ARCHITECTURAL RESEARCH, Vol.24, No.2(June 2022). pp.21-27 pISSN 1229-6163 eISSN 2383-5575

Applying Fire Risk Analysis to Develop Fire-safe Modular Walls: Guidance to Material Selection, Design Approach and Construction Method

Seokho Lim, Joonsoo Chung and Mihyun Esther Kim
Senior Research Fellow, Korea Institute of Civil Engineering and Building Technology, Goyang-Si, South Korea
Senior Researcher, Korea Institute of Civil Engineering and Building Technology, Goyang-Si, South Korea
Representative, Risk Engineering Service Co. Ltd, Seoul, South Korea

https://doi.org/10.5659/AIKAR.2022.24.2.21

Abstract For the past decade, South Korea had experienced catastrophic building fires, which resulted in consider-ably high number of casualties. This motivated research to develop fire-safe wall assemblies. In this study Fire Risk Analysis (FRA) is conducted as part of the project designing phase to ensure fire safety of the final product. Traditional approach was to consider fire performance at the end of the designing stage, when PASS/FAIL fire test results are required to be submitted to the Authority Having Jurisdiction (AHJ). By applying a fire risk analysis to guide the designing phase, overall fire safety of a wall assembly can be achieved more systematically as conducting FRA allows designers to clearly identify elements that are more vulnerable to fire and simply replace them with other practical options. Severity of fire risk is determined by considering the fire hazards of a wall assembly such as the exterior layer, insulation, vertical connectivity, and external ignition sources (e.g., photovoltaic panels). Frequency of fire risk is assessed based on the factors affecting fire likelihood, which are air cavity and fire-stopping applied in the design, and random design changes occurring during on-site construction. Fire risk matrix is proposed based on these fire risk factors and efforts to reduce the fire risk level associated with the wall assembly are given by systematically assessing the fire risk factors identified from fire risk analysis. Current study demonstrates how fire risk analysis can be applied to develop fire-safe walls by reducing the relevant fire risks– both severity and frequency.

Keywords: Fire Risk Analysis (FRA), flame spread, design, modular walls

1. INTRODUCTION

For the past decade, South Korea had experienced catastrophic building fires, which resulted in considerably high number of casualties. Some of the examples are the Jecheon Sports Center fire, occurred in 2017. This fire resulted in 29 lives lost and 37 injured. In 2018, fire accident at Miryang S Hospital took place, which took away 46 lives and left 109 injured. Within that same year, another tragic fire accident occurred at Jongno Gosiwon leaving 7 casualties and 11 injured. In 2019, Daegu Sauna Fire took place where 3 people had died and 88 people were injured. These non-stop fire incidents have forced awareness to the public and government to increase the level of fire safety for buildings.

In this study, effort is given to analyze the fire risk of a modular wall assembly composed of both noncombustible and combustible components. The Fire Risk Analysis (FRA) is conducted as part of the project designing phase to ensure fire safety of the final product. Traditional approach was to consider fire performance at the end of the designing stage, when PASS/FAIL fire test results are required to be submitted to the Authority Having Jurisdiction (AHJ). However, by applying a fire risk analysis to guide the designing phase, overall fire safety of a wall assembly can be achieved more systematically because conducting FRA allows designers to clearly identify elements that are more vulnerable to fire and simply replace them with other practical options.

This research discusses the fire performance requirements for wall assemblies set forth by the local laws and codes and standards of other countries (section 2). Then a Fire Risk Analysis (FRA) method is proposed to give guidance for

Corresponding Author : Mihyun Esther Kim
Risk Engineering Service Co. Ltd, 1, Wonhyo-ro 19-gil, Yongsan-gu, Seoul, South Korea

e-mail : esther.kim.an@gmail.com

This study is a part of the research result conducted with research fund supporting in 2022 of Ministry of Science and ICT. The project code: 20220149-001

developing a fire-safe wall assembly (section 3). Finally, FRA is applied to the modular wall assembly currently under development by the research group and material selection, design approach and construction method is advised according to the FRA results (section 4).

