Development of the vulnerability assessment model of explosive terrorism in multi-use buildings

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\textbf{ABSTRACT}

The purpose of this study is to develop a vulnerability assessment model of explosive terrorism in multi-use buildings focusing mainly on architectural design elements. First, in order to extract the weights of each assessment element, expert surveys with four anti-terrorism specialists were conducted twice. The results imply that the risk of bomb attack in buildings is influenced more by the vulnerability of the layers of defense, the supplementary groups, and the scenarios of explosion than by the vulnerability of assessment elements. Second, the vulnerability assessment model was developed to calculate the vulnerability level of each layer of defense and scenario of explosive terrorism individually as well as the overall vulnerability level of a building. This model reflects the relative importance and supplementary effects of elements. Third, two multi-use buildings were assessed using the developed model to analyze the vulnerability level of each layer of defense, supplementary group, and the entire building. Based on the results of the case study, cost-efficient design alternatives to reduce the vulnerability of a building were presented.

\textbf{INTRODUCTION}

The types of buildings in which terrorism occurs have recently changed. In contrast to the terrorism of the past, which mainly targeted governmental or military facilities, terrorism targeting public facilities such as hotels, subway stations, airport terminals, and shopping malls has recently increased. Terrorists tend to use explosives more frequently than other methods because explosives are simple to manufacture and can cause extensive damage in terms of casualties and destruction. In addition, terrorists can use explosives selectively depending on the target and purpose of terrorism.

As the risk of explosive terrorism in multi-use facilities increases, the government of South Korea has developed architectural design guidelines to prevent terrorism for multi-use facilities. However, these guidelines have some limitations since they provide only general descriptions without consideration of the types of buildings. Therefore, excessive security equipment could be installed in some cases, which can cause economical burden to the owner. Therefore, it is necessary to evaluate the explosive terrorism risk of the specific facility, identify vulnerable architectural design elements of the buildings, and find cost-effective alternatives for reducing vulnerability to terrorism.

The purpose of this study is to determine the relative importance of the architectural design elements affecting the risk of explosive terrorism and to develop an assessment model that includes the weights of elements and supplementary effects among the elements with the same design purposes or functions.

\textbf{METHODS}

\textbf{Determining the weights of each element}

\textbf{Hierarchy of elements for assessment}

In the precedent study (Kang et al. 2018), the hierarchy of elements for vulnerability assessment of a bomb attack was developed, as shown in Table 1. The hierarchy consists of the architectural design elements, which can be adopted for preventing from bomb attack or mitigating damage. In this study, the hierarchy was used to develop 27 questionnaire tables for expert survey to determine the relative importance of each element for vulnerability assessment.

Each questionnaire consisted of a minimum of two and a maximum of seven comparison elements.

\textbf{The first expert survey}

Four experts\textsuperscript{1} in anti-terrorism design participated in the first survey at the same time. After briefly...
| Scenarios of Explosion | Layers of Defense | Supplementary Groups (Purpose of Design) | Assessment Elements | Weight | A  | B  |
|------------------------|-------------------|------------------------------------------|---------------------|--------|----|----|
| Surroundings (0.385)   |                   |                                          |                     |        |    |    |
| Architectural Design   | Vehicle Bomb      | 1st Layer (0.435)                        |                     |        |    |    |
| (0.615)                | (0.602)           | (0.291)                                  |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
|                         |                   |                                          |                     |        |    |    |
| Mitigation of explosive |                   |                                          |                     |        |    |    |
| impact from the         |                   |                                          |                     |        |    |    |
| perimeter (0.287)      |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| Reinforcement of the    |                   |                                          |                     |        |    |    |
| perimeter against      |                   |                                          |                     |        |    |    |
| vehicles (0.257)       |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| Surveillance of the     |                   |                                          |                     |        |    |    |
| perimeter (0.165)      |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| Mitigation of explosive |                   |                                          |                     |        |    |    |
| impact from the inside  |                   |                                          |                     |        |    |    |
| of the site (0.323)    |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| Vehicle circulation     |                   |                                          |                     |        |    |    |
| control (0.274)        |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| Surveillance of the     |                   |                                          |                     |        |    |    |
| exterior space (0.226) |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| Protection of major     |                   |                                          |                     |        |    |    |
| hazardous equipments   |                   |                                          |                     |        |    |    |
| (0.177)                |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| 3rd Layer (0.315)      |                   |                                          |                     |        |    |    |
| Mitigation of explosive |                   |                                          |                     |        |    |    |
| impact from the         |                   |                                          |                     |        |    |    |
| underground parking    |                   |                                          |                     |        |    |    |
| area (0.294)           |                   |                                          |                     |        |    |    |
|                        |                   |                                          |                     |        |    |    |
| (Continued)
explaining the purpose of the survey and the hierarchy of elements, cards with the name and meaning of the comparison element were given to each expert. In every comparison task, the meaning of each element and the purpose of the comparison were explained. In addition, the experts were asked to make comparisons of the elements according to the following procedure:

