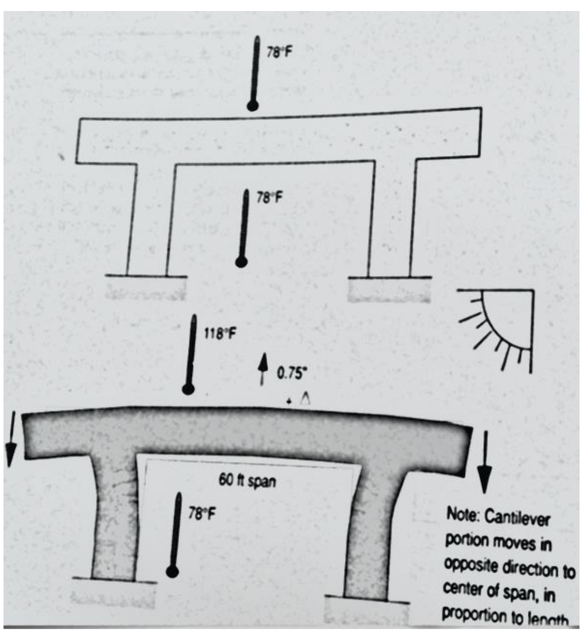
**Thermal changes:-**

Thermal volume change:-

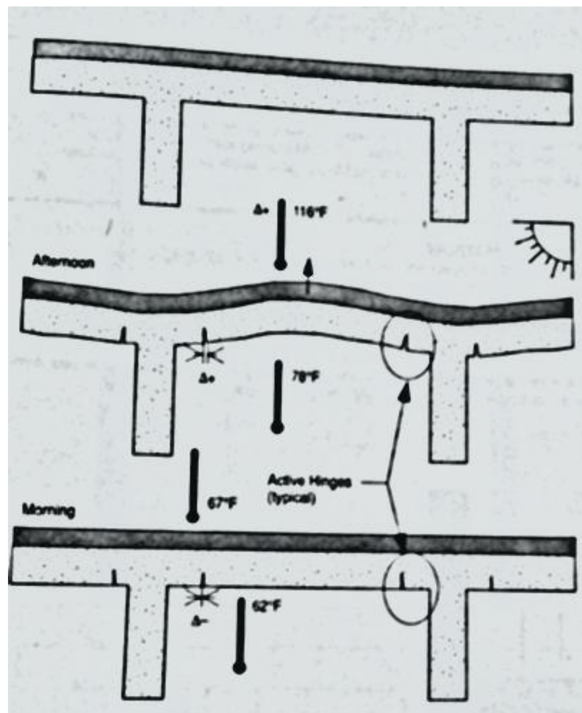



**UNEVEN THERMAL LOADS:-**

Temperature gradients exist in many structures. The temperature of the deck slab exposed to direct sunlight may reach 48$^{o}$C, while the underside of the deck slab may be only 26$^{o}$C. A 22$^{o}$C difference known as **diurnal solar heating.** This causes the top surface to have a tendency to expand more than the bottom surface. This results in a upward movement during heating and downward movement during cooling

