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The First Performance-based Structural Fire Design for Office Building in Korea

Min Jae Park†

Department of Architectural Engineering, Pukyong National University, Republic of Korea

Abstract In this study, the fire resistance performance of the concrete-filled steel tube (CFT) columns and thin steel-plate composite (TSC) beams installed at a 20-story office building were designed using a performance-based structural fire design. Because of the lack of any specific provisions in the building code and guidelines for structural engineers about the performance-based approach, the only prescriptive approach has been selected for designing fire-resistant structures in Korea. To evaluate the fire resistance performance of the CFT columns and TSC beams, finite element analysis verified by the experimental results studied by several researchers was conducted with ABAQUS. From the fire scenario, the temperature distributions of the CFT columns and TSC beams were found via finite element analysis and the behaviors of the CFT columns and TSC beams were investigated in the structural field based on the temperature distribution.

Keywords Performance-based structural fire design, CFT columns, TSC beams, Fire resistance

†Corresponding author:
Min Jae Park
E-mail: mjp@pknu.ac.kr

1. Introduction

In general, prescriptive designs for fire-resistant structures were widely adopted due to the lack of any specific provisions in building codes and guidelines for structural engineers about performance-based approaches in Korea. However, the prescriptive design provided the same way to decide the fire resistance performance of fire-resistant structures regardless of individual characteristics of the structural elements, such as the kind of materials. In contrast, performance-based design can adopt several ways to decide the fire resistance of the performance of fire-resistant structures depending on those materials, structural behaviors, and compartments of the building. Especially it is an efficient and economical design approach for concrete-filled steel tube (CFT) columns and thin steel-plate composite (TSC) beams that are regarded as non-fire-resistant members according to prescriptive approaches in Korea because the outer surfaces of CFT columns and TSC beams were steel plates that are vulnerable materials under fire. In this study, the fire resistance performances of the CFT columns and TSC beams were decided through the performance-based design. From various studies about the fire resistances of CFT columns and TSC beams, they actually have non-negligible fire resistance performance. The target CFT columns and TSC beams in this study were installed at a 20-story office building, of which the structural system was steel and composite structures. In the case of the CFT columns and TSC beams, they should have 3 hours fire resistance rating based on the regulation. The significant points of this building are the exterior structural members, which consist of exterior columns and exterior beams located outside the curtain wall, as shown in Figure 1. The exterior columns are CFT columns and the exterior beams are TSC beams.

To satisfy both owner's demands regarding aesthetic points about this building and building codes about fire-resistant structures, the exterior structural members should be installed without fireproofing materials. The performance-based structural fire design must be adopted to remove the fireproofing materials of the CFT columns and TSC beams. Thus, the performance-based structural fire design for the exterior structural members in this building was conducted using finite element analysis verified by the experimental results studied by other researchers.

2. Performance-based Structural Fire Design

The typical process of structural fire design is shown in Figure 2 (Hurley and Rosenbaum, 2015). To conduct the structural fire design, compartments, fire scenarios, objectives and criteria should be decided first and the performance of structural elements in the compartment under the fire scenarios will be decided. In general,

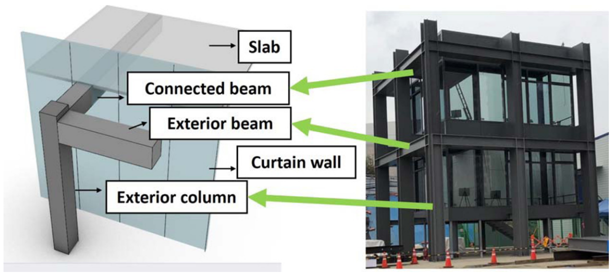

Figure 1. Components of exterior structural members in the building.

