Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 5154309, 13 pages
https://doi.org/10.1155/2019/5154309

Research Article

Semiquantitative Fire Risk Grade Model and Response Plans on a National Highway Bridge

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Received 11 October 2018; Accepted 25 December 2018; Published 17 January 2019

Academic Editor: Abdul Aziz bin Abdul Samad

For the last ten years, the number of cases of large-scale fires which occur on bridges, tunnels, and underpasses has increased. Such fires cause primary and secondary damage, including loss of human life, traffic congestion, and extensive financial damage. Therefore, a risk grade model and effective response plan need to be established for such cases in order to minimize the social and economic costs of bridge fires. In this study, the hazard factors contributing to bridge fires were selected to apply a risk grade model. A total of 144 bridge fire simulations were performed to calculate a surface temperature based on time by using Fire Dynamics Simulation (FDS). A risk grade in accordance with the degree of surface damage state caused by temperature of bridges was presented, and the mobilization time criteria for fire suppression were proposed. The surface temperatures based on time can be classified according to the vertical clearance and mobilization time criteria for fire suppression. Through the classified maximum surface temperatures based on time for bridges, the risk grade can be estimated according to the degree of surface damage state caused by temperature. In order to evaluate the applicability of the established risk grade model to the actual bridge, the arrival time taken from the bridge to the fire station was calculated through a Geographic Information System (GIS) network analysis, and the grades for actual bridge cases were assessed. The purpose of this bridge fire risk grade model is to establish a disaster prevention strategy based on risk grades and to minimize the subsequent social damage by determining a priori the disaster scale.

1. Introduction

Fire accidents on bridges mainly occur in enclosed spaces such as the space under the bridge and underpasses and are caused by various factors such as collision of vehicles, collision with combustible materials, and gas explosion from a leaking pipeline attached to the bridge's structure [1–3]. In addition, a fire that occurs in the vicinity of a bridge can damage the bridge structure and can even lead to catastrophic collapse in extreme cases [4]. While a variety of response plans have been proposed to mitigate fire damage, the number of large-scale fire incidents that result in considerable loss of life and structure has been increasing. Bridges are a major transportation route for public transportation to allow freight, population, and other materials to enter the city, and it is highly likely to spread to large-scale disasters in the event of a fire. Also, as the social structure becomes complicated, the people are exposed to a risk of the bridge fire due to the increase of various fire accidents. Therefore, an expeditious response plan is necessary to minimize damage to property and loss of human life. In the case of a domestic response plan, while manuals are available that shows how to cope with crisis, and while emergency investigations have been carried out for tunnels, a manual for coping with a bridge fire has not been presented. Unfortunately, this area is so overlooked that fundamental facilities such as hydrants for damage prevention on bridges are seldom installed [5, 6]. As shown in Figure 1, the representative example of an accident in Korea is the case of an accident on the Bucheon overpass located on a beltway around Seoul. An illegally parked hazardous material transport vehicle ignited, and the sparks from the explosion

Figure 1: Bucheon overpass.

Figure 2: MacArthur Maze bridge.

ignited twenty-nine vehicles and containers located under the bridge. This eventually caused a large fire. The girders and major components of the steel bridge were consequently damaged, with a large displacement of the slab and deterioration in the reinforced concrete. The fire also destroyed various accessory structures such as optical fiber cables and the noise barrier [6, 7].

Figure 2 shows another incident of the collapse of the MacArthur Maze interchange in Oakland, California, in April 2007, when a fuel tanker caught fire below the bridge and caused the collapse of two spans, after which the interchange remained closed to traffic for 26 days. According to the California Department of Transportation (CDT), 75,000 vehicles use this road section every day. Also, as more than 280,000 drivers from California commute to work through the MacArthur Maze bridge to San Francisco, this fire caused intense traffic congestion. The economic impact of the closure was estimated at $6 million per day, for a total of $156 million, which was 17 times greater than the direct cost of reconstructing the bridge [8, 9]. Bridges are critical elements of transport infrastructures, the disappearance of which can have a serious economic impact, not only in regard to the direct cost of repairs or replacement of the structure but also in terms of the indirect costs of closing a bridge, which can substantially exceed the direct cost of bridges built at strategic points. Damage or collapse of bridge structures caused by the fire, such as domestic Bucheon overpass or the MacArthur Maze bridge fire accident, can cause massive damage such as traffic paralysis and restoration costs, both socially and economically [5, 9–12].

While quantitative risk assessment is important to minimize the gravity of a fire, in Korea, research on fire prevention in civil structures has primarily focused on tunnel fires and has been scarce in comparison with that in building structures. In South Korea, the risk assessment of fire accidents on highways has been carried out using the risk assessment method by C. Cremona (2012) [13] to classify the permissible risk groups and the mitigating risk groups in order to select bridges that require fire protection design [14].

In foreign precedent research, case studies of an actual fire that occurred in bridges such as that on the I-65 Birmingham bridge were used as models to verify the degree of collapse through computational fluid dynamics (CFD) in consideration of the fire source, the intensity of the fire source, the location of the fire, and the vertical clearance; response plans were also suggested for the bridge fire [9].

However, domestic and foreign precedent research for the fire risk grade model is difficult to apply to actual bridges. Therefore, to minimize damage caused by bridge fires and the subsequent social costs, a pragmatic risk assessment model is needed that can be applied for immediate decision-making and response plans.

In this study, in response to social demand, the risk of fire in bridge structures was evaluated. The risk grades according to the degree of surface damage of bridges and mobilization time criteria for fire suppression (fire engine arrival time) were suggested. The risk grade model based on the grade model was established. The response plans according to the risk grade were proposed. Through Fire Dynamics Simulator (FDS) analysis, a surface temperature curve based on time was calculated. In consideration of the environmental parameters (fire intensity, fire location, and fire duration) and design parameters (vertical clearance and bridge materials), the bridge fire severity was confirmed. The surface temperatures of bridges based on time can be classified according to the vertical clearance and the mobilization time criteria for fire suppression. Through the classified surface temperatures based on time for bridges, the risk grades were determined according to the degree of surface damage state of bridges. In order to evaluate the applicability of the established risk grade model to the actual bridge, the arrival time taken from the bridge to the fire station was calculated through a Geographic Information System (GIS) network analysis function, and the grades for actual bridge cases were assessed.

The purpose of this bridge fire risk grade model is to establish a disaster prevention strategy based on risk grades and to minimize the subsequent social damage by determining a priori the disaster scale.

