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Safe and Sustainable Tall Buildings: Current Practice and Challenges For the Future

PROF. DR. PRIYAN MENDIS
Department of Civil Engineering, University of Melbourne, Australia

Email: pamendis@unimelb.edu.au

ABSTRACT:

There are currently a number of buildings in excess of 300m under construction in the world and further tall buildings are planned for both residential and commercial markets. The design and construction of tall buildings present many challenges for the design team, from engineers, Architect through to the concrete technologist and the builder. Both safety and sustainability aspects are important in planning and designing tall buildings. Current practice, trends, improvements and some mistakes in designing buildings will be highlighted in this key note address.

1 INTRODUCTION

Modern tall buildings have become more and more flexible and taller than in the past owing to the growing use of high-strength concrete or lighter weight materials and advanced construction techniques. Therefore the role of the engineer in design of high-rise buildings has changed significantly primarily due to the increasingly competitive nature of the building industry.

In terms of structural considerations, a building can be defined as tall, when its strength and behavior, in terms of serviceability (deflections) and accelerations, is governed by lateral loads. The lateral loads are caused either by wind and/or earthquake. Although there is no specific value for height that defines a tall building, a commonly acceptable dividing line is where the structural design moves from the field of statics into the field of dynamics.

The Petronas Towers in Kuala Lumpur, Taipei Financial centre and Burj Kalifa Tower in Dubai represent a few examples of super tall buildings which were constructed during recent times, as shown in Figure 1. Although the definition will change with time, buildings with height more than about 400 m can be considered to be super tall buildings.

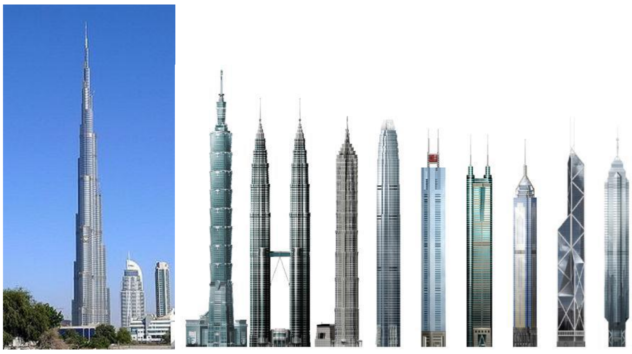
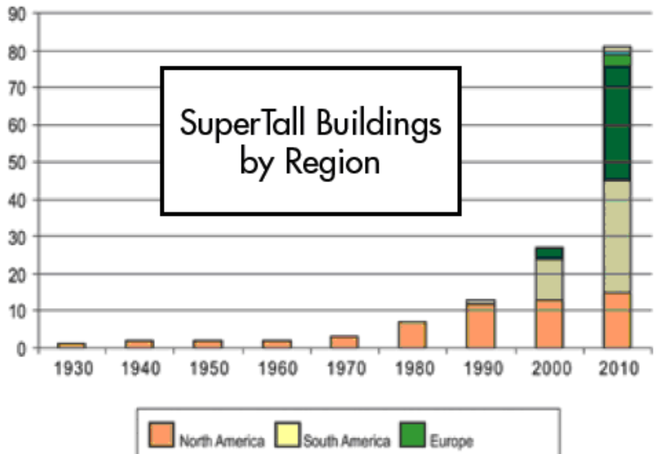


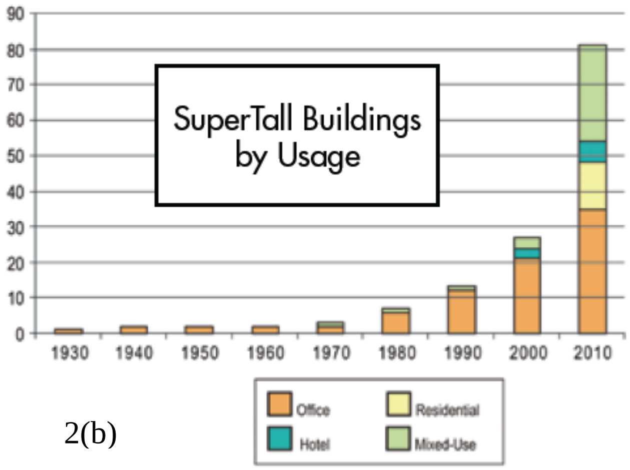
Figure 1: Recent super tall buildings in the world

2 DEVELOPMENT OF TALL BUILDINGS

Tall buildings are currently undergoing resurgence around the world for different purposes, primarily due to the high growth economy in some countries. Due to the excessive increase in height of buildings in this era, there is a significant impact on the methods used to analyse and design tall buildings. According to the Council on Tall Buildings and Urban Habitat (CTBUH,2008) reports, the tall buildings are classified according to the region and the usage as shown in Figures 2(a) and 2(b). CTBUH estimated that by the end of the decade, the number of super tall buildings in the world, especially in Asia, would more than double as shown in Figs 2(a) & 2(b). It is very clear that the epicenter for super tall buildings is moving towards Asia.



2(a)



2(b)

Figure 2(a) Total number of super tall buildings in the world by region; 2(b) Total number of super tall buildings in the world by usage

2.1 Structural and Architectural evolution

The significance of lateral loading increases with increasing height, in terms of serviceability, strength and stability limit states. For the taller and more slender buildings the structural form becomes increasingly important. The structural system for tall buildings can essentially be broken down into two distinct categories. They are the gravity load resisting structural system (GLRSS) and the lateral load resisting structural system (LLRSS).

Tall building development involves various complex factors, such as economics, aesthetics, technology, municipal regulations, and politics. Among these, economics has been the primary governing factor. However, construction of super tall buildings itself would not have been possible without supporting technologies. Structural systems for tall buildings have undergone dramatic changes since the demise of the conventional rigid frames in the 1960s as the predominant type of structural system for steel or concrete tall buildings (Ali and Moon, 2007). However, the structural form of a tall building is influenced strongly by its function, whilst having to satisfy the requirements of strength and serviceability under all probable conditions of gravity and lateral loads. The latest developments in the design of tall buildings are the innovations in construction technology, advances in structural systems and improvements in concrete technology (ultra high strength concrete) (Mendis, 2001).

Over the past five decades, six categories have been identified to classify tall building structural systems. These are:

i. framed tube (system of rigid frames)
ii. bundled tube (combination of framed tubes)
iii. tube in tube (central and peripheral framed tubes)
iv. diagonalised (trussed tubes, diagrids or braced frames)
v. core + outrigger (central lateral system linked to the perimeter system through outriggers)
vi. hybrid (combined use of any two or more structural systems).