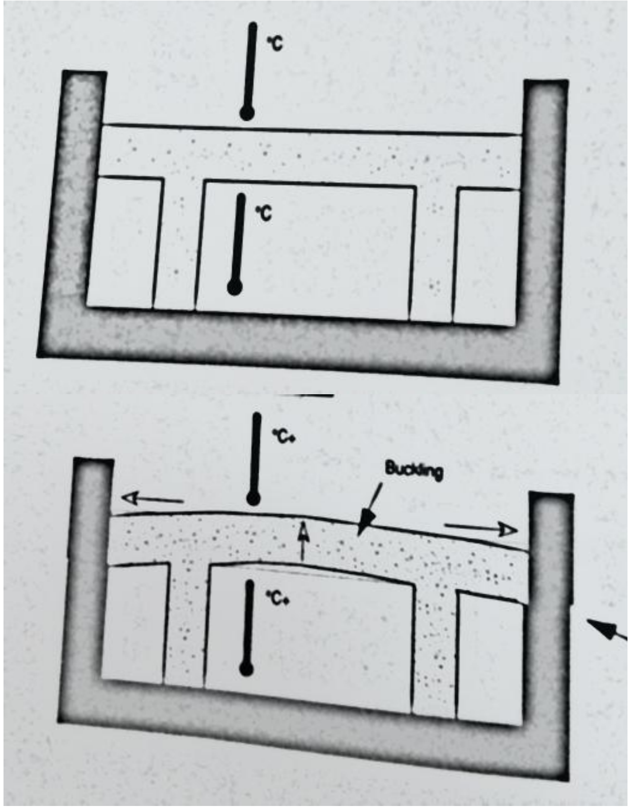



Diurnal solar heating affects structures differently depending on the configuration. Simple span structures deflect up and down and are free to rotate at end supports. Continuous spans behave differently because they are not free to rotate at end supports. If enough thermal gradient exists along with insufficient tensile capacity in the bottom of the member, a hinge may form. Hinges forms randomly in newly formed cracks or near construction joints of the columns. Hinges open and close with daily temperature changes.




**Restrain to volume changes:-**

If a structural member is free to deform as a result of changes in temperature, moisture or loads, there is no build-up of internal stress. If the structure is restrained, stress build-up occurs and can be very significant. The stress may result in tension cracks, shear cracks, and buckling.




## Bad design

Bad design includes not only errors of computation, but failure to take into account all the loads the structure should be able to carry for the building's intended use. Prudent design is based on established theories, reliance on accurate data, cognizance of the effects of repeated or impulsive stresses, and proper choice of materials based on in-depth understanding of their properties. Failures many a time enters a building project at the drawing board itself due to lack of due diligence by the engineer. A case in point is the Singapore New World Hotel collapse cited where the structural engineer blundered by forgetting to consider the dead load of building itself in the 'design loads'!

**The Hotel New World Collapse (**March 15, 1986)

**Introduction**

On March 15, 1986, the Hotel New World Collapsed in less than 60 seconds at approximately 11:30 am.

It had thirty six reinforced concrete columns that supported six concrete floors, totaling a weight of 6,000 tons. And basically the building experienced no severe impact or structural damage during its lifetime.

**Speculations and Forensic Study**

First, many engineers who examined the rubble and the speed of the collapse thought of the incident as out of the ordinary and unexpected internal explosion caused by a bomb or terrorist attack was responsible for the collapse. As any investigators would do, the engineers evaluated the building's history. They concluded that a gas leak was the only incident that occurred. It was feared to have re-occurred, resulting in an explosion that brought down the entire building.

However, as investigations progressed, no evidence of an explosion was found, as this type of disaster has its own distinctive footprints.

- ✓ Evidence of explosions include shattered glass, small debris of walls and crushed rubble blown to tens, even hundreds, of meters away.

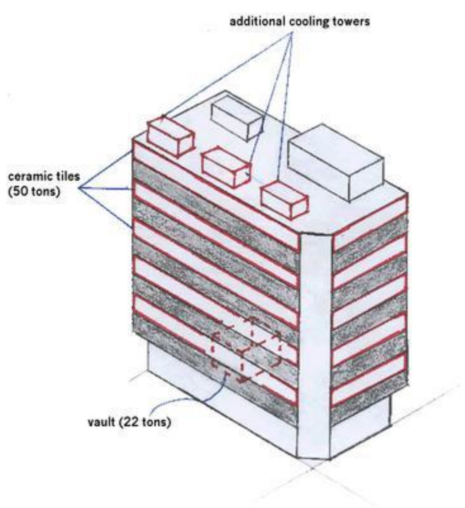
Secondly, the building failed suddenly and vertically. This vertical failure provoked curiosity amongst the engineers, so they investigated all the witnesses. The first sign of progress happened when they debriefed the rescuers. They reported that when drilling through the concrete, the drills were very smooth and quick like a knife cutting butter. This result can come from the following two theories:

- ✓ One is that the concrete was badly mixed and caused the strength of the concrete to decrease or

- ✓ That softness of the concrete was due to the fractures of the collapse.

Samples were brought into labs for strength and consistency testing. The concrete met all of the international safety standards, concluding that the strength of the material was not the problem. This theory of defective building materials was ultimately eliminated from the list.

Third, the investigators then turned to another dangerous hypothesis. They examined the land under the building and realized that it used to be a swampy flat plane drained since the 19th century. It was not an issue in the past as buildings were not as tall as the New World Hotel, but this scenario caused panic as it could have propagated to an island wide devastation. Nevertheless, engineers looked at the surviving foundation and basement walls of the structure. If movement had occurred, it could have been easily noticed




as the walls would have had big cracks but nothing was found. The forensic team double checked by analyzing the composition of the soil and tested the strength of the surviving foundations. Hence, there was no failure in the foundation even though minor movements had occurred.

