Risks in high-rise buildings and countermeasures

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Abstract. In the last half century, high-rise buildings have entered a phase of rapid development as a result of the swift growth of economy especially in Asia's developing countries. Despite the optimistic prospect of the development of high-rise buildings, risks exist perpetually. The risks of high-rise buildings consist not only in structures, but also in environmental, social and cultural facets. However, those engaged in the latter one was often ignored, which is not conducive to a thorough assessment. This paper considers and analyses risks in a more integral and comprehensive approach. In this paper risks are divided into three categories: construction, structure and utility based on the building's entire life cycle. In each category, in order to analyze in more detail, risks are further divided into sub-categories with dropping, mechanical injury, fire and finance in construction, failing and fire in structure and fire, surrounding effects and acceptance in utility. In tune with the risks, countermeasures contain both the concept of solving as well as the exact action to take, including enhance risk prevention measures and ensure risk control measures in construction, adopt the best structural plan, and guarantee structural performance in structure, take effective measures against fire and maintain environmentally and socially friendly in utility. In future study, the risks defined by numerical values and those defined by verbal expressions are expected to get combined through some ingenious way of incorporating. This paper serves as a synthesized analysis of risks in various domains and puts forward corresponding countermeasures.

Keywords: High-rise building; risk; countermeasure; synthesized analysis.

1. Introduction

Since the first high-rise buildings appeared in Chicago in 1880s, substantial changes have taken place not only in their height, but also in their entire life cycle involved. And undoubtedly, with the development of design and construction technique, the number of high-rise buildings especially skyscrapers have been increasing greatly since the last century. In accordance with the data of Council on Tall Buildings and Human Habitat (CTBUH), which provides the most reliable information regarding high-rise buildings, hitherto, there are 1,968 buildings which have a height of more than 200 meters in the world. In the last half century, high-rise buildings have entered a phase of rapid development as a result of the rapid growth of economy especially in Asia's developing countries. And high-rise buildings are expected to grow in these areas for decades to come due to soaring demand of residences, trades and offices. In these areas, not only are high-rise buildings skyrocketing in numbers, but they are also reaching even taller: Nine out of ten tallest buildings in the world come from Asia and several more are being constructed. Despite the optimistic prospect of the development of high-rise buildings, risks exist perpetually: Examples of high-rise buildings which collapsed, caught fire, got unfinished are not even rare, bringing about serious economic and social consequences. Considering the magnitude of influence and coverage of high-rise buildings, especially skyscrapers, it is vital to consider the possible risks associated with the entire life cycle of high-rise buildings.

Several research has been conducted to analyze the risks engaged in buildings and the structural stability of high-rise buildings under different types of loads. Based on preceding research and study, the possible risks related to the entire life cycle of high-rise buildings and countermeasures can be generally summarized. Besides, some more specific study which investigated into certain areas of the risks of high-rise buildings could give much insight into analysis, such as the building's response to wind loads and earthquake loads. However, the risks of possible effects on environment, society and culture have yet to be critically analyzed. The point of writing this paper is to synthesize what has

been done concerning the topic as well as provide some thoughts on those possibly neglected fields of risks.

This paper aims to analyze risks and countermeasures in a more integrated manner, especially those involved in environmental and social sectors. This paper firstly evaluates risks in construction, structure and utility while discussing risks in a more detailed pattern under these three categories. In risk analysis, this paper pays more attention to the risks involving people while still laying emphasis on the structural stability of the building. In tune with risks, countermeasures are put forward in construction, structure and utility and are a combination of overall methodology and exact measures. By looking into different domains including architecture, civil engineering, environmental protect and sociology and examining the overlaps of these disciplines, a more comprehensive analysis of the relevant risks and countermeasures of high-rise buildings is expected to be concluded.

2. Risks

The properties of high-rise buildings make them more susceptible to natural environment as well as human activities. A venial mistake in an ordinary structure may bring about catastrophic consequences for a high-rise building. Considering the risks in the building's lifelong perspective, they can mainly be classified into construction, structure and utilities.