Core and outrigger system is a common and very popular system among the other systems. In total, 73% of the tall buildings built in the 2000s have adopted a core + outrigger system, and approximately 50% of them are constructed with concrete (CTBUH, 2010). Figure 3 shows the tall buildings marked according to these categories.

3 WIND LOADS FOR DESIGN OF TALL BUILDINGS

3.1 Types of Wind Designs

Lateral loading due to either wind and/or seismic loading, generally dominates the structural system of very tall buildings, therefore significantly influencing the overall structural cost. Wind is a phenomenon of great complexity because of the many flow situations arising from the interaction of wind with structures. Wind is composed of a multitude of eddies of varying sizes and rotational characteristics carried along in a general stream of air moving relative to the earth’s surface. These eddies give wind its gusty or turbulent character. Typically for tall building design three basic wind effects need to be considered.

□ ***Environmental wind studies*** *to* study the wind effects on the surrounding environment caused by erecting a tall building. This study is particularly important to assess the impact of wind on pedestrians and motor vehicles etc., which utilise public domain within the vicinity of the proposed structure.

□ ***Wind loads for facade*** – to assess design wind pressures throughout the surface area of the building to design the cladding system. Due to the significant cost of typical facade systems in proportion to the overall cost of very tall buildings, engineers cannot afford the luxury of conservatism in assessing design wind loads. With due consideration to the complex building shapes and dynamic characteristics of the wind and building structure, even the most advanced wind codes generally cannot accurately assess design loads. Wind tunnel tests to assess design loads for cladding, is now a normal industry practice, with the aim to minimize initial capital costs, and more significantly to avoid expensive maintenance costs as-

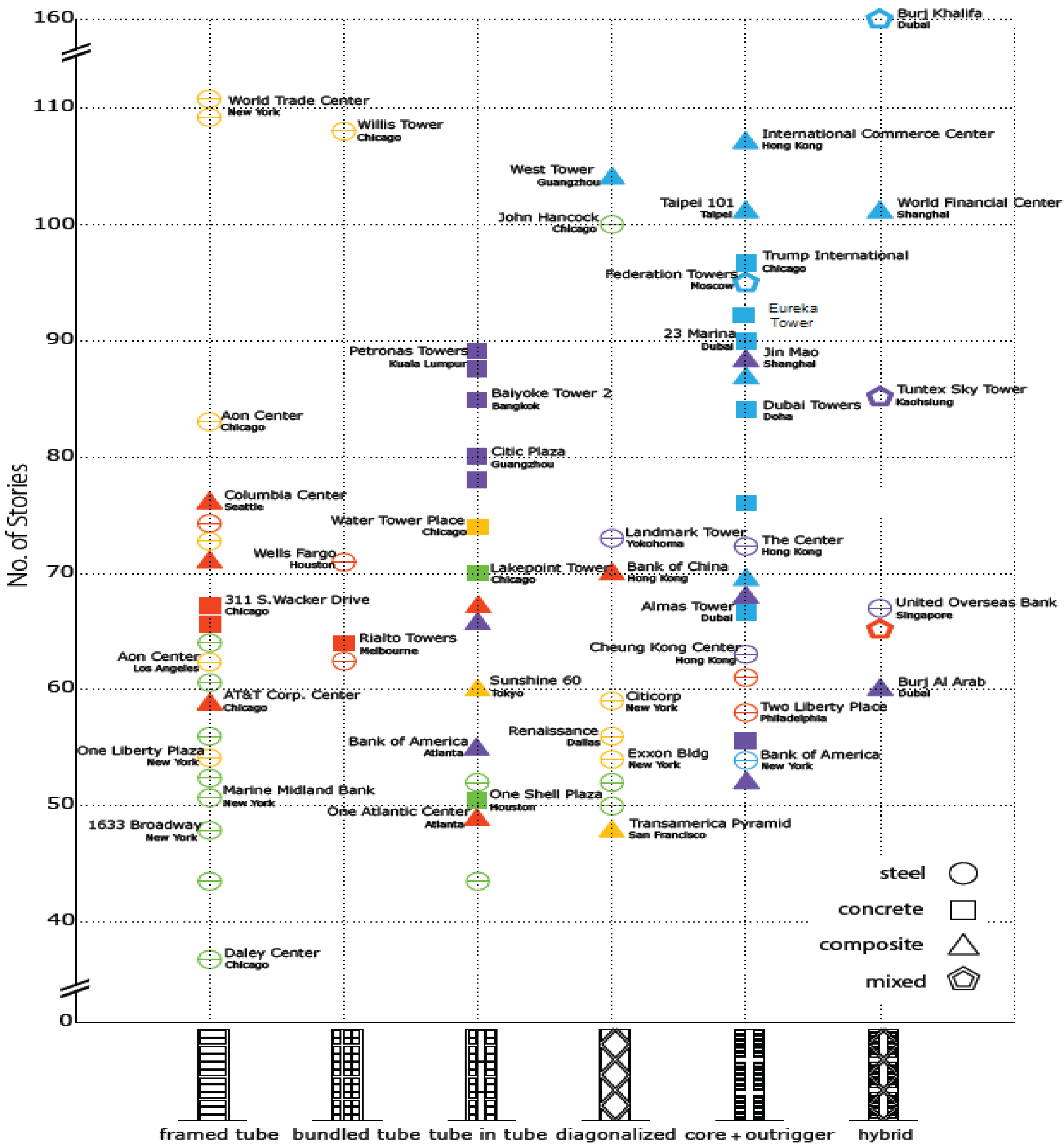


Figure 3: Structural system categorization for tall buildings completed 1961-2010 (Modified from CTBUH, 2010)

sociated with malfunctions due to leakage and/or structural failure.

 Wind loads for structure – to determine the wind loads to design the lateral load resisting structural system of the building to satisfy the various design criteria.

3.2 Criteria Design

In terms of designing a tall building for lateral wind loads the following design criteria needs to be satisfied. The three design criteria that are considered in wind design are stability, strength and serviceability. As adopted by most international codes, to satisfy stability and strength limit states requirements, ultimate limit state wind speed (e.g. 1 in 1000 year return periods) is used.

In majority of the super tall buildings designed now, accelerations govern the overall selection and design of the structural system. Acceptability criteria for vibrations in buildings are frequently expressed in terms of acceleration limits for a one or five years return period wind speed and are based on human tolerance to vibration discomfort in the upper levels of buildings. Wind response is relatively sensitive to both mass and stiffness, and response accelerations can be reduced by increasing either or both of these parameters. However, this is in conflict with earthquake design optimization where loads are minimized in tall buildings by reducing both the mass and stiffness. Increasing the damping, results in a reduction in both the wind and earthquake responses.

