Vulnerability Assessment Model for Cost Efficient Anti-terrorism Design of Super High-Rise Buildings

Kyung-Yeon Kang1 and Kyung-Hoon Lee*2

1Research Professor, Research Institute of Engineering and Technology, Korea University, Korea
2Professor, Department of Architecture, Korea University, Korea

Abstract

The purpose of this study is to select architectural design elements of super high-rise buildings to protect them from terrorism using explosives and to develop a vulnerability assessment model which can take into account the relative importance of each design element in anti-terrorism and the supplementary effects among them for achieving cost efficient architectural design.

Four layers of defense and 27 architectural design elements were selected and the design elements were categorized into 7 supplementary groups based on their purpose and function. Then, design guidelines for each element were classified into 5 grades on the basis of its protection or risk level.

Weights of each element were extracted through an AHP survey by anti-terrorism specialists. The results imply that the vulnerability of high-rise buildings to terrorism would be affected the most by the circumstances of the building and neighborhood, and the modification of heavily weighted design elements for separating unauthorized vehicles from a tower and blocking them outside of the site could be the most efficient design measures to counter terrorism.

As a vulnerability assessment model, a bottom-up formula was suggested. To reflect the supplementary effects among design elements in the same group, an evaluation level integration methodology was included.

Keywords: anti-terrorism; high-rise building; design guideline; vulnerability assessment; AHP

1. Introduction

In recent decades, the target of terrorism has been changed from public buildings like government buildings to private buildings such as hotels, shopping malls, subway stations, etc. This is partly due to the fact that relatively less considerations are given to security issues in the designing and running of private buildings than public buildings, and therefore, private buildings are potentially easier targets for terrorists.

In this context, super high-rise buildings are at a greater risk of being targeted by terrorists. The super high-rise building industry has been growing continuously around the world, and super high-rise buildings are considered as a symbolic icon of a nation's wealth.

However, as witnessed in the 9/11 attacks, the damage caused by terrorism to super high-rise buildings is greater than that of any other private building in terms of casualties, economic loss, public fear, and loss of national prestige.

Since the 9/11 attacks, various design guidelines for preventing and mitigating the damage of terrorism such as the 'Security Risk Management Series' of the Federal Emergency Management Agency (FEMA), have been developed in the United States. The National Counter-Terrorist Security Office (NaCTSO) has developed the 'Counter Terrorism Protective Security Advice Series' for the design of private buildings. However, there are no guidelines specifically developed for protecting super high-rise buildings against bomb attacks.

In Korea, there are 125 buildings higher than 50 stories, 86 of which are under construction, while 10 over 100 stories are under construction or in the planning stage. The government has already legislated several laws for protecting them from terrorism. According to the Metropolitan City of Seoul Ordinance, anti-terrorism design is required in the design of super high-rise buildings, and the deliberation of disaster effects is required in the design of super high-rise buildings or any complex buildings larger than 20,000 square meters connected to the underground.

The 'Rapid Visual Screening (RVS) (FEMA, 2009)' is one of the commonly used tools for assessing vulnerability to terrorism, which was simplified from...
the 'Risk Assessment (FEMA, 2005)' for the purpose of rapid and effective evaluation of terrorist attack on commercial and conventional buildings. In RVS, the overall risk of a building is extracted from the results of evaluation of three factors, i.e., consequences, threat, and vulnerability, for nine threat scenarios consisting of intrusion into the building, vehicle borne improvised explosive device, and a chemical, biological or radiological (CBR) release. There are differences in the weights of evaluation elements depending on the relative importance of the incidence and the damage from terrorism. Most of the heavily weighted are social and economic elements including the number of occupants, site population density, replacement value, visibility or symbolic meaning, the number of high value targets around the building, and so on. But most of the elements concerning architectural design are regarded as less important than others in RVS.

Therefore, this study aims to develop a vulnerability assessment model focused on architectural design elements in order to predict the vulnerability to terrorism using explosives, at the schematic design stage, and accordingly, supplement the weak points selectively to lighten the burden of building owners.