**Reason behind the failure**

Buildings don't spontaneously collapse, therefore a critical clue or piece of evidence was missing to unveil the mystery of the Hotel New World building. The report and description given by the witness who reported the cracks in the column on the second floor the night before offered the first clue to determining the true cause of the collapse. In fact, all the witnesses' reports together unveiled everything. Each report contained unique failures throughout the building. The investigators referred back to the plans and realized that each failure corresponded to different columns; they failed because they were stressed to their limit. This was proven by examining the concrete on the microscopic level. In fact, when concrete is stressed to the limit, tiny cracks-- also known as micro-cracks invisible to the naked eye in the particles are developed.

Furthermore, these micro-cracks that were found in laboratory testing explained the description of the cracking columns reported by the witnesses. Such cracks reduced the weight that is supported by the piers and initiated a progressive collapse. Hence, the loads on the building needed to be rechecked by the investigators to recognize the origin of the cracks. It could have been that either the supporting elements were under-designed in the construction phase, or the building saw extra and uncalculated weight throughout its lifetime. As expected, the investigators found heavy equipment in the rubble that was not in the original design plans. During its fifteen years of life span, the owner of the building had added extra weight:

*In 1975, the bank added a vault weighing twenty-two tons on the ground floor. *In 1978, the building owner added two additional cooling towers on the roof. *In 1982 for architectural reasons, the

building owner fixed heavy duty ceramic tiles on each exterior face on every floor weighing a total of fifty tons. *In 1986 the owner installed an additional cooling tower on the roof.
However, all this extra weight that was added to the structure fell under the live load category and was already accounted for. In detail, the calculations of the engineers proved that the one hundred and ten tons of extra weight was trivial to the collapse.
Finally, the engineers returned to their blue prints and calculations. They pulled out the plans and calculations of the draftsmen and realized that the building's dead load was not accounted for in the original design. This monumental mistake meant that the building was on the verge of collapse since its construction. The building columns were stressed to their limit from day one and their collapse was inevitable.

**Result:-**

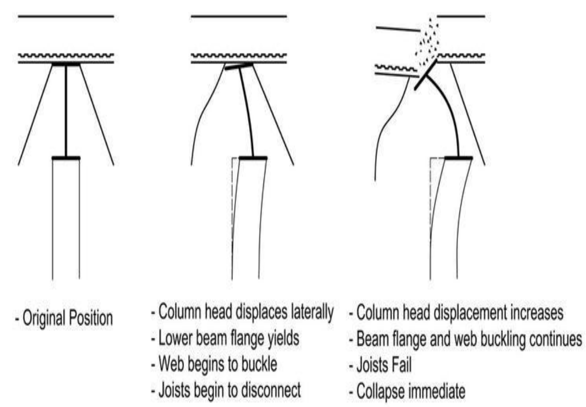
After the Hotel New World collapsed, building codes and standards were improved throughout Singapore as well as the implementation of engineering ethics.

The progressive collapse, which is defined as the spread of an initial local failure from element to element, eventually resulted in bringing the structure down.
New legislation was passed and the Building Control Act of 1989 was endorsed along with the Building Control (Accredited Checkers) Regulations of 1989. The formation of the Accredited Checkers was the unique feature of the 1989 Building Control Act. The "accredited checker" aids in providing additional help and inspection over the design of the engineers in charge. The government enforces that owners conduct maintenance every five years by professional engineers.

**Faulty construction:-**

Faulty construction perhaps is the most important cause of structural failure. The lack of proper construction supervision and timely inspection by engineer & architect is a key contributor. Some faulty practices to be firmly checked and stopped are the use of salty sand to make concrete, the substitution of inferior steel for that specified, bad riveting, improper tightening torque on nuts, excessive use of the drift pin to make holes line up, bad welds, and all such practices well known as taboo in construction field.

**Faulty construction practices:-**
**Insufficient beam- column joint support:-**




**Supermarket Roof Collapse - Burnaby, B. C., Canada**

## POOR COMMUNICATION BETWEEN THE DESIGNER AND THE FABRICATOR

### Hyatt Regency Walkway Collapses

The case study presented here focuses on the professional responsibilities of structural engineers as they assume overall responsibility for their designs. It also focuses on the need for a uniform understanding of the means by which specific responsibilities are communicated between the members of project team.