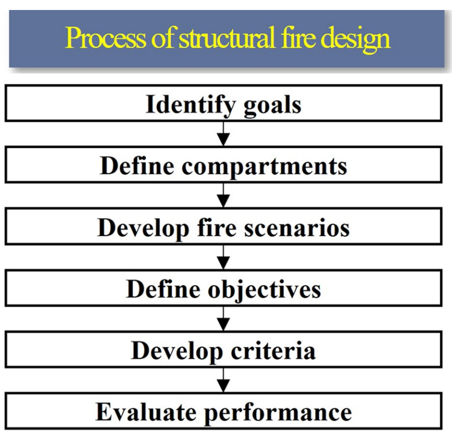

Figure 2. Process of structural fire design.

prescriptive designs for fire-resistant structures were widely adopted due to the lack of any specific provisions in building codes and guidelines for structural engineers about performance-based approaches in Korea. But the prescriptive design provided the same way to decide the fire resistance performance of fire-resistant structures regardless of individual characteristics of the structural elements, such as the kind of materials. In contrast, performance-based design can adopt several ways to decide the fire resistance of the performance of fire-resistant structures depending on those materials, structural behaviors, and compartments of the building. Because the PBSFD decides the fire scenario that was obtained from the room and opening properties, whereas prescriptive structural fire design adopted only the standard fire curves. Both prescriptive and performance-based designs are shown in Figures 3.

The first thing for performance-based design is deciding the fire scenarios. The possible fire scenarios for exterior structural members can be divided into two groups (Figure 4). The first group is generated by indoor fires caused by natural fires, explosions, and gasoline. And the second group is generated by outdoor fires caused by terrors, explosions, and vehicles. The outdoor fire was decided by the worst case for fire scenario

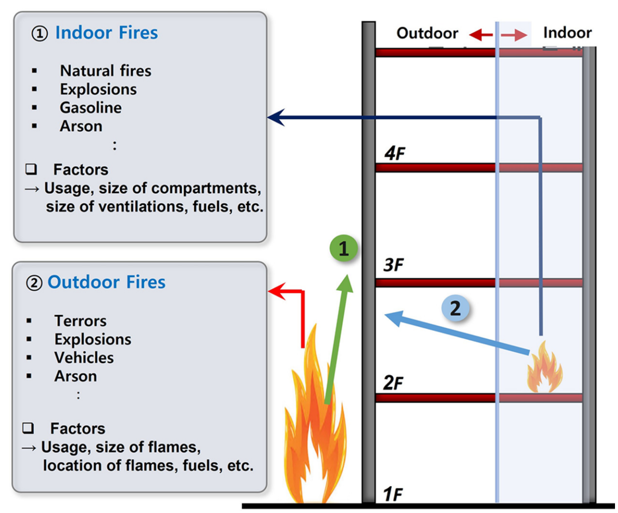

Figure 4. Expected fire scenarios.

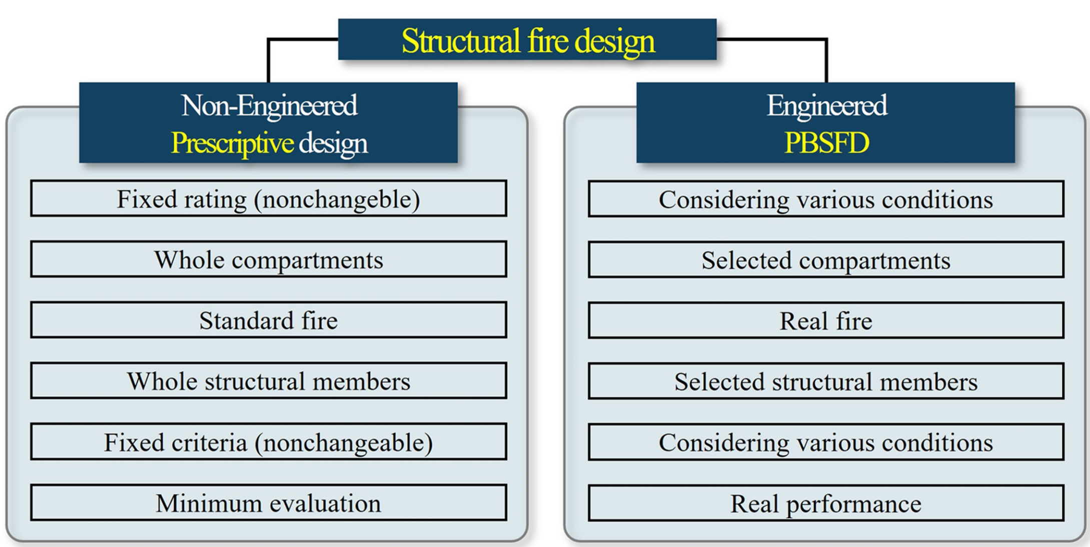

Figure 3. Process of prescriptive and performance-based design.