2. Risk Grade Procedure

Risk assessment is the process of establishing information regarding acceptable levels of a risk and/or levels of risk for an individual, group, society, or the environment. Risk estimation is the scientific determination of the characteristics of risks, usually in a quantitative way [15, 16]. These characteristics include the magnitude, spatial scale, duration, and intensity of adverse consequences and their associated probabilities as well as a description of the cause and effect of the damage [15, 16].

However, due to the lack of accumulated data on bridge fire accident cases, the risk grade procedure in this study differed to that in existing studies that are based on probability, as shown in Figure 3. Although various fire scenarios are used, an analysis was only performed for the case of a bridge under fire, which is the most problematic in terms of the structural system, and for a typical concrete bridge and steel bridge almost not equipped with a design of fire resistance on national roads except for a special bridge such as a suspension or cable-stayed bridge. The flow of research for the risk grade of a bridge fire model and the response plans is shown in Figure 3. The research can be classified into five phases as follows.

2.1. Identification of Risk Factors. A risk factor that significantly degrades the safety or serviceability of bridges in the event of a fire should be reflected in the risk grade model. In this study, the locations of fire stations and bridges were mapped for calculation of the mobilization time for fire suppression using GIS. In order to build FDS modeling, environmental parameters (fire intensity, fire location, and fire duration) and design parameters (vertical clearance and bridge materials) were analyzed. In addition, through web-based satellite photographic investigations, the presence of risk factors was confirmed by gathering the condition of overhead clearance.

2.2. FDS Analysis. The FDS program was chosen to calculate the surface temperature of the bridge when the fire occurred under the bridges. Through Fire Dynamics Simulator (FDS) analysis, a surface temperature curve based on time was calculated (Figures 4 and 5). In consideration of the environmental and design parameters, the degree of the bridge fire severity was confirmed. Since the fire heat has a tendency to rise, a fire under the bridge causes damage to both the superstructure and the substructure supporting the bridge [6, 9, 13]. It is therefore assumed that the fire is centered at midspan because the largest vertical deflection magnitudes occurred when the fire location was centered at midspan, both longitudinally and transversely [9].

2.3. Risk Grade Model Associated with Design and Environmental Parameters. To connect a mobilization time for fire suppression and each of the FDS analysis results about the bridge fire, the surface temperature curve based on time was classified into a maximum surface temperature regarding bridges (Tables 1 and 2). The risk grade in response to the maximum surface temperature regarding bridges can be determined according to the risk grade (Tables 3 and 4) based on the degree of surface damage caused by temperature. The X axis and the Y axis indicate the vertical clearance and fire intensity, respectively, while the Z axis indicates the mobilization time criteria for fire suppression.

2.4. GIS Analysis and Web-Based Satellite Photographic Investigations. After establishing the risk grade model to determine the risk grade of the actual bridge using the established risk grade model, the arrival time from the fire station to the bridge needs to be confirmed. For this purpose, GIS mapping of each bridge and fire station was performed, and the arrival time of the fire engine and the closest distance for the fire station were calculated through the network analysis of ArcGIS 10.1. Also, web-based satellite photographic investigations were used to identify the bridges through satellite images provided by domestic and overseas portal sites (Naver, Google Earth, etc.) and to verify the presence of combustible materials and conditions of the overhead clearance.

2.5. Response Plans. Once the risk grade is determined in the risk grade model, to apply systematically its response plans, the existing response plans for the bridge fire were divided into the prevention and the mitigation response plans. Response plans can be applied to the bridges in response to each risk grade of the bridges classified from a very low grade to a critical grade.

3. Mobilization Time Criteria for Fire Suppression

In order to determine the mobilization time criteria for fire suppression, the firefighting practice of each country and the "mobilization time criteria for fire suppression" in the United Kingdom were confirmed and are presented as references [9, 13].

3.1. Mobilization Time Criteria for Fire Suppression. In most building fires, the suppression of the fire should be achieved within 5 to 8 minutes of the fire outbreak; otherwise, the property can be unprotected or the fire can spread to neighboring buildings [24]. Currently, the number of timber structural buildings in Japan is decreasing and an 8-minute response time has thus been implemented, replacing the previous 5-minute response time. This implementation was motivated by a fire model experiment, in which the fire growth curve demonstrated that the fire must be extinguished within 5 to 8 minutes of the outbreak. The fire growth curve has been used in computation as fundamental criteria of fire suppression mobilization in many countries including Korea, Japan, and the United Kingdom [24]. Consequently, the fire growth curve is the basic standard for the arrangement of fire station procedures. The arrival time of the fire engine is very important for fire suppression, and in events in the United Kingdom (UK), a fire suppression

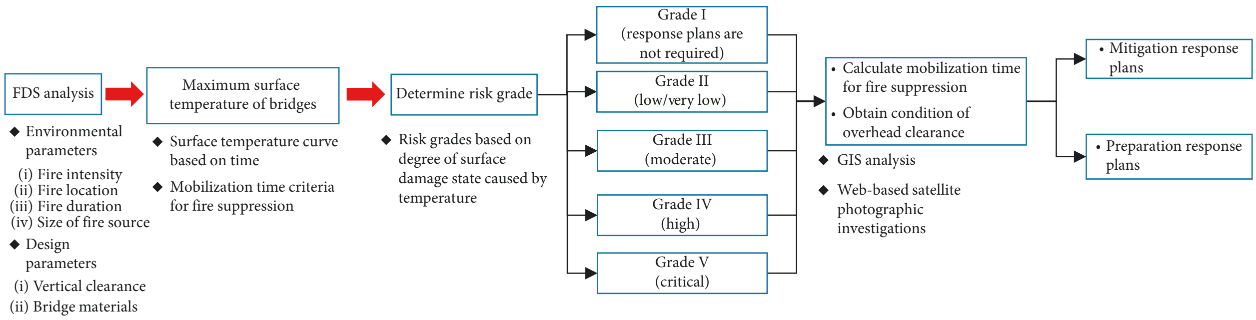


Figure 3: Risk grade process and response plans.