2. Methods

In order to employ the AHP (Analytic Hierarchy Process) method and to develop the assessment model, design elements of super high-rise buildings were selected and categorized into several groups for structuring the hierarchy. The relative importance of the elements of defense in preventing and mitigating the damages of terrorism was determined through AHP survey. Based on the weights of design elements, the vulnerability assessment model which takes into account the protection level and supplementary effects was developed and a case study was carried out to test its applicability.

(1) Hierarchy of elements of defense

The concept of layers of defense refers to the setup of successive security measures for protecting major properties. In this study, 4 layers of defense composed of surroundings affecting the incidence of terrorism, perimeter of the site, exterior space between the perimeter of the site and the building envelope, and building itself, were selected.

Twenty seven design elements were selected based on the results of analysis of several anti-terrorism guidelines, such as: Design Guidelines of Multi-use Facilities for Protecting from Terrorism, Ministry of Land, Transport and Maritime Affairs of Korea, 2010; DoD Minimum Anti-terrorism Standards for Buildings, Department of Defense, U.S., 2002; Risk Management Series, FEMA, 2003a; 2003b; 2005; 2007; 2009; Counter Terrorism Protective Security Advice Series, NaCTSO, 2006; 2008a; 2008b. Considering the complementary reinforcing effect of design elements within the same layers of defense, the design elements were categorized into 7 groups based on their function and purpose. For assessing vulnerability, applicable design guidelines of each element were classified into 5 grades on the basis of its protection or risk level.

(2) Weights of design elements

The AHP method was employed to determine the relative importance of each layer of defense, supplementary groups, and each design element in terms of protecting from terrorism and mitigating damage. In order to determine the relative importance of the elements (weights), 12 questionnaire tables were developed for expert survey. Experts in anti-terrorism and design of super high-rise buildings participated in the survey, and they were asked to make pairwise comparisons for each level of hierarchy and determine which element is more important and by how much. From the results of each expert's judgment, individual comparison matrices were constructed separately for the participants and the questionnaire tables. The consistency ratio (CR) of each matrix was calculated to measure the consistency in the judgments of each expert.

To interpret the experts' decisions, the group judgment matrices were obtained through the aggregation method using the geometric mean of the individual judgment matrices, and from these, group priorities of each element of defense were derived separately for matrices through the eigenvector method and the CR was examined.

(3) Vulnerability assessment model

As a result of the expert survey, a vulnerability assessment model reflecting the hierarchy and weights of elements of defense was suggested. This is a bottom-up method, in which vulnerability of element is calculated sequentially from low to high hierarchically. To reflect mutual supplementary effects among design elements within the same group, an evaluation level integration method using weighted geometric mean was used.

---

Fig. 1. The Framework of the Study
In order to test the applicability of the model developed, the vulnerabilities of two super high-rise buildings (one constructed and one in the planning stage) were assessed using the vulnerability assessment model by two experts through field observation and architectural documents analysis. As a result, the vulnerability level of each building was evaluated and the measures of reinforcing vulnerable elements were suggested. Fig. 1 outlines the procedure of this study.

3. Elements of Defense

(1) The hierarchy of elements of defense

The highest level of the model is composed of four layers of defense including surroundings, the first, second and third layer of defense. The middle level of the hierarchy consisted of 7 groups of which the design elements have the supplementary effect of reinforcing each other. The 27 design elements that were selected from the result of analysis of anti-terrorism guidelines consist of the lowest level of the hierarchy. Since there was no supplementary effect among the design elements of the surroundings, the hierarchy was composed of only two levels. Table 1 shows the structure of the elements of defense.

The surroundings refer to the circumstances of the site and neighborhood which strongly affect the risk of terror attacks. This layer is composed of 4 design elements as follows: (1) the occupancy use of the building, (2) the number of occupants, (3) the building height, i.e. the number of floors above ground level, and (4) the target density which means the number of critical infra-structures and facilities of high risk (Table 2) within certain distances of the tower.

