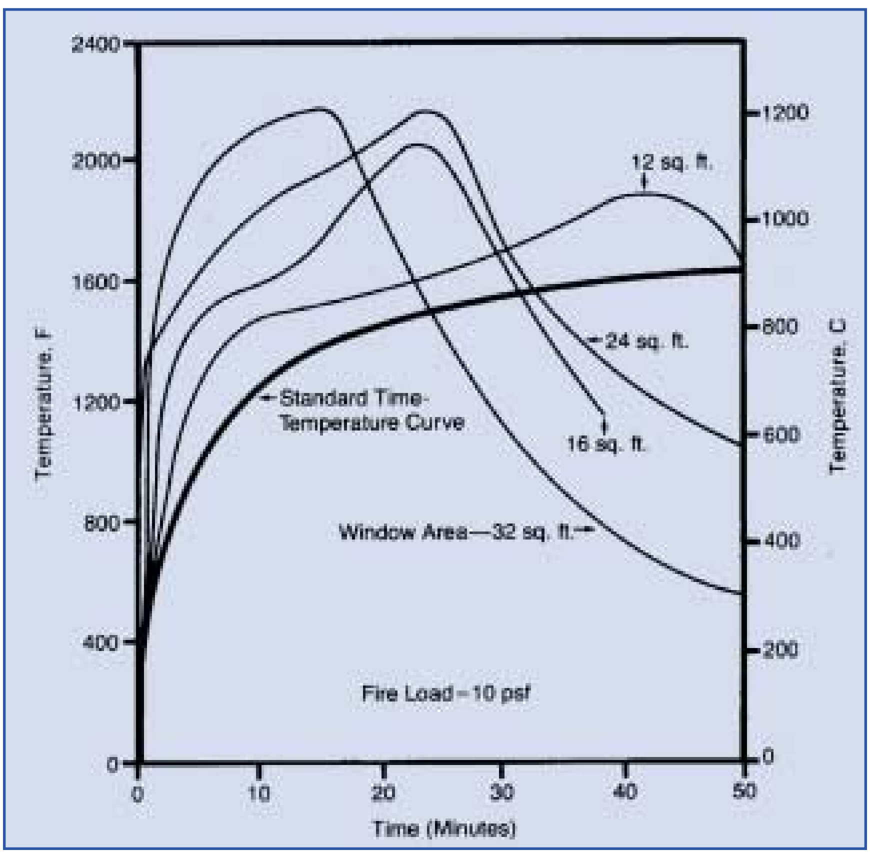
Performance-Based Design for Fire Resistance

By Barbara Lane, Ph.D.



Effect of window area on fire temperatures during burnout tests with natural ventilation (SCI 1991).

The standard fire resistance test

Fire resistance requirements in the US building codes are based on the presumed temperature profile and duration of a standard fire, as described in ASTM E119. The test determines load bearing capacity (the ability of a building element to continue its function for a period of time without collapse), integrity (the passage of flames or gases hot enough to ignite cotton waste) and insulation (assuring the temperature on the unheated side of the element does not exceed 250°F).

In the test, a beam, column, wall or floor under its calculated design load is exposed to a standard fire defined by a prescribed temperature/time curve. Programming the temperature of a test furnace through controlling the rate of fuel supply achieves this curve. The fire resistance of the element is taken as the time to the nearest minute, between commencement of heating and failure under one or all of the criteria outlined above (load bearing capacity, integrity or insulation). Periods of fire resistance are normally specified as half hour, one hour and/or two hours up to four hours.

This test is based on methods first developed in the early 1900s when there was very little knowledge of how fires behave and their effect on structural performance (AISI 1981). The standard fire test has been widely criticized. The difference between the standard test temperature-time curve and temperature–time curves measured in real compartment fires is considerable (see graph).

The graph shows the temperature/time curve for the standard test compared to real fire temperatures from compartment fires with various window areas. The differences are clear. The duration and severity of a real fire is not defined well as the standard fire test curve. This figure also shows that in many cases periods of fire resistance are over-specified where the standard test results are applied, specifically where the decay phase of the real fires has begun but the standard fire test curve still increases. This figure also illustrates that the maximum fire temperatures will vary as a function of the window area, or ventilation conditions of the fire compartment. This is not considered when the standard fire test curve is assumed.