2.1. Risks in construction

Constructing a building involves a set of complex procedures. From preparation to construction and completion of each project, the content and conditions of the buildings in question have changed dramatically. Because of its complexity and variability, something could go wrong anywhere in the process. Meanwhile, a project is usually built by multiple construction units, and covers multiple disciplines, which inevitably results in the varying makeup of staff and calls for a better coordination between each side. In order to enhance the understanding of risks in construction, these aspects following should be addressed [1].

Risks of dropping. The construction of high-rise buildings inevitably entails the presence of people at high places, which contributes greatly to the danger of dropping. Considering the altitude of the construction site, the results of dropping, whether for a person or an object, are disastrous. Personnel's negligence, a lack of safety-insuring facilities and an unexpected change of natural conditions can all lead to a fatal accident.

Risks of mechanical injury. The heavy machinery, if used improperly, could put people's lives at risk. During the construction, the tower crane, excavator, pump truck and other mechanical equipment shall be operated in strict accordance with corresponding regulations [2]. However, a lack of coordination and proficiency makes the workers onsite more susceptible to accidental contact with the machinery.

Risks of fire. The high-rise building under construction not only has the inherent fire risk of high-rise buildings resultant from the combustible items used, but it also has its uniqueness, including a lack of fire extinguishing facilities and emergency exit routes. This makes high-rise structures under construction more likely to catch fire and more difficult to extinguish, resulting in an increase in the fire risk of high-rise building construction [3].

Risks of finance. High-rise buildings, unlike other ones, poses a greater challenge to construction and thus entail more funding to get completed. When it comes to the skyscrapers which are an important part in high-rise buildings, the economic burden can be even worse, which often leads to a state of incomplete and a waste of resources without enough financial support.

2.2. Risks in structure

Structure is the skeleton of the building with which the building can support itself. Risks in structure are also the fundamental risks concerning a building and are discussed most frequently among researchers and engineers. This type of risks could come from various reasons, but they can

be mainly divided into two categories: capacity and load. The risks in the former group can be attributed to weak materials and poor constructing methods while those in the latter one can be aroused by self-weight, human and natural conditions. A building's capacity can be compromised by insufficient amount or poor quality of building materials and a lack of rigid connection between different elements, both of which indubitably damage the structure's strength. Loads acting on a specific building pose a challenge to its structural stability. Dead loads and live loads both call for corresponding rigidity to carry. Once the loads exceed the building's capacity, there's a great possibility that it will fail.

Risks in structure mainly reside in risks of failing. Here, the definition of failing is that the building has lost its utility and was not be remedied. As a result, if the building still exists but was not function, it is considered a failed structure. So are the severest situations where the building simply collapses.

For high-rise buildings especially, wind load can account for most of the risks even though it's relatively minor compared with the building's dead loads. The wind-induced vibration response of low damping and high flexible structures becomes more relevant as structure height and the use of high-strength materials grow, indicating a greater possibility of failure [4]. Besides, considering a high-rise building is often adjoining other ones, the flow fields between adjacent buildings will interfere with each other, magnifying the magnitude and behavior of the wind load greatly [5]. In some cases, the wind pressure may far exceed the wind force when the building exists alone. Strong winds could put the already tense foundation pit and low levels even more at hazard.

In addition, fire is also a factor worth contemplation. A building is initially designed to function under normal conditions, but when a fire occurs, the safety of the structure is really at risk on account of the extreme situations the building faces. Without proper and potent fire extinguishing facilities, the materials made to act as the building's skeleton, mainly steel and concrete, could lose their mechanical properties in hours even minutes due to the exceedingly high temperature, which inevitably contributes to the failure of structure.

2.3. Risks in utility

The ultimate goals of a high-rise building is to serve people's needs. Where there is use, there is risk. Improper uses often lead to instability of the structure. What's more, a high-rise building can even have an impact on surroundings and even, the image of the city it sits in.

Risks of fire. Due to high floors, once a fire occurs, it's probable that it cannot be extinguished from the outside like ordinary ones, which brings great difficulties to fire fighting and personnel evacuation, causing major losses and casualties [6]. Various facilities and items, especially inflammable, can also play a crucial role in setting off the fire. What's more, plenty of materials used either in structure or decoration could emit poisonous gases, which account for deaths when a fire occurs [7]. In addition, high-rise buildings' elevator shaft has a chimney effect that will hasten the spread of a fire [8]. Besides, on account of the high density of people and an elongated evacuation route in a high-rise building, the evacuation process is often a total mess, killing people in an imperceptible way.