The detailed procedure described in the Code is sub-divided into Static Analysis and Dynamic Analysis methods. The static approach is based on quasi-steady assumption; it assumes that the building is a fixed rigid body in the wind. Static method is not appropriate for tall buildings of unexceptional height, slenderness, or susceptibility to vibration in the wind. In practice, static analysis is normally appropriate for structures up to 50 metres in height. The dynamic method is developed for exceptionally tall, slender, or vibration-prone buildings. Usually a dynamic analysis must be undertaken to determine overall forces on any structure with both a height (and length) to breadth ratio greater than five and a first mode frequency less than 1 Hertz. Approximate frequency of a building is 46/height. Therefore generally slender buildings with 50 m height are wind sensitive as mentioned earlier.

3.3 Background to Wind Loading

Not only is the wind approaching a building a complex phenomenon, but the flow pattern generated around a building is complicated by the distortion of the mean flow, the flow separation, the vortex formation, and the wake development. Large wind pressure fluctuations due to these effects occur on the surface of a building. As a result, large aerodynamic loads are imposed on the structural system and intense localised fluctuating forces act on the facade of such structures. Under the collective influence of these fluctuating forces, a building vibrates in rectilinear and torsional modes, as illustrated in Figure 4. The amplitude of such oscillations is dependent on the nature of aerodynamic forces and the dynamic characteristics of the building.

3.4 Along-wind Loading

The along-wind loading or response of a building due to the gusting wind can be assumed to consist of a mean component due to the action of the mean wind speed (eg, the mean-hourly wind speed) and a fluctuating component due to wind speed variations from the mean. The fluctuating wind is a random mixture of gusts or eddies of various sizes with the larger eddies occurring less often (i.e. with a lower average frequency) than smaller eddies. The natural frequency of vibration of most structures is sufficiently higher than the component of the fluctuating load effect imposed by the larger eddies. i.e. the average frequency with which large gusts occur is usually much less than any of the structure's natural frequencies of vibration and so they do not force the structure to respond dynamically. The loading due to those larger gusts (which are sometimes referred to as "background turbulence") can therefore be treated in similar way as that due to the mean wind. The smaller eddies, however, because they occur more often, may induce the structure to vibrate at or near one of the structure's natural frequencies of vibration. This in turn induces a magnified dynamic load effect in the structure which can be significant.

The separation of wind loading into mean and fluctuating components is the basis of the so-called "Gust-factor" approach or more recently presented as “Dynamic response factor”, which is introduced in major wind codes around the world. The mean load component is evaluated from the mean wind speed using pressure and load coefficients. The fluctuating loads are determined separately by a method which makes an allowance for the intensity of turbulence at the site, size reduction effects, and dynamic amplification.

The dynamic response of buildings in the along-wind direction can be predicted with reasonable accuracy by this approach, provided the wind flow is not significantly affected by the presence of neighboring tall buildings or surrounding terrain.

3.5 Cross-Wind Loading

Tall buildings are bluff (as opposed to streamlined) bodies that cause the flow to separate from the surface of the structure, rather than follow the body contour. The wake flow thus created behind the building exhibits various degrees of periodicity, ranging from virtually periodic with a single frequency to fully random. In each of the cases, at any given instant, the wake flow is asymmetrical. The across-wind response (i.e., motion in a plane perpendicular to the wind direction) is due to the asymmetry, although the lateral turbulent fluctuations in the oncoming flow may also contribute to the across-wind forces.

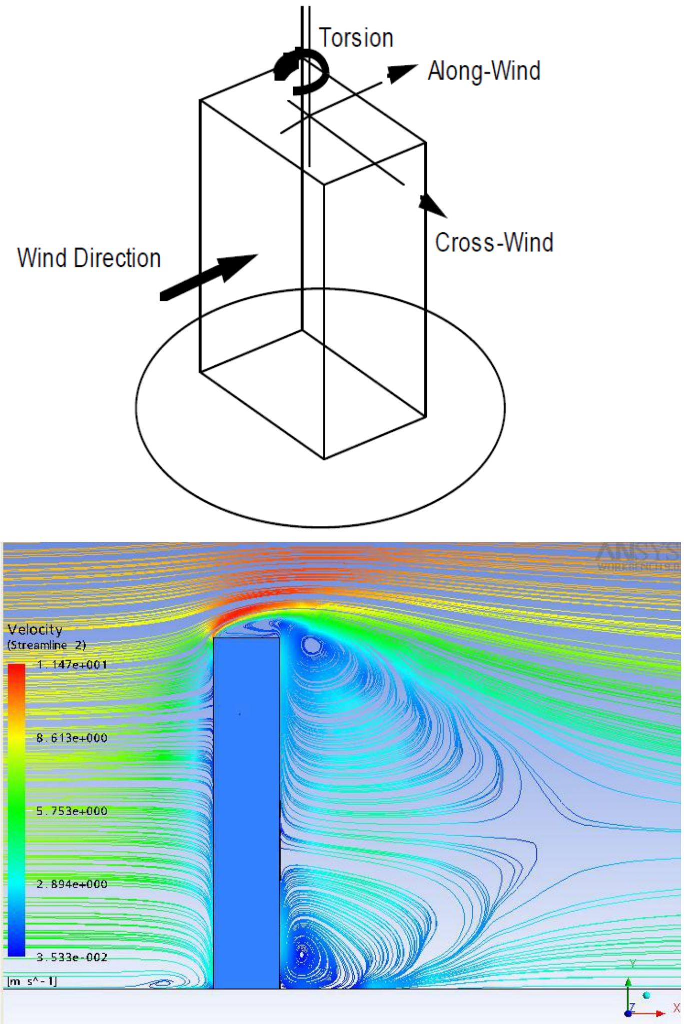


Figure 4: Wind response

The complex nature of the across-wind loading which results from an interaction of incident turbulence, unsteady wake effects, and building motion has inhibited reliable theoretical predictions. However, empirical information obtained from wind tunnel measurements is available for cross-wind response of tall buildings not subjected to interference effects, and expressions based on such information appear in the AS 1170.2 -2011(Australian Wind Code). The response of the tall buildings to wind depends on its shape, stiffness distribution, mass distribution and damping. Some common problems associated with wind loading for base of tall buildings are shown in Figure 5.