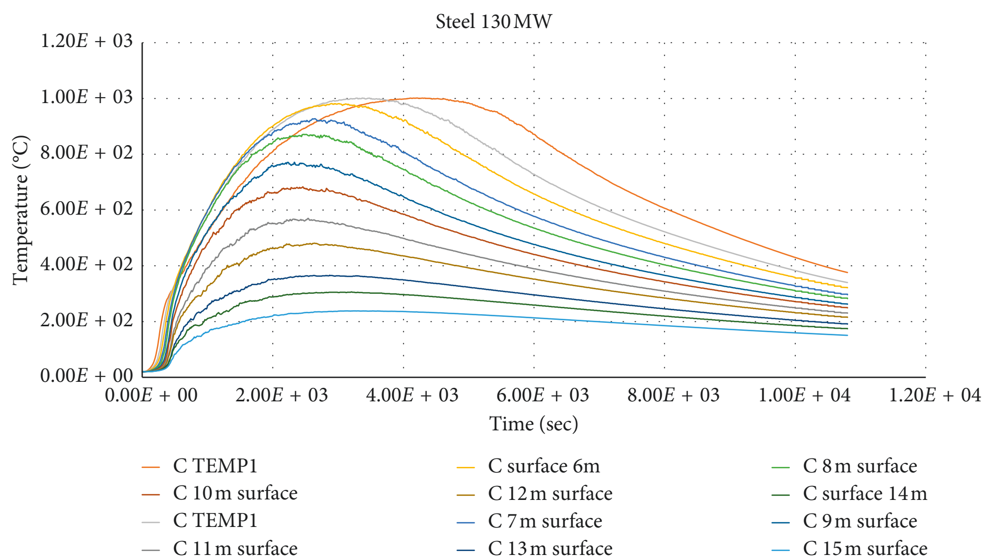


Figure 4: 130 MW steel bridges temperature-time curve.

mobilization time has been used and organized for each of the hazard areas shown in Table 5. The entire region type was divided into five regions, A, B, C, D, and RR, representing the region type such as major commercial, small business, and high-rise apartment building, according to an arrival time of the fire engine [25, 26].

In the case of bridges, the mobilization time criteria for fire suppression were based on that used for buildings similar to bridges because no criteria are available for the arrival time of the fire engine. Considering the properties of the standard fire curve of vehicle fires as shown in Table 6, characteristics that the fire should be extinguished before it lasts for 5 minutes are similar to a case of the bridge fire. Also, as the practice of a 5-minute arrival time has been adopted in the UK and Korea, this study referred to mobilization time criteria for fire suppression in the UK. The suggested criteria for the risk grade model are shown in Table 7.

4. FDS Analysis

Fires that occur at the bottom of a bridge are more dangerous than those occurring on the upper part of a bridge. This is because a fire under the bridge causes damage to both the superstructure and the substructure supporting the bridge [6, 9, 10, 13]. The types of fire damage occurring at the bottom of bridges vary significantly depending on the fire intensity and location, the vertical clearance, and the materials of the bridge [9]. Therefore, in order to determine the severity of various bridge fire accidents with respect to the properties of these bridges, the Fire Dynamics Simulator 5.3 (FDS 5.3) was used for this study. FDS is calculated based on Computational Fluid Dynamics (CFD) theory, which focuses on the heat and smoke flow emitted from the flames [28, 29]. This analysis was used for the fire simulation, and the surface temperatures of the bridges were calculated in order to reflect the risk grade model.

4.1. Standard Fire Curve. When designing the fire simulation, the standard fire curve is determined based on one of the following assumptions [28, 29].

4.1.1. Assumption of Steady Fire. This hypothesis assumes that the same amount of energy is consistently emitted from the beginning of the fire to the end.

4.1.2. Assumptions of Growth Fire. This hypothesis assumes that the fire increases to a designated size, then remains stable.

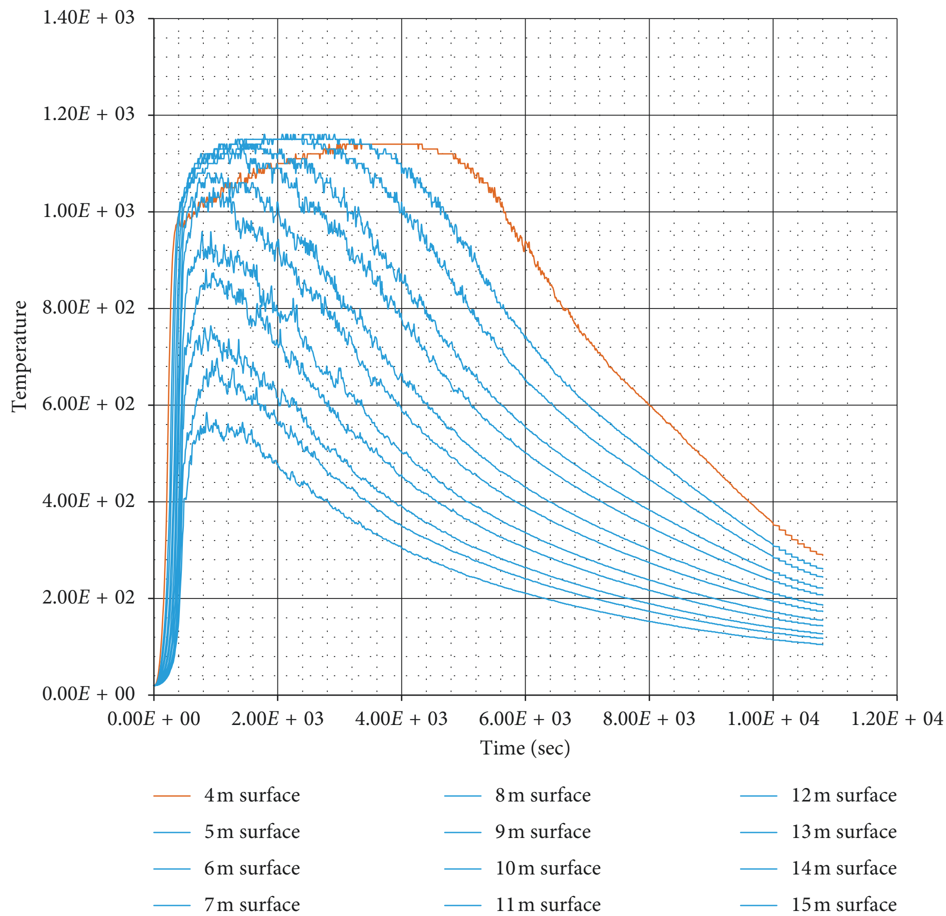


Figure 5: 130 MW concrete bridges temperature-time curve.

Table 1: Maximum surface temperature of concrete bridges according to mobilization time criteria and vertical clearance (130 MW). Unit: °C.

Mobilization time criteria for fire suppression (min)	Vertical clearance (m)											
	4	5	6	7	8	9	10	11	12	13	14	15
I (0–5)	909	726	567	364	288	202	157	124	104	81	74	64
II (5–8)	969	1030	1030	1020	1010	961	889	761	681	590	480	406
III (8–10)	987	1060	1080	1080	1060	1030	971	887	762	680	539	477
IV (10–20)	1050	1130	1130	1130	1120	1070	1030	906	856	725	641	561
V (more than 20)	1140	1160	1160	1150	1130	1070	1030	908	856	737	676	564

Table 2: Maximum surface temperature of steel bridges according to mobilization time criteria and vertical clearance (130 MW). Unit: °C.

Mobilization time criteria for fire suppression (min)	Vertical clearance (m)											
	4	5	6	7	8	9	10	11	12	13	14	15
I (0–5)	209	148	107	79	60	48	41	35	32	29	28	26
II (5–8)	323	327	323	302	285	242	215	169	155	111	103	78
III (8–10)	371	396	402	393	377	337	295	243	220	165	137	110
IV (10–20)	589	658	684	678	659	595	533	449	370	284	226	178
V (more than 20)	1001	1000	981	927	871	764	679	570	480	365	305	237

4.1.3. Assumption of Fire according to Growth and Change. This hypothesis assumes that the fire intensity increases, and the process includes the growth, progress, and decrease of the fire intensity.

The above standard fire curve properties are provided by the Korean Ministry of Land, Infrastructure and Transport (MOLIT) and follow the National Guidelines for the Installation of Road Tunnel Fire Safety Facilities (2018) [27].

This study refers a standard fire curve that considers the growth and change of the fire, as shown in Table 8 and Figure 6. The standard fire curve [27] is reflected in the FDS

Table 3: Risk grades of concrete bridges [17, 18].

Risk grades	Degree of surface damage state caused by temperature
I (none)	The possibility of fire ignition is insignificant due to presence of streams or rivers.
II (low)	The structural components are obviously damaged. The maximum temperature reaches less than 300°C [17, 18]
III (moderate)	The structural components are slightly damaged. None of the reinforcing bars are exposed, and the damage depth is less than 20 mm. The bond strength between the concrete and the steel bars is slightly weakened. The maximum temperature ranges from 300°C to 600°C.
IV (high)	The structural components are obviously damaged. The steel bars are exposed in the local area, and the damage depth is greater than 20 mm. The bond strength between the concrete and the steel bars is seriously weakened. The maximum temperature ranges from 600°C to 900°C.
V (critical)	The structural components are seriously damaged. The bond strength between the concrete and the steel bars is seriously weakened, and several steel bars are burnt or distorted. The maximum temperature reaches more than 900°C.

Table 4: Risk grades of steel bridges [9, 15, 19–23].

Risk grades	Degree of surface damage state caused by temperature
I (none)	The possibility of fire ignition is insignificant due to presence of streams or rivers.
II (very low)	Less than 460°C creep, while minimal deformation of steel members occurs.
III (low)	Creep, the time-dependent deformation of a material, may be significant in structural steel at temperatures in excess of 460°C. The maximum temperature ranges from 460°C to 538°C.
IV (moderate)	The yield strength is approximately 60 percent of the value at normal room temperature. The modulus of elasticity decreased appreciably from the value at normal room temperature. The maximum temperature ranges from 538°C to 700°C.
V (high)	Steel retains about 20 percent strength and stiffness. The steel surface is noticeably oxidized and possibly pitted, with some accompanying erosion and loss of cross-sectional thickness. Also, members heated beyond 700°C usually show large deflection or localized distortion when heated in a structural system. The maximum temperature ranges from 700°C to 1000°C.
VI (critical)	Extreme overheating beyond the rolling temperature can be expected to reduce steel properties to a larger degree. Evidence of pitting and flaking appears on the steel surface if this extreme heating has occurred. The high temperature strength loss and thermal expansion are extreme at these temperatures, and structural damage or collapse will likely precede any overheating material damage. The maximum temperature reaches more than 1000°C.

Table 5: Mobilization time criteria for fire suppression in the UK [25, 26].

Hazard area	Region type	Fire suppression mobilization time (min)		
		First arrival time of fire engine	Second arrival time of fire engine	Third arrival time of fire engine
A	Major commercial, business, industrial	5	5	8
B	Small business, industrial, high-rise apartment building	5	8	—
C	Residential	8–10	—	—
D	Regions in which A, B, and C are not applied	20	—	—
RR	Country	—	—	—

Table 6: Properties of standard fire curve [27].

	Car	Bus	Truck	Hazardous material transport
Fire strength (MW)	10.0	20.0	30.0	100
Growth rate (α)	0.05	0.1	0.15	0.5
Decay ratio (β)	0.002	0.001	0.001	0.001
Growth time (sec)	450	450	450	450
Maximum burning time (sec)	268	455	102	350

Table 7: Mobilization time criteria for fire suppression.

Time criteria	Mobilization time criteria for fire suppression
I (1 level)	Less than 5 minutes
II (2 level)	5~8 minutes
III (3 level)	8~10 minutes
IV (4 level)	10~20 minutes
V (5 level)	More than 20 minutes

Table 8: MATL input of bridge [28, 29, 30].

Division	Explanation	Concrete	Steel
Emissivity	Emissivity	1.0	1.0
Conductivity	Heat conductivity (W/m/K)	1.7	45.8
Specific_heat	Specific heat (kJ/kg/K)	0.75	0.46
Density	Density (kg/m^3)	2400	7850

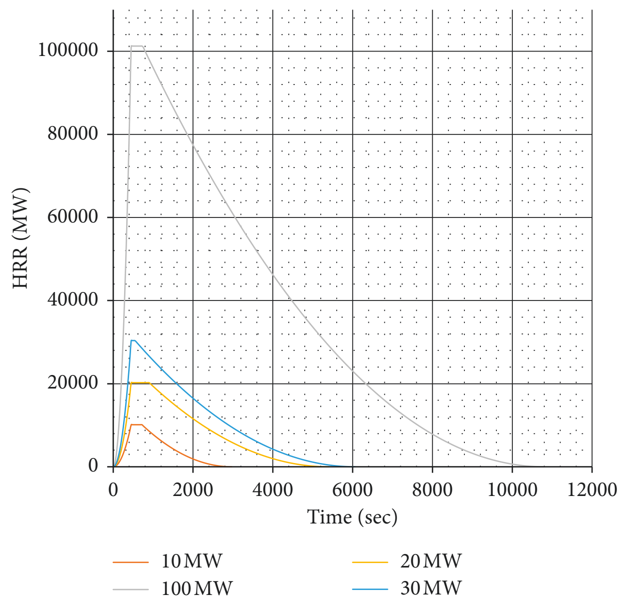


Figure 6: Standard fire curve for FDS model [31].

analysis. It also refers to foreign cases with the fire intensity based on an experimental fire test.

