# A Review on Structural Fire Resistance

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**Abstract**
This paper summarizes the state-of-the art of the concept, methodology and knowledge for engineering approach for structural fire resistance. First of all, the role of structural fire resistance in fire safety engineering (FSE) is summarized. Then possible engineering approach and the state of the knowledge is described in terms of design fire exposure to structure, transient temperature state and structural behavior. The bottlenecks and the needs for research are identified for several types of structures.
**Keywords**: Fire Resistance, Fire Safety Engineering, Design Fire, Temperature State, Structural Behavior

## 1. Introduction

The concept of FSE (Fire Safety Engineering) is widely spreading to take over the experience-based rules in fire safety design. In FSE frameworks, trial design parameters are examined against fire impact so that specific design meets the intended objectives of the society and/or of the building owners. This is especially done for the safety of occupants during evacuation. In the framework, we assume worst credible (realistic) size of fires to check if the evacuation is feasible.

The framework is simple enough to be transferred into design of structural stability during fire. This paper summarizes the state-of-the art of the concept, methodology and knowledge for engineering approach for structural fire resistance. First of all, the role of structural fire resistance in fire safety engineering (FSE) is summarized. Then possible engineering approach and state of the knowledge is described in terms of design fire exposure to structure, transient temperature state and structural behavior.

## 2. The Role of Fire Resistance in FSE

### 2.1 Design Objectives

Traditionally the fire safety design was just to follow the rules (regulation, typically) that have been established based on the past fire experience. However, the concept of FSE is widely spreading to take over the experience-based rules. In FSE frameworks, trial design parameters

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are examined against fire impact so that specific design meets the intended objectives. In case of building fire safety, common FSE goals are as follows:

(1) Safety of Occupants during Evacuation
(2) Safety of Fire Fighters during Rescue and Fire Fighting
(3) Prevention of Fire Spread to/from Adjacent Properties
(4) Property Loss Mitigation
(5) Business Continuation

The first three objectives tend to be in regulation because they correspond with societal values. In some cases, the last two (and more) are additionally required depending on owner's needs.

### 2.2 Framework

In the area of building fire safety, international organization for standardization (ISO) has a framework documents for FSE. Figure 1 shows the framework proposed in ISO/TR 13387. In the framework, design parameters are estimated from trial design solution. Then fire behavior is analyzed with interaction between subsystems on initiation and development of fire and fire effluent, spread of effluents (mainly smoke), structural response and integrity, detection and suppression, life safety and so on. After the analysis, the results are subjected to value judgement. As can be seen in the framework, fire resistance is one of the means to achieve design objectives in parallel with other provisions.

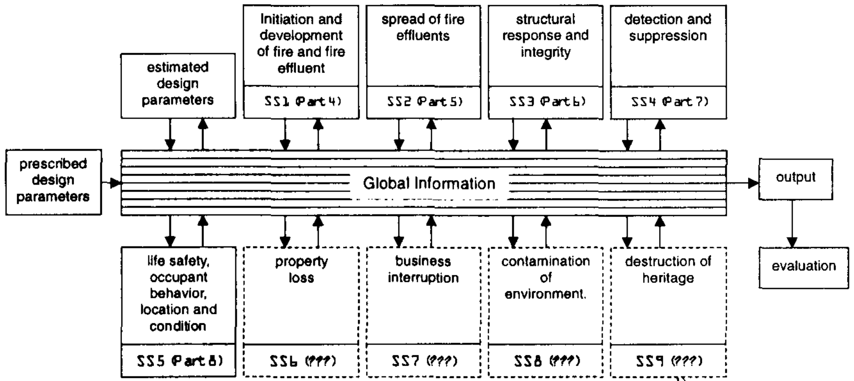


Figure 1 An Example of Fire Safety Engineering System in ISO/TR 13387[1)]

### 2.3 Common Functional Requirement

To meet with the objectives above, the role of fire resistance are quite often to:
(a) protect escape routes such as stairwell, lobby, temporal refuge area
(b) confine fire and smoke within containment
(c) structural stability during evacuation, rescue and fire fighting.