2. BACKGROUND

This kind of approach has been developed based on Risk-based Thinking set forth by ISO 9001. Risk-based think-ing is about incorporating risk into decision-making process based on the Plan-Do-Check-Act (PDCA) cycle.

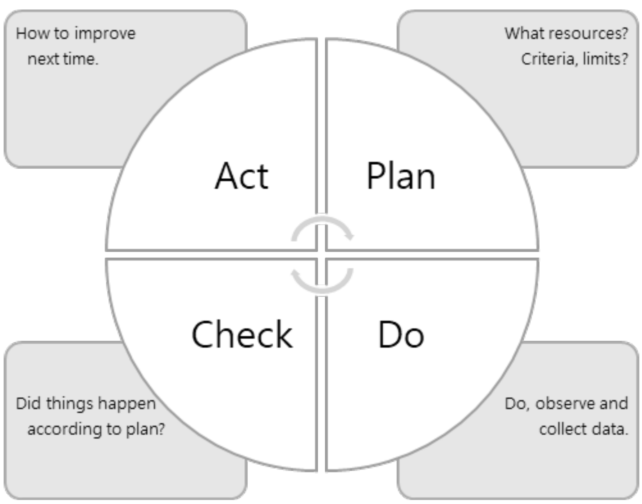

Figure 1. Plan-Do-Check-Act (PDCA) Cycle

Per ISO's definition, risk-based thinking is applied to areas such as organizational context, leadership, planning, operation, performance evaluation, and improvements. Over the years, risk-based thinking concept has been applied to analyzing and developing new fire safe designs for various structures including buildings[2,3,4,5] . Unfortunately, despite these research efforts, still most of the fire-related designs are developed based on developers' experience and by applying the minimal legal requirements due to lack of resources. This research sets apart from previous research works as it demonstrates the efforts of utilizing risk-based thinking approach to aid decision making process for designing new fire-safe modular building components.

3. FIRE PERFORMANCE EVALUATION TESTS: LOCAL VS. INTERNATIONAL

According to the Enforcement Decree of the Building Act[6] and the Rules on the Evacuation Fire Protection Structure of Buildings[7] revised in August 2019, following local requirements should be met for building walls:

- Enforcement Decree of the Building Act: Expansion of exterior wall fire finishing materials (Article 61 (2), buildings with 3 to 5 floors, or 9 to 22 m in height, and buildings used as parking lots are added, and medical facilities, educational research facilities, elderly facilities, and training facilities are restricted to meet exterior wall finishing material requirements.
- Rules on the criteria for evacuation fire protection structures of buildings: Exterior fire wall finishing materials (Articles 24 (5) through 7) and regular exterior wall finishing materials should be non-combustible or limited-combustible materials. Flame retarded materials may be used if they meet the fire spread prevention structure standards. On the first and second floors of the pilotis building should have noncombustible or limited-combustible materials as exterior finishing.

To determine whether a material is *non-combustible, limited-combustible, or flame-retarded grade,* local regulations require building materials to be tested via bench-scale fire tests. Performance evaluation is conducted by taking material samples from actual products and conducting small-scale fire tests – KS F ISO 1182 for non-combustible materials or KS F ISO 5660-1 combustion performance test heat dissipation, smoke generation, mass reduction rate, and first sub-thermal emission rate (cone calorimetry method) for limited-combustibility or flame-retarded grade materials. In addition to these bench-scale fire tests, a mouse test should be conducted using KS F 2271 test, which commonly evaluates the toxicity of gas generated by the fire involving the sample material.

Compared to the international standards, the major difference is that the fire performance is evaluated through a **coupon size sample**. In this case, it is difficult to evaluate the fire spread prevention performance of the entire wall assembly/system. Despite the drawbacks, this approach was chosen by the local authorities to simplify the administrative part of the certification process. However, to compensate for this deficiency in the fire performance evaluation process, a large-scale fire test procedure is proposed to be added to the local requirements as an option (expected by end of 2021).