Each expert arranges the cards according to their importance in terms of reducing vulnerability of bomb attack.

The element(s) determined as the most important are given 10 points. And then, for the rest of the elements, a relative importance score is given to each element on a scale of 1 to 10 with 1 as the least important and 10 as the most important element.

The same comparison process is repeated for 27 questionnaires.

After the first survey was completed, the mean and standard deviation of the importance scores of each element were calculated from the results of four expert questionnaires.

Asterisks in Table 1 shows the elements with large and small standard deviations between the scores given by the experts.

\*: The results of the first survey showed that the standard deviations among the scores were less than 0.5

\**: The results of the first survey showed that the standard deviations among the scores exceeded 2.5
Developing the vulnerability assessment model

A vulnerability assessment model of explosive terrorism was suggested including the hierarchy of the elements and the derived weight of each element. The model was developed with a bottom-up formula in which the vulnerability is calculated from the elements at the low hierarchical level to the elements at the high hierarchical level sequentially. To integrate the vulnerability levels of several elements, considering the weight of each element, the weighted arithmetic mean was adopted. However, if meaningful supplementary effects are found among the elements, the weighted geometric mean was used to reflect these effects.

Case study

The vulnerabilities of two multi-use buildings in Korea, which were subject to the Preliminary Disaster Impact Inspection and Consultation System, were assessed using the developed assessment model. Based on the results of the assessment, several design alternatives for reducing the risk of explosive terrorism cost-efficiently were proposed. For the assessment, the four experts analyzed the architectural documents and determined the grade of each assessment element. The overall vulnerability levels of the two buildings were then calculated.

Literature review

Analysis of RVS

"Rapid Visual Screening" (RVS) (FEMA 2009) is one of the broadly used tools to assess vulnerability to terrorism, which enables rapid and effective assessment in urban commercial buildings. In RVS, the overall risk level of a building is calculated from the evaluation results of the nine terrorism scenarios including internal attack (intrusion, explosive, CBR), explosive attack (zone I, zone II, zone III), and CBR attack (zone I, zone II, and zone III). The score of each scenario is obtained by the product of three factors: consequences (C), threats (T), vulnerability (V). The composition of the evaluation elements and the weight of each element are set differently for each scenario according to the characteristics of the scenario.

RVS has some limitations, since it is not able to assess individually the risk level of explosive terrorism, which is the most common scenario of terrorism. Also, it cannot reflect the relative importance of each scenario. In addition, as the relative importance of socio-economic elements and the elements related to architectural structures and security system is high, the overall risk level of urban multi-use buildings, of which occupancy use, location, number of occupants, and type of architectural structure are similar, do not significantly differ. RVS classifies the evaluation elements of V into six types: site, architecture, building envelope, structural components, MEP systems, and security. If these elements are classified based on spatial criteria such as 1st, 2nd, and 3rd layers of defense and purposes or functions, vulnerable spots will be able to be precisely identified and ways to respond effectively can be found.

