Title: **Risk-Based Approach of Achieving Code Compliance in Tall Buildings: Case Study**

Author: John Devlin, Senior Vice President, Aon Fire Protection Engineering

Subjects: Building Case Study
Fire & Safety
Structural Engineering
Vertical Transportation

Keywords: Code Compliance
Elevators
Evacuation
Fire Safety
Life Safety
Risk

Publication Date: 2015

Original Publication: Global Interchanges: Resurgence of the Skyscraper City

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Risk-Based Approach of Achieving Code Compliance in Tall Buildings: Case Study

John Devlin
Senior Vice President

Aon Fire Protection Engineering Corporation,
Greenbelt, Maryland, USA

John F. Devlin, PE is Senior Vice President of US East operations and served as lead fire protection engineer on the Nakheel Tower project. John has extensive experience in developing performance-based approached to code compliance in tall buildings and complex structures. He is a registered professional fire protection engineer in several USA states and earned a BSc and MSc in Fire Protection Engineering from University of Maryland. John is actively involved in the codes and standards development process and serves on several technical committees including NFPA Life Safety Code where his chairperson of the Features of Fire Protection.

Abstract

This paper is a case study of Nakheel Tower, Dubai, UAE – a proposed 1,000m and 200 plus story tall building – and the risk-based approach used for the design of the fire protection, life safety, and occupant evacuation systems. An elevator-centric occupant evacuation strategy formed the foundation to which the tower's fire safety sub-systems were designed. The residential towers occupant evacuation systems included multiple elevators and a single exit stair for egress to the sky bridges. The risk analysis revealed the risk of death from fire in the residential tower of Nakheel Tower is 15 times less than in a code compliant high-rise building.

Keywords: Code compliance, elevators, evacuation, fire safety, life safety, risk

Introduction

Tall buildings pose unique challenges in the design of fire safety systems. Nakheel Tower, proposed in Dubai, U.A.E., was envisioned to be one of the world's tallest buildings at over 1,000 m high creating a vertical city with over 15,000 people. Nakheel Tower's design included four separate towers each with their own core and structurally linked at every 25 levels by sky bridges. Each of these sky bridges acts as a podium for each of the towers above it and serves as transfer points between elevators and as refuge areas in a fire emergency (see Figures 1 and 2).

The intent of Nakheel Tower's design was to incorporate novel approaches to building fire safety, thereby increasing the overall reliability and performance above that of a "code-compliant" traditional high-rise building, such that building disruptions are minimal. The connectivity created by the sky bridges allowed the design team to create redundancies within Nakheel Tower fire safety and life safety systems. These redundancies, coupled with the tower's efficient vertical transportation system, lead the design team to an elevator-centric occupant evacuation approach. The challenge to the Nakheel Tower design team, specifically the fire safety engineers, was how to demonstrate the tower's design including the elevator-centric evacuation strategy provided a level of fire safety and life safety equal to or exceeding that intended by the building and fire codes.

Figure 1. Tower components (Source: Woods Baggot)

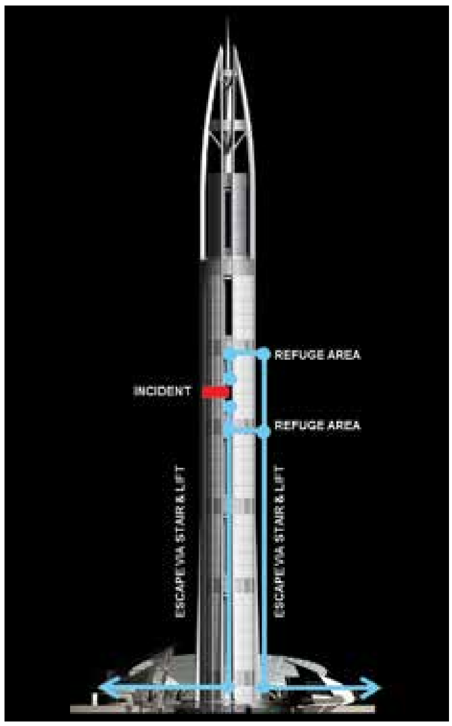

Figure 2. Tower Evacuation Concept (Source: Woods Baggot)