The first layer of defense, the perimeter of the site, consists of 2 supplementary groups. A group for creating a standoff distance between the building and unauthorized vehicles is composed of 3 design elements: (1) distance from the tower to the nearest public road, (2) separation of vehicular access points according to the purpose of their visit, and (3) prevention of surface parking along the street adjacent to the site. The other group for preventing vehicles from penetrating the perimeter of the site is made up of 3 design elements: (1) the location where the perimeter barrier was set up, i.e. distance from the tower, (2) the type of perimeter barrier for resisting the impact of a vehicle and protecting the tower, and (3) prevention of surface parking along the street adjacent to the site.

The second group for circulation control consists of 3 design elements: (1) prevention of high-speed approach, (2) prevention of leaving roadway, and (3) prevention of access to high risk facilities. The third group for separation of building from a roadway is composed of 3 design elements: (1) distance from the tower to the roadway, (2) garage location, and (3) separation of public and secured areas.

The third layer of defense consists of 4 supplementary groups. The group for building envelop includes 3 design elements: (1) building configuration, (2) window support type, and (3) glass type. The group for space zoning includes 4 design elements: (1) loading dock location, (2) mail screening measures, (3) access control by space zoning and security check, and (4) separation of public and secured areas.

Table 1. Structure of Elements of Defense

| Layers of defense | Supplementary groups | Design elements |
|-------------------|----------------------|-----------------|
| L1. Surroundings  |                      | E1. Occupancy use |
|                   |                      | E2. Number of occupants |
|                   |                      | E3. Building height |
|                   |                      | E4. Target density |
| L2. 1st layer     | G1. Stand off        | E5. Distance from the tower to a public road |
|                   | G2. Prevention of penetration | E6. Separation of vehicular access points |
|                   |                      | E7. Prevention of adjacent surface parking |
| L3. 2nd layer     | G3. Access control   | E11. Location of vehicle access control |
|                   | G4. Circulation control | E12. Type of vehicle access control measures |
|                   | G5. Separation from building | E13. Prevention of high speed approach |
|                   |                      | E14. Prevention of leaving roadway |
|                   |                      | E15. Prevention of access to high risk facilities |
|                   |                      | E16. Monitoring for preventing concealment |
| L4. 3rd layer     | G6. Building envelop | E17. Distance from the tower to a roadway |
|                   | G7. Space zoning     | E18. Garage location |
|                   |                      | E19. Building configuration |
|                   |                      | E20. Window support type |
|                   |                      | E21. Glass type |
|                   |                      | E22. Publicly accessible column |
|                   |                      | E23. Shedding inner air-blast load |
|                   |                      | E24. Loading dock location |
|                   |                      | E25. Mail screening measures |
|                   |                      | E26. Access control by space zoning and security check |
|                   |                      | E27. Separation of public and secured area |

Table 2. Critical Infra-Structures and Facilities of High Risk

| Type of high risk | Facilities |
|-------------------|------------|
| Critical infra-structures | Telecommunications and media: broadcasting, newspaper, internet publishing, telephone exchange center |
|                     | Energy: power plant building, petroleum refinery building |
|                     | Chemical: petrochemical manufacturing, hazardous chemical transport |
|                     | Banking and Finance: bank, insurance company, stock exchange |
|                     | Transportation: port, airport, terminal, rapid transit stations |
|                     | Water Supply: treatment plant, dam |
|                     | Government: federal, state or city building |
|                     | Emergency: emergency control center, police station, emergency medical service |
| Facilities of high risk | Commercial: company building, hotel, convention center |
|                     | Event: amusement arcade, theme park |
|                     | Political: embassy |
|                     | Recreational and retail: performing art center, gymnasium, shopping center |
### Table 3. Grades of Design Guidelines of Each Element