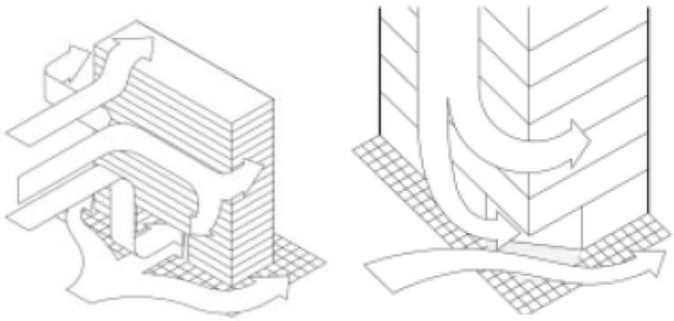


Figure 5: Wind related problems in Tall buildings (From internet sources)

3.6 Wind tunnel testing for tall buildings

Different wind tunnel testing techniques are used for determining the overall wind loading and the wind-induced dynamic response of tall buildings. The most commonly used techniques are: (1) the pressure test using a rigid model; (2) the aerodynamic test using a rigid model mounted on a High Frequency Force Balance (HFFB); and (3) the two degrees-of-freedom aeroelastic test using a base balance. Due to its simplicity and effectiveness, the HFFB has gained its popularity within wind engineering community. However, the accuracy varies from wind tunnel to wind tunnel.

The numerical simulations using Computational Fluid Dynamic (CFD) techniques to study the wind loads on tall buildings has improved the accuracy and solving time due to advanced developments in numerical techniques as well as the computer hardware. The Large Eddy Simulation (LES) turbulent model has been approved as a suitable model for solving wind engineering problems with a reasonable solving time using current computer power (Cuong, 2009; Tamura, 2008).

A CFD-based virtual wind tunnel (CFD-VWT) can be used to predict accurately the mean and resultant peak base bending moments in along-wind direction. It can also capture accurately the vortex shedding, which is the primary cause of the cross-wind responses in tall buildings. This work is continuing at the University of Melbourne. In the future these methods will be used more often than experimental techniques to predict the wind behaviour around the super tall buildings including pedestrian comfort at the base of the building.

3.7 Comfort criteria: Human response to building motion

There are no generally accepted international standards for comfort criteria in tall building design after decades of research. A considerable amount of research has however been carried out into the important physiological and psychological parameters that affect human perception to motion and vibration in the low frequency range of 0-1 Hz encountered in tall buildings. These parameters include the occupant's expectancy and experience, their activity, body posture and orientation, visual and acoustic cues, and the amplitude, frequency, and accelerations for both the translational and rotational motions to which the occupant is subjected. Table 1 gives some guidelines on general human perception levels. More information can be found in Mendis et al, (2007).

Generally the acceleration is the predominant parameter in determining the nature of human response to vibration, and this, with knowledge of the frequency of oscillation, can define all other relevant parameters of sinusoidal vibration. Human perception levels for different accelerations suggested by Yamada and Goto (1975) are listed in the following table:

Table 1: Human Perception Levels

Level	Acceleration (m / sec^2)	Effect
1	<0.05	Humans cannot perceive motion
2	0.05 - 0.1	a) Sensitive people can perceive motion; b) hanging objects may move slightly
3	0.1 - 0.25	a) Majority of people will perceive motion; b) level of motion may affect desk work; c) long - term exposure may produce motion sickness
4	0.25 - 0.4	a) Desk work becomes difficult or almost impossible; b) ambulation still possible
5	0.4 - 0.5	a) People strongly perceive motion; b) difficult to walk naturally; c) standing people may lose balance.
6	0.5 - 0.6	Most people cannot tolerate motion and are unable to walk naturally
7	0.6 - 0.7	People cannot walk or tolerate motion.
8	>0.85	Objects begin to fall and people may be injured

Acceleration limits are a function of the frequency of the vibration felt. Upper limits have been recommended for corresponding frequencies of vibration with the relationship suggested by Irwin and these are widely used around the world. Other peak acceleration limits are also plotted along with the Irwin's E2 curve in Figure 6.

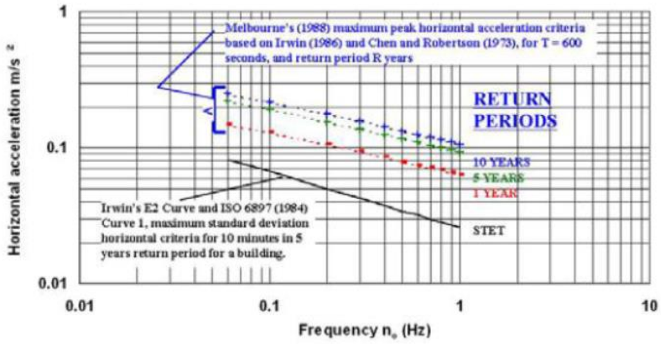


Figure 6: Horizontal acceleration criteria for occupancy comfort in buildings

3.8 Earthquake design for tall buildings

In general, tall buildings respond to seismic motion in a different manner than low-rise buildings due to the flexibility of these buildings. The design of these tall buildings in seismically active regions varies dramatically from region to region. It is well known that the behaviour of a structure during an earthquake depends on two basic parameters: (a) the intensity of the earthquake, and (b) the quality of the structure. The quality of the structure is a parameter that exhibits a sufficient level of reliability, since it depends on the configuration of the structural system, the design procedure, the detailing of the structural elements and careful construction.

Analysis procedures for buildings can be classified as force-based design and performance-based design. Traditionally, seismic structural design has been based primarily on forces. However, the economic losses resulting from several earthquakes, has prompted the earthquake engineering community to embrace the concept of performance-based earthquake engineering. Although the basic objective of performance-based earthquake engineering is to produce structures that respond in a more reliable manner during earthquake shaking, many engineers associate performance-based earthquake engineering with overall enhanced performance. Design professionals in the USA have come to believe that the design of tall buildings using the current US building code does not allow for the best use of structural systems and building materials to provide safe and predictable performance when subjected to strong earthquake ground motions (Lew, 2007).

In performance-based design, Structural Engineers Association of California SEAOC (1999) suggested the following levels for the design and verification of tall buildings:

Table 2: Earthquake levels for the design of tall buildings

Event	Recurrence Interval	Probability of exceedance
Frequent	43 years	50% in 30 years
Occasional	72 years	50% in 50 years
Rare	475 years	10% in 50 years
Very rare	975 years	10% in 100 years

In 2005, the Los Angeles Tall Buildings Structural Design Council (LATBSDC) produced an alternative procedure for a performance-based approach to seismic design and analysis of tall buildings. This alternative procedure was revised and updated in 2008 (LATBSDC, 2008). The procedure given in LATBSDC (2008) is based on capacity design principles, followed by a series of state-of-the-art performance-based design evaluations. Capacity design principles are applied first to design the structure to have a suitable ductile yielding mechanism, or mechanisms, under non-linear lateral deformations. Then linear analysis is used to determine the required strength of the yielding actions.