4. FIRE RISK ANALYSIS FOR WALL ASSEMBLIES

In this study, Fire Risk Assessment (FRA) tool developed by National Fire Protection Association (NFPA, USA[8]) is applied. This tool was originally developed to evaluate fire risks associated with high-risk buildings with combustible exterior wall assemblies. As with any risk analysis approach, this tool considers both the fire severity and frequency (see eq(1)). Severity quantifies the outcome of a fire accident, while frequency considers the likelihood of a fire accident. Total fire risk can be increased when severity and/or frequency increase(s).

$$\text{Fire Risk} = \text{Severity} \times \text{Frequency} \quad \text{Equation (1)}$$

The basic structure of this FRA tool is composed in two parts: (1) Tier 1 – document review of a building to establish a priority ranking for further assessment. This part of the tool allows identification of the people at risk and fire hazards, and assessment of the fire hazard likelihood and consequence. To do so, the tool asks questions related to building characteristics and people at risk (construction type, evacuation strategy, building height, occupancy at risk), fire hazards associated with exterior walls (insulation, cladding, façade vertical connectivity, external ignition sources/fire hazards, internal ignition sources), fire hazards associated with deficient fire safety provisions (fire containment and extinguishment, means of escape and warning), and likelihood of the fire hazards to gather information. (2) Tier 2 – more in-depth evaluation including on-site inspections, review of as built information and maintenance records, and even sampling and laboratory testing of unknown façade materials. However, same approach to identifying people at risk and fire hazards and assessing the fire hazard likelihood and consequence is taken as in Tier 1 evaluation.

Among the various factors considered in this FRA tool, current research focuses on analyzing *fire hazards associated with exterior walls, its likelihood, and consequences.* The main purpose of conducting this FRA is to aid the designing process of a fire-safe modular walls. The building characteristics, occupancy, and fire safety provisions are beyond this research scope as the modular walls designed from this research may be applied in different building circumstances down the road.

As shown in Table 1, risk factors included in this study are related to fire hazards – exterior layer of the modular wall (typically noted as cladding), insulation layer, vertical connectivity of the combustible component of the wall extending over more than one-story, and external ignition source as PV panels attached to the wall – and fire likelihood – air cavity within the wall assembly, fire stopping placed within wall layers and construction method.

Table 1. Factors Related to Fire Severity and Frequency Analysis

Fire Severity (hazard)	Fire Frequency (likelihood)
Exterior Layer (Cladding) Insulation Vertical Connectivity External Ignition Sources/Fire Hazards (PV panels)	Air Cavity Fire-stopping Unwanted Design Changes

In the analysis, the risk factors can be grouped into the following – related to material selection, design approach and construction method (see Table 2). In the first group of material selection, exterior layer and insulation are placed. The exterior wall layer is one of the following materials – noncombustible, limited-combustible, or flame-retarded grade as defined by the local regulations. Insulations considered are one of the followings – non-combustible (e.g., mineral wool, glass wool), limited-combustible (e.g., phenolic foam, certain expanded polystyrene), or flame-retarded grade (e.g., non-existing up to date) as defined by the local regulations. The risk associated with these factors can be effectively mitigated by changing the materials.

In the second group of design approach, vertical connectivity, external ignition sources (PV panels), air cavity, and fire-stopping are placed. The risk associated with these factors can be effectively reduced by changing the wall assembly design.

In the third group of construction method, any improvised design changes applied during construction phase is considered. There are two options for construction method – on-site or off-site/prefabricated construction approach. The fire risk relevant to this factor can be effectively managed by limiting on-site construction and maximizing the off-site construction.