| Design element | Grade | T  | U  | V  | W  | X  |
|----------------|-------|----|----|----|----|----|
| L1 E1. Occupancy use | Group A | 8,000 | 8,000–12,000 | Group B | 12,000–16,000 | 16,000–20,000 | Group C |
| E2. Number of occupants | < 8,000 | 51–70 | 71–90 | 91–110 | > = 20,000 |
| E3. Building height | 0 | 1 | 2 | 3 | > = 4 |
| E4. Target density | 0 | 1–3 | 4–6 | 7–9 | > = 10 |
| E5. Distance from the tower to a public road | > = 25m | 15–25m | 7.5–15m | 3–7.5m | < 3m |
| G1 E6. Separation of vehicular access points | VIP and occupant Visitor Service | VIP and occupant | Authorized vehicle (sedan only) | Authorized vehicle | Sedan only | All vehicle |
| E7. Prevention of adjacent surface parking | No parking | Authorized vehicle (sedan only) | Authorized vehicle | Sedan only | All vehicle |
| G2 E8. Location of perimeter barrier | > = 25m | 15–25m | 7.5–15m | 3–7.5m | < 3m or no barrier |
| E9. Type of perimeter barrier | Resisting impact of vehicle (without moving) | Resisting impact of vehicle (with moving) | Not Resisting | Curb only | No barrier |
| E10. Surveillance of the perimeter | No blind spot (all monitoring) | No blind spot (partially monitoring) | No blind spot (no monitoring) | Blind spot (monitoring) | Blind spot (no monitoring) |
| G3 E11. Location of vehicle access control | Perimeter of the site | Between perimeter and building | Entrance to parking (without other path) | Entrance to parking (without other unclosed path) | Not controlled |
| E12. Type of vehicle access control measures | Personnel and equipment Control, screen, and block | Personnel and equipment Control and block | Personnel and equipment Control | Equipment Control | Not controlled |
| G4 E13. Prevention of high speed approach | Retractable bollard | Shape of road or traffic calming measures | Not effective or not planned |
| E14. Prevention of leaving roadway | Resisting impact of vehicle (without moving) | Resisting impact of vehicle (with moving) | Not Resisting | Curb only | No barrier |
| E15. Prevention of access to high risk facilities | No high risk facility | Monitoring and control | Control | Monitoring | No monitoring and control |
| E16. Monitoring for preventing concealment | No places for concealment | Monitoring and control | Control | Monitoring | No monitoring and control |
| G5 E17. Distance from the tower to a roadway | > = 25m | 15–25m | 7.5–15m | 3–7.5m | < 3m |
| E18. Garage location | Not under the tower (authorization) | Edge of the tower (authorization) | Under the tower (authorization) | Under the tower (not controlled) |
| G6 E19. Building configuration | Circular or convex | Rectangular box | Re-entrant corners or concave |
| E20. Window support type | No windows | Punch | Glass and metal framing | Ribbon |
| E21. Glass type | Laminated glass | Security film | Tempered glass | Heat strengthened glass |
| E22. Publicly accessible column | None | Massive | Slender |
| E23. Shedding inner air blast load | Void or skylight | Open-sided | Enclosed |
| G7 E24. Loading dock location | Outside of site | Outside of building | Perimeter of building | Adjacent to critical area | Under building |
| E25. Mail screening measures | All screening (Check the suspicious in detail) | All screening | Screening the suspicious only |
| E26. Access control by space zoning and security check | Separated clearly (Security check) | Separated clearly | Separated (with uncontrolled route) | Checked on the ground floor | Not checked |
| E27. Separation of public and secured area | Visually and spatially | Visually or spatially | Not separated |

* The occupancy use was classified into 3 grades as shown in Table 4.
tower, concrete walls, fixed bollards, planters, kiosks, street trees, etc.), and (3) surveillance of the perimeter for preventing blind spots.

The 2nd layer of defense refers to the outside space between the building and the perimeter of the site. For the purpose of controlling vehicle access to the site, 2 design elements are selected: (1) the location of the entry control point for vehicle access, and (2) the type of access control measures in terms of controlling, screening, and blocking suspicious vehicles. And 4 elements for controlling vehicle circulation within the site are included in this layer: (1) measures for preventing vehicles from approaching the tower at high speed, (2) measures for preventing vehicles from leaving the roadway to approach the tower, (3) measures for preventing access to high risk facilities outside the tower, and (4) monitoring for preventing concealment. The other 2 elements comprise the 3rd supplementary group for separating vehicles and the building: (1) the distance from the tower to a roadway, and (2) the garage location for authorized or unauthorized vehicles.