The EUREKA Fire Tests [32] presented fire test results of 100~130 MW fire intensity caused by a heavy goods vehicle, whereby in this study, the fire intensity of the transport vehicle with hazardous materials of 100 MW, which increased to 130 MW. According to Permanent International Association of Road Congresses (PIARC) report 1995 [33], in the event of a petrol/gasoline tanker with a leak, the maximum fire intensity considered is that for more than 30 MW; the cases of 50 MW and 100 MW were thus additionally analyzed as shown in Table 9.

4.2. Size of Fire Source and FDS Fire Field Model. The size of the fire source is determined based on the average length of a vehicle [27, 31]. Furthermore, it is assumed that a vehicle accident occurs at a height of 1 m, considering the height of the fire source in the case where a vehicle accident occurs. In conclusion, the six different sizes of the fire source were reflected in the FDS modeling as shown in Table 9.

4.3. FDS Analysis Model. FDS analysis was performed for a typical concrete bridge and steel bridge because most of an existing bridge on national roads consists of typical bridges in South Korea. Furthermore, the bridges on the national highway were almost not equipped with a design of fire resistance because it has been considered a safe zone from

Table 9: FDS model showing fire intensity and size of fire source.

Model	Fire intensity	Size of fire source (W × D ×H)
Car	10 MW	4.34 m × 1.7 m × 1.0 m
Bus	20 MW	4.5 m × 2.0 m × 1.0 m
Truck-A	30 MW	6.1 m × 2.0 m × 1.0 m
Truck-B	50 MW	6.1 m × 2.0 m × 1.0 m
Truck-C	100 MW	6.1 m × 2.0 m × 1.0 m
Transport vehicle with hazardous materials	130 MW	8.74 m × 2.5 m × 1.0 m

the fire, especially the fire occurred under the bridge, due to a small amount of traffic volume. Thus, this FDS analysis covered the typical bridges not equipped with the design of fire resistance.

As shown in Table 8, steel and concrete bridges were divided and their data were then entered into the FDS according to the material properties of the bridge. Since it is impossible to consider all types of geometric shapes of bridges, the modeling was based on a slab type bridge due to its simplicity and commonality on national highway roads. In order to reflect the various vertical clearances of actual bridges, the FDS analysis was performed according to the increment of 1m vertical clearance from 4 m to 15 m. Moreover, Figures 7(a) and 7(b) show the position of the temperature measurement and examples of the FDS analysis model. Since the vertical deflection is the largest when a fire occurs at the center under the bridge [9], the fire location is set centered at midspan to obtain conservative results. As the position of temperature measurement should be able to be used to calculate the direct influence by the fire source, it was located under the bridge surface centered at midspan, both longitudinally and transversely, which was the vertical distance from the center of the fire source. The size of the space in the FDS analysis was set at 9 m × 8 m × 16 m. The size of the slab bridges was modeled as 9 m × 8 m × 1 m, and the suggested fire source was used as shown in Table 9. The FDS analysis time, boundary condition, and mesh size are shown in Table 10.

4.4. FDS Analysis Results. The fire intensities were selected as 10 MW, 20 MW, 30 MW, 50 MW, 100 MW, and 130 MW, and the bridge materials were classified into steel and concrete bridges. A total of 144 FDS analyses were performed based on the bridge materials, the fire intensity, and the vertical clearance of bridges ranging from a minimum of 4 m to a maximum of 15 m. Based on the FDS analysis results, it was considered that a bridge with a vertical clearance of 15 m would not be affected by a fire [9, 13]. The FDS analysis time was determined according to the fire ending time depicted in the standard fire curve for the FDS model shown in Table 6 and Figure 6, and the properties of the standard fire curve are shown in Table 10.

Among the above-mentioned various sizes of design fire intensities, the FDS analysis results of 130 MW for concrete and steel bridges are shown in Figures 4 and 5, which is

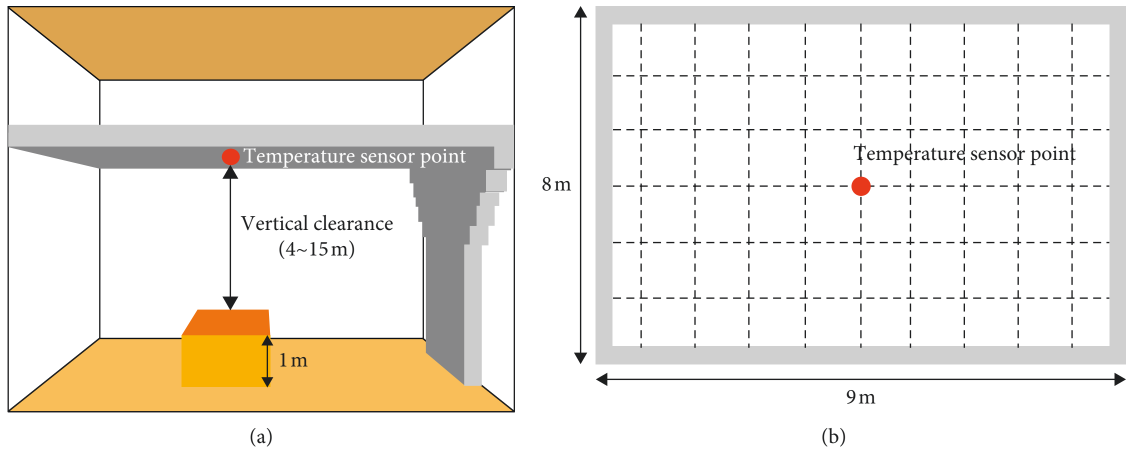


Figure 7: (a) FDS analysis model and (b) position of temperature measurement.

Table 10: Characteristics of analysis model.

Division		Content
FDS analysis time	10 MW	2980 sec
	20 MW	5600 sec
	30 WM	
	50 MW	6060 sec
	100 MW	
	130 MW	10800 sec
Size of slab bridge (W × D × H)		9 m × 8 m × 1 m
Mesh size		24 × 20 × 40 = 19,200 (0.4 m × 0.4 m × 0.4 m)
Atmosphere temperature (°C)		20°C
Boundary condition	Floor and ceiling	Heat-insulated structure
	Others	Atmosphere air condition

considered the most dangerous case in terms of safety or serviceability of bridges when exposed to a fire. As the vertical clearance of the bridge increases, the surface temperature of the bridge tends to decrease, and other FDS analysis results showed the same tendency. In the case of steel bridges, the high conductivity causes much faster inflows and outflows of heat. The surface temperature of the steel bridges is also relatively low compared to that of the concrete bridges. In contrast, concrete has a low conductivity, causing slow heat movement, and a high temperature can thus be measured.