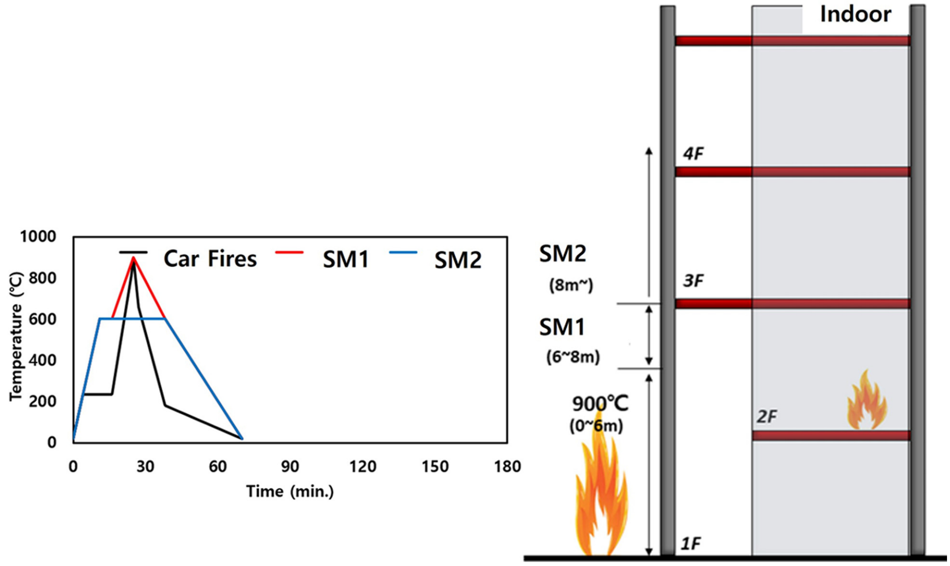

Figure 5. Fire scenarios depending on the height of fires.

suggested by FEMA (FEMA, 2006), which is scenario 12: explosive attack - bombing using improvised explosive devices. This scenario is equal to car fires and the worst case for exterior structural members was fire scenarios caused by a small moving van fire can be calculated as time-temperature graphs by previous studies (Twilt et al., 2002). Thus, the time-temperature graphs that simulated the fire scenarios to exterior structural members depending on the height of the fires and were simplified are shown in Figure 5.

3. Finite Element Analysis

To evaluate the fire resistance performances of exterior structural members under expected fire scenarios in this building based on the performance-based structural fire design, the finite element analysis using ABAQUS was conducted. The heat transfer analysis should be conducted before structural analysis. Heat transfer analysis provides temperature distribution of structural members depending on the time considering thermal properties of materials such as density, conductivity, specific heat, and thermal contact conductance. Based on the temperature distribution, depending on the time, the structural analysis can be conducted with mechanical properties such as tensile, compression strength, elastic modulus, Poisson's ratio, and bond strength. The aforementioned procedure of finite element analysis is shown in Figure 6. Thermal and

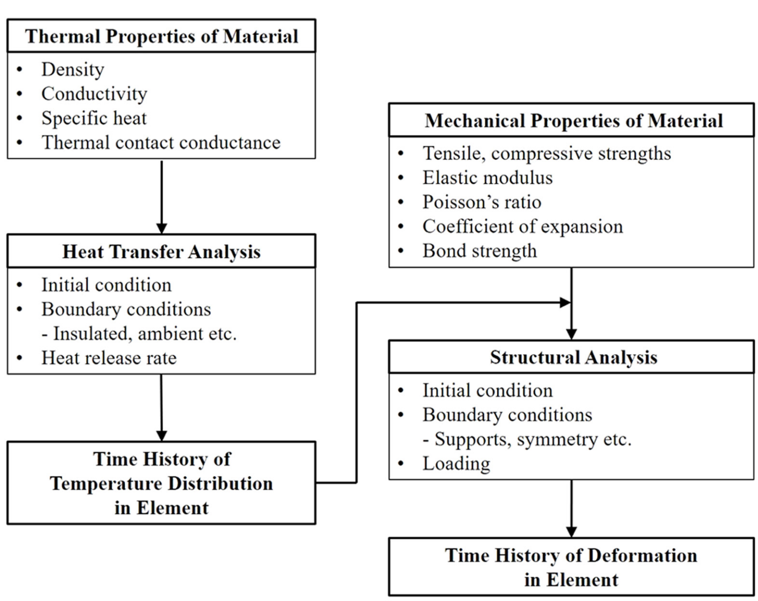

Figure 6. Procedure of finite element analysis.