In the 3rd layer of defense, which refers to the building itself, there are 2 supplementary groups. For the group that concerns building envelop for mitigating the effects of potential terror attacks, 5 elements are selected: (1) building configuration to shed the air-blast load rather than amplify it, (2) the typical window support type on the building side closer to the roadway for resisting air-blast load, (3) the glass type to prevent glass fragments from being thrown from the window and to mitigate the effects of explosive attack, (4) publicly accessible columns in relation to their exposure to potential attacks, and (5) design measures to shed inner air-blast load. The other group is composed of 4 elements relating to space zoning: (1) the location of loading dock for separating the unscreened service vehicles from the tower, (2) external mail screening measures for preventing an explosive device from being delivered to the building undetected, (3) access control through clear space zoning and checking security clearance grades, (4) design measures for separating the secured area from the public area visually or spatially.

(2) Grading design guidelines

For assessing the level of vulnerability, the design guidelines of each element were classified into 5 grades, on a scale of 1 to 5 with 1 as the least vulnerable and 5 as the most vulnerable design, based on its protection or risk level (Table 3., 4.).

Table 4. Classification of Occupancy Use

| Group A          | Group B          | Group C          |
|------------------|------------------|------------------|
| Agricultural plants | Nuclear materials | Food             |
| Chemical         | Energy           | Banking and finance |
| Critical manufacturing | National monuments | Commercial |
| Dams             | Public health    | Educational      |
| Defense industrial base | Telecommunications | Emergency services |
| Drinking water systems | Government | Information technology |
| Postal and shipping | Transportation systems |

(1) Weights of each design element

According to Saaty (1983), consistency ratio (CR) should be about 10 percent or less to be acceptable. Since the CR of all individual comparison matrices constructed by experts' judgment was below 0.1, all elements satisfy the consistency criteria.
data from an AHP survey were included in the analysis. These matrices were aggregated into group judgment matrices, of which CR was also below 0.1. Then, the weights of the design elements were extracted for each group judgment matrix through eigenvector method. As seen in Fig.2., the weights of surroundings and the 1st layer were higher than those of other layers.

Table 5. The 10 Highest Weighted Design Elements

| Layers of defense | Design element                                      | Adjusted weight |
|-------------------|----------------------------------------------------|-----------------|
| 1st layer         | E5. Distance from the tower to a public road       | 0.209           |
| Surroundings      | E1. Occupancy use                                  | 0.185           |
| Surfaces          | E4. Target density                                 | 0.094           |
| 2nd layer         | E11. Location of vehicle access control            | 0.086           |
| Surroundings      | E3. Building height                                | 0.065           |
| Surfaces          | E2. Number of occupants                            | 0.051           |
| 1st layer         | E8. Location of perimeter barrier                  | 0.048           |
| 1st layer         | E7. Prevention of adjacent surface parking         | 0.042           |
| 2nd layer         | E18. Garage location                              | 0.034           |
| 1st layer         | E6. Separation of vehicular access points          | 0.031           |

Table 5. shows the 10 highest weighted design elements, of which the adjusted weight for relative importance among 27 design elements was above 0.03. First of all, the distance from the tower to a public road (E5) and occupancy use (E1) were verified as the most important elements for protecting super high-rise buildings from terrorism. Except for the elements of surroundings, most design elements were related to creating sufficient distance between buildings and unauthorized vehicles. But, the adjusted weights of all elements of the 3rd layer were lower than 0.02. In summary, these results of AHP survey imply that the vulnerability of super high-rise buildings to terrorism would be affected the most by the circumstances of the building and neighborhood. These also indicate that separating unauthorized vehicles from the building and blocking them outside of the site is the most efficient and effective way to counter terrorism.

(2) Reflecting supplementary effects among design elements

In general, the weighted arithmetic mean is employed for calculating the overall score from the assessed value of each weighted element. It should be a prerequisite that there are no supplementary effects among evaluation elements. However, there were meaningful supplementary effects among several design elements suggested in this study. With this in consideration, 7 supplementary groups were established and arranged as the middle level of the hierarchy. Their vulnerability was calculated from the weighted geometric mean of assessed value of design elements in the lower level of the hierarchy (Fig.3.).