The maximum surface temperature was the most dangerous temperature that can be reached in the structure in the mobilization time, and therefore, the risk grades were set according to the degree of surface damage state caused by temperature. As shown in Tables 1 and 2, the maximum surface temperatures shown in FDS analysis at 130 MW were classified according to the vertical clearance and the mobilization time criteria for fire suppression. By classifying these temperatures according to the risk grades of bridges shown in Tables 3 and 4, the risk grade of the bridges can be assessed according to the degree of the surface damage state (Tables 3 and 4) caused by the temperature.

5. Risk Grade Model Associated with Design and Environmental Parameters

In order to classify the risk grade over the bridge fire, it is necessarily required to establish a grade model. For this purpose, two types of the risk grades table were suggested. As a bridge structure is mainly composed of steel and concrete, the risk grades for steel and concrete bridges are presented. The risk grade models were established by applying the classified maximum surface temperatures in Tables 1 and 2 to the risk grades table as shown in Tables 3 and 4. The risk grade model consists of three axes shown in Figures 8 and 9. The X axis and the Y axis show the vertical clearance (4~15 m) and fire intensity (10~130 MW), respectively, while the Z axis shows the mobilization time criteria for fire suppression in Table 7 (less than 5 minutes, 5–8 minutes, 8–10 minutes, 10–20 minutes, and more than 20 minutes). Also, to establish effective response plans from the risk grade models, an existing response plan for the bridge fire [9, 13, 34] was classified into mitigation and preparedness response plans.

5.1. Risk Grades in Concrete Bridges. The risk grades of concrete bridges according to the degree of surface damage state caused by temperature are shown in Table 3. Grade I (none) was also presented to indicate the case where there was no cause for combustion under the bridge due to existing water bodies such as streams or rivers. On the contrary, the remaining grades are presented as the risk grades of the degree of surface damage of bridges by fire as follows: Grade II (low), Grade III (moderate), Grade IV (high), and Grade V (critical). The remaining risk grades indicate the degree of bleaching and torsion of steel elements when the temperature of the concrete members reaches 300°C, 600°C and 900°C, 300°C, 600°C, and 900°C [17, 18].

5.2. Risk Grade of Concrete Bridge. The surface temperatures under the bridges calculated from the FDS analysis were classified into the maximum surface temperature as shown in Tables 1 and 2, and the risk grades were then assessed according to the degree of surface damage state caused by

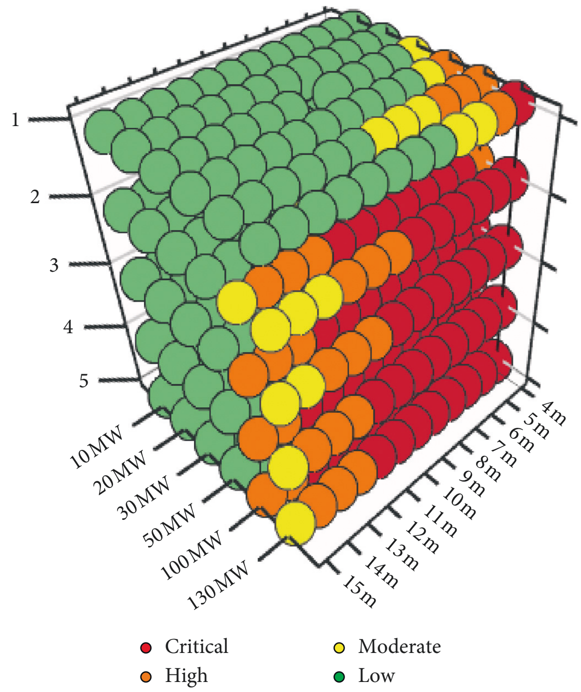


FIGURE 8: Risk grade model for concrete bridges.

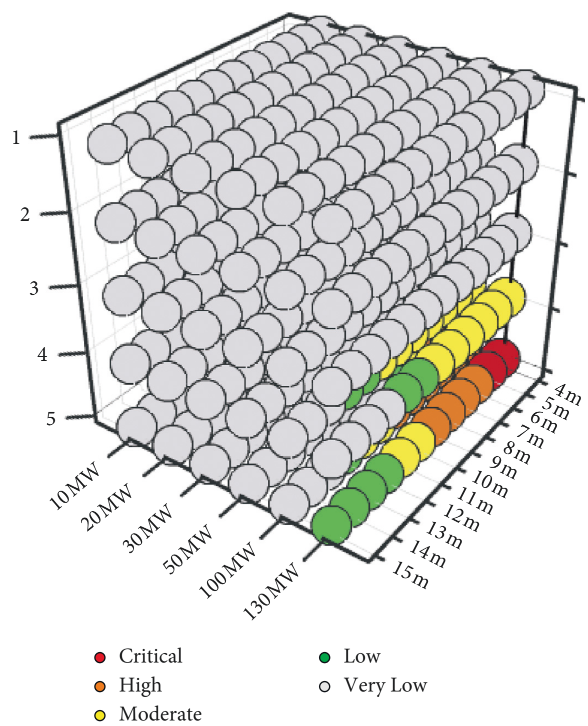


FIGURE 9: Risk grade model for steel bridges.

temperature in Table 3. As shown in Figure 8, the risk grade model for concrete bridges was presented. The suggested triaxle risk grade related to the concrete bridges includes the three axes of the fire intensity, vertical clearance of bridges (4~15 m), and mobilization time criteria for fire suppression as shown in Table 7. According to the risk grades of concrete bridges in Table 3, the classification of Grade (none) differed to that of the other risk grades because of the low possibility of fire occurrence due to the presence of streams or rivers, and the remaining risk grades of concrete bridges, II (low), III (moderate), IV (high), and V (critical), were represented depending on the degree of surface damage state caused by temperature.

5.3. Risk Grades of Steel Bridges. The risk grades of the degree of surface damage caused by the temperature of the fire in concrete bridges are shown in Table 4. Grade I (none) refers to the case where the possibility of fire ignition is insignificant due to a presence of streams. The remaining risk grades, Grade II (very low), Grade III (low), Grade IV (moderate), Grade V (high), and Grade VI (critical), are classified according to the degree of damage at a certain surface temperature caused by fire.

Particularly, Grade II (very low) and Grade III (low) were categorized according to the property transformation of structural steel [15, 19]. Grade IV (moderate) is presented in accordance with the temperature limit standard of ASIC that the maximum permissible design stress started to decline from 538°C to 60% in Grade IV (moderate) [20, 21]. Grade V (high) refers to a structure with a surface temperature of 700°C, which is the temperature reached with increased oxidization and possibly causes pitting in the structure system [9].