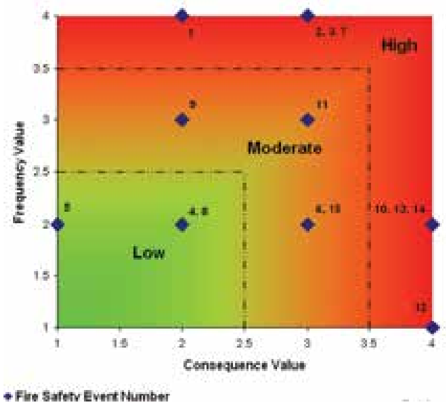

Figure 3. Fire safety event risk ranking (Source: Aon Fire Protection Engineering)

Code Compliance Strategy

NFPA 5000 [1] served as the building code to which the fire protection and life safety (fire safety) systems were designed. The fire engineering strategy for determining specific fire safety sub-systems and their features to achieve the project fire safety goals was accomplished via several evaluation methods. A performance-based approach to fire safety using the SFPE Engineering Guide to Performance-Based Fire Protection [2] served as the basis of the overall strategy. Objectives were derived from the fundamental fire safety goals recognized for building design and included:

- Establishing the Nakheel Tower life safety performance criteria;
- Evaluating the building's response when subjected to probable fire safety events;
- Quantifying the risk to life safety from a fire;
- Identifying the requisite fire safety sub-systems and their performance requirements.

Nakheel Tower's fire emergency occupant evacuation concept was multi-phased and was elevator-centric. In the residential towers, the first phase of evacuation was limited to the fire floor; the floors above and below the fire event are automatically evacuated upon fire confirmation. Should the fire escalate, additional floors are evacuated and occupants relocated to the sky bridges are evacuated from the building via the elevators and, if necessary, the exit stairs (see Figure 2).

Risk analyses were performed to determine the relative risk of probable fire safety events. Fire modeling and evacuation modeling analysis were used to compare Available Safe Egress Time (ASET) to Required Safe Egress Time (RSET) for evacuation of the building occupants from the fire incident floors to the refuge areas at each sky bridge. Each fire safety event was evaluated to determine its expected life safety consequence and frequency. A risk estimate was established for each event scenario and was used to determine which events require mitigation and which events are considered to have low enough life safety risk such that no additional action is required in the design process to meet the desired risk level. The risk to life safety was quantitatively evaluated for each fire safety event considered, with all fire safety sub-system features included.

To maximize the effectiveness of Nakheel Tower's many elevators for occupant use in a fire emergency, an elevator-centric occupant evacuation strategy was used. The strategy in the residential portion of the tower included multiple elevators and one exit stair for occupant evacuation to a sky bridge. To demonstrate that a single exit stair tower provides an acceptable level of occupant fire safety, a maximum acceptable risk target of $5.0E^{-5}$ deaths per year as identified in PD 7974-7 [3] was established against which trial designs of the fire safety sub-systems were evaluated.

A comparative analysis was performed to determine the maximum risk value for a high-rise building designed in compliance with the minimum requirements prescribed by NFPA 5000. The NFPA 5000 risk value was considered the "benchmark" to which Nakheel Tower's building fire safety would be evaluated.

Frequency Level	Event Description	Median Time to Event
Anticipated	Incidents that could occur several times during the lifetime of the building	1 to 100 years
Unlikely	Events that are not anticipated to occur during the lifetime of the building	100 to 10,000 years
Extremely Unlikely	Events that will probably not occur during the life cycle of the building	10,000 to 1,000,000 years
Beyond Extremely Unlikely	All other incidents	> 1,000,000 years

Table 1. Frequency Ranking
(Source: Aon Fire Protection Engineering)

Risk Methodology

Fire Safety Events

Fifteen fire safety event scenarios were identified as being probable in Nakheel Tower. These events were classified as being either "ordinary" or "extraordinary" fire emergency incidents. An ordinary fire emergency incident is considered an unintentional event and includes:

Scenario 1: Residential occupancy room and contents fire;

Scenario 2: Skybridge level fire impacting the public space(s);

Scenario 3: Observation Deck level fire impacting the public space(s);

Scenario 7: Precinct building retail space fire (Retail Fire).