Although there are many methods available for the seismic analysis of buildings, there is a common acceptance within the community that the existing methods are not very suitable for the analysis of very tall buildings, since most of these methods were derived based on low- to medium-rise buildings. Moreover as discussed above, the methods that are available for the seismic design for tall buildings consume a considerable amount of time for the analysis even with the use of sophisticated computers. Therefore a simple and versatile method was developed, at the University of Melbourne, based on direct displacement based design for outrigger braced tall buildings. A systematic approach was presented for the calculation of design displacement profile based on the moment profiles of the outrigger braced tall buildings by Herath (2011).

Traditional engineering practice is mainly focused on only first translational mode when setting strength requirements and lateral force distributions in earthquake design for buildings. As mentioned earlier, the reason behind this phenomenon was that most of the existing building codes of practice were developed based on the behaviour of low-rise buildings, which are not influenced much by higher mode effects. However the higher mode participation in tall buildings cannot be neglected as there is a significant impact from these mode responses for the overall response of the building. A study conducted at University of Melbourne investigated the higher mode participation in the design of tall buildings under earthquake loads for outrigger braced tall buildings and the significant impact on the behaviour of such buildings from higher mode participation including period lengthening was highlighted (Herath, 2011).

Table 2: Earthquake levels for the design of tall buildings

Design / Evaluation Step	Ground Motion Intensity[1]	Type of Analysis	Type of Mathematical Model	Accidental Torsion Considered?	Material Reduction Factors (φ)	Material Strength
1	Non-linear Behaviour Defined / Capacity Design					
2	50/30	LDP[2] or NDP[3]	3D[4]	Evaluated	1.0	Expected properties are used throughout, except when calculating the capacity of brittle elements where specified strength values shall be used.
3	MCE[5]	NDP	3D[4]	Yes, if flagged during Step 2. No, otherwise.	1.0	

1 probability of exceedance in percent / number of years
2 linear dynamic procedures
3 non-linear dynamic procedures
4 three-dimensional
5 per (ASCE, 2005)

3.9 Progressive collapse

Progressive collapse is characterized by the loss of load-carrying capacity of a relatively small portion of the structure due to an abnormal load which can trigger a cascade of failures affecting a major portion of the structure (Figure 7). Several buildings have collapsed in this fashion such as the Murrah building in Oklahoma (1995) and the collapse of the World Trade Centre (2001). Lessons learnt from these events were that special attention must be given to the behavior of the structural elements to improve their redundancy, toughness, and ductility under extreme events. The ultimate goal of the protection is to minimize injuries and loss of life and facilitate the evacuation and rescue of survivors. The casualties that will occur to occupants in the immediate vicinity of the explosion or impact may be unavoidable, but by preventing progressive collapse, the remaining occupants may be spared injury or death.

Performance of typical Australian tall buildings under the extreme events was carried out at the University of Melbourne. Several extreme event scenarios involving a bomb blast or an aircraft impact were identified, and their effects were investigated. A typical floor of each building was examined to determine the vertical load capacity of the beam-slab system. The objective of this study was to develop a preliminary method of assessing the structural consequences of extreme event impacts with focus on progressive collapse prevention and suggest design directions for enhancing the performance of existing and future buildings. A vulnerability assessment procedure was proposed, which consists of three main steps: (i) Determination of hazard levels and load conditions, (ii) Global and local damage assessment, and (iii) Progressive collapse assessment.

Figure 7: World Trade Centre 1 & 2

An accurate advanced analysis procedure has been developed by the Advanced Protective Technologies for Engineering Structures group (APTES) at the University of Melbourne to predict the progressive collapse of tall buildings using advanced finite element techniques. This work was funded by the Dept of Prime-Minister and Cabinet in Australia. An example is given below.

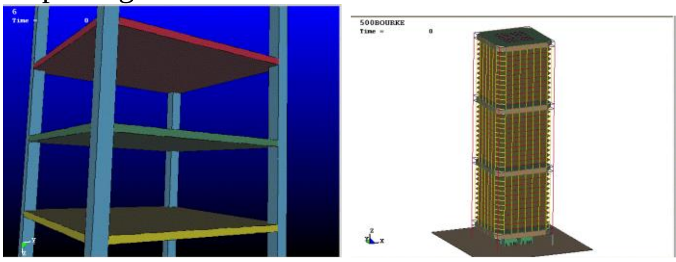


Figure. 8: Advanced numerical models for progressive collapse

In this building, every element and reinforcement details were modeled and the progressive collapse was initiated by removing a column. Many weaknesses were identified in the present design methods which need to be taken into account in developing innovative and effective mitigation technologies for the protection of critical, high rise facilities say from shock, blast, impact, earthquakes etc.

The technical hazards to tall buildings may range from an accidental gas explosion to a car bomb, an impact of a missile to a jet airplane collision. For these assaults, the source can originate either external or internal to the structure. The difference between technical hazards (accidental or terrorist) and other natural hazards is that the risks of technical hazards are very hard to quantify. For these types of hazards the performance-based approach can be used as a rational method for assessment or design of buildings against extreme events. Example of the performance level – hazard matrix of a bomb blast event is shown in Figure 9.

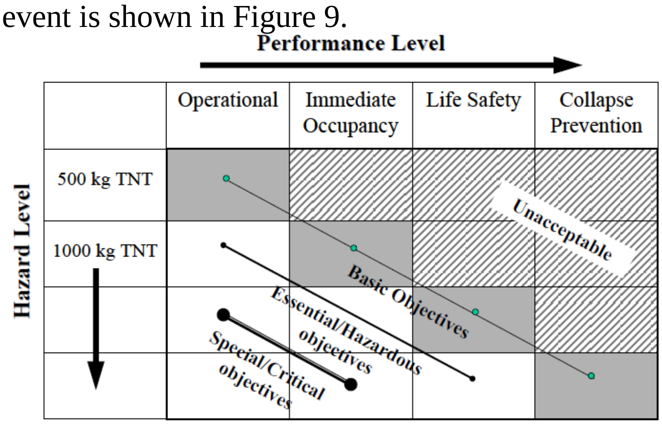


Figure 9: Performance-based approach

3.10 Blast Loading

The threat for a conventional bomb is defined by two equally important elements, the bomb size (or charge weight (W), which is normally measured using the equivalent amount of TNT), and the standoff distance (R) between the blast source and the target. For example, the blast occurred at the basement of World Trade Centre in 1993 has the charge weight of 816.5 kg TNT. The Oklahoma bomb in 1995 has a charge weight of 1814 kg at a standoff of 4.75m (Longinow, 1996).