Analysis of previous studies

Kang and Lee (2014) selected architectural design elements of super high-rise buildings to reduce the risk of terrorism using explosives and suggested design guidelines for each element with 5 grades based on its protection performance. The weights of each element were also derived from an Analytic Hierarchy Process (AHP) survey and, from which a vulnerability assessment model was proposed.

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Footnotes:
1. Assessment elements with similar purposes or functions in terms of preventing explosive terrorism were classified as the same supplementary effect group, considering that they complement each other. Also, it was considered that a supplementary effect exists between the surroundings and the architectural design on the overall vulnerability level of the building.
2. The preliminary disaster impact inspection and consultation system is based on the ‘Special Act on Disaster Management of Super high-rise and Underground Complex buildings’, which was implemented in 2012. It is a system used to inspect the impacts of disasters and to consult in advance when super high-rise or underground complex buildings need to be designed or approved.
3. The selected facilities have the following common features: large-scale, mixed-use, located in the city center, and well-known as landmarks of the city.
4. On the other hand, they have differences in architectural design strategies to prevent and mitigate terrorism so that it is possible to make a meaningful comparison. In addition, they are considered to be suitable for verifying the usefulness of the model in terms of identifying vulnerable elements and considering design alternatives to reduce the overall vulnerability of the building efficiently.
5. The vulnerability level of the i-th scenario is calculated by the product of Cl, Ti, and Vi which are derived by summing the scores of evaluation elements suitably selected for the i-th scenario.
focusing mainly on architectural design elements. However, they did not distinguish the scenarios of explosive terrorism and selected only 27 major architectural design elements for the assessment. In addition, the grade of each design element was divided into five steps with the same intervals.

In a follow-up study, as a preliminary step for this study, Kang et al. (2018) suggested classification of architectural design elements related to explosive terrorism of various multi-use buildings including super high-rise buildings and underground complex buildings. In the suggested assessment system, all of the elements are classified into two major categories, ie, surroundings and architectural design. Architectural design is then divided into two scenarios, ie, vehicle bomb attack and hand-carried bomb attack, which consist of three layers of defense. Fifty-eight assessment elements related to each scenario and layer of defense were then categorized into 18 supplementary groups according to the purpose and function of each element, and the design methods applicable to each element are presented with 10 grades based on their protection levels.

Subsequent to the work by Kang et al. (2018), this study derived the relative importance between surroundings and architectural design, between two scenarios of explosive terrorism, among three layers of defense, among 18 supplementary groups, and among 58 assessment elements. In addition, the assessment model was developed, which can calculate the integrated vulnerability level and reflect the relative importance of each element as well as the supplementary effects among elements.

Vulnerability assessment model

Weights of elements

The results of deriving weights were analyzed focusing on the cases where the weight of the most important element is 1.5 times higher than the weight of the least important element in the same comparative evaluation group. Figure 1 shows the distribution of weights of elements.

Architectural design and surroundings of the building

From the comparison of the importance between architectural design and surroundings of the building, the architectural design is about 1.6 times more important than surroundings. This means that even if the characteristics of the surroundings are vulnerable to terrorism, the risk of terrorism can be reduced through architectural design. In the comparison group of surroundings, the occupancy use, the number of occupants, and the number of floors are more important than the number of high-risk facilities nearby and the length of adjacent roads.

Scenarios of explosion

In the comparison group of explosive terrorism scenarios, countermeasures for a vehicle bomb appear to be about 1.5 times more important than countermeasures for a hand-carried bomb. This reflects a difference in the amount of explosive that can be carried and the damage caused by the explosion between a vehicle bomb and a hand-carried bomb.

Layers of defense and supplementary groups

For protecting from vehicle bomb attack, the first layer of defense, ie, the design of the site perimeter, was verified as the most important element among the three layers. Among the supplementary groups for the first layer of defense, controlling the access of vehicles, reinforcing the site perimeter against vehicles, and mitigating the effects of explosions at the site perimeter are more important than monitoring suspicious vehicles.

For protecting from hand-carried bomb attack, the third layer of defense, ie, the design of the building itself, was verified as the most important element among the three layers. Among the supplementary groups for the third layer of defense, controlling

![Figure 1. Distribution of weights of elements.](image-url)
pedestrian access to the building and controlling the route connected to the secured area is more important than protecting the main system of the building.

Assessment elements

No significant difference in the importance of each assessment element was found in most comparative evaluation groups, except several elements related to terrorism using vehicles.

Among the assessment elements to control the access of vehicles on the first layer of defense, the importance of "access control for authorized vehicles" and "type of access control for emergency vehicle" was relatively low. In the elements group of ways to minimize the impact of the explosion at the site perimeter, the importance of "elevation difference between the ground and adjacent public road" was relatively low.

Among the assessment elements of ways to control the circulation of vehicles within the second layer of defense, "continuity of barrier for preventing leaving the roadway" was most heavily weighted.

In the elements group of ways to mitigate explosive impact from the underground parking area within the third layer of defense, the importance of "separating the underground parking area spatially" was relatively high. Among the assessment elements to mitigate explosive impact from the ground, "avoiding exposure of main structural members" and "window support type of lower level of the building" were heavily weighted.

These results indicate that the risk of explosive terrorism in buildings would be more influenced by the vulnerability of the layers of defense (the location of each element), the supplementary groups (the purpose of the elements) and the scenarios of explosion than the vulnerability of each assessment element.

Therefore, in order to reduce the risk of terrorism, more consideration should be given to countermeasures against terrorism using vehicles. To reduce the vulnerability of vehicle bomb attack, it is more effective to reinforce the first layer of defense. In addition, for a hand carried bomb attack, improving the third layer of defense primarily would be more effective.

Assessment model

The assessment model, including the hierarchy and weights of elements, and supplementary effects among elements, was developed using a bottom-up formula. The weighted arithmetic mean (Table 2(a)) was used to calculate the overall vulnerability level of a building reflecting the score and relative importance of each element. If the elements have supplementary effects, the overall level was calculated by weighted geometric mean (Table 2(b)) since the weighted arithmetic mean cannot reflect these effects.

The lowest hierarchical level of assessment element consists of assessment elements, which should be directly evaluated and graded by the evaluators. Assessment elements with the same purpose or function are classified into the same supplementary group, and the vulnerability level of each supplementary group is calculated using the weighted geometric mean of the scores of the assessment elements in the same group. In addition, the weighted arithmetic mean of the levels of supplementary groups is used to derive the vulnerability level of each layer of defense.

Similarly, the weighted arithmetic mean of the levels of layers of defense represents the risk level of each scenario of explosive terrorism, and the weighted arithmetic mean of two scenarios represents the vulnerability level for the entire architectural design.

On the other hand, the vulnerability level of the surroundings, which is in the same hierarchical level as that of architectural design, is calculated by the weighted arithmetic mean of the elements of the surroundings. Since a supplementary effect occurs between the surroundings and the architectural design, the weighted geometric mean of the vulnerability levels of them is used to derive the overall vulnerability level of a building to explosive terrorism (Figure 2).

Case study

Overall vulnerability of the buildings

Figure 3 shows the results of the vulnerability assessment of the two buildings. It indicates the differences in the level of vulnerability between the two calculating methods. One method employs a weighted arithmetic mean and a weighted geometric mean as suggested in this study in order to reflect the relative importance and supplementary reinforcing effects of the elements. The other method employs an arithmetic mean.

The vulnerability level of the surroundings of building B was remarkably high at 9.88, which was higher than that of building A. However, the overall vulnerability of building B appeared lower than that of building A. This can be explained as follows. The vulnerability level of the architectural design of building B was relatively low at 4.16. The weight of the architectural design was high at 0.615, which is higher than the weight of the surroundings. Therefore, the supplementary effect between the surroundings and the architectural design reduced the overall
vulnerability to 5.80, which was lower than that of the vulnerability of building A. This shows that even if the characteristics of the surroundings are vulnerable to terrorism, the overall risk of terrorism can be reduced through proper architectural design.