An extraordinary emergency incident is an intentional or a severe unintentional event and includes the following scenarios:

Scenario 9: Electrical failure with loss of power to one building sub-tower with simultaneous ordinary fire emergency incident occurring;

Scenario 13: Tsunamis, earthquakes, or other natural disasters;

Scenario 14: Single small aircraft impact.

While the likelihood of an extraordinary event in any building is low, the consequences of such an event in the Nakheel Tower could be significant. Accordingly, extraordinary events were considered to determine the potential impact on the stated fire safety goals.

Table 1 and Table 2 summarize the criteria used to categorize the expected frequency

Consequence Level	Occupant Impact
Negligible	Negligible injuries occur
Low	Minor personal injuries No permanent disabilities No hospitalization
Moderate	Serious injuries Permanent disabilities among occupants Hospitalization required for some occupants
High	Fatalities Immediate life threatening or permanently injuries

Table 2. Consequence Ranking
(Source: Aon Fire Protection Engineering)

and consequence, respectively, of each fire safety event. This is consistent with the consequence ranking schedule used by the Society of Fire Protection Engineers [1].

Figure 3 is a graphic plot of the numerical values established in Tables 2 and 3 for each fire safety event. Fire safety events classified as being beyond extremely unlikely and having negligible consequences are in the green area as having a very low risk ranking. The events with a high anticipated frequency and high consequence are in the red area. All other event scenarios that fall in the hazy orange area are considered to be of moderate risk. Trial design evaluations were conducted on the high frequency and high consequence events to identify fire safety strategies that reduce the frequency or mitigate the outcome of the events.

Mitigation of the high risk events will inherently decrease the risk of the events in the moderate range.

Risk Analysis

Frequency of Scenario / Probability of Event

The generalized Barrois model was used to calculate the probability that a fire will occur within a building [4]. This model recognizes that ignition frequency is dependent on the floor area of a space and the occupancy housed within that space. As a comparison to the Barrios prediction, the Lin [5] method was used to analyze data taken from high-rise residential fires in the United States combined with estimates from U.S. Census Bureau on the total number of residential units located in high-rise building[6][7][8]. An average frequency over a ten year period was used to estimate the probability of fire occurrence based on the area of a typical residential quadrant in the Nakheel Tower. The probability was considered to be conservative since the trend of fire occurrence, based upon U.S. fire data, per unit area is decreasing. Findings by Alqassim and Daeid [9] of U.A.E. fire data over a more recent eight year period confirm the U.S. fire data used in the analysis is a reasonable predictor.

A similar methodology was used for determination of fire frequency in the other occupancy areas of the tower.

Event Trees and Fault Trees

Event Trees and Fault Trees were developed to quantify the expected reliability of each Nakheel Tower fire safety sub-system. Six fire safety sub-systems were evaluated:

- Fire detection system;
- Emergency notification system;
- Fire suppression system;
- Interior (horizontal) fire barriers;
- Floor compartmentalization (vertical fire barriers);
- Building's egress system.

A diagrammatic illustration of these fire safety sub-systems present in the residential portion of Nakheel Tower is shown in Figure 4.

The event trees list all fire safety sub-systems expected to be present within the Tall Tower as they relate to occupant evacuation. Each sub-system may or may not be working at the time it is needed thus creating two branches on the tree with each branch with a probability of occurrence based on the reliability of each system feature including any redundant features of that system. Events were assumed to be independent of one another, however, in some cases it is noted that a system will not be initiated without the proper function of the initiating system. For example, the "egress

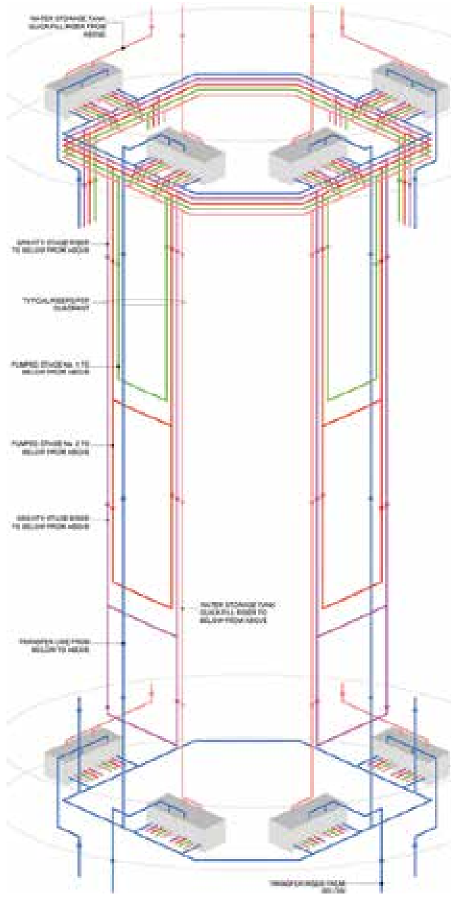

Figure 5. Typical fire protection water supplies and riser piping network for each sky bridge and tower section (Source: Aon Fire Protection Engineering Corporation)

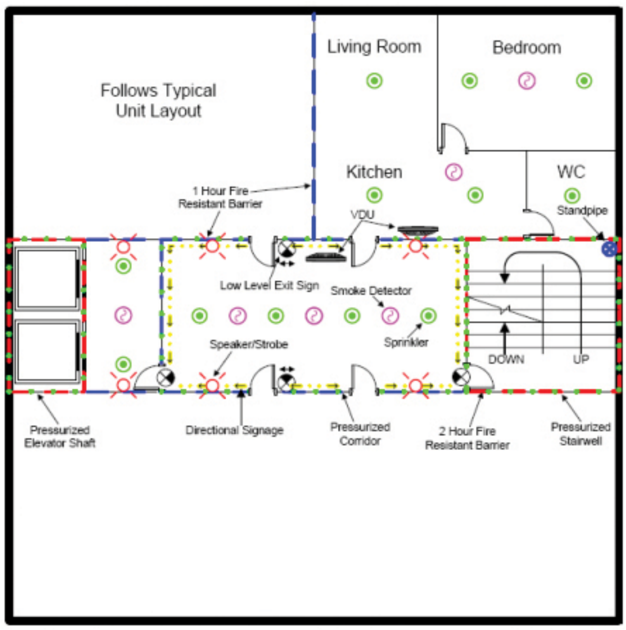

Figure 4. Diagrammatic illustration of a Tower residential floor and its fire safety sub-systems (Source: Aon Fire Protection Engineering Corporation)

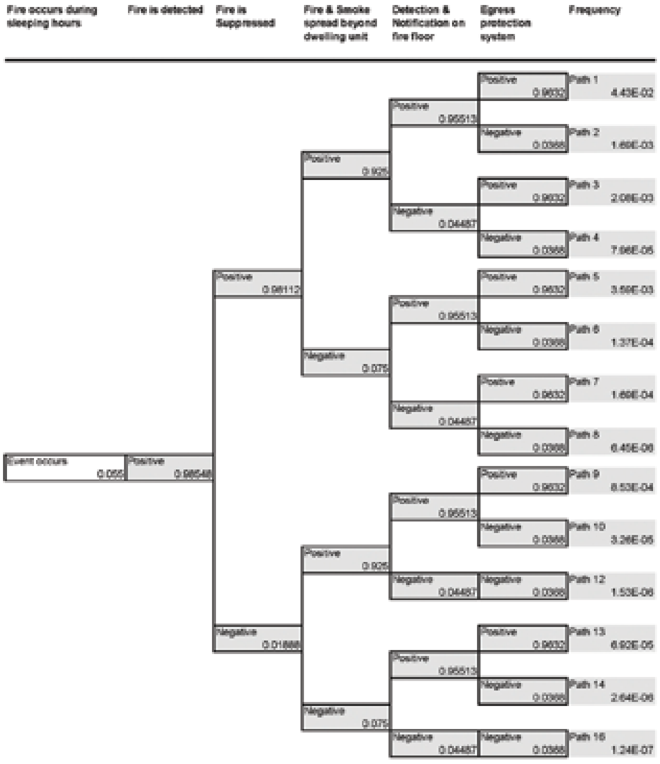

Figure 6A. Event tree, Tower residential fire scenario, Part 1 (Source: Aon Fire Protection Engineering Corporation)