With the detonation of a mass of TNT at or near the ground surface, the peak blast pressures resulting from this hemispherical explosion decay as a function of the distance from the source as the expanding shock front dissipates with range (Figure. 10). The incident peak pressures are amplified by a reflection factor as the shock wave encounters an object or structure in its path. The reflected pressure is at least twice that of the incident shock wave and is proportional to the strength of the incident shock, which is proportional to the charge weight. The blast pressure decays exponentially and eventually becomes negative as shown in Figure 11. Then the building is subjected to pressures acting in the direction opposite (suction pressure) to that of the original shock front. Peak blast loads may be several orders of magnitude larger than the largest loads for which conventional buildings are designed (Table 4).

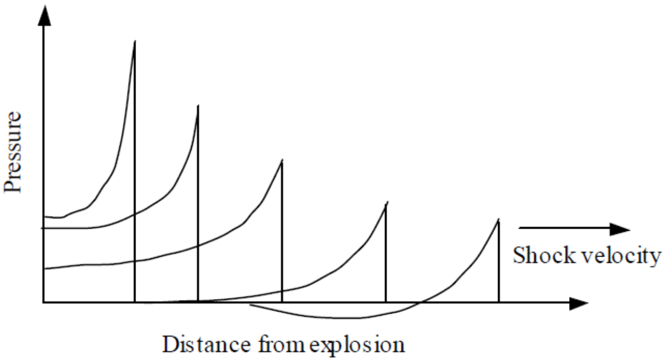


Figure. 10: Variation of pressure with distance

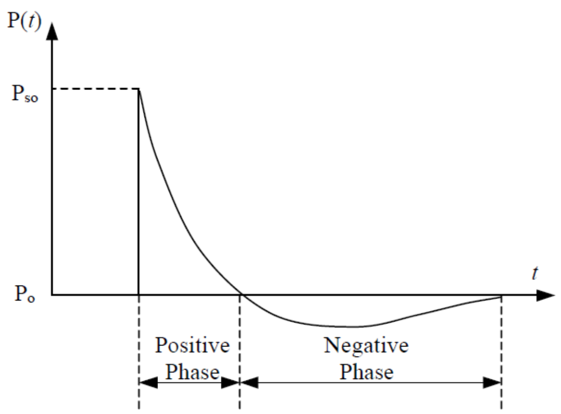


Figure. 11: Blast wave pressure – Time history

Table 1: Table 4:Peak reflected overpressures (MPa) with different W-R combinations (TM5-1300, 1990)

	W			
R	100 kg TNT	500 kg TNT	1 ton TNT	2 ton TNT
1m	973	4883	9769	19543
2.5m	59	309	622	1247
5m	6.1	36	75	153
10m	0.7	3.9	7.8	17.03
15m	0.2	1.0	2.2	4.72
20m	0.1	0.4	0.87	1.82

3.11 Aircraft impact loading

It is essential to design tall buildings for at least an impact from a small aircraft. Design loads resulting from aircraft impacts are governed by the absorption of kinetic energy from the aircraft by the building at its maximum deflection. These loads are limited by the yield, buckling and crushing of the aircraft. Total impactive load F(t) at the interface of the collapsing aircraft and the building is given by Kar, (1979):

$$F(t) = F_c + \mu\,[m(t)]\,V(t)$$

Where m(t) is the mass of the aircraft reaching the building per unit time;
- μ is a coefficient for change in momentum (which can be taken conservatively as 1);
- Fc is a constant which can be determined from the design acceleration for failure of the aircraft;
- V(t) is the velocity of the aircraft.

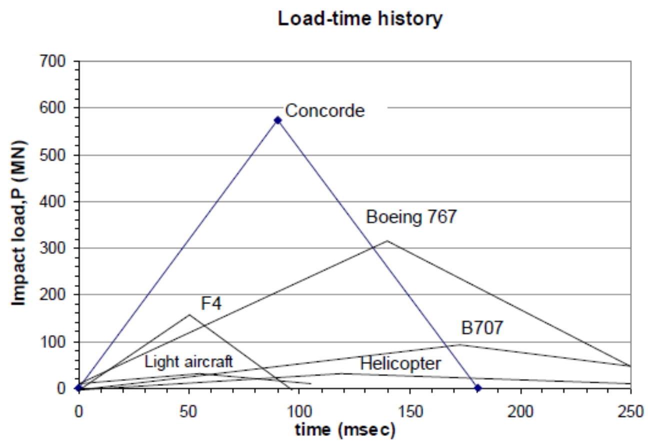


Figure. 12: Impact load-time history for aircraft impacts

The frame is classed as a soft missile which will suffer considerable deformation and a finite difference method of calculation is employed to describe its perfectly plastic impact. The engines which are considered separately are assumed to constitute a much harder missile which will undergo little deformation. Figure. 12 compares the impact loads produced by different aircrafts. The peak loads and impact durations are given in Table 5. More details are given elsewhere (Mendis & Ngo., 2002).

Table 5: Examples of aircrafts and peak impact loads

Aircraft	M (t)	L (m)	Vo (m/s)	Peak Load (MN)	Duration (ms)
Aust. SUPAPUP Light Air-craft	0.34	5.7	51.3	4.6	111
Westland Sea King Helicopter	9.5	17	63.9	19.6	266
Boeing 707-320	91	40	103.6	92	386
Phantom F4 aircraft	22	19.2	210	145	91
Boeing 767-300 ER	187	54.9	140	320	362

3.12 Post 9/11- 10 years on: Any changes in tall building design?

The areas that attracted the special attention of engineers, architects and developers in designing tall buildings can be categorised into the following areas:

Structural Integrity

The main issues are:

• Possibility of progressive collapse;
• The need for the buildings to be strengthened;
• Whether certain types of construction are more susceptible to collapse than others.
• The design hazards;
• If the triggering event is an explosion from a car or truck bomb, then there is a need to provide adequate “stand-off distance” to mitigate the damage.

The WTC collapse has not brought about any major changes in the design of buildings for structural integrity; however some significant changes can be incorporated with only an extra cost of about 5% of the total cost of the building. Some simple detailing rules, which would improve building performance, have not been considered, such as the continuous top and bottom reinforcement of floor slabs. Currently, Design Standards only require top reinforcement. Under loads the top reinforcing steel of floor slabs will rip out, resulting in collapse of the floor. If a piece of bottom reinforcement is run through the slab into the column, when the floor slab fractures, the bottom reinforcement acts like a net, catching the floor and holding it in place.

Researchers at the University of Melbourne are also looking at ways of designing buildings so that their vertical load is distributed throughout a range of support areas. This way, if one or more support columns and beams are destroyed, progressive collapse is prevented, as the load from above is distributed laterally and onto other columns and beams. These suggestions have not yet been adopted in practice.

Emergency Management, Resilience and Building egress

It is very important for buildings to recover within a short time after an event. Although this was Considered to be of great importance following 9/11, no special strategy has been adopted in planning tall buildings except for the introduction of refuge floors in some buildings. There were also suggestions that fire fighters should be given basic training in the structural performance of buildings, and that structural drawings of major buildings should be provided, to allow fire fighters to make more informed decisions when entering a building damaged by an explosion or any other hazard. Building designers were encouraged to prepare detailed emergency response plans before a building was built. But many of these suggestions have not been followed in the last ten years, although there is more awareness about these issues.

As mentioned earlier, many people who were below the impact locations survived in WTC 1 and WTC 2. It must be noted that occupants in these buildings had frequent emergency evacuation drills after the 1993 bombing of the WTC. Occupants in other tall buildings may not be prepared in emergency evacuation procedures to this extent. Many questions were asked about building egresses; such as, should more exit stairs be required? Should exit stairs be wider to accommodate two-way traffic? Should the stairs be located inside the building core or at the perimeter of the building? Should the stairs be located in hardened enclosures? Should lighting be improved? Should there be a staged evacuation or a mass evacuation?

Some buildings are now provided with refuge floors and pressurized staircases to avoid smoke getting into stairs and lift wells. This is one of the major changes since 9/11. Refuge floors are areas with special fire protection and hardened walls. In an event, occupants can gather in these intermediate floors rather than needing to evacuate to the ground level, avoiding the congestion of stairs.

Fire Protection

The most significant amount of investigation and research is being conducted in the area of fire protection. The fire proofing of structural steel members has been called into question in the aftermath of 9/11. A large amount of fireproofing was dislodged from the steel members as a result of the initial impact and the explosion of the aircraft. Questions have been raised as to whether the fire-proofing should be thickened, and whether there is a requirement to develop new products to improve the bonding to the structural members at elevated temperatures.

The fire designs carried out now are based on standard fires. Fires originating from jet fuel, such as in the WTC, are hydrocarbon fires, which are different to standard fires. In hydrocarbon fires the temperature increases rapidly (in a few seconds) compared to a standard fire, in which the maximum temperature is reached after some time. Concrete, which is the main construction material for tall buildings, is susceptible to shattering (spalling) under rapid and high intensity heat; for example, following the ignition of hydrocarbon fuel. Even steel members may behave differently under a hydrocarbon fire. The collaborative research project at the University of Melbourne conducted by Quynh Nguyen (with Permasteelisa Ltd) will investigate the fire performance of new generation GFRP facades in tall buildings. As tall buildings continue to be built to meet the need for space in cities, it is essential for planners and builders to pay attention to disasters that have already occurred, to visualise the possibility of these events in the future, and conduct research and development work that mobilises the support of practising engineers and scientific personnel, including collaborating with specialists in universities and other research organisations. This will mean that designers will begin to do things differently, and this will enhance the safety of the occupants of tall buildings that are susceptible to extreme loads (Mendis and Ngo, 2006).

3.13 Sustainable design of tall buildings

Sustainable design, which is one of the most important considerations in any building project these days, implies many factors such as energy efficiency, environmental friendliness, adaptability and efficient use of resources.

As a result of population growth and increasing standard of living, energy consumption around the world is steadily increasing. The built environment has been recognized as the largest contributor for the climate change. Globally, 50% of all energy usage and more than 50% of all climate change emissions are associated with construction, operation and maintenance of buildings (Smith, 2005).

Historically, tall buildings have been perceived as inefficient users of energy. However, with time, their role in supporting the sustainable growth of cities was gradually increased and tall buildings were considered sustainable structures as they optimize the use of limited land resources (Smith, 2007). Constructing tall buildings poses inherent challenges to safe and efficient movement of people, materials and equipment.

By close collaboration between architects and structural engineers, many wonderful and well-designed buildings have been built all over the world. However, with the increasing concern over the environment, the engineer finds themselves once again faced with new challenges. This time, the challenge is to find out how the structure can fit within the energy conservation strategy. Generally 75% of the energy consumption in high rise buildings is allocated for heating, ventilation and air conditioning (Yeang, 1999). A study conducted on high rise office buildings in Malaysia supported that study and it was concluded that 57% of energy is used for air conditioning and lighting, lifts and pumps and other equipment consume 19%, 18% and 6% respectively.

Studies on the total energy usage in these tall buildings during the life cycle of the buildings are crucial as these tall buildings consume large amount of energy as described above. Life cycle energy consumption requires a comprehensive energy analysis to cover energy consumption throughout the lifespan of the building. In life-cycle energy analysis (LCEA), the energy embodied in a building and the energy used in the operation of the building are calculated for the anticipated lifetime of the building. However in tall buildings, the energy consumption for vertical transportation is also very important and this component needs to be addressed in the energy consumption calculations.

Integrated design is different than conventional design in its focus on active collaboration within a multidisciplinary team. In sustainable tall buildings especially, an integrated process is necessary because of their scale and the fact that green design affects so many different elements of a building, such as day lighting, which in turn concerns sitting, orientation, building form, facade design, floor to-floor heights, interior finishes, electric lighting controls, and cooling loads, among other things. Green or vegetated roofs, with their impact on storm water runoff, building structure, building form, thermal insulation, and plantings, are another example where integration must be considered (Malin, 2006).

Environmental factors can contribute significantly to the sustainability of a tall building. Using the mid-level floor of Burj Khalifa as an example, the total amount of cooling load reduction at the summer peak design hour can be as much as 11% (Leung and Weismantle, 2008)

The buildings are one of the largest energy consumers in any industrialised country and the commercial buildings carry a significant share. The construction and operation of buildings requires energy, and the production of that energy emits greenhouse gases (GHG). While there has been much research into the possibilities of reducing operational energy consumption, there has been very little investigation into reducing the whole life cycle energy required for the buildings.

A study was conducted at Universuty of Melbourne to quantify and compare the embodied energy, operational energy and green house gas emission of concrete and steel framed options, which are commonly used in commercial buildings. A typical high rise office building in Melbourne has been chosen for this exercise. The studied building is a 50 storey with a flat roof and the total net-lettable area of 75,570 square meters. The embodied energy contribution of the substructure, the super structure with the structural elements namely foundation, beams, columns roof, facades and stairs were investigated.