Table 6. shows the effect of weights of design element to vulnerability and explains the difference between weighted arithmetic mean and weighted geometric mean. Although other elements were assessed as most vulnerable (grade 5), the distance from the tower to a public road, the most heavily weighted design element, was assessed as the least vulnerable (grade 1). So, the overall vulnerability of this supplementary group was not high. Also, as a result of the supplementary effect among design elements, the weighted geometric mean was lower than the weighted arithmetic mean.

(3) Process of vulnerability assessment

As a vulnerability assessment model, a bottom-up formula including the hierarchy and weights of elements of defense was suggested (Fig.4.). As the first step in the assessment process, the vulnerability of each hierarchically low level design element is graded by experts in anti-terrorism.

Subsequently, the vulnerability of each supplementary group of middle hierarchy is extracted by calculating the weighted geometric mean of the vulnerability of design elements within the same group. Then, the vulnerability level of each layer of defense is calculated by the weighted arithmetic mean of vulnerability of supplementary groups within the same layer. Finally, the overall vulnerability of a building is extracted by calculating the weighted arithmetic mean of vulnerability of layers of defense.

Table 7. shows the result of vulnerability assessment of two buildings. In both buildings, vulnerability of surroundings was almost the same (a little higher than

5. Case Study

Table 7. shows the result of vulnerability assessment of two buildings. In both buildings, vulnerability of surroundings was almost the same (a little higher than
Table 7. The Assessed Vulnerability Level of 2 Buildings

| Design elements | Supplementary groups | Layers of defense | Overall vulnerability |
|-----------------|-----------------------|-------------------|----------------------|
|                 |                       | A     | B     | A  | B  | A  | B  |
| E1              | 5                     | 5     | L1    | 3.28| 3.49| 2.86| 2.21|
| E2              | 3                     | 2     |       |     |     |     |     |
| E3              | 1                     | 4     |       |     |     |     |     |
| E4              | 1.67                  |       |       |     |     |     |     |
| E5              | 2                     | 1     | G1    | 1.89| 1.13| 1.90| 1.13|
| E6              | 3                     | 3     |       |     |     |     |     |
| E7              | 1                     | 1     |       |     |     |     |     |
| E8              | 3                     | 3     | G2    | 1.96| 1.15|     |     |
| E9              | 1                     | 1     | G3    | 4.00| 1.15| 4.11| 1.57|
| E10             | 1                     | 2     | G4    | 2.39| 1.42|     |     |
| E11             | 4                     | 1     | L3    | 1.67| 1.13|     |     |
| E12             | 4                     | 2     | L4    | 2.30| 2.12|     |     |
| E13             | 3                     | 3     | L5    | 2.54| 2.24|     |     |
| E14             | 4                     | 1     | L6    | 2.49| 2.28|     |     |
| E15             | 1                     | 1     | L7    | 2.16| 2.12|     |     |
| E16             | 4                     | 2     | G5    | 5.00| 2.51|     |     |
| E17             | 5                     | 4     | G6    | 2.49| 2.28|     |     |
| E18             | 5                     | 2     |       |     |     |     |     |
| E19             | 5                     | 3     | G7    | 2.19| 2.07| 2.30| 2.12|
| E20             | 4                     | 3     | G8    | 2.19| 2.07|     |     |
| E21             | 3                     | 1     | G9    | 2.19| 2.07|     |     |
| E22             | 1                     | 3     |       |     |     |     |     |
| E23             | 3                     | 1     |       |     |     |     |     |
| E24             | 5                     | 5     | G10   | 2.54| 2.24|     |     |
| E25             | 5                     | 3     |       |     |     |     |     |
| E26             | 1                     | 1     |       |     |     |     |     |
| E27             | 1                     | 1     |       |     |     |     |     |

* The 10 highest weighted design elements

3.00); this indicates that the difference in the overall vulnerability level between 2 buildings was mainly caused by the variance of the 1st, 2nd, and 3rd layer of defense.

Fig.5 indicates the differences in calculated vulnerability level by various assessment methods, i.e. not using weighted elements, employing weighted elements, and reflecting the weights and supplementary effect of elements. In this case study, employing weights of design element influenced the vulnerability of each layer of defense differently according to the protection level of the design elements applied.

If the vulnerability level of a certain layer is reduced as a result of reflecting the weight of design elements, it indicates that relatively heavily weighted design elements were applied more safely than others. On the contrary, increased vulnerability of a layer means that relatively important elements are more vulnerable than others. This implies that it is more desirable to prioritize the heavily weighted elements to reduce the vulnerability of a building in a cost efficient way. When the effects of supplementary reinforcing among design elements were employed, the vulnerability of all layers was reduced in different degrees.

(1) Building A

Overall vulnerability of building A was 2.86, which is moderate. Compared to Building B, the vulnerability level of the 1st layer was relatively high at 1.90, which was mainly due to the inability to achieve an appropriate distance from the tower to a public road (E5) or perimeter barrier (E8) due to the location of the site.

The most vulnerable part was the 2nd layer, where the vulnerability level was increased to 4.11 by reflecting the weights and supplementary effects of the elements. It was mainly caused by the high vulnerability level of heavily weighted elements, such as the location of vehicle access control (E11) and garage location (E18). To reduce vulnerability of the 2nd layer efficiently, reinforcement of these elements should be considered as a priority. For example, if the location of vehicle access control is changed to the perimeter of the site, and the parking area under the tower is limited to authorized vehicles, the vulnerability level of the 2nd layer could be decreased to 2.30 and overall vulnerability of the building would be reduced to 2.54.

However, the effects of weights and mutual supplements were significant in the 3rd layer where the risk level of the most heavily weighted element, i.e. publicly accessible column (E22), was very low at 1.

(2) Building B

The vulnerability level of the surroundings of building B was a little higher than that of building A, mainly because of the difference in building height (E3). But, the overall vulnerability level of building B was 2.21 which was relatively low, as a result of appropriate application of design elements to the other three layers.

Except for the surroundings, the vulnerability of the 3rd layer was relatively high. The vulnerability level of the publicly accessible column (E22), which was the most heavily weighted element in the 3rd layer, was 3. So, the vulnerability of the layer increased under the influence of its weight, and then decreased to 2.12 due to the supplementary effect of the elements. Therefore, architectural features to protect columns from direct contact with the public could be one of the most cost efficient modifications in building B. In this way, the vulnerability level of the 3rd layer could be decreased to 1.64 and the overall vulnerability of the building would be reduced to 2.18.
6. Discussion

In this study, a hierarchy of architectural design elements for anti-terrorism was constructed and the weights of each design element were extracted through the AHP method, and a vulnerability assessment model reflecting the supplementary effect among design elements was suggested.

The result of an AHP survey indicates that the vulnerability level of high-rise buildings is affected most by the circumstances of the site and its perimeter design for separating unauthorized vehicles from the tower.

As shown in the result of the case study, the vulnerability of surroundings was above the middle level due to the specific characteristics of high-rise buildings, such as the occupancy use, the number of occupants, and the building height. The architectural design of the 1st, 2nd, and 3rd layer supplemented the vulnerability of surroundings and reduced the overall vulnerability of the building.

This implies that the vulnerability of high-rise buildings can be largely affected by the way architectural design elements were applied because, in most cases, the conditions of surroundings are not meaningfully different between high-rise buildings and the elements of surroundings are not easy to modify. Therefore, it could be stated that architectural design is one of the important factors for reducing the risk of terror attacks.

For the cost-efficient architectural design for protecting from terrorism, a priority consideration should be given to the heavily weighted design elements, such as stand-off distance, the location of vehicle control, and the garage location, and so on. Alternative designs of other elements applicable to the building should be examined based on their weights and vulnerability of their supplementary group.

The vulnerability assessment model suggested in this study focused mainly on architectural design, while the social and economic value of the building was prioritized in RVS (FEMA, 2009). Therefore, it is expected that this model could be used not only for supplementing weak points in the architectural design process and achieving a cost-efficient design, but also listing or managing buildings with a high risk of terrorism.