Risks of surrounding effects. High-rise building could easily change its surrounding natural conditions and consequently affect its vicinity in a harmful way. A high-rise building's flow field may interfere with that of adjacent buildings', amplifying the wind load on each of these buildings [5]. This could make the wind load acting on adjacent buildings much greater than their design values, jeopardizing their structural reliability. Apart from this, the glass facade frequently seen in high-rise offices can reflect sunlight to its surrounding area, causing light pollution, intensifying urban heat island effect (UHII), and even giving rise to fires especially in summer.

Risks of acceptance. High-rise buildings, especially skyscrapers, serve not only residential and commercial purposes, but they also often stand on behalf of the land where it sits. Due to economic incentives, some high-rise buildings are designed completely independently, without any communications with the city and its citizens, which leads to a discrepancy with the city's culture and what the city really needs. It can be concluded that such high-rise buildings, however magnificent,

will indubitably be ostracized. The categories and sub-categories in risk analysis are shown in the Figure 1.

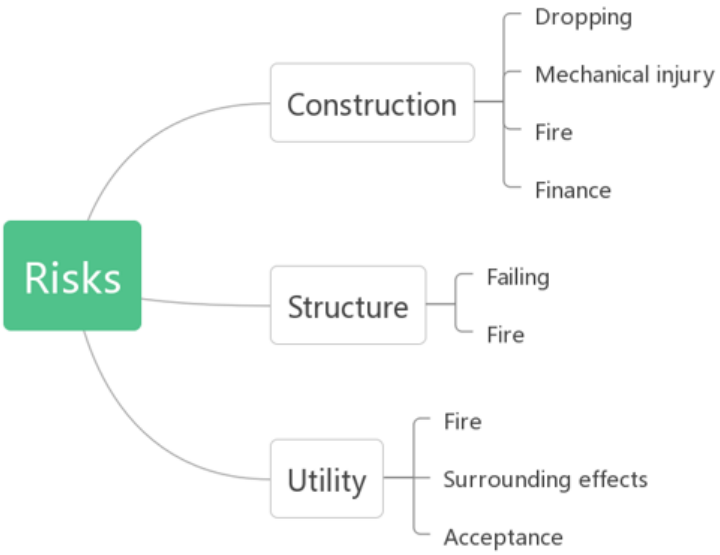

Fig 1. Risk analysis.

3. Countermeasures

Risks cannot be completely eliminated, but they can be subdued thanks to potent corresponding countermeasures. Risks must happen out of some reason, which is the very point to cut in with interventions. Because the risks are mainly classified due to the reasons why they happen, by keeping in line with the classification of risks, countermeasures can get straight to the point and bring about the optimal result.

3.1. Countermeasures in construction

Enhance risk prevention measures. Risks can't be absolutely eliminated, but they can be best prevented through effective risk prevention measures. The absence of risk prevention measures is a major contributor to the risk factors in the construction of high-rise buildings. Establishing a strong risk prevention measure, implementing pertinent systems and standards is thus a crucial first step in raising the caliber and effectiveness of safety management. As for the specific work, the construction firms are supposed to frequently organize staff for training in risk prevention and management. The work obligations of every employee must be specified, and the system of responsibility must be properly followed [8]. Paying close attention to the integral construction process and emergency plans is conducive to less potentially hazardous construction phases [2].

Ensure risk control measures. Due to the size of high-rise buildings and the complexity of construction process, it's common to have lots of risk factors. When a risk has turned into danger, meaning there is no turning back, it's critical to bring the danger under control to avoid bigger losses. As a result, emergency plans are desperately needed. Safety incidents like collapses, explosions, fires, and injuries can happen at any time. To improve the response time in such events, emergency plans should also be practised repeatedly. What needs to be clarified is that the emergency plan should not be used as a backup of poor risk prevention measures, but should be founded on those measures with the intention of controlling the consequences of the accidents to the minimum [8].