In addition, a temperature above the rolling temperature can seriously weaken the strength of the steel members. Before reaching the rolling temperature, collapse or severe damage occurs in most cases. Since the rolling temperature is formed at a temperature of 1000°C, or even higher, bridges can collapse or excessive vertical deflection can occur at 1000°C, which is shown for Grade VI (critical) [9, 22, 23].

5.4. Risk Grade of Steel Bridge. Similar to the risk grade of concrete bridges, the FDS analysis results were adapted based on the risk grades of steel bridges shown in Table 4. Except for Grade I (none), representing a relatively lower possibility of fire occurrence, the remaining damage grades of II (very low), III (low), IV (moderate), V (high), and VI (critical) are shown as Figure 9, while Tables 11 and 12 show the exemplary result of the risk grade of bridges.

5.5. For Application of Risk Grade Models, GIS Network Analysis, and Web-Based Satellite Photographic Investigations. In order to evaluate the applicability of the established risk grade model to actual bridges, the risk grades of 10 concrete bridges in Gyeonggi-Do Province, Korea, were evaluated. The fire intensity was selected as 130 MW, which is considered the most dangerous case in terms of safety or serviceability of bridges when exposed to a fire. To determine the risk grade of the actual bridges using the established risk grade model, the arrival time from the fire station to the bridge needs to be determined. For this purpose, the mobilization time for fire suppression and the closest distance to the fire station were calculated through GIS network analysis. Also, web-based satellite photographic investigations were used to identify the bridges through satellite images provided by

Table 11: Risk grade on concrete bridge with 130 MW applied.

Fire intensity	Bridge name	Risk grade	Suburb fire station	Mobilization time for fire suppression	Vertical clearance (m)	Conditions of overhead clearance
130 MW	Gasan IC bridge	V (critical)	Yeoju fire station	7 min	4.6	General road
—	Gung nonbridge	V (critical)	Pyungtaik fire station	8 min	7	Unpaved road
—	Neung won bridge	V (critical)	Bundang fire station	11 min	4.5	General road
—	Duksung bridge	V (critical)	Yongin fire station	7 min 30 sec	4.3	General road
—	Deade bridge	V (critical)	Yangpyeong fire station	20 min	4.5	General road
—	Gilmeung bridge	V (critical)	Pocheon fire station	11 min	6	General road
—	Ganmea bridge	IV (high)	Yeoju fire station	7 min 30 sec	4.5	General road
—	Bonghwa bridge	V (critical)	Hwaseong fire station	15 min 30 sec	4.6	General road

Table 12: Risk grade on steel bridge with 130 MW applied.

Fire intensity	Bridge name	Risk grade	Suburb fire station	Mobilization time for fire suppression	Vertical clearance (m)	Conditions of overhead clearance
130 MW	Damyang bridge	IV (moderate)	Hwaseong fire station	18 min	4.5	General road
—	Neri overpass bridge	II (very low)	Anseong fire station	4 min	4.5	General road
—	Dongrim bridge	II (very low)	Bundang fire station	9 min	4.8	General road
—	Geumnam bridge	IV (moderate)	Namyangju fire station	12 min	4.5	General road
—	Goduk bridge	II (very low)	Pyungtaik fire station	7 min	4.8	General road
—	Gosan bridge	II (very low)	Gwangju fire station	7 min 30 sec	4.3	Highway
—	Dongbang bridge	I (none)	Hwaseong fire station	7 min	5.3	Only stream existing
—	Balahn bridge	II (very low)	Hwaseong fire station	1 min 30 sec	4.5	General road

domestic and overseas portal sites (Naver, Google Earth, etc.) and to verify the presence of combustible materials and conditions of the overhead clearance.

5.5.1. Mobilization Time Calculation for Fire Suppression through GIS Network Analysis. It is important that a fire is suppressed within a short period of time since the damage of fire is likely to rapidly spread to neighboring structures. Thus, network analysis using ArcGIS 10.1 was used to calculate the arrival time at the bridge from the fire station. GIS, which integrates and manages spatial data and attributes data to objects with geographical locations, provides various types of information such as maps, diagrams, and pictures. Using the spatial data and attribute data of bridges and fire stations, the fire station closest to the bridge can be determined, and it is even possible to calculate the arrival time of fire brigade from the fire station. In the GIS, the network is a series of linear objects. For example, objects include highways, railroads, streets, rivers, transportation routes (public transportation, school bus, refuse cart, and mail delivery), and public facilities (electricity, communication, and waterworks) [35]. Typical methods used to analyze a street network through ArcGIS include OD cost matrix using network analyst, facility analysis, and service area analysis [35]. The OD cost matrix function was used in this study because it relates to the network distance and time.

Raw data necessary for the space analysis could be listed as follows:

(i) Network data set: includes information on the length of routes and design speed

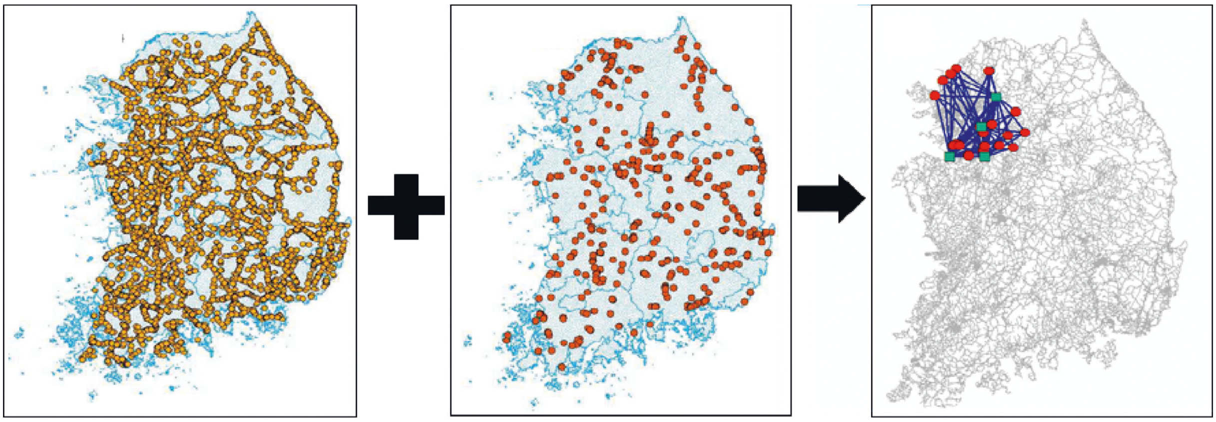
(ii) Location information of bridges and fire stations on national roads: point data (shp file)

Among the attribute data, speed data reflect the design speed of each road. Moreover, since point data need to be constructed for use in the network analysis, 7343 national highway bridges and 1246 fire station points were established from the GIS map.