Table 2. Fire Risk Factors in Three Groups – Material Selection, Design Approach, and Construction Method

Material Selection		Design Approach	Construction Method
Exterior Wall	Insulation	Vertical Connectivity, External Ignition Sources (PV panels), Air cavity, Fire-stopping	Design Changes
Noncombustible (NC) Limited-comb. (LC) Flame-retarded (FR)		Fire-safe Design (Y/N)	On-site (ON) Off-site (OFF)

Good fire performance of a wall assembly can only be achieved when materials are well chosen, designs are well engineered, and lastly the walls are built properly following all the specific guidelines at the construction stage. Unfortunately, when construction is conducted on-site, many times various modifications from the original design are made during construction stage to overcome unexpected obstacles occurring in the field. For these reasons, in this research, credit is given when wall assemblies are constructed via pre-fabrication or off-site factory manufacturing method. By conducting off-site manufacturing of the modular wall assemblies, all the pre-engineered elements can be applied without adjustments which may downgrade its fire performances.

The advantage of off-site manufacturing of modular buildings or building elements were identified in the FEMA report[9] released in 1992 where houses in areas affected by hurricanes in the United States were analyzed – "Building performance: Hurricane Andrew in Florida." (FMEA, 1992). According to the report, the pre-engineered, factory-built modular houses suffered the least damage, which was structurally secured by rigidly designed modules and pre-engineered connections between the modules compared to the houses built on-site. In addition, pre-fabrication or off-site factory manufacturing construction method provide additional advantages as minimizing construction waste, reducing overall construction time and on-site construction time, optimizing consumption of construction materials, reducing carbon emissions/footprints, and more.

Based on the above analysis and considering large-scale fire test results gathered so far[10] , fire risk matrix is created as shown in Table 3. As noted, fire risk is composed of fire severity and frequency. In this analysis, fire severity is determined by material selection for the exterior wall layer and the underlying insulation. Fire frequency is determined by the design approach taken and the construction method applied. The medium fire risk noted in red is high-lighted in the table below because based on actual large-scale fire test results5, its fire performance showed to have high risk; however, under the current local law requirements in South Korea, these combinations are allowed. Therefore, these cases are considered as medium risk in this study, but their actual risk is known to be closer to high risk.

Table 3. Fire Risk Matrix for Wall Assemblies

Severity		Frequency				
Ext. Wall	Insul-ation	Y	Y	N	N	Design Approach
		OFF	ON	OFF	ON	Const-ruction Method
NC	NC	Low	Low	Medium	Medium	
NC	LC	Low	Medium	Medium	Medium	
LC	NC	Medium	High	High	High	
LC	LC	Medium	High	High	High	
FR	NC	Medium	High	High	High	
FR	LC	Medium	High	High	High	

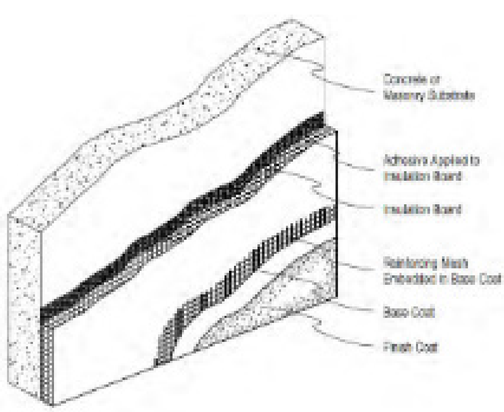

Figure 2. EIFS applied to Masonry construction, reproduced from Ref [6]

5. GUIDANCE TO MATERIAL SELECTION, DESIGN APPROACH AND CONSTRUCTION METHOD BASED ON FIRE RISK ANALYSIS

Throughout the years, the research team has been giving effort to develop modular construction methods. Recent research focus was given to develop modular systems with good insulation properties to reduce energy loss and help reduce carbon emissions during its life span of the building. Initial target was set to find a replacement for the Exterior Insulation Finish Systems (EIFS)[11]. EIFS is a typical approach utilized locally when exterior insulation is required for a low story (up to 5th floor) buildings so far. Until now expanded polyester foams were generally used as the insulation layer within these systems and they have shown to significantly increase the building's overall fire risks, which were lessons learned from past fire accidents. Currently, the relevant regulations are being updated to better govern usage of combustible wall components to reduce the associated fire risks.