3.2. Countermeasures in structure

Countermeasures are to intervene with the happening of risks by means of cutting off their possible causes. As is mentioned in analysis of risks in structure, the origin of risks could be generally divided into capacity and load. In line with these causes, countermeasures in structure, in concept, principally deal with the capacity in that the loads won't pose much threat since the capacity is strong enough.

Adopt the best structural plan. The aim of the selection of the optimal structural plan is to make the most output out of given input. The choosing of the most reasonable structural plan is the most important phase in structural design of high-rise buildings in that it serves as the first need for subsequent work. The choice and application of the structural plan directly affects the building's structural soundness. It is also indispensable for ensuring that the structural design of buildings satisfies the using criteria [9]. When it comes to choosing the optimal structural plan, there are a lot of issues to consider. In order to prevent the chosen structural plan from not complying with the requirements of pertinent codes and regulations, these codes and regulations for the structural design of high-rise buildings should be studied carefully and the structural plan should meet the requirements for the structural design of high-rise buildings. In the structural analyses, the stress conditions and transfer of forces between each component should be not so complicated and clear without sacrificing the rigidity of the building [10]. Apart from this, the specific structural plan of a particular high-rise building shall be carefully considered in the light of the actual condition of the construction site. In order to choose the optimal structural plan, the scale of the project and the construction site's foundation condition must be thoroughly investigated [11]. In summation, a scientific structural plan's economic and scientific nature will allow it to produce the best outcomes at the lowest possible cost.

Guarantee structural performance. The primary goal of structural design of a building is to satisfy all criteria of applications. Only by meeting the relevant performance requirements can buildings designed satisfy safety standards in later usage processes and keep stable in a relatively long period of time. That's what is called a scientific structural design [9]. In particular, the relationship between the downward forces and the foundation's bearing capacity in the chosen structural plan should be made clear in the structural design for high-rise buildings. It is also vital to meticulously consider the overall design of the layout and quantity of main load-bearing sections of the high-rise buildings [12].

3.3. Countermeasures in utility

The foundation on which countermeasures concerning utility are based is people's behaviors. Better communication, more efficient management and more aware cognition can all be conducive to a safer high-rise building. Countermeasures in fire, environment and society are the first to consider in that they are most closely regarding people's needs.

Take effective measures against fire.The formulation of countermeasures against fire is based on the idea of self-rescue, whether it's for the building or the people. The features of high-rise buildings make it almost impossible to put out the fires conventionally especially for those high above the ground. Therefore, the firefighting of high-rise buildings must be based on self-rescue, that is, the fire resistance ability of the building itself and the automatic fire extinguishing system installed. In order to give time for evacuation and minimize fire losses, high-rise structures' fire resistance ability must be guaranteed. This way, in the event of a fire, the building's structure won't be damaged quickly. Along with guaranteeing the main structure's fire resistance ability, the design must take the fire resistance of the ceiling, walls, and other decorating components into account [13]. The automatic fire extinguishing system is the primary method of coping with fires and a crucial assurance for the personnel's safe evacuation. It is able to fully defend the security of evacuation facilities while simultaneously putting out the initial fire, lowering temperature, eliminating smoke, and limiting the spread of the fire [14]. In order to ensure safe and adequate water supply, the water supply of high-rise buildings' automatic fire extinguishing system should adopt an independent source [7]. Overall, the fire prevention design of high-rise buildings shall be carried out in strict accordance with relevant regulations, with the overall layout reasonably arranged, the ventilation design and evacuation system strengthened, fire extinguishing equipment of various functions installed, and emergency evacuation plans carefully designed [15]. In skyscrapers where all the people inside are unable to leave very shortly, the arrangement of refuge floors and related evacuation routes and facilities should be taken into consideration [16]. As for the equipment, standard fire protection design and perfect fire protection facilities are the key to fire protection of high-rise buildings. However, the panacea for

preventing fire and minimizing fire consequences lies in the law enforcement and people's awareness of disaster prevention [13]. Further improvements of various laws and supervision of fire safety and work implementation are expected; targeted publication of fire prevention knowledge, especially self-rescue knowledge, helps improve the awareness of safety and fire prevention of the public; regular fire drills can also serve to bolster public's ability to fully utilize fire-fighting facilities and evacuate [14].