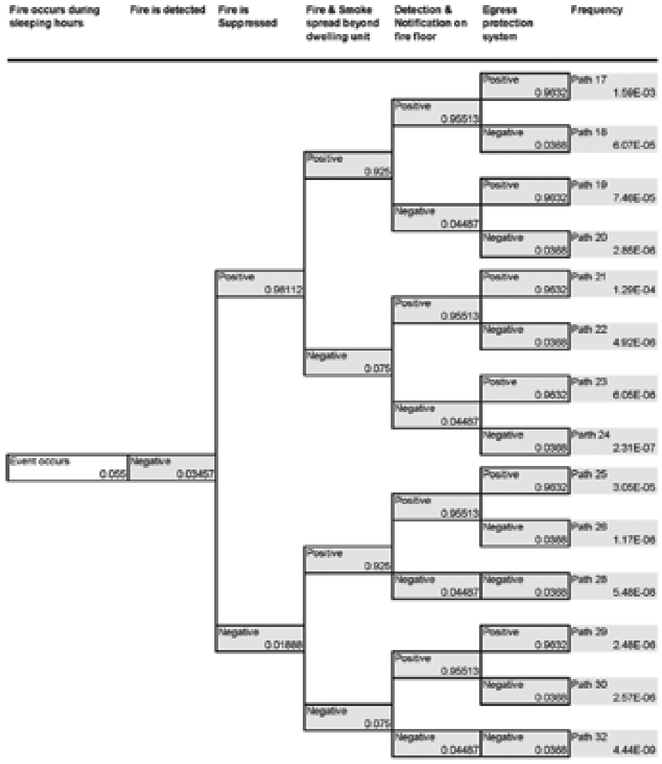

Figure 6B. Event tree, Tower residential fire scenario, Part 2 (Source: Aon Fire Protection Engineering Corporation)

protection system" for the event floor will not activate if the detection system does not detect a fire. In this case, the probability of failure for the Egress Protection System is considered to be 100 percent. This method is acceptable since it provides the most conservative approach for determining frequency.

Fault tree analysis was used to evaluate each fire safety sub-system and their primary components to determine the sub-system's reliability and consideration of the probability that a sub-system will not function as designed when required during a fire event. Nakheel Tower's fire safety sub-systems were designed with redundancies to eliminate potential single-point failures. Each sky bridge included a floor dedicated to MEP plant space serving the four towers above. The central core and four towers above each sky bridge provided multiple pathways for fire safety sub-systems. Figure 5 provides an illustration of the fire protection water supplies and riser piping network for each of the sky bridges and the tower section, and vertical connectivity to the other sky bridge MEP plants. When functional, fire safety sub-system operations will increase the ASET for occupants and decrease the RSET.

Mean Time Between Failure (MTBF) and Constant Failure Rates used in the analyses for the fire safety subsystem elements were obtained from various sources including product test reports, historical data, the estimated MTBF based on manufacturer's recommended maintenance schedules, or engineering judgment [10 – 18].

Figures 6A and 6B illustrate an event tree for the tower residential scenario. This particular event tree contained 32 paths; due to the impossibility of some of the occurrences of events, only 24 paths were considered for Nakheel Tower.

Figure 7 illustrates the fire sprinkler system components and failure modes evaluated. Each fire safety sub-system was evaluated based on factors such as human intervention, component reliability, etc. A fire will not be controlled if the fire sprinkler system is not functioning properly. When the sprinkler system is activated, fire growth is halted and likely decays. If the sprinkler system is not working, the fire continues to grow and the tenability in the space and the available safe egress time, ASET, will continue to decline with time.