Figure 3. Examples of Wall Assemblies Mock-up : Pre-finished off-site factory manufactured wall (top), wall assembly mounted on two-story building (middle), wall assembly with BIPV attached (bottom)

The major concerns identified with EIFS are the following: (1) limitations in design flexibility – typically cannot apply different finishing materials other than stucco-type paste; (2) low-cost bidding between builders for projects, which results in poor quality of the system. Both factors were considered in developing the new modular wall assembly design.

The problems associated with EIFS were mostly caused by drawbacks of on-site construction. Therefore, large improvements were made by taking full advantage of off-site/prefabricated construction approach. First, good quality wall assemblies produced at off-site, at factories allowed quality control of the wall system and consideration of various design candidates such as metal sheet-type finishes, Building Integrated Photovoltaic (BIPV) panels, etc. Second, factory manufacturing allows mass production. This supports reduction in cost for the wall assembly as well as cost for labor.

As the last step of the design development, fire risk analysis is conducted and following adjustments to the wall assembly design is made. Based on the identified fire risk factors and the relevant fire risk matrix proposed, following analysis and improvements are discussed below for material selection, design approach, and construction method:

(1) Fire Risk Severity – Material Selection

To reduce severity of the fire risk related to the wall assembly developed by the research team, first, consideration is given to exterior wall layers – metal sheet type, ceramic type and BIPV. Exterior wall layer is the outer-most layer to be affected by an outside fire as the flame is impinging from outside of a building to the building exterior. The metal sheet type exterior wall layers can delay ignition of the combustible component of a wall such as insulations, etc. For aluminum-type finishing, they can only delay ignition until the surface temperature is 600˚C and below. Beyond this point, the layer can melt away while exposing the underlying wall layers. Knowing that the flame temperatures are typically above 1000˚C, the delaying effect can only last for few minutes. Metal-type finishing also have problems due to high expansion characteristics when exposed to fire conditions. For example, metal skinned sandwich panels with combustible core can result in fire quickly once exposed to high temperature condition as the metal skins expand sideways and bends, allowing connections to open and leaving the core uncovered. As for the ceramic finishings, they are noncombustible materials which are good for fire conditions; however, because they are fragile, they need certain thickness to perform well mechanically. Due to this characteristic, they are heavy-weight finishing compared to other materials. However, this limitation can be overcome by factory laminating fiber-reinforced polymer (FRP) layers to increase its mechanical properties while reducing its weight. Lastly, BIPV is considered. The BIPV applied as a finishing layer of a wall is not a simple matter in terms of mitigating fire risks of a wall system. Although BIPV is highly being favored due to carbon emission reduction policy all over the world these days, adding a BIPV increases the fire risk of the wall as BIPV can become an ignition source by producing high energy arcs during its normal operation or aid flame spread by providing combustible surface area exposed to an ignition source[12]. According to the International Building Code (IBC[13]), BIPVs need to be tested as the roof systems – testing for fire and mechanical stability performances. Fire tests for roof systems are composed of the followings – flame spread test and burn through test. Unfortunately, although PV panels which passed these kind of fire tests are the ones with glass finishing, the BIPV type applied to this wall design originally were the ones with polymer finishing. This will be revised to reduce its relevant fire risk.

Figure 4. Examples of arc occurring in PV panels (top) and BIPV fires (bottom)

Second, insulation layer is considered. In the original design, extruded and expanded polystyrene foams, which do not meet the local fire requirements, were applied. Unfortunately, the fire risks associated with these combustible foams are significantly high as shown in the fire risk matrix; therefore, replacing these to more fire-safe options such as limited combustible foams or noncombustible foams such as glass or mineral wool types is necessary.

Third, light-weight fiber-reinforced polymer (FRP) composite sandwich panel is examined. FRP composite is an uncommon building material in South Korea. However, research has been conducted for FRPs in great depth internationally for the past few decades. IBC currently have a separate section for FRP composites because although FRP composite incorporates polymer (i.e., plastic) component in the material system, it can possess good fire and mechanical properties based on how the polymer and reinforcing materials are formulated and fabricated. The FRP composite sandwich panel applied in the original design provides design flexibility to the system due to their lightweight, non-corrosive, and good mechanical strength characteristics. Improvements for fire characteristics are advised for the FRP skin and cores.

Fourth, adhesive system is evaluated. In the original design, polyurethane-type adhesives were applied without considering any relevant fire risks as these products are most widely used at on-site construction projects locally. These adhesives starts to thermally decompose when temperatures increase above 250˚C. At temperatures slightly below this point, the adhesives soften, possibly resulting in weakening of the adhesion strength of the two surfaces and detaching of the adhered layer. In this case, it can lead to collapsing of the entire wall system. To reduce its fire risk, following modifications should be made - either replacing the adhesive to a non-combustible system, or applying the adhesive to at depth where even during fire exposure local temperature will not rise beyond its softening point.

In addition, the underlying oriented strand board (OSB) is considered as this is one of the combustible components in the wall assembly. OSBs have been around for numerous years and their performances have been studied significantly over the years. Because they are combustible, they decompose with respect to temperature increase. Based on thermal analysis, it is known that beyond 300˚C their weight loss exceeds 70%, leaving no mechanical strength. To avoid increasing fire risks associated with OSBs, replacing regular OBSs with flame retarded OBSs are recommended or ensure that OBSs will not be exposed to temperatures above 300˚C by locating them at depth where even under harsh fire conditions heat penetration to OBS layer is restricted, allowing its body temperature to remain below 300˚C.

(2) Fire Risk Frequency – Design Approach and Construction Method

Reducing fire risk frequency associated with the wall assembly developed requires evaluation of the method of attaching different component layers, e.g., attaching metal sheet and BIPV exterior layers to the layers below. In the original design, exterior layers were glued to the wall assembly with a combustible polyurethane-based adhesive. Unfortunately, in case of a fire, whether heated from out-side or inside, the adhesive tends to lose mechanical strength significantly under elevated temperatures as shown in Figure 4. As the adhesive fails to hold the layers together, fire risk can escalate by flames quickly spreading throughout the wall layering. To avoid this fire risk, replacing combustible adhesive to inorganic-type and applying physical fixation such as nailing or utilizing a fixing piece for additional sturdiness is needed.

Figure 5. Insulation layer detachment due to adhesive loosing mechanical strength under elevated temperature condition

Second, BIPV related fires are considered. According to the German statistics related to BIPV fires7, root cause for these fires were from product defects, basic design problems, construction defects, and external factors. Product defects were found from modules and inverters, mostly. Basic design problems are related to machine design and electrical layout, which can result in arcs, heat accumulation, etc. Construction defects caused by the electricians conducting the installation are the most frequent cause for fire. External factors include damages caused by animals, lightning, careless person. Knowing these main causes for BIPV fire risks in the wall assembly, caution should be given to (1) use only safety certified products for BIPV system components; (2) only allow certified engineers to design and install the system, and (3) ensure good fire separation between the combustible components and BIPV components for passive fire protection measures.

Third, air gaps between layers are examined. Based on full-scale fire experiments of several wall systems3, it was found that when there is an air gap greater than 75mm the vertical flame spread rate increases significantly. Also, research[14] showed that the incident heat flux impinging on the layer standing in front of a wall on fire can become up to 70kW/m^2 depending on the size of the air gap. Therefore, air gaps in the current design should be minimized to avoid vertical flame spread through these gaps.

Figure 6. Flame extending from inside of building

Fourth, the design of uncovered part of the insulation layer being exposed at the lower bottom end of the wall assembly is considered. As shown in Figure 5, when a fire extends to outside from inside of a building through an opening, the lower part of the wall is directly affected by the flame. Heat from the flames travels upward and affects the lower bottom end of the wall assembly. If there is a combustible insulation layer within the wall, by having the lower part exposing the insulation layer can significantly increase the overall fire risk. Hence, good fire stoppers should be designed and included to update the original design.