On *7th* July *1981*, a walk way collapsed in Hyatt Regency Hotel, Kansas City. As spectators gathered on suspended walkways above the dance floor, the support gave way and the upper walkway fell on the lower walkway, and the two fell onto the crowded dance floor, killing *114* people and injuring over *200*.

The two walkways were supported above one another and suspended from the ceiling by hanger rods.

The walkways were supported on box beams, which were made of two steel channels, welded together.

In the original design a single rod supported the two walkways as shown in Fig5(a).

But the originally designed hanger detail for the two walkways was altered at the time of fabrication as shown in Fig. *5(b)*.

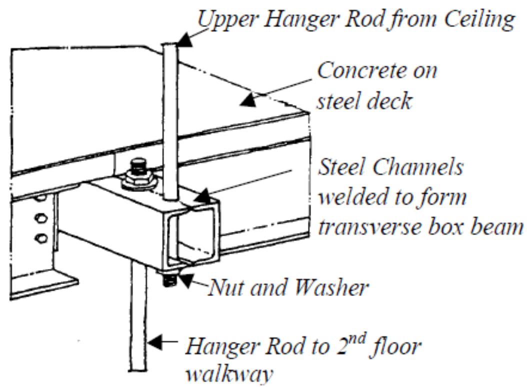
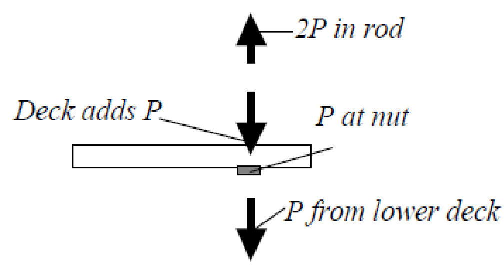
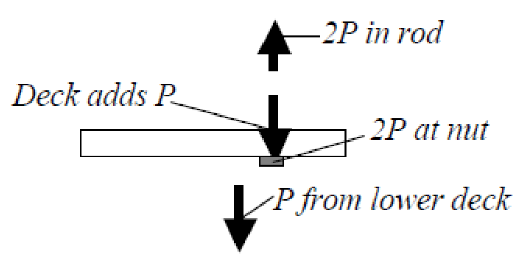



***Fig. 5(b): Hyatt Regency Hanger Details As-Built***

Second floor walkway was suspended from the fourth one as shown. As a result, the connection between the fourth floor cross beam and the hanger supported double the load originally intended as shown in Fig.




(a)




(b)

This condition was aggravated by the increased load on the nut. The nut pulled through the box beam as shown in Fig.

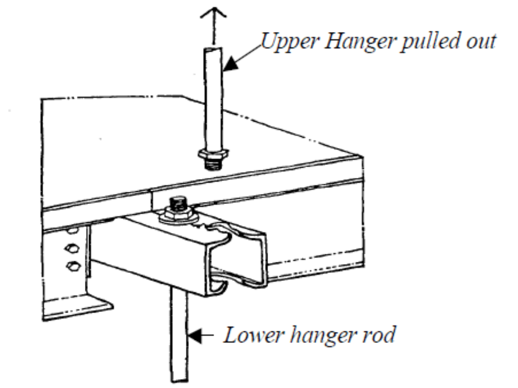
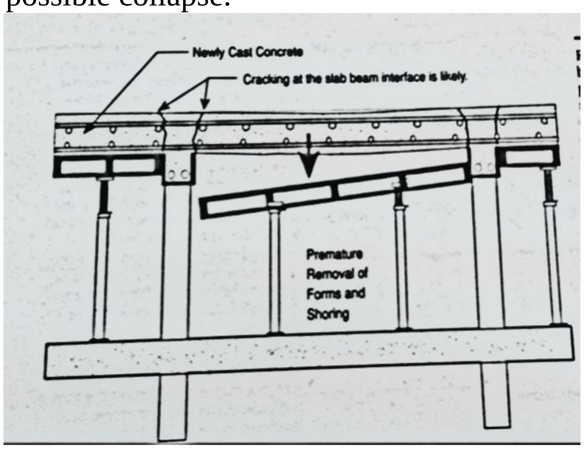



*Fig. 7: Pulled -Out Rod at Fourth-Floor Box Beam*

**PREMATURE REMOVAL OF FORMS:** Removal of forms (including shoring) before the concrete has reached its proper strength may result in compression and tension stresses, causing cracking, and possible collapse.