In conventional approach, required fire resistance time is assigned to building elements such as beams, columns, walls and floors. Specific elements are subjected to standard fire resistance test to check if it can survive for specified duration of fire. Namely standard fire test was the only way to verify the fire resistance without the concept of FSE.

By applying the FSE approach, there is an opportunity to make use of engineering methods. The possible solutions are shown in Figure 2. We can select among realistic design strategies (a) to resist fire as is in conventional approach, (b) to mitigate fire severity by designing the fire compartment geometry to prevent severe fires, (c) to separate fire so that the structural deterioration by fire is negligible, and (d) to choke fire to extinguish, and so on.

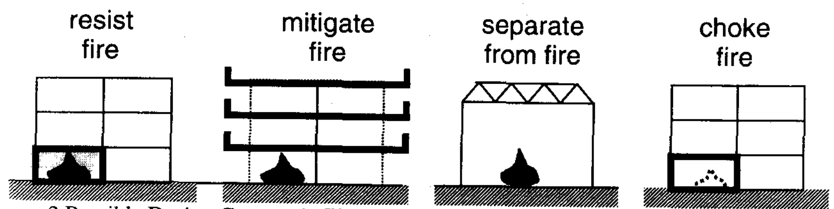


Figure 2 Possible Design Concept in Fire Safety Engineering of Structural Fire Resistance

## 3. State-of-the-art of Structural Fire Design in FSE

To be able to make selection among the possible fire resistance strategies, we should have engineering methods to estimate fire behavior and structural response. Again in ISO series documents, we have a technical report[2)] ISO/DTR 12471 "Computational Structural Fire Design", which contains the state-of-the-art of available knowledge in three categories of design fire exposure, transient temperature state and structural behavior.

In the document, the combinations of design fire exposure and temperature state- structural behavior are classified as in Figure 3. As to the design fire exposure, we have traditionally adopted standard fire ($H_1$) mainly for testing of elements ($S_1$). Thus we have vast of knowledge in the combination of $H_1$-$S_1$, and some knowledge in $H_1$-$S_2$ through specially devised tests. To include FSE concept, inclusion of design fire ($H_2$) is indispensable. However, at the same time, we have to admit that we have relatively small knowledge on the behavior of elements, sub-structure and complete structure under design fires ($H_2$). Thus we have to follow calculation methods when we make evaluation by using design fire. In the followings, state-of-the-art and bottle necks are described.

| design fire exposure \ models for temperature state and structural behavior | | S1 element | S2 sub structure | S3 complete structure |
|---|---|---|---|---|
| H1 | standard fire (temp. / time) | test or calculation | special test | - |
| H2 | design fire (temp. / time) | calculation | calculation | calculation |

Figure 3 Matrix of Available Engineering Methods for Computational Structural Fire Design (ISO/DTR 12471)

### 3.1 Design Fire Exposure

To calculate the strength of fire source, we will need the knowledge of fuel characteristics. Behavior of fully developed fires depends on the fuel characteristics and building geometry. If the fuel amount is small enough, fire is localized to one object or to successive burning of several objects (we call moving fire). If the fuel amount is large, the full area is involved. Even so, we must know the fuel characteristics well. Fuel amount corresponds with fire duration. But it should be noted that fuel surface area and arrangement influences the fire severity. So far, fire load density (fuel amount) is relatively well investigated[3], but the fuel surface area, fuel arrangement is not well known. Thus there is a need for further investigation for the realistic arrangement of fuels depending on the use of building.

In case of localized fires, empirical relationships of axial temperature profile are often used in engineering calculations. An example is shown in Figure 5. We have well-established correlation for unconfined fires and wall-corner fires. But good correlation is not established for wall fires and for more complex geometry. Trials are found in literatures[4].

As to the fully developed fires, we can just assume that the fuel is randomly distributed throughout the compartment. Under this assumption, fire behavior is calculated for the combination of degree of openness and fuel amount. Figure 4 shows the results. Characteristic range of parameters are plotted for several use group of rooms considering the scatter in fuel load density and ventilation factor in existing buildings[5]. The other unsolved problems are the fires in big compartment, where it is not realistic to assume uniform burning in the compartment.



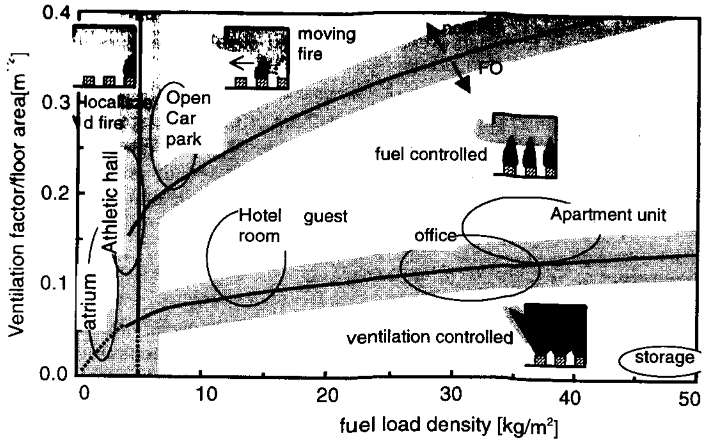


Figure 4 classification of fire type and corresponding use of the rooms

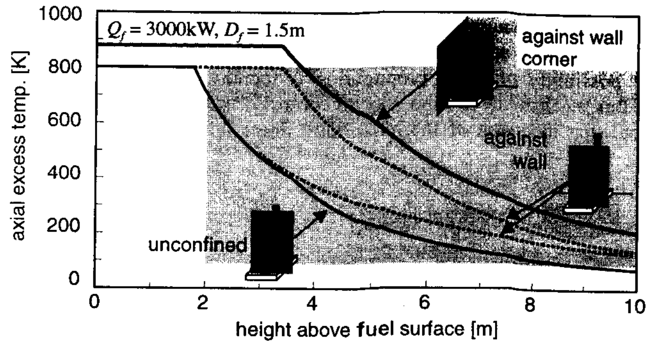


Figure 5 Axial Temperature of Localized Fires

### 3.2 Transient Temperature State and Structural Behavior

#### 3.2.1 Steel Structure

Among all, fire resistance design of steel structure is most advanced. Steel temperature is relatively easy to be calculated using the heat conduction equation. This is especially true in case of non-insulated steel elements. However the use of heat conduction equation is relatively limited for insulated steel elements because of the difficulty in estimating the *effective* thermal conductivity of insulation materials. More or less, any kinds of insulation materials make changes in its thermal property during fire. In addition, some of the materials make significant change in geometry such as pop out, spalling, crack and so on. In those cases, partial failure in integrity may increase the heat transfer rate. Thus the *effective*, not nominal, values of thermal properties must be applied. One of the ideas is to make use of inverse approach to estimate the effective thermal conductivity of materials from the measured steel temperature during fire resistance tests[6)].

As to the structural response, detailed calculation methods[7)] are utilized in practical designs. It includes the whole structural frame. However in more practical way, partial frame method was developed and published as a design guideline[8)]. Even if it deals with only part of the structural frame, the design calculation allows for re-distribution of structural loads between adjacent elements.

### 3.2.2 Concrete Structure

Concrete is a fire resistant structure. For most cases, it is designed to sustain other loads such as wind, earthquake and so on. As a result, concrete structure has large structural redundancy for fire effect. Therefore little should be considered as to normal concrete. However, so-called high performance concrete is relatively poor in fire resistance.

The material has high strength at normal temperature, but the degree of reduction in strength is more than the normal concrete. In addition, the risk to spalling is not negligible. Figure 6 shows a possible mechanism of spalling of compressed concrete members[9)]. During fire, pore pressure is significantly increased because of the small permeability of the material. If it has certain internal defects, pore pressure acts on the internal surface together with the axial force and thermal stress. The possibility of crack propagation is increased to cause destructive spalling. The validity of this mechanism and the way to control it is still under development. However it is pointed out that inclusion of thermo-plastic fibers will reduce the degree of spalling[10)].

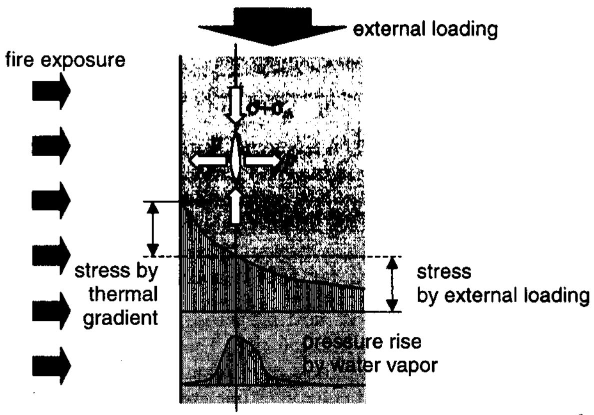


Figure 6 Possible Mechanism of Explosive Spalling of Concrete[9)]

### 3.2.3 Timber Structure



If wood element is large-sectioned, char layer is formed at the surface as shown in Figure 7. The surface char layer serves as a heat resistance to mitigate the degradation of core layer. The charring layer corresponds with the zone above 500°C. Inside of the zone, there exist a pyrolysis zone, where the temperature is above 200-280°C.

The rate of charring was extensively measured under standard fire tests. Table 1 summarizes some of the data[11,12)]. In practical design of timber structures, charring rate are assumed to 0.6-0.7 [mm/min.] in the direction perpendicular to tree rings. It is pointed out that the rate of charring is approximately twice in the direction parallel to annual ring[11)].

As to the non- standard fires such as parametric fires, it is hard to estimate the rate of charring in a simple way. Detailed model for heat, moisture and volatile compounds are proposed for comprehensive numerical analysis[13)].

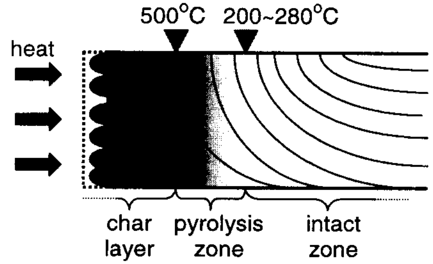


Figure 7 degradation of wood by temperature

Table 1 Charring Rate of Wood

| Wood species | water cont. [%-weight] | Density [kg.m3] | charring rate [mm/min] | ref. |
|---|---|---|---|---|
| Western red cedar | - | - | 0.83 | 11 |
| Oak | - | - | 0.50 | |
| Other common structural species | - | - | 0.66 | |
| Fir (laminated, heated on all sides) | 6.0-9.5 | 380-440 | 0.67 | 12 |
| Fir (sawed, heated on all sides) | 40.9 | 560 | 0.52 | |
| Douglas fir (laminated, heated on all sides) | 8.6-9.6 | 550-580 | 0.67 | |
| Cedar (laminated, heated on all sides) | 15.2 | 420 | 0.74 | |
| Cedar (sawed, heated on all sides) | 30.9 | 500 | 0.66 | |

## 4. Summary

In summary, the followings are the author's points of view for the possible development of FSE approach to structural fire resistance.

(1) Needs for model improvement
As to the fire exposure, modeling of localized fires close to complex geometry, fuel-to-fuel fire

spread processes, behavior in large compartment are under urgent needs. As to the thermal analysis, integrity modeling is desired to expand the area of application. Emphasis is on the spalling of brittle materials such as high strength concrete. As to the structural behavior, modeling of joints and composite structures are needed.

(2) Needs for Data Collection

To make use of FSE approach, material data such as high temperature strength will have to be established in the format of database. Closer linkage with database in normal temperature design is suggested.

(3) Meeting FSE requirements

FSE (Fire Safety Engineering) approach often needs fire and smoke containment in order to meet the objective of safety of occupants, fire fighters and so on. At this moment, containment design is difficult to carry out. Establishment of frameworks and engineering models are needed.

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