Finally, traditional on-site construction method is examined. As noted in the previous sections, on-site construction method can substantially increase the fire risks of a wall assembly as various modifications from the original design are made often during the construction stage to overcome unexpected difficulties occurring in the field. Therefore, wall assemblies constructed via pre-fabrication or off-site factory manufacturing method is highly recommended. During the off-site manufacturing of the modular wall assemblies, all the pre-engineered elements carefully designed based on fire risk analysis can be applied without adjustments to maximize its fire performances.

6. RESULTS AND DISCUSSION

In this study, fire risk analysis is applied to guide development of fire-safe modular wall assembly. Considering that fire risk is a product of two parts – fire risk severity and frequency – factors which may increase fire risks are evaluated and possible design changes to improve overall fire-safety of the wall assembly are proposed based on fire risk analysis.

Severity of fire risk is determined by considering the fire hazards of a wall assembly such as the exterior layer, insulation, vertical connectivity, and external ignition sources. Frequency of fire risk is assessed based on the factors affecting fire likelihood, which are air cavity and fire-stopping applied in the design, and random design changes occurring during on-site constructions. Fire risk matrix is proposed based on these fire risk factors.

Efforts to reduce the fire risk level associated with the wall assembly developed by the research group were given by systematically assessing the fire risk factors identified from fire risk analysis. During the evaluation and design improvement process, risk factors were considered in groups – material selection, design approach and construction method. Current study demonstrates how fire risk analysis can be applied to develop fire-safe walls by reducing the related fire risks – both severity and frequency. Further research is needed to analyze the effects of these design changes via full-scale fire tests, which will be considered in the next phase.

REFERENCES

[1] ISO 9001:2015 Quality management systems-Requirements, [online] Available: https://www.iso.org/standard/62085.html.

[2] Vrijling, J. K., W. Van Hengel, and R. J. Houben(1998).“Acceptable risk as a basis for design.” Reliability Engineering & System Safety 59.1 : 141-150.

[3] Hanea, Daniela, and Ben Ale(2009).“Risk of human fatality in building fires: A decision tool using Bayesian networks.” Fire Safety Journal 44.5 : 704-710.

[4] Khan, Mustesin Ali, et al(2021).“Framework for fire risk assessment of bridges.” Structures. Vol. 33. Elsevier.

[5] Brown, Gavin D., et al(2022). “Fire safety protection motivation and preparedness in Irish apartments: A Post-Grenfell analysis.” Safety Science 148 : 105630.

[6] The Enforcement Decree of the Building Act

[7] Rules on the Evacuation Fire Protection Structure of Buildings

[8] Lamont, Susan, and Sigurjon Ingolfsson(2018). “High Rise Buildings with Combustible Exterior Wall Assemblies: Fire Risk Assessment Tool.” NFPA Research, February.

[9] FEMA. “Building performance: Hurricane Andrew in Florida.” (1992).

[10] BRE Gkibak Client Report: BS 8414-1:2015 + A1:2017 Test referred to as DCLG test 7, Report No. B137611-1037 (DCLG test 7) Issue: 2.0

[11] “Guide to Exterior Insulation and Finish System Construction.” 2000.

[12] RUME, K., and J. VIEHWEG(2018). “Assessing Fire Risks in Photovoltaic Systems and Developing Safety Concepts for Risk Minimization. Bundesministerium für Wirtschaft und Technologie, TÜV Rheinland, Fraunhofer.”

[13] IBC. International Building Code. Washington, DC: International Code Council.

[14] Livkiss, Karlis, et al(2018). “Flame heights and heat transfer in facade system ventilation cavities.” Fire technology 54.3 : 689-713.

(Received Nov. 9, 2021/Revised Dec. 9, 2021/Accepted Apr. 13, 2022)