

**FIRE-RESISTANT DESIGNS:
PRESCRIPTIVE APPROACH vs PERFORMANCE-BASED DESIGN**

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OVERVIEW

Fire can happen anytime and a fire hazard can cause a huge impact on a structure. It can change the behavior of beams and columns and cause the structure to deform. Typically, a prescriptive method is used in the design; however, there is a current shift in the structural engineering to start focusing on a performance-based design. This article will discuss generally about the prescriptive approach and the performance-based design including fire hazards, heat transfer analyses, and a case study of structural analysis.

THE PRESCRIPTIVE APPROACH

The current typical approach to a fire analysis is the prescriptive fire-resistant design which is what a majority of fire designs base on. Usually, architects are responsible to determine the fire protection and specify the fire-resistance rating.¹ The required fire protection will be determined based on many factors such as intended use and occupancy of the structure, area, height, fire department accessibility, distance from other buildings, sprinklers and smoke alarm systems, and construction materials.² Once these factors are resolved, the fire-resistance rating can be identified. The International Building Code (IBC) provides the fire-resistance rating based on building types, elements, and occupancy in Table 601 which is shown below. This rating is an amount of time (in hour) that an element can be exposed to fire before a failure is likely to occur. Because the strength and stiffness of steel are hugely reduced at elevated temperatures, passive fire protection is required in order to increase the fire-resistance rating.

**TABLE 601
FIRE-RESISTANCE RATING REQUIREMENTS FOR BUILDING ELEMENTS (HOURS)**

BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A ^a	B	A ^a	B	HT	A ^a	B
Primary structural frame ^c (see Section 202)	3 ^a	2 ^a	1	0	1	0	HT	1	0
Bearing walls									
Exterior ^{d, e}	3	2	1	0	2	2	2	1	0
Interior	3 ^a	2 ^a	1	0	1	0	1/HT	1	0
Nonbearing walls and partitions	See Table 602								
Exterior	See Table 602								
Interior ^f	0	0	0	0	0	0	See Section 602.4.6	0	0
Floor construction and associated secondary members (see Section 202)	2	2	1	0	1	0	HT	1	0
Roof construction and associated secondary members (see Section 202)	1 1/2 ^g	1 ^{h,c}	1 ^{h,c}	0 ^c	1 ^{h,c}	0	HT	1 ^{h,c}	0

For SI: 1 foot = 304.8 mm.

a. Roof supports: Fire-resistance ratings of primary structural frame and bearing walls are permitted to be reduced by 1 hour where supporting a roof only.

b. Except in Group F-1, H, M and S-1 occupancies, fire protection of structural members shall not be required, including protection of roof framing and decking where every part of the roof construction is 20 feet or more above any floor immediately below. Fire-retardant-treated wood members shall be allowed to be used for such unprotected members.

c. In all occupancies, heavy timber shall be allowed where a 1-hour or less fire-resistance rating is required.

Figure 1. Fire-Resistance Rating Requirements in IBC³

According to the Underwriters Laboratories, Inc. (UL) Fire Resistance Directory, there are two main types of fire protection systems. They are membrane protection systems and direct applied protection systems. Examples of membrane protection systems are ceiling grid systems, mineral and fiber board products, batts and blankets materials, metal lathe and plaster systems, and gypsum wallboard. Examples of direct applied protection systems are spray-applied fire-resistive materials (SFRM), intumescent paints/coatings, mastic coatings, and masonry and concrete.⁴ SFRM is commonly used to prevent fire. The SFRM thickness can be determined through fire tests using ASTM E119. Alternatively, Underwriters Laboratory's database uses

equations to determine the thickness of SFRM based on a limited variety of steel shape and assemblies.



Figure 2. Spray-applied Fire-Resistive Materials (SFRM) ⁵

A TREND IN FIRE DESIGNS

For the prescriptive fire design, designers or architects only rely on the IBC to determine the fire-resistance rating in order to meet the required fire protection on steel components of the structure. This approach doesn't accurately determine the real behavior of the entire structure subjected to a non-uniform temperature distribution during fire hazards. Therefore, the prescriptive approach doesn't do a good job in identifying the performance of the structure during fire hazards especially when the structure is very complex.

According to the International Association for Fire Safety Science, it said," Various sectors of the United States' building and fire communities have recently begun to transition their predominantly prescriptive-based building and fire regulations to one incorporating more performance-based language." ⁶

According to the IBC, it allows both prescriptive and performance-based fire resistant designs as long as each method meets the fire exposure and criteria specified in the American Society for Testing and Materials (ASTM) fire test standard ASTM E119.² A performance-based design (PBD) allows designers to consider the real fire scenario and the effect of fire on the whole unique structure. Therefore, designers can provide more safety by designing the structure according to the impact of fire hazards. Moreover, PBD will be handled by structural engineers unlike the prescriptive approach.

The following section will discuss more about PBD, specifically on fire hazards, heat transfer analyses, and a case study of structural analysis.

FIRE HAZARDS

In the performance-based design, a fire hazard is considered as a thermal load and is classified into localized and compartment fires. Localized fires do not cause a flashover due to a low rate of released heat. Compartment fires produce large post-flashover fires. There are many

ways to determine the thermal load such as computational fluid dynamics (CFD), two-zone models, time-temperature curves from a standard, and actual fire tests.¹

In the CFD model, growth and the behavior of fire are modeled by dividing the compartment into different sections. This model is very complex and many detailed assumptions are made. There are many existing programs that perform the CFD model such as Fire Dynamics Simulator.

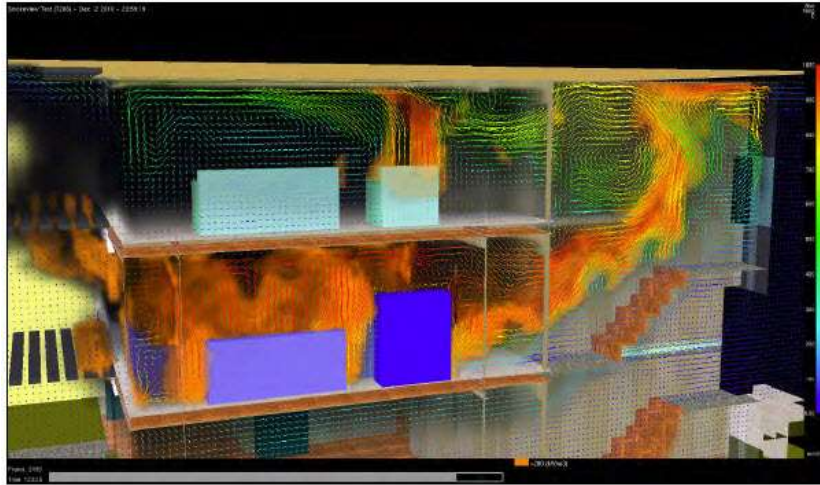


Figure 3. One Example of CFD using Fire Dynamics Simulator⁷

On the other hand, one example of the time-temperature curves which is shown in Figure 4 describes the behavior of fire using different methods. As shown in the figure, when fire occurs, the ISO 834 and ASTM E119 only have a heating phase. These methods are commonly used for fire furnace testing and are not influenced by other factors. However, the Eurocode (EN 1991-1-2) has a heating and cooling phase because it depends on three factors which are the thermal inertia of enclosure (b), opening factor (O), and fire load density ($q_{t,d}$). The cooling phase in the Eurocode is very crucial because contraction occurs and produces tensile forces that fail the connections.

