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Structural Failure of Buildings: Issues and Challenges

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ABSTRACT

This paper discusses a list of information and issues that causes of structural failure of buildings. Structural failure begins to occur when the material is stressed to its upper strength limit causing to rupture or extreme deformations. The ultimate strength of the material or the system is the limit of the load bearing capacity. On reaching this limit, the construction materials could already been damaged, and their load carrying capacity is suddenly decreased permanently. If the system is properly designed, a local collapse should normally not be a cause of instant or gradual failure of the complete building. The ultimate failure strength of the construction elements should be carefully considered in the design of structures to prevent failure.

Keywords: Buildings, bracing structures, construction materials, earthquake, structures, structural failure, seismology

1. INTRODUCTION

Buildings are designed to support certain loads without deforming excessively. The loads are the weights of people and objects, the weight of rain and snow and the pressure of wind--called live loads--and the dead load of the building itself. With buildings of a few floors, strength generally accompanies sufficient rigidity, and the design is mainly that of a roof that will keep the weather out while spanning large open spaces. With tall buildings of many floors, the roof is a minor matter, and the support of the weight of the building itself is the main consideration. Like long bridges, tall buildings are subject to catastrophic collapse.

The causes of building collapse can be classified under general headings to facilitate analysis. These are bad design, faulty construction, foundation failure, extraordinary load, unexpected failure mode and a combination of causes

Bad design does not mean only errors of computation, but a failure to take into account the loads the structure will be called upon to carry, erroneous theories, reliance on inaccurate data, ignorance of the effects of repeated or impulsive stresses, and improper choice of materials or misunderstanding of their properties. The engineer is responsible for these failures, which are created on the drawing board.

Faulty construction has been the most important cause of structural failure. The engineer is also at fault here, if the inspection has been lax. This includes the use of salty sand to make concrete, the substitution of inferior steel for that specified, bad riveting or even improper tightening torque of nuts, excessive use of the drift pin to make holes line up, bad welds, and other practices well known to the construction worker.

Even an excellently designed and constructed structure will not stand on a bad foundation. Although the structure will carry its loads, the earth beneath it may not. The Leaning Tower of Pisa is a famous example of bad foundations, but there are many others. The old armory in St. Paul, Minnesota, sank 20 feet or more into soft clay but did not collapse [1]. The displacements due to bad foundations may alter the stress distribution significantly. This was such a problem with railway bridges in America that statically determinate trusses were greatly preferred since they were not subject to this danger.

Extraordinary loads are often natural, such as repeated heavy snowfalls, or the shaking of an earthquake, or the winds of a hurricane. A building that is intended to stand for some years should be able to meet these challenges. A flimsy flexible structure may avoid destruction in an earthquake, while a solid masonry building would be destroyed. Earthquakes may cause foundation problems when moist filled land liquefies.

Unexpected failure modes are the most complex of the reasons for the collapse, and we have recently had a good example. Any new type of structure is subject to unexpected failure until its properties are well understood. Suspension bridges seemed the answer to bridging large gaps. Everything was supported by a strong cable in tension, a reliable and understood member. However, sad experience showed that the bridge deck was capable of galloping and twisting without restraint from the supporting cables. Ellet's bridge at Wheeling collapsed in the 1840's, and the Tacoma Narrows bridge in the 1940's, from this cause [1,2].

The conservative, strong statically determinate trusses were designed with pin-connected eyebars to be as strong and safe as possible. The sad experience brought the realization of stress concentration at the holes pierced in the eye bars. From earliest times, it has been recognized that tension members have no surprises. They fail by pulling apart when the tension in them becomes too high. If you know the tension, then proportioning a member is easy. A compression member, a column, is different. If it is short and squat, it bears its load until it crushes. But if you try to support a load with a 12-foot column that will just support the load with a 1-foot column, you are in for a surprise. The column bends outward, or buckles and the load crashes to earth [3].

Tall buildings have generally been made with a rigid steel skeleton, sheathed in the lightest materials to keep out the weather. Alternatively, reinforced concrete, where the compression-resisting and protecting concrete surrounds the tough, tension-resisting steel, integrated into a single body, has been used. Such structures have never failed (when properly built on good foundations), and stoutly resist demolition. When the lower supports of a steel

skeleton are destroyed, the weight of the building seems to crush the lower parts and the upper parts descend slowly into the pile of debris. Monolithic reinforced-concrete buildings are difficult to demolish in any fashion.

The World Trade Centre 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.

The slumped floors pushed the steel modules outwards, separating them from the floor beams. The next floor then collapsed on the one below, pushing out the steel walls, and this continued, in the same way that a house of cards collapses. The debris of concrete and steel modules fell in a shower while the main structure collapsed at almost the same rate. In 15 seconds or so, 110 stories were reduced to pile 9 stories high, mainly of steel wall modules and whatever was around them. The south tower collapsed 47 minutes after impact, the north tower 1 hour 44 minutes after impact. The elapsed times show that the impacts were not the proximate cause of collapse; the strong building easily withstood them. When even one corner of a floor was weakened and fell, the collapse would soon propagate around the circumference, and the building would be lost.

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. There were central tubes in the towers, for elevators and services, but they appeared to play no substantial role in the collapse and were not evident in the pictures or wreckage.

2. COLLAPSE BUILDINGS

2. 1. Sampoong Department Store, South Korea

The Sampoong Department Store collapse was a structural failure that occurred on June 29, 1995, in the Seocho-gu district of Seoul, South Korea. The collapse is the largest peacetime disaster in South Korean history as 502 people died and 937 were injured. It was the deadliest modern building collapse until the September 11 attacks in New York City, and the deadliest non-terror-related building collapse until the 2013 Savar building collapse near Dhaka, Bangladesh [4].

The Sampoong Group began construction of the Sampoong Department Store in 1987 over a tract of land previously used as a landfill. The building's plans originally called for a residential apartment with four floors, and the apartments were to be built by Woosung Construction. Instead, the blueprints were changed to that of a large department store during

the building's construction by the future chairman of the building, Lee Joon. This involved cutting away the number of support column to install escalators. When Woosung refused to carry out the changes, Lee ignored its warnings, fired him, and used his own building company to complete construction. The building was completed in late 1989, and the Sampoong Department Store opened to the public on July 7, 1990, attracting an estimated 40,000 people per day during the building's five years of existence. The store consisted of north and south wings, connected by an atrium.



Figure 1. Sampoong Department Store, South Korea

The completed building was a flat-slab structure, without crossbeams or a steel skeleton, which effectively meant that there was no way to transfer the load across the floors. To maximize the floor space, Lee Joon ordered the floor columns to be reduced to be 24 inches (61 cm) thick, instead of the minimum of 31 inches (79 cm) in the original blueprint that was required for the building to stand safely. In addition, each column was 36 feet (11 m) apart to maximize retail space, a decision that also meant that there was more load on each column than there would have been if the columns were closer together.

A fifth floor was originally planned to house a roller skating rink; it was added later to comply with zoning regulations that prevented the entire building from being used as a department store. However, Lee changed the plan for the fifth floor to include eight restaurants instead. A construction company tasked to complete the extension advised that the structure would not support another floor but was fired, and another company was hired to complete the project. The restaurant floor had a heated concrete base referred to as “ondol”, which has hot water pipes going through it; the presence of the 4-foot-thick (1.2 m) “ondol”

greatly increased the weight and thickness of the slab. As a result of the fifth floor's presence, the columns held up four times the maximum weight that they were supposed to support.

In addition, the building's air conditioning unit was also installed on the roof, creating a 45-tonne (50-ton) load that was four times the design limit. In 1993, the air conditioning units were dragged across the delicate roof, where the cracking started. The units were moved over the column 5E, where the most visible cracks in the floor of the fifth level were seen before the collapse. The cracks in the columns worsened because the columns supporting the fifth floor were mismatched with the ones supporting the floors below it.

In April 1995, cracks began to appear in the ceiling of the south wing's fifth floor. The only response by Lee and his management staff involved moving merchandise and stores from the top floor to the basement [5].

On the morning of June 29, the number of cracks in the area increased dramatically, prompting managers to close the top floor and shut the air conditioning off. The store management failed to shut the building down or issue formal evacuation orders as the number of customers in the building was unusually high, and it did not want to lose the day's revenue. However, the executives themselves left the premises, as a precaution.

Civil engineering experts were invited to inspect the structure, only a cursory check revealing that the building was at risk of collapse; the National Geographic Channel documentary programme *Seconds From Disaster* indicates that the facility's manager was examining the slab in one of the restaurants on the fifth floor, only hours before the collapse, when, unknowingly, vibration from air conditioning was radiating through the cracks in the concrete columns, and the floor opened up.

Five hours before the collapse, the first of several loud bangs was heard emanating from the top floors, as the vibration of the air conditioning caused the cracks in the slabs to widen further. Amid customer reports of vibration, the air conditioning was turned off, but the cracks in the floors had already grown to 10 cm wide. Around then, it was realized that collapse of the building was inevitable, and an emergency board meeting was held. The directors suggested to Lee that all customers should be evacuated, but Lee angrily refused to do so for fear of revenue losses. However, Lee himself left the building safely before the collapse occurred. Lee did not even inform his own daughter-in-law, Chu Kyung Young, who was one of the employees in the building, of the imminent danger. She became trapped in the rubble and was rescued only days later [2,4].

At about 5:00 p.m., Korea Standard Time, the fifth-floor ceiling began to sink, and store workers blocked customer access to the fifth floor. According to *Seconds From Disaster*, the store was packed with hundreds of shoppers 57 minutes before the collapse, but Lee did not close the store or carry out repairs during that time. When the building started to produce cracking sounds at about 5:52 p.m., workers began to sound alarms and evacuate the building, but it was too late.

Around 5:52 p.m., the roof gave way, and the air conditioning units crashed through into the already-overloaded fifth floor. The main columns weakened to allow the insertion of the escalators, collapsed in turn, and the building's south wing pancaked into the basement. Within 20 seconds of the disaster, all of the building's columns in the south wing gave way, killing 502 people and trapping more than 1,500 inside.

2. 2. Hotel New World, Singapore

The Hotel New World, previously known as the New Serangoon Hotel until 1984, was the main tenant occupying the top three floors, and a branch of the Industrial and Commercial Bank took up the ground level. A nightclub, Universal Neptune Nite-Club, and Restaurant, was also situated on the second level of the building at the time of the collapse. The building had previously experienced a poisonous gas leak (caused by carbon monoxide) in some of the hotel rooms, first hitting the headlines on 30 August 1975, the day after the poisonous gas leak was reported [5].

Many potential causes of the accident were investigated. Surviving sections of concrete were tested to ensure they were to proper construction standards, and it was found that they were. Even the construction work of the underground railway tunnels who had assisted in the rescue was investigated, even though the excavations were more than 100 yards from the collapsed building. It was found they had no effect on the building's stability. Also investigated were the various additions made to the building after its initial construction. Air conditioning systems had been constructed on the roof of the building, the bank had added a large safe, and ceramic tiles had been fixed to the building's exterior, all adding considerably to the building's weight. It was found that the weight of these additions was inconsequential.



Figure 2. Hotel New World, Singapore

However, this line of investigation into weight led to the discovery that the original structural engineer had made a serious error in calculating the building's structural load. The structural engineer had calculated the building's live load (the weight of the building's

potential inhabitants, furniture, fixtures, and fittings) but the building's dead load (the weight of the building itself) was completely omitted from the calculation. This meant that the building as constructed could not support its own weight. Collapsing was only a matter of time. After three different supporting columns failed in the days before the disaster, the other columns which took on the added weight no longer supported by the failed columns—could not support the building.

According to Channel New Asia, Lian Yak Building was designed by unqualified draftsman instead of a professional structural engineer. An investigator found that he had under-estimated the dead weight which the columns and walls could support. The investigator also found that Ng requested to use inferior materials to build Lian Yak Building in order to reduce the cost.

2. 3. Katowice Trade Hall, Poland

The roof of one of the buildings at the Katowice International Fair collapsed in Chorzów / Katowice, Poland [6]. The central section of the roof of the hall collapsed, possibly due to the weight of snow on the building. According to the police, there were roughly 700 people in the hall at the time of the collapse. A forensic investigation found numerous design and construction flaws that contributed to the speed of the collapse. The snow from the roof was not being removed which resulted in construction overload by more than 100%. In 2002, the construction buckled under the heavy snow; contrary to the regulations the hall was repaired without getting a building inspector's clearance and without doing necessary tests and calculations to determine if the construction was stable and had sufficient strength.