Maintain environmentally and socially friendly. When referring to a high-rise building, the idea of analyzing in a building's entire life cycle is crucial: every aspect of a building's impacts on environment and society at every stage of its life, including planning, design, construction, utility, and demolition should be contemplated. Besides, the input-output relationships are supposed to be carefully weighed with an appropriate technical path chosen and put into practice [17]. Reducing, reusing, and recycling (or 3R) will naturally reduce the need for new construction materials, thus saving natural resources and lowering pollution [18]. When it comes to green buildings, lightweight design is of great emphasis, which reduces the consumption of building materials and lowers CO_2 emissions. In utilization, energy and water saving can be quite important. By lessening the roughness of the building surface and carefully examining building's orientation, spacing, and shape, it’s easier for heat dissipation and natural ventilation. of the underlying surface [19]. By prioritizing the use of recycled water and rainwater and emphasizing water conservation, there’s a great possibility that the building can have a sustainable way of water consumption. To prevent negative effects on human health, efficient water quality detection and health assurance techniques are to be developed for the usage of non-traditional water sources like recycled water [20]. High-rise buildings, especially those which often convey special meanings, should be carried out in strict accordance with relevant regulations and should seek feedback from its location’s citizens in every process. The design should rather be congruent with the city’s spirits than be captivating while the implementation process should not be offensive to most engaged neighborhoods. After completion, it’s vital for that specific building to stay conducive to a better and friendlier atmosphere not only in its surroundings but in farther places beyond, which can be accomplished by organizing activities which arouse familiarity, serving as an example of environmental protection, and most importantly for a building, serving the people heart and soul. The categories and sub-categories in risk analysis are shown in the Figure 2.

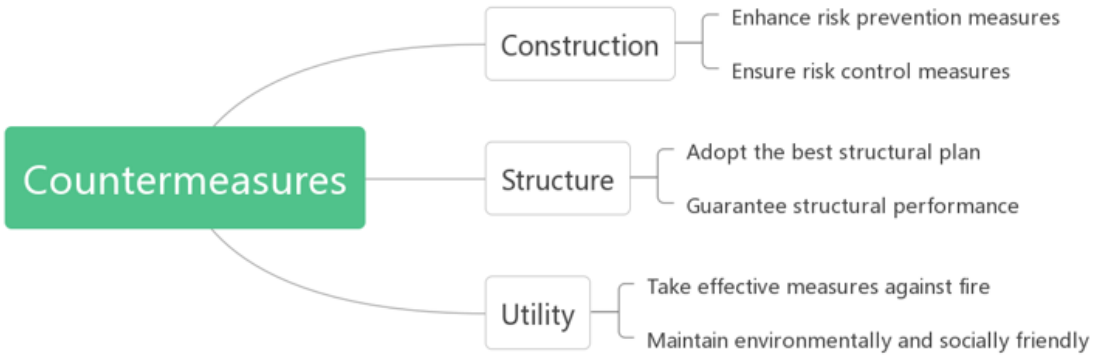

Fig 2. Countermeasure analysis.

4. Conclusion

Around the globe especially in Asia, high-rise buildings are developing at an unprecedented speed, reaching ever taller into the sky. Nevertheless, risks concerning the entire life cycle of them can lead to adverse consequences if left untreated. This paper considers risks in various aspects and proposes corresponding countermeasures. Risks in construction, structure and utility are discussed respectively and more details are mentioned in a sub-category, including fire and so on. Possible cause, interacting relationship and consequence of risks are considered in each sub-category. Targeted at risks, countermeasures, which are each a combination of relative methodology and specific measures, are put forward starting from the cause and relevant influencing factors of risks. It turns out that risks,

considered in an integrated approach, which features combination of structural, environmental and social analysis, could provide more insights into the study of risks and thus facilitate the research on countermeasures. In future study, risks evaluated by different criteria are expected to combine more efficiently, benefiting a more integrated and comprehensive methodology of risk analysis and prevention. This paper analyses the possible risks regarding the entire life cycle of high-rise buildings, offers concerning countermeasures, and provides some suggestions on future study in risk analysis.

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