Reducing vulnerability by weights and supplementary effects of elements

If the relatively heavily weighted elements are designed more safely than other elements, the
vulnerability of a certain layer of defense would be reduced. This effect is most evident in the first layer of defense against vehicle bomb attack of building A. The vulnerability level calculated by arithmetic mean was 5.46, which is moderate. However, when the weights and supplementary effects of elements were employed, the vulnerability level was significantly reduced to 3.96. This is because, in the first layer of defense, the group of elements of ways to mitigate the explosive impact from the site perimeter is heavily weighted. Within this group, the weights of elements related to increasing the distance between the building and the road are high. Because these elements are designed to be very safe and secure in building A, the vulnerability level calculated by the suggested model was lower than the level calculated by arithmetic mean.

Increasing vulnerability level by weights and supplementary effects of elements

If the relatively important elements are more vulnerable than other elements, the vulnerability of a certain layer could be increased. This is shown in the second layer of defense against the vehicle bomb attack of building A. Because the elements of the heavily weighted group, i.e., “mitigating of explosive impact from the inside of the site” and “controlling vehicular circulation,” were designed to be vulnerable, the risk level calculated by the suggested model was slightly higher than the risk level calculated by arithmetic mean.

Alternatives for reducing the overall vulnerability of building A

For reducing the vulnerability of the building in a cost efficient way, it is more effective to prioritize the heavily weighted elements. In the case of building A, seven assessment element groups, of which the vulnerability was higher than 7.00, are selected. Within each group, assessment elements which were heavily weighted and could be modified relatively easily were adjusted as shown in Table 3.

From the alternation, the vulnerability level of vehicle bomb attack decreased from 4.65 to 3.85 and the vulnerability level of hand-carried bomb attack decreased from 5.89 to 3.64. Accordingly, the vulnerability level of architectural design decreased from 5.14 to 3.77. The overall vulnerability of the building was reduced from 6.37 to 5.26.

Discussion

This study was conducted to develop a vulnerability assessment model of bomb attack in multi-use buildings focusing mainly on architectural design elements. The weights of each element were derived through expert surveys. The analysis of the derived weights indicates that the weights of the assessment...
elements, which are at the lowest level of the hierarchy, did not significantly differ. On the other hand, the weights of other evaluation elements showed some differences. This could suggest that the risk of bomb attack in buildings is influenced more by the vulnerability of the layers of defense, the supplementary groups, and the scenarios of explosion than by the vulnerability of assessment elements.

The vulnerability assessment model was developed, which can calculate the vulnerability level of each layer of defense and scenario of explosive terrorism individually as well as the overall vulnerability level of a building. In order to reflect the relative importance of each element and the supplementary effects among the elements this model adopts a bottom-up formula and uses the weighted arithmetic mean or the weighted geometric mean, depending on whether the elements have mutually supplementary effects.

Two multi-use buildings in Korea were selected and assessed using the developed model. In addition to the analysis of the overall vulnerability of both buildings, the cases where the vulnerability decreases or increases due to the weights and supplementary effects of elements were also analyzed. Based on the results of analysis, cost-efficient design alternatives to reduce the overall vulnerability of a building were suggested.

This study presents a more advanced assessment model than the risk assessment model suggested in the previous study (Kang and Lee 2014), since the model developed in this study classifies the assessment elements in more detail and adopts a more sophisticated hierarchy of evaluation elements. In addition, this model reflects the relative importance and the supplementary effects of elements. It is expected that the model developed in this study will enable cost-efficient anti-terrorism design by allowing related practitioners to identify the overall risk of explosive terrorism and vulnerable layers of defense or supplementary groups in buildings, and to effectively find appropriate design alternatives.

Disclosure statement

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