Figure 3. Katowice Trade Hall, Poland

2. 4. World Trade Center, USA

The Twin Towers of the World Trade Centre collapsed on September 11, 2001, as a result of being struck by two jet airliners hijacked by 10 terrorists affiliated with al-Qaeda, during the September 11 attacks. Two of the four hijacked airliners crashed into the Twin Towers, one into the North Tower (1 World Trade Centre) and the other into the South Tower (2 World Trade Centre). The collapse of the Twin Towers destroyed the rest of the complex, and debris from the collapsing towers severely damaged or destroyed more than a dozen other adjacent and nearby structures [7,9].

The cause of the tower's collapse is that the high temperatures in the fires weakened the steel beams and columns, causing them to become "soft and mushy", and eventually were unable to support the structure above. The fireproofing became dislodged during the initial aircraft impacts. The initial structural failure occurred; the progressive collapse of the entire structure was inevitable. The heat from the fires was a key factor, causing steel columns in both the core and the perimeter to weaken and experience deformation before losing their carrying capacity and buckling. Once more than half of the columns on a particular floor buckled, the overhead structure could no longer be supported and complete collapse of the structures occurred. Bažant later published an expanded version of this analysis [10,11].

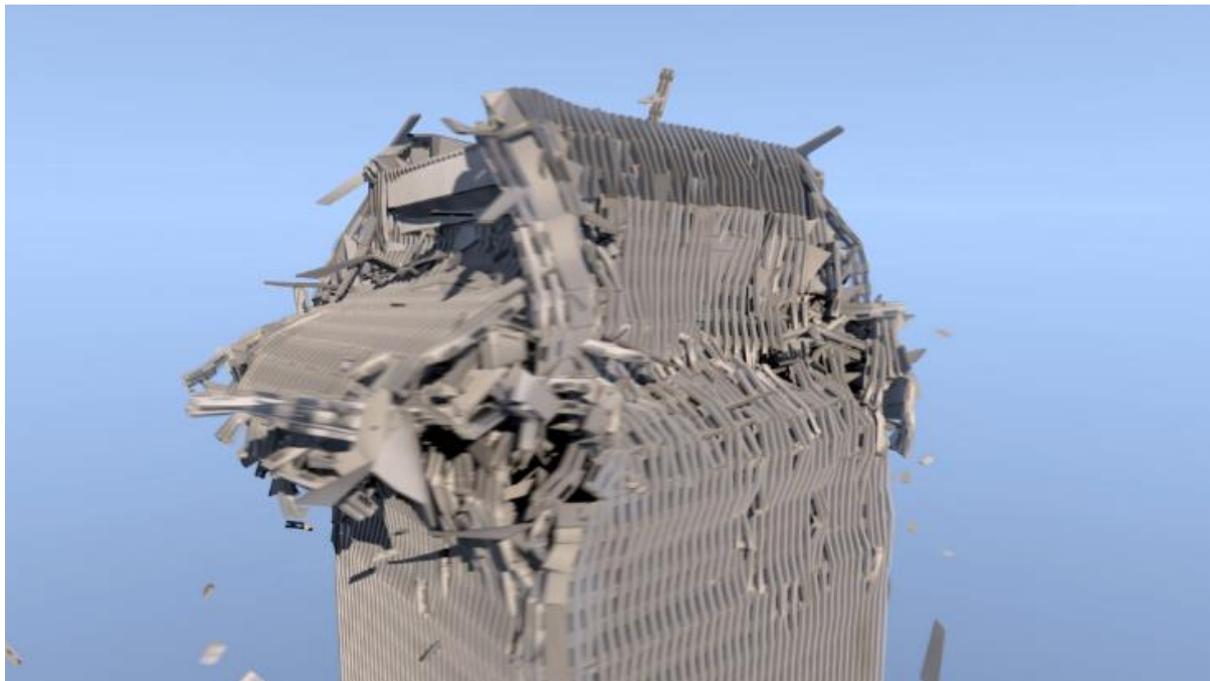


Figure 4. World Trade Center, USA

3. CAUSES OF BUILDINGS COLLAPSE

Building failure and collapse all over the world had been attributed to two phenomena: natural and man-made. The natural phenomenon aspect is triggered off by natural occurrences such as earthquakes, typhoons, and tsunamis, etc. and when occurred is regarded as the natural disaster. The manmade aspect is borne out of man's negligence in areas of soil type test,

building design and planning for extra loads and stress from strong wind and earthquakes for tall buildings, foundation works, quality of building materials, lack of inadequate monitoring of craftsmen and poor quality of workmanship. Both scholars and industry professionals are consensual about the causes of building failures and collapses. Common causes of building failure have been traced to bad design, faulty construction, foundation failure, extraordinary loads, use of unqualified contractors and poor project monitoring, lack of enforcement of building codes by the relevant authorities and /or industry professionals.