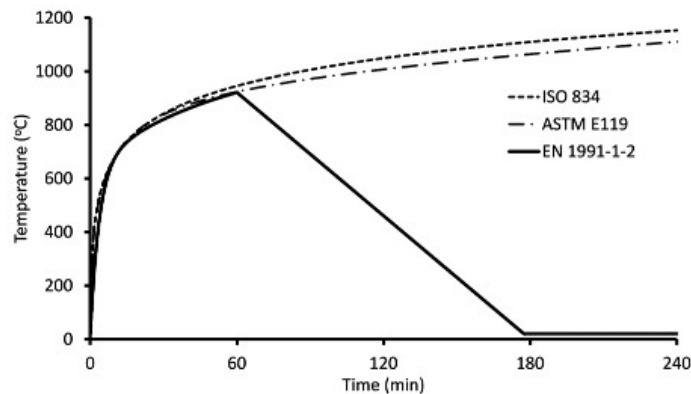


Figure 4. Design Fires using ISO 834, ASTM E119, and Eurocode (EN 1991-1-2)¹

HEAT TRANSFER ANALYSES

Once the time-temperature curve is generated, finite element method (FEM) models can be used to conduct a heat transfer analysis in order to determine the temperature of each element throughout its cross-section. In the FEM models, a few properties of structural members need to be known such as thermal expansion, specific heat, density, and thermal conductivity. These models determine the temperature of the members through conduction, convection, and radiation. On the other hand, there is a simplified method called “lumped mass method” which assumes that the entire cross-section has the same temperature. However, this only applies for steel thickness less than 100 mm and the structure is exposed to a quick rise in temperature. The AISC Specification (AISC 360-10) allows designers to use this assumption.⁸

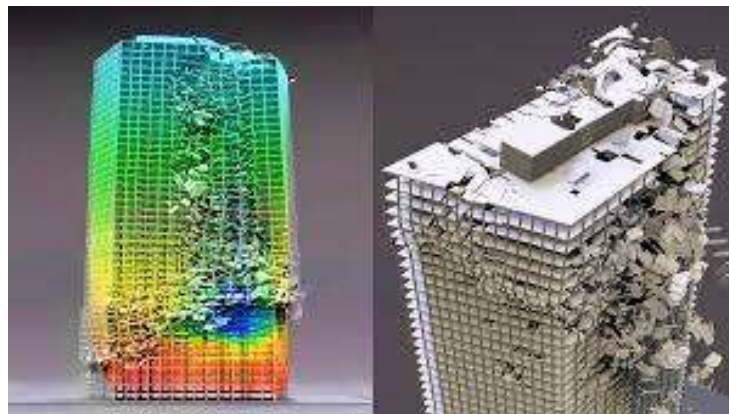


Figure 5. Finite Element Method Simulation of the World Trade Center⁹

A CASE STUDY OF STRUCTURAL ANALYSIS

One of the most familiar experiments is Cardington fire tests, which consisted of six full-scale fire tests on an 8-story structure in the United Kingdom (Figure 6). This large experiment helps to inform and benchmark computational modeling of fire. The result shows that the beam experienced a significant deflection which led to catenary action but no collapse (Figure 7). A fracture in the end-plate beam to column connection occurred during cooling due to a thermal contraction which induced tensile forces in the connection. The top of columns near connections where fireproofing was not present, resulted in buckling failure.¹⁰

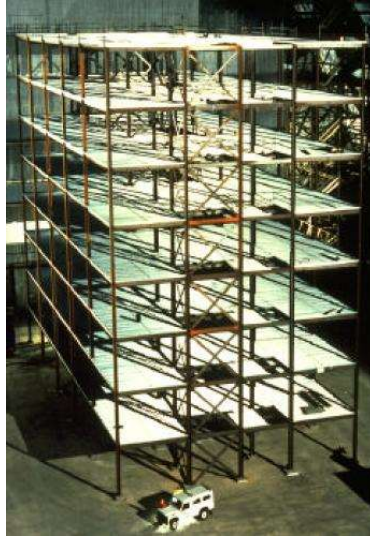


Figure 6. Cardington Fire Test with 8-Story Structure ¹⁰



Figure 7. Beam Deflection after the Fire ¹⁰

CONCLUSION

Choosing a fire design approach is very important in determining the behavior of the structure affected by fire. Currently there are still a majority of fire designs that base on the prescriptive approach. However, there is a gradual shift from the prescriptive approach to the performance-based design in order to provide a more reliable prediction of the fire impacts on a specific structure.

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