Consequences

The consequence of a fire safety event varies depending on the outcome scenario (i.e., the branch of the event tree chosen). The result of a fire spreading beyond the area of origin is directly related to the probability that one or more sub-system does not perform as intended. The number of tower occupants exposed to the fire event is a function of the number of occupants in the area of fire origin at the time of fire occurrence or when untenable conditions are experienced in the means of egress. Therefore, the number of occupants affected, or "consequence," is dependent on the reliability of the detection, suppression, notification, containment, and egress sub-system systems.

A tenability analyses for each fire scenario using fire modeling to determine ASET was compared to RSET obtained by evacuation modeling analyses. Where RSET is greater than ASET, adverse consequences were assumed.

The negative effects of a fire, such as heat and smoke, spreading throughout the building are directly related to the reliability of each sub-system. Systems performing as intended were found to elongate the ASET thereby giving occupants more time to reach their destination. The number of consequences is dependent on the reliability of the detection, suppression, notification, containment, and egress sub-system systems.

Findings

Nakheel Tall Tower versus Code Compliant High-Rise

The risk analyses concluded that the Nakheel Tower residential tower with its redundant fire safety sub-systems, with

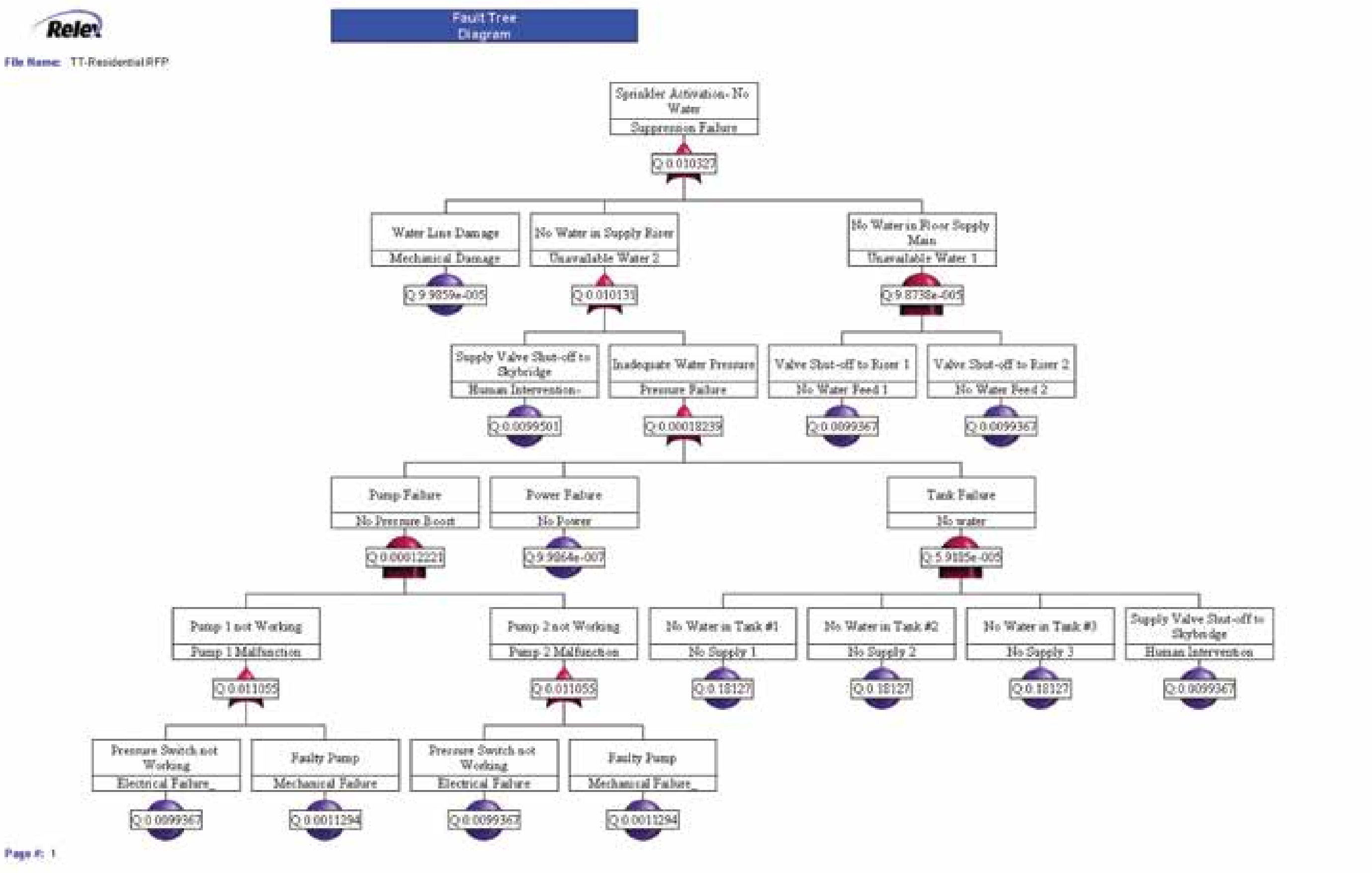

Figure 7. Fault tree, Tower fire sprinkler system (Source: Aon Fire Protection Engineering Corporation)

features that eliminate the potential for a single-point sub-system failure, can achieve the desired maximum risk value target of $5.0E^{-5}$ deaths per year for the identified fire safety events. In the residential towers with the elevator-centric evacuation strategy of multiple elevators and a single exit stair, a maximum risk value of $4.01E^{-5}$ deaths per year was achieved. A code compliant tower with two exit stairs yields a maximum risk value of $6.52E^{-4}$ deaths per year. The risk of death from fire in Nakheel Tower is 15 times less than in a code compliant high-rise building.

The hotel portions of Nakheel Tower posed a different risk to life safety as compared to the residential towers. The hotel tower, which is comprised of two towers situated atop a sky bridge and beneath the observation deck levels, is more than twice the floor area of the residential towers and has a significantly higher occupant population per tower floor level that may be exposed to an event. The higher population also increases the probability that a hotel fire