**Skyline Plaza, Virginia, USA**

On March 2, 1973, one of the sky line Plaza complex's towering apartment buildings collapsed, leaving where it once stood, a huge cloud of dust and debris.

Construction hadn't even been completed in the complex in Bailey's Crossroads, Virginia at the time of the disaster and the building was not due to open until six months.

Failure Cause: There was no flaw in the design.

Investigation showed that:

- During construction the forms supporting the concrete columns on the 22nd floor were prematurely removed. The cement had not set fully by then. As a result the columns couldn't bear the weight of the 24th floor and failed.
- The failure put an increased amount of pressure on the rest of the columns on the 23rd floor until the entire floor buckled and slammed down on the floor below.
- The building had not been engineered to withstand such a huge increased load, and the tremendous weight proved catastrophic. Each floor gradually succumbed and plummeted onto the story below in a devastating ripple effect.

Fourteen construction workers died and 34 were injured.

Lesson Learnt: Though design may be sound but so should be the execution per design and observing right construction which practice, in this case has been found wanting. Inspection & testing coupled with regular supervision are not mere formalities but activities that can make or mar a project; or shall we say, make or break a building!

**PRECAST CONSTRUCTION:**

**Ronan Point**

On 16 May 1968 the 22 storey residential tower Ronan Point in the London Borough of Newham collapsed when a relatively small gas explosion on the 18th floor caused a structural wall panel to be blown away from the building. The tower was constructed of precast concrete, and the failure of the single panel caused one entire corner of the building to collapse. The panel was able to be blown out because there was insufficient reinforcement steel passing between the panels. This also meant that the loads carried by the panel could not be redistributed to other adjacent panels, because there was no route for the forces to follow.

Aftermath & Lessons Learnt: 'Tie them well' is the lesson learnt. Reinforcements reinforce! Use them as much as needed. As a result of the collapse, building regulations were overhauled to prevent disproportionate collapse. The understanding of precast concrete detailing was greatly advanced. Based on this many similar buildings were altered or demolished.

**FOUNDATION FAILURE:-**

Houses and commercial buildings usually look very solid. Built with concrete, and beams, it's hard to imagine what could cause them to crack and shift other than an earth quake.

A foundation rightly designed is a pre-requisite for every structure to stand on, with ability to bear loads that the structure is carrying. The earth beneath the building should be (or made such) that structural loads can be sustained.

There are many causes of foundation failure, here are the five main ones.

1. Soil type – especially expansive clay soil
2. Poorly compacted fill material
3. Slope failure, mass wasting
4. Erosion
5. Poor construction

**SIGNS:-**

- Cracks in walls and floors;
- Doors and windows that won't open;
- Stairs that come away from porches,
- Chimneys that separate from the house siding, and much more…..

**Soil Type – Expansive Clay Soil**

The most common kind of expansive clay can absorb so much water that it can swell by several hundred percent. The pressure from this degree of swelling can easily lift or "heave" most residential homes. Soils expand with moisture and they contract with desiccation, causing up and down movements known as differential settlement. To preserve structural integrity of the building, we have to provide underpinning for the foundation.

**Poorly Compacted Fill Material**

If the fill material on a lot is not sufficiently compacted to support the weight of the structure above it, there will be foundation problems. The problem can be from the mix of odd fill materials, and from poorly compacted fill, or both.

**Slope Failure / Mass Wasting**

Geologists use the term "mass wasting" to describe the movement of earth downhill. It could be "creep" which is slow, or "landslides" which are sudden. Slope failure as we use it refers to "creep".

Underpinnings can act as a barrier to "creep", but the power of gravity is such that unless the underpinnings were specifically designed to stop slope failure, warranties can't usually cover this in sites exposed to slope failure.

**Erosion**

Erosion may be the most straightforward cause of settlement issues. It can come from poor drainage, uncontrolled water flow or lack of ground cover. If not identified early, erosion can wear away the soil around foundations, creating a new need for underpinning.