A structured GIS analysis procedure is shown in Figure 10. The left side shows maps of the national highway bridges shown in Figure 10(a) and fire stations shown in Figure 10(b). The figure also shows the combined results of the OD cost matrix analysis of Figure 10(c) based on the network data set. If the point data such as the fire stations and the national highway bridges overlap the network data set, the times from the departure point to the destination can be calculated as shown in Figure 10(c). Although the results of the OD cost matrix analysis are shown as a straight line, the times were calculated based on the network data set, so that it is possible to classify an actual bridge to the mobilization time criteria for fire suppression in Table 7.

5.5.2. Web-Based Satellite Photographic Investigations. To obtain the conditions of overhead clearance, investigations of satellite photographs and photographs taken at the road level were performed based on the web-based satellite photographs shown in Figures 11 and 12. The satellite images were provided by domestic and overseas portal sites (Naver, Google Earth, etc.) to verify the presence of combustible materials and conditions of the overhead clearance.

Through this process, it was possible to verify the risk factors such as the presence of combustible materials under the bridge, conditions of overhead clearance, and vertical clearance. The mobilization time for fire suppression can be



(a) (b) (c)

Figure 10: GIS analysis. (a) Bridges; (b) fire stations; (c) OD cost matrix analysis.

Figure 11: Satellite photograph of investigation example.

Figure 12: Road level photograph of investigation example.

calculated from GIS analysis. Therefore, it is possible to determine the risk grade of an actual bridge when a 130 MW fire occurs under the bridge. These results are shown in Figures 8 and 9, and the risk grades were then estimated as shown in Tables 11 and 12.

6. Response Plans of Bridge Fire

It was important to establish effective response plans for each risk grade in order to ensure bridge survivability and safety. The final goal of the risk grade model was to identify the cause, to determine the risk grade, and to establish effective response plans to mitigate the risk grade. Thus, this study established the appropriate response plans for each risk grade of the bridges.

After the risk grades of the bridges were determined, similar to the results in Tables 11 and 12, the response plans for bridges were designed and applied according to the risk grades in order to mitigate and prepare for bridge fire accidents in advance. According to Table 13, based on a suggested existing response plan [9, 13, 34], factors such as reducing the possibility of fire occurrence or removing combustible materials could be classified as a mitigation response plan, while factors related to reactions that deal with the situation after the fire occurs were categorized as a preparedness response plan.

It was considered that bridges with risk grades such as low/very low did not need an active response plan because these bridges did not pose any threat in terms of safety or serviceability even if a bridge fire occurs. Therefore, regular mitigation plans to remove combustible materials were considered sufficient to manage bridge fire.

Bridges with a moderate risk grade, such as the low/very low grade, had a low probability of bridge collapse. When weighed against time, cost, and the effort needed to implement the response plan, it was considered sufficient to manage the bridge fire by simply eliminating combustible materials regularly and applying rapid fire suppression linked to the firefighting headquarters or fire department.

For bridges estimated to be high/critical risk grades, the response plans showed fireproof design and firefighting equipment because fire safety and serviceability can be a serious problem in the case of a bridge fire. In addition, the preparedness response plan consists of the installment of equipment such as surveillance equipment or a fire alarm box.

7. Result and Conclusion

Bridge fires are caused by a variety of events and situations, such as the burning of petrol in parked vehicles, the ignition of spilled material under the bridge, or a gas explosion due to leaking gas from a gas pipeline attached above the bridge. If a fire occurs adjacent to a bridge, it will cause damage to the structure as well as additional economic losses such as human casualties and traffic paralysis [1–4]. In this paper, recent accident cases and the extent of damage of bridges, in

Table 13: Mitigation and preparation response plans depending on risk grade.

Risk grades	Critical	High
Response plan	*Mitigation response plans* Control combustible materials Remove bus stops and parking lots. Propose detours for hazardous material truck Install speed dump Install reflector for a blind spot Install speed indicator Improve drainage system. Traffic control. *Preparedness response plans* Install fire surveillance equipment Install fireproof equipment Install fire suppress equipment Establish contingency plans linked to fire department and secure fire Reinforce the bridge with fire resistance design/rehabilitation Manual fire alarm boxes	*Mitigation response plans* Control combustible materials Remove bus stops and parking lots. Propose detours for hazardous material truck Install speed dump Install reflector for a blind spot Install speed indicator Improve drainage system *Mitigation response plans* Establish contingency plans linked to fire department and secure fire
Risk grades	Moderate	Low/very low
Response plan	*Mitigation response plans* Control combustible materials Remove bus stops and parking lots. Propose detours for hazardous material truck *Preparedness response plans* Establish contingency plans linked to fire department and secure fire	*Mitigation response plans* Control combustible materials Remove bus stops and parking lots.

cases of both domestically and abroad, were analyzed, and a quantitative fire risk grading methodology and pragmatic response plans for bridges were proposed. The risk grade model and response plans were established through an analysis of environmental parameters (fire intensity, fire location, and fire duration) and design parameters (vertical clearance and bridge materials). Based on the proposed risk grade model, the risk grades of bridges on the national highway can be determined. The mitigation and preparedness response plans were suggested based on the risk grade model. Through the risk grade model, it is expected that fire damage to the bridge can be prevented and preparedness for the event of a severe risk fire can be achieved.

The results in this study are as follows.

The risk factors that significantly can cause degraded bridge safety or serviceability in the event of a fire were selected. The risk grades according to the degree of the surface damage state caused by temperature in bridges and the mobilization time criteria for fire suppression were presented to be reflected in the risk grade model. Through the risk assessment model, it was possible to semiquantify the risk and to present the fundamental model for future bridge fire risk grade model. Also, in GIS analysis, it is shown that this model can be applied in actual bridge cases and the response plan according to the risk grades. In the future, given the location of the fire and the wind intensity, this risk grade model will be more sophisticated. In conclusion, a semiquantitative evaluation was conducted in the fire occurring in the lower part of the bridge and tried to make the qualitative value to be a quantitative value. In addition, it is considered that it can contribute to the basis on a methodology of quantification of the risk.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by a grant (13SCIPA01) from Smart Civil Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport (MOLIT) of Korea government and Korea Agency for Infrastructure Technology Advancement (KAIA)

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