The foundation contributed to the highest embodied energy of 24.5% in case of the concrete building, whereas for the steel building, beams represented the highest embodied energy of 36.9% of the total (Figure 13). The results also showed for a 50 year period the operational GHG emission was significantly higher that the initial embodied GHG emission.

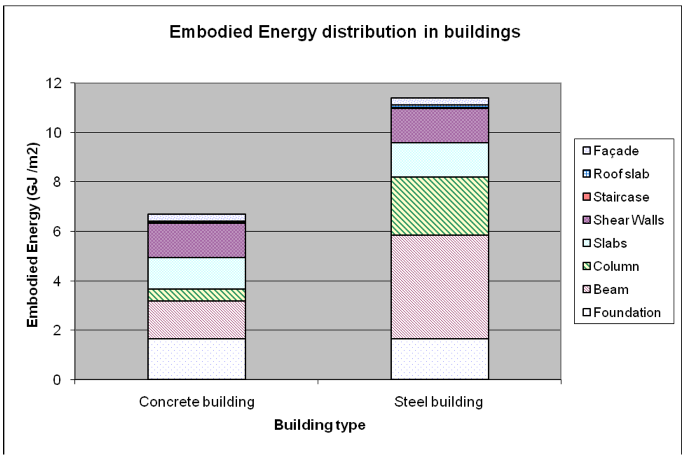


Figure 13: The Embodied Energy distribution between concrete and steel buildings

Further it was shown that the steel framed building has 68% more embodied green house gas emission as compared to the concrete framed building. The operational energy was calculated using the TRANSYS 16 simulating software which is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings to validate energy requirements and concepts.

The operational energy over a period of one year simulation clearly indicate that for Melbourne weather the cooling load is very much lower and majority of energy used is for heating purposes. There was no significant difference in operational energy between the steel and concrete framed structure. The total operational energy heating and cooling observed was 69.3 and 68.8 kWh/m2/yr for concrete and steel respectively (Figure 14).

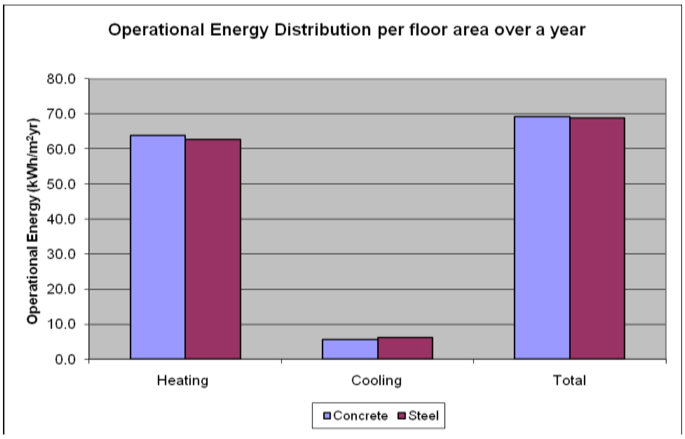


Figure 14: Operational energy distribution per floor area in kWh between concrete and steel buildings

There are many building evaluation tools that focus on different areas of sustainable development and are designed for different types of projects. Examples are BREEAM, LEED, GREEN STAR and Home Grown (developed to be suitable for local conditions) rating tools such as Malaysian GBI Index, Singapore's Green Mark system and Sri Lanka's Green Rating System for Built Environment (GRSBE).

The categories available in LEED and GREEN STAR –AUS can be grouped in broad form as below:

- Building energy consumption
- Water efficiency
- Indoor and outdoor environmental quality & emissions
- Material & resources
- Site development strategies

3.14 New sustainable design concepts for tall buildings

New approaches to the design of tall buildings can have a major impact on sustainability. In some tall buildings, temperature control is achieved without the use of air conditioning. Sustainable energy options, such as CHP, borehole cooling and fuel cells, can cut fossil fuel consumption. Building facades offer significant opportunities for creating buffer zones and thermal flues for cooling and heating, and for electricity generation from PV panels. A tall building can also benefit from a sky garden with a rich variety of vegetation, and such an option is being incorporated in buildings across Europe, America and Asia.

Large glass surfaces can significantly reduce the need for artificial lighting. Eco-architects are beginning to design and construct tall buildings which offer natural lighting for most desks. While the ubiquitous use of glass as a cladding material is not particularly energy-efficient, double- and triple-glazing and new types of laminated glass can reduce energy consumption of tall buildings. A large R & D project is conducted at the University of Melbourne with the support from Permasteelisa Ltd and Australian research council to improve the facades of tall buildings.

Tall buildings cannot be viewed in a vacuum: they exist within a specific environment and a human context. They contain their own community of residents and/or workers, but they are also part of the wider urban community. The dynamic relationship between these two communities must be considered both at the planning and the detailed design stages. Towers should be designed for mixed use wherever possible to create balanced functions and communities. The functions of a building at ground level should contribute to the quality of the city, with shopping, eating and entertainment opportunities.

Day-lighting, natural shading, energy-efficient and PV facades, wind power systems, and sky gardens within buildings add up to a significant shift towards more sustainable design of tall buildings. Lifecycle analysis of construction materials is also the key to the process. The combination of such design features is becoming common among architects. The main stumbling block to implementation is owner occupiers who are mainly concerned with the prestige and appearance of their building, and commercial developers who have only a limited interest in its sustainability. In the future, they may find that they change their minds as stringent new regulations concerned with sustainability come into force.

Most contemporary skyscrapers are designed so that the internal environment is completely enclosed and disengaged from the climatic conditions of the site. They are 100% reliant on mechanical air conditioning for the comfort of their occupants. Another feature of several new eco-towers is landscaping and planting in buildings. Continuous ramps of vegetation around a building and sky gardens built into internal spaces can bring positive benefits to local ecology rather than attempting to minimise impacts (Faber Maunsell Report 2002).

4 CONCLUDING REMARK

Although structural systems could be developed and construction solutions could be found to design and construct very tall buildings in excess of 1 km (even 1 mile), other aspects such as fire and egress, long-term differential shortening, environmental wind and perception of motion (including damping for dynamic effects), transportation (lifts) issues, durability and maintenance will govern and may even restrict the heights. New high-performance materials such as composites (fibre reinforced polymers), nanomaterials, very high-strength steels, bio-inspired materials etc. will be introduced in the future to overcome some difficulties. Advanced computational techniques are also very useful to quantify and optimize the systems. These methods are becoming popular for design of super tall buildings for safety and sustainability.

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