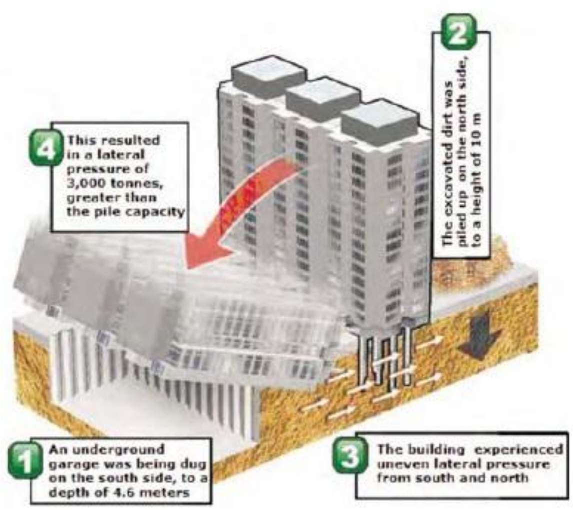
**CASE STUDY:-**

**Rare Foundation Failure of a Building in Shanghai, China**

At around 5:30am on June 27, 2009, an unoccupied 13-storey block of flat building, still under construction toppled over and ended up lying on its side in a muddy construction field.

**Cause of Failure**

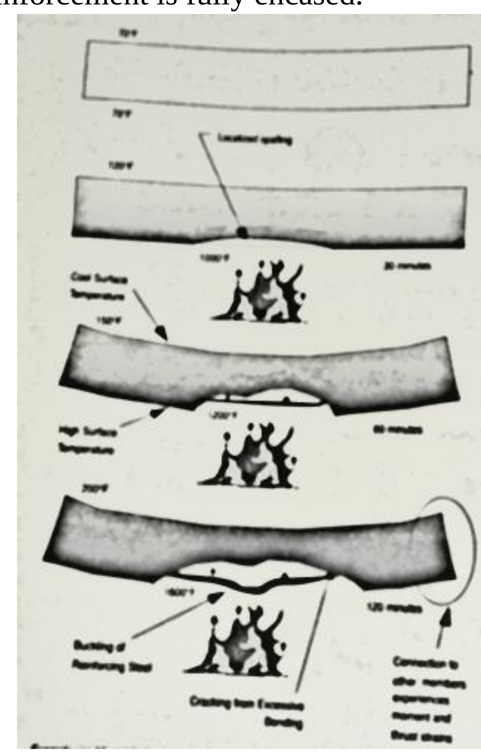
The cause of the building collapse in Shanghai was due to a pressure difference on two sides of the structure. The collapse was caused by earth, excavated along the building on one side with a depth of 4.6 m, for an underground car park, and piled up to depths of up to 10 m on the other side of the structure (see Fig. 2). The weight of overburden earth created a pressure differential, which led to a shift in the soil structure, eventually weakening the foundations and causing them to fail. This situation might have been aggravated by several days of heavy rain leading up to the collapse, but investigators did not site this as a crucial factor.




**FIRE ACCIDENTS:-**

Fire affects concrete in extreme ways, some of which are listed below-

a) Uneven volume changes in affected members, resulted in DISTORTION, BUCKLING & CRACKING.
b) Spalling of rapidly expanding concrete surfaces from extreme heat near the source of fire. Some aggregates expand in bursts, spalling the adjacent matrix. Moisture rapidly changes to steam, causing localized bursting of small pieces of concrete.
c) The cement mortar converts to quick lime at temperatures of $400^{o}C$, thereby causing disintegration of the concrete.
d) Reinforcing steel loses tensile capacity as temperature rises.
e) Once the reinforcing steel is exposed to the spalling action, steel expands more rapidly than the surrounding concrete, causing buckling and loss of bond to adjacent concrete where the reinforcement is fully encased.



**FAILURE ANALYSIS OF THE WORLD TRADE CENTER**

Everyone are familiar with 9/11 attacks on the World Trade Center, which resulted in the collapse of the two towered structure.

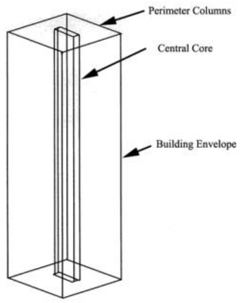



Figure shown is a simplified drawing of one of the tower structures.

- A central core houses elevators and supports the weight of the floors.
- Around the outside of the building are closely spaced (39 inch centers) perimeter columns that are designed to resist lateral wind loads and support the outer edge of each floor.
- Floor trusses, under a 4-inch concrete floor, are connected between the perimeter columns and the core structure.