In this study, 27 design elements were selected and the design guidelines of each element were classified into 5 grades based on the results of analysis of existing anti-terrorism guidelines. It requires further examination of suitability of criteria for grading design guidelines and congruity between the vulnerability level assessed by this model and the judgment made by anti-terrorism experts.

Note

1. The Analytic Hierarchy Process (AHP) is a systematic procedure for representing the elements of any problem. It organizes the basic rationality by breaking down a complex problem into its smaller constituent parts and then calls for only simple pairwise comparison judgments for the relative importance of the elements in each level of hierarchy. (Saaty, 1983) The AHP weighting is mainly determined by the experts who conduct the pairwise comparisons, so as to reveal the comparative importance between two elements. There are n(n-1)/2 judgments required to construct the set of pairwise comparison matrices, where n is the number of evaluation criteria. Saaty used the eigenvector of the pairwise comparison matrix contrived by scaling ratio to find comparative weights among the elements. (Wang et al., 2010)

Acknowledgements

This study was supported by a Korea University Grant.

References

1) Choi, J.W. et al. (2012) A study on a risk assessment model of bomb attack for high-rise buildings based on the analytic hierarchy process. Korean Review of Crisis & Emergency management, 8 (1), pp.127-139.
2) DoD (2002) DoD minimum antiterrorism standards for buildings. Washington, D.C.: DoD.
3) FEMA (2003a) FEMA 426. Reference manual to mitigate potential terrorist attacks against buildings. Washington, D.C.: DHS.
4) FEMA (2003b) FEMA 427. Primer for design of commercial buildings to mitigate terrorist attacks. Washington, D.C.: DHS.
5) FEMA (2005) FEMA 452. Risk assessment: a how-to guide to mitigate potential terrorist attacks against buildings. Washington, D.C.: DHS.
6) FEMA (2007) FEMA 430. Site and urban design for security: guidance against potential terrorist attacks. Washington, D.C.: DHS.
7) FEMA (2009) FEMA 455. Handbook for rapid visual screening of buildings to evaluate terrorism risks. Washington, D.C.: DHS.
8) Forman, E. and Peniwati, K. (1998) Aggregating individual judgments and priorities with the analytic hierarchy process. European Journal of Operational Research, 108 (1), pp.165-169.
9) Kang, K.Y., Park, B.J. and Lee, K.H. (2011) A study on the vulnerability assessment of high-rise buildings in Korea. Journal of the Architectural Institute of Korea (Planning & Design), 27 (11), pp.125-133.
10) Kang, S.J., Lee, S.J. and Lee, K.H. (2009) A study on the implementation of non-structural measures to reduce urban flood damage. Journal of Asian Architecture and Building Engineering, 8 (2), pp.385-392.
11) Lee, K.H. (2012) Design of super high-rise buildings for protecting from terrorism. Design and Crime International Conference Proceeding, Sydney, Australia, pp.75-78.
12) Ministry of Land, Transport and Maritime Affairs of Korea (2010) Design guidelines of multi-use facilities for protecting from terrorism. Seoul: Ministry of Land, Transport and Maritime Affairs of Korea.
13) NaCTSO (2006) Counter terrorism protective security advice for shopping centres. London: NaCTSO.
14) NaCTSO (2008a) Counter terrorism protective security advice for commercial centres. London: NaCTSO.
15) NaCTSO (2008b) Counter terrorism protective security advice for hotels and restaurants. London: NaCTSO.
16) Saaty, T.L. (1980) The analytic hierarchy process. New York: McGraw-Hill.
17) Saaty, T.L. (1983) Priority setting in complex problems. IEEE Transactions on Engineering Management, EM-30 (3), pp.140-155.
18) Seoul Metropolitan Government (2009) Design guidelines of high rise buildings. Seoul: Seoul Metropolitan Government.
19) Wang, H.J. et al. (2010) Evaluation of designs for reuse of Japanese style houses in Taiwan. Journal of Asian Architecture and Building Engineering, 9 (1), pp.117-124.