scenario will occur as compared to the residential fire scenario. The hotel floors are provided with multiple elevators and two exit stairs for occupant evacuation. Varying trial designs and enhancements in the fire safety sub-system features, identified by the systems event trees and fault trees, was required to achieve the desired maximum risk value of $5.0E^{-5}$ deaths per year. A code compliant hotel high-rise yields a maximum risk value of $1.5E^{-2}$ deaths per year.

All Nakheel Tower sky bridges were required to have an equal to or less associated risk than the sub-tower. Varying the fire safety sub-systems' trial designs to achieve a frequency of failure less than or equal to $1.42E^{-8}$ failures per year achieved a maximum risk value of $1.0E^{-6}$ deaths per year.

Elevator versus Stair

Potential vulnerabilities and enhancements were incorporated in the risk analysis to reduce the vulnerability and bolster the level of fire safety performance afforded by the elevators. Enhancements identified included:

- Fire rated elevator lobby enclosures with smoke management systems to restrict smoke movement;
- Installation of real-time display terminals in elevator lobbies indicating arrival time of the next elevator;
- Redundant power supplies;
- Installing service elevator controllers in a separate control room from passenger elevator controller and located in a different sky bridge fire compartment;
- Shielding and relocating the elevator hoistway components from possible water damage.

Analysis conducted to compare the risk to life safety associated with an exit stair to the risk to life safety associated with an elevator concluded that enhanced elevator design features can greatly improve overall reliability. Fault trees of Nakheel Tower's egress protection system were used to determine stair and elevator reliability.

An exit stair might not be available at the time of need due to pressurization system failure, enclosure failure, or opening protection failure. Elevators might not be available when required due to electro-mechanical failure, human intervention, power outages, shaft enclosure failure, or pressurization system failure.

The fault tree indicates a stair unreliability of $2.3E^{-2}$ equivalent to 97.7% reliability. Elevator unreliability was determined as $1.57E^{-1}$, equivalent to 84.3% reliability. Although the elevator system is less reliable than a traditional stair on a component by component basis, when used as part of a holistic fire protection strategy, its inclusion in the egress system is shown to provide an acceptable risk to life safety in line with the stated project goals and less risk when compared to a code compliant building which uses no elevators.