The design is efficient and attractive in that there are no columns in the work space area. The buildings were 208 feet wide, about 1360 feet tall with 110 stories. After the aircraft impacts, the towers remained in place for about an hour, attesting to the robust structural design. The World Trade Center towers used neither a steel skeleton nor reinforced concrete. They were designed as square tubes made of heavy, hollow welded sections, braced against buckling by the building floors. Massive foundations descended to bedrock, since the towers had to be safe against winds and other lateral forces tending to overturn them. All this was taken into consideration in the design and construction, which seems to have been first-rate. An attempt to damage the buildings by a bomb at the base had negligible effect. The strong base and foundation would repel any such assault with ease, as it indeed did. The impact of aircraft on the upper stories had only a local effect, and did not impair the integrity of the buildings, which remained solid. The fires caused weakening of the steel, and some of the floors suddenly received a load for which they were not designed.Each tower contains about 1,00,000 tons of steel and concrete. Assuming the aircraft damaged the north tower structure at about 80% of the total height, then roughly about 20,000 tons would be borne by the structure that survived. The reduced structural capacity was the first ingredient in the failure. The second was the heating effect brought on by the burning jet fuel. As temperatures approach 1500 F, structural steel loses its ability to support weight and begins to deform which is known as thermal creep. Figure 2 shows a view of typical steel beams and columns after a fire.

It is clear that buildings built in this manner have a catastrophic mode of failure ("house of cards") that should rule out their future construction. It is triggered when there is a partial collapse at any level that breaks the continuity of the tube, which then rolls up quickly, from top to bottom. The collapse has a means of propagation that soon involves the whole structure, bypassing its major strengths and impossible to interrupt. There is no need for an airliner; a simple explosion would do the job.

EXTRORDINARY LOADS:-

**The Kemper Arena Collapse**

The Crosby Kemper Memorial Arena (Basketball stadium), was built in Kansas City, Missouri in 1973.

It had 17,600 seats, and the roof was about 3 acres of steel and concrete. The roof alone weighed over 1,500 tons. The building had even won an Honor Award from the American Institute of Architects (AIA) because the structure will not be having any columns, Instead the massive roof was suspended on hangers from 3 space frame cantilever trusses. Each truss was 54 feet wide and they were spaced 99 feet apart. The roof was designed to hold water as a temporary reservoir in order to reduce the amount of storm water runoff into the sewers of the surrounding area, which could not handle too much water. "It had only eight 5 in. diameter drains; the local code actually required 8 times as many,"

Day of collapse:-

On June 4, 1979, there was a tempestuous storm. At 6:45 p.m., the storm was dumping approximately 4 inches of rain an hour. This rate was too fast for the drains to empty out enough rain fast enough. The way the drains were built, rainwater could pour out over the drains at the amount of only 2 inches of rainwater. This caused the water to "pond" on top of the roof, which added weight to the tremendous burden the bolts already had to carry. This, combined with the 70 mph wind speeds, was too much for the Kemper Arena roof. About 1 acre of the roof collapsed into the unoccupied stadium.

**Major Causes of the Collapse**

1. the building had drain deficiencies
2. choice of materials for bolts("Steel codes[the ASTM A490] suggests not to use bolts under variable loads,")
3. lack of redundancy under partial failure.

**CONCLUSION:**

Post mortem is an exact science. By employing it, we can establish the illness, which caused the death of the patient with a high degree of certainty. Many advances in Medical Sciences have been made possible by a systematic compilation of the results of postmortem studies.

Engineering Designers, on the other hand, have been reluctant to reflect openly upon the causes of design failures, thus denying themselves and the profession an opportunity to understand the limitations of the particular design concept and improve the methodology.

For example, by 1840 the British Engineers had simply abandoned the design development of suspension bridges, following the collapse of Menai Strait Bridge and suspension structures at Brighton Pier. All these failed in high winds, due to inadequate stiffening of the decks, a deficiency not recognized by the designers at the time.

Rather than interpreting the failures as an indictment of the form chosen, a contemporary American Engineer John Roebling collected case studies and established the forces – which must be designed against in order to build a successful suspension bridge. This encouraged the suspension bridge technology. Design is a process of the anticipation of failure, and as such the more knowledgeable the designer is about failures, the more reliable his designs will be. Design is a human endeavor and thus it is subject to error. Due to this, some designs are destined to fail.

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