mechanical properties of steel were proposed by Eurocode 3 and those properties of concrete were proposed by Eurocode 2. Thermal contact conductance between steel and concrete was selected as the contact model suggested by the previous study (Ding and Wang, 2008). Both the friction coefficient (Lu et al., 2011) and bond strength (Espinos et al., 2010) between steel and concrete were suggested by previous studies.

In finite element analysis, DC3D8, which is an 8-node linear heat transfer brick, was selected in the thermal field and C3D8, which is an 8-node linear brick for structural analysis, was selected in the structural field to evaluate the fire resistance of the CFT columns and TSC beams. The fire resistance performances of CFT columns without fireproofing materials under both standard fire curve and car fire are shown in Figure 7 and the detailed ratings were 1.1-hour and 2.9-hour, respectively. In addition, the fire resistance performance of TSC beams without fireproofing materials was validated by the experimental results (Choi and Kim, 2008) that showed 1-hour rating.

To obtain the reliability of the finite element model for the CFT columns, the experimental result (Hong and Varma, 2009) was selected to compare the result with the proposed finite element model in this study. In addition, the finite element model for TSC beams was verified by the experimental results to obtain the reliability of the model. Figure 8 and Figure 9 show the comparison between the analysis and experimental results of CFT columns and TSC beams, respectively.

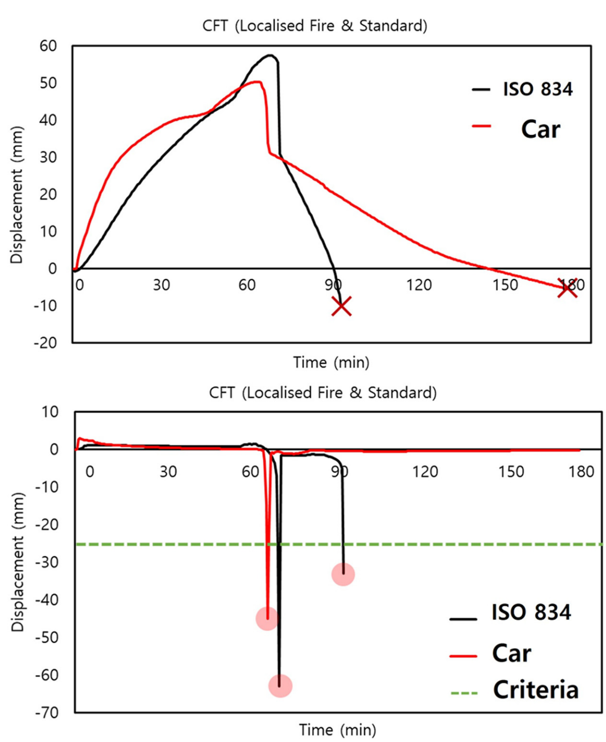

Figure 7. Fire resistance performance of CFT columns under both standard fire curve and car fire.

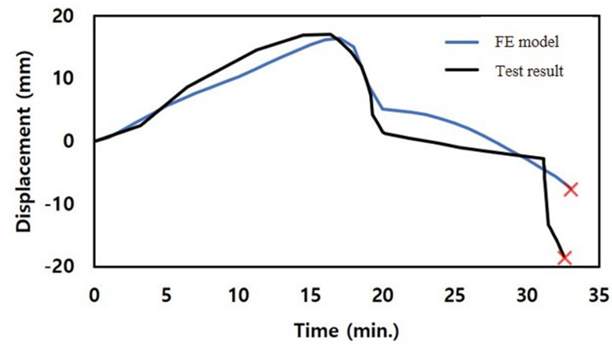

Figure 8. Comparison between the analysis and experimental results of CFT columns.