Building failures could be as a result of the defect under any or all of the stages in design approval of drawings and the supervision/ construction stages. Tragic incidents of building failures or collapses recorded in major cities and towns have been blamed on either the developers for failure to comply with building regulations or professional builders, architects and engineers, as well as government agencies whose duty is to ensure compliance.

In Nigeria, some clients have penchant for cutting corner by not employing qualified personnel to produce the contract documents and supervise the building construction, as they want to spend minimum (not optimum) amount of money on the construction. Even where qualified professionals are the final say on what goes on in the site to the detriment of proper execution of the contract”.



Figure 5. Collapse of Buildings

Related to the above scenario is the compromising attitude of some workers of the town planning authority; and lack of sanctions against erring professionals and landlords. Substandard materials especially reinforcement rods and cement can contribute greatly to the failure of building. Recent studies have validated this assertion, “low-quality materials is one

of the causes of structural failure. In efficient and fraudulent labour input contributes to failure of building. When a contractor cannot read drawings or refuses to listen to the instruction of consultants, anything can happen. Other corrupt practices in the built environment/building industry that are direct consequences of building failures and collapse include illegal alteration of existing buildings; approval of technical deficient drawings, building without building drawings, deficient structural drawing and alteration of approved drawings. Buildings fail when structural drawings are based on false assumptions of soil strength or as a result of faulty structural details.

4. PREVENTING STRUCTURAL COLLAPSE

4. 1. Control Measures

Structures should be able to resist extreme weather including high winds and surface water or run-off. They should be capable of withstanding dynamic forces and have solid foundations [12]. If unstable or likely to become unstable, a suitable large exclusion zone should be established around the structure until rectification works are completed. Temporary bracing should be considered if the structure is incomplete or works may affect stability where lateral support from piers, cross-walls, floors, and roof framework is missing or being altered, temporary bracing should also be used. Temporary bracing or other stability controls should be designed by a competent person who is experienced in such works e.g. professional engineer. To ensure work will not compromise stability, a competent person should be consulted before adding or making changes to or undertaking any structural work on the structure, or before excavating near the structure.

4. 2. Temporary Bracing Inspections



Figure 6. Preventing structural collapse with wallpaper

A competent person should inspect the temporary bracing arrangements and verify in writing the stability of the structure when the bracing is first installed. A competent person should regularly assess the stability of the structure while temporary bracing is required. Inspections should be done at regular intervals, based on a risk assessment that takes into account the structure's condition, environmental factors and length of time the bracing has been in place. In addition, an inspection should occur as soon as possible after an extreme weather event or another incident that could affect stability.

5. CONCLUSIONS

Considering the magnitude of human loss associated with building collapse and other disaster and the ineffectiveness of the emergency management, there is the need for immediate review of practical policy guidelines by the government that should be carried out to letter to make safe for living. In view of this, the following recommendations are necessary for implementation by all stakeholders in disaster management generally and building collapse. Policy review of the emergency agencies to simplify their hitherto bureaucratic procedures of operations; Adequate funding and monitoring of the activities of all emergency management agencies (NEMA, SEMA, LEMA, Red Cross Society, Fire Services, NGO's, among others); Creation of adequate emergency management awareness to the Nigerian populace, both rural and urban; Appointment of qualified and expert building professionals - architects, and engineers by building clients for design and supervision; Statutory implementation of all physical development planning regulations, acts, bye-laws and codes in the processing of building permit, actual construction and post occupancy follow-up; Prosecution of physical development and planning culprits.

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Biography

Dr. Mohammed Almarwae received his Ph. D degree in Architecture specialized in Alternative Energy Engineering in 2006 and subsequently earned his Bachelor of Engineering and Islamic Architecture in Umm Al Qura University (KSA) in 1994. He is the current Dean of Architecture in Qassim University (KSA). He served as Assistant Professor of Civil and Architectural Technology in Jeddah Technical College (KSA) and School of Architecture in King Abdulaziz University (KSA). Dr. Almarwae has been a consultant of many architectural projects in KSA and researcher of scientific journal in the field of traditional architecture, tubular daylight guidance system, urban planning and artistic techniques in Architecture

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