Conclusions

Nakheel Tower's design of separate towers, each with their own core that is structurally linked by sky bridges, provides a backbone to which redundancies in the tower's fire safety sub-systems can be incorporated. Using a risk-based approach for achieving building occupant fire safety, various fire safety sub-systems and their redundancies can be evaluated through trial design to identify enhanced design features which greatly improve system reliability. When analyzing the tower and its various fire safety sub-systems holistically it can be demonstrated that an elevator-centric evacuation strategy with multiple elevators and only one exit stair in the residential towers provides a greater level of occupant fire safety as compared to a traditional high-rise building with two exit stairs.

References:

NFPA 5000 (2006), **Building Construction and Safety Code, 2006 edition.** National Fire Protection Association, Quincy, MA

SFPE Engineering Guide to Performance-Based Fire Protection (2007), 2nd Edition. Society of Fire Protection Engineers, Bethesda, MD

PD 7974-7 (2003), **'Application of Fire Safety Engineering Principles to Design of Buildings – Part 7: Probabilistic Risk Assessment,'** British Standards Institution, London, UK

Hasofer, A.M., Beck, V.R., and Bennetts, I.D., (2007) **Risk Analysis in Building Fire Safety Engineering,** Butterworth-Heinemann, Elsevier, Oxford, UK

Lin, Yuan-Shang, (2005) **'Estimations of the probability of Fire Occurrences in Buildings,'** Fire Safety Journal, September 2005.

Hall, John R. (1997), **'The lowdown on High-rise Fires,'** NFPA Journal, Nov/Dec 1997, p. 84-90.

Hall, John R. (2005). **'High-Rise Building Fires,'** National Fire Protection Association, Fire Analysis and Research Division, Quincy, MA, August, 2005.

U.S. Census Bureau, Housing Units—Characteristics by Tenure and Region: 2005, http://www.census.gov/compendia/statab/tables/08s0951.xls, accessed November 20, 2008.

Alqassim, Mohammad and Daeid, Niamh Nic (2014). **'Fires and related incidents in Dubai, United Arab Emirates (2006–2013).'** Case Studies in Fire Safety – 2. Elsevier, B.V. October 29, 2014, pp. 28-36.

Bruck, Dorothy, and Mahmut Horasan (1995), **'Non-Arousal and Non-Action of Normal Sleepers in Response to a Smoke Detector Alarm.'** Fire Safety Journal 25: pp. 125-139.

Department of the Army, US Army Corps of Engineers (2001), **'Reliability Analysis of Navigation Lock and Dam Mechanical and Electrical Equipment,'** Technical Letter No. 1110-2-560, June 30, 2001.

Hall, John R. (2007) **'U.S. Experience with Sprinklers and other Automatic Fire Extinguishing Equipment,'** National Fire Protection Association, June 2007.

Dahlin, T., Higinbotham, W., Ward, S. (2004), **'Improving Reliability for Power System Protection,'** April 2004.

Bukowski, R. W.; Budnick, E. K.; Schemel, C. F. (2002). **'Estimates of the Operational Reliability of Fire Protection Systems.'** Fire Protection Strategies for 21st Century Building and Fire Codes Symposium. Proceedings. Society of Fire Protection Engineers and American Institute of Architects. September 17-18, 2002, Baltimore, MD, pp. 111-124.

Richardson, J. (1984). **'An Assessment of the Performance of Automatic Sprinkler Systems.'** Society of Fire Protection Engineers, Technology Report 84-2. Bethesda, MD.

Bennetts, I.D., Thomas, I.R., Poons, S.L. and Sims, J.A. (1992) **'The Effect of Fire in the Building at 140 William Street: A Risk Assessment.'** BHP Research – Melbourne Laboratories, Report No. BHPR/ENG/92/044/SG2C.

Blanton, Connie, and Coutts, D. Allen, (2007) **'Quantitative Evaluation of Fire Separation and Barriers,'** Washington Group International, Savannah River Site. Energy Contractors Facility Group.

Zhao, Longde (1998). **'Reliability of Stair Pressurisation & Zone Smoke Control Systems.'** Centre for Environmental Safety and Risk Engineering, Victoria University of Technology, Sydney, NSW.