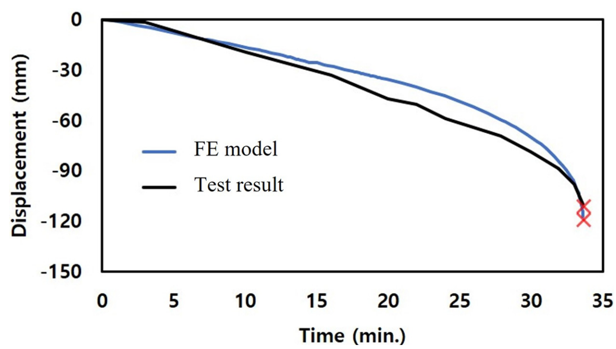

Figure 9. Comparison between the analysis and experimental results of TSC beams.

4. Reinforcing elements

To remove the fireproofing materials for the CFT columns and TSC beams, reinforcing elements were additionally installed at the structural members. In the case of the CFT columns, the shear connectors were installed between concrete and steel to prevent separation under fire conditions. In addition, steel rebars were installed to improve the structural capacity when the steel loses its strength due to elevated temperatures. In the case of the TSC beams, the fire resistance performance without fireproofing materials satisfied the failure criteria. Therefore, the reinforced section of only CFT columns is shown in Figure 10.

For CFT columns, the maximum temperature reached 812ºC. In addition, the maximum displacement and the rate of displacement were 54.6 mm and 4.15 mm/min, respectively. For TSC beams, the maximum temperature reached 384ºC. In addition, displacement and the rate of displacement were 17.0 mm and 2.04 mm/min. Both CFT columns and TSC beams with reinforcing elements satisfied the allowable criteria even though fireproofing materials were removed.

5. Conclusions

In this study, performance-based structural fire design

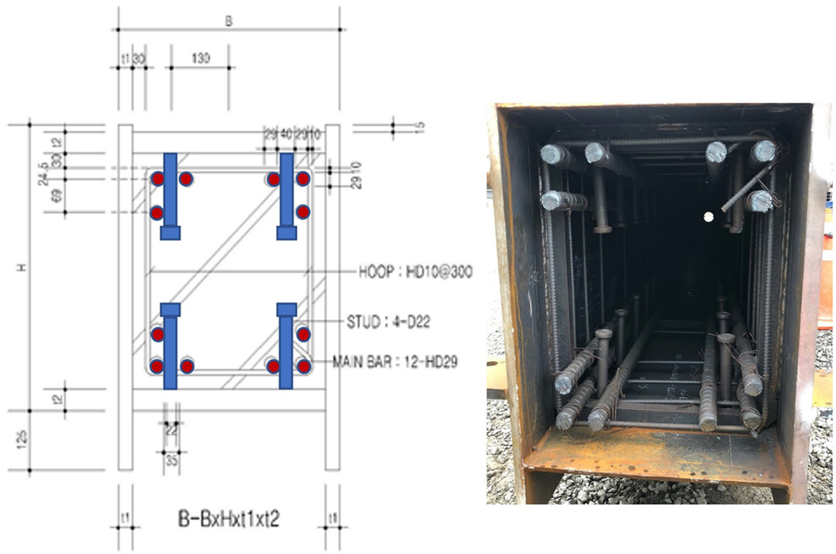

Figure 10. Reinforcing section of CFT columns.

Table 1. An example of table style

Member	Max. Temp. (°C)	Max. Disp. (mm)	Max. rate of Disp. (mm/min)	Allowable Disp. (mm)	Allowable rate of Disp. (mm/min)
CFT Column	812	54.6	4.15	80.0	24.0
TSC Beams	384	17.0	2.04	101	4.50

for CFT columns and TSC beams installed outside the curtain wall in a Korean office building was conducted to remove the fireproofing materials to satisfy the owner's demand and the building codes. The expected fire scenarios were proposed by the FEMA and European technical reports. In addition, the verified finite element analysis was conducted to evaluate the fire resistance performances of CFT columns and TSC beams with performance-based design approaches. In the case of TSC beams, fire resistance performance satisfied the required rating because the fire loads were decreased. However, the CFT columns must be reinforced to remove the fireproofing materials. Therefore, steel rebars and shear connectors were installed to improve the structural capacity when the steel plates lose their strength due to elevated temperatures and prevent separations, respectively. Finally, CFT columns and TSC beams installed outside the curtain wall in a Korean office building were applied without fireproofing materials using performance-based structural fire design methods.

Acknowledgments

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