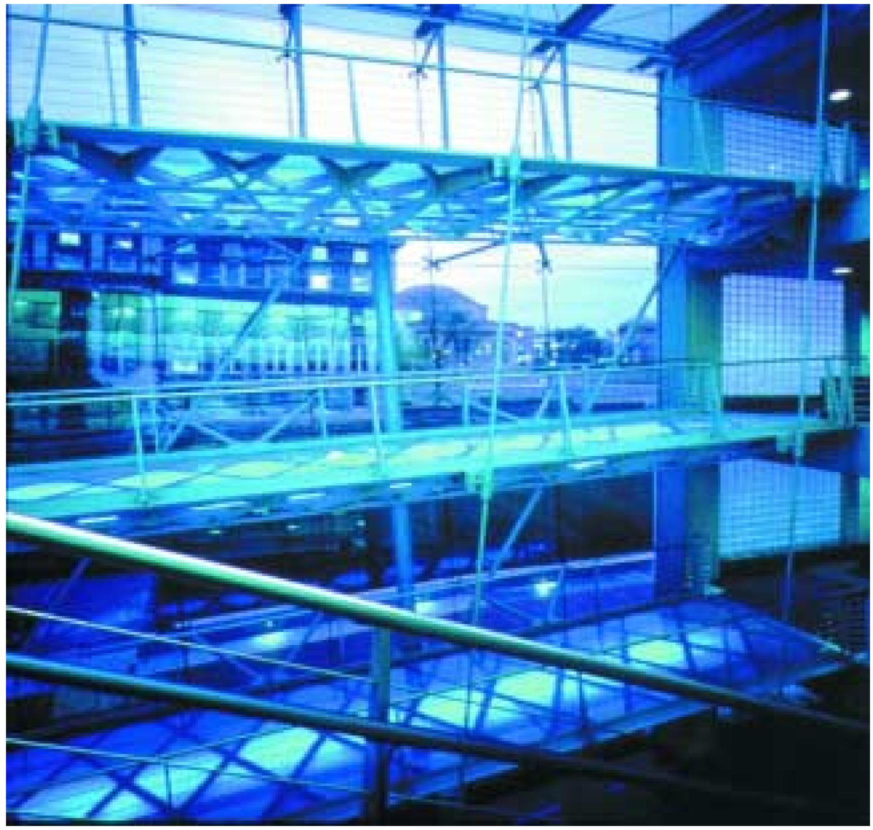
Real fire behavior

Extensive research has been devoted to determine the factors that contribute to the behavior of fires in enclosures and examine the resulting structural mechanisms. Real fires are a function of the area and height of the compartment, ventilation provision, type, configuration and quantity of fuel in the compartment and whether or not sprinklers are provided (Drysdale 1990). When levels of fire resistance are derived from a fire test using a furnace with a defined temperature-time curve these factors are ignored.

Another major criticism of the standard fire resistance test is that single elements are tested although they are normally designed as component parts of complex two or three-dimensional structures. This means the beneficial effects of load transfer where a relatively hot member can transfer load to a cooler member thereby maintaining the overall frame stability is ignored.

The beginnings of change – the practical evidence

No major structural frame failures as a result of fire have been recorded in recent times. The standard fire resistance test methods are considered effective for design requirements. However, a growing belief has arisen that the recommendations in Building Regulations throughout the world are too conservative, lack cost-effectiveness and overlook many real fire behaviors that may affect the necessary levels of fire protection.



(photo by Esto Photographics, Peter Mauss)

Exposed steelwork supporting the North façade atrium enclosure at the Alfred Lerner Student Center, Colombia University, New York City.

In Broadgate, UK, a large fire in a multi-story, steel framed building that was under construction and only partially fire protected caused the steel industry to reconsider its approach to the fire protection of structures (SCI 1991). The structure was only partially protected. Despite some large deflections, the structure behaved well and did not experience the failure of members expected from standard codes at the high temperatures experienced.

As a result of this real fire evidence, a major initiative to better understand structural behavior in realistic fires was established to refine current fire protection levels.

A series of full-scale fire tests occurred at Cardington, UK by British Steel and the Building Research Establishment. The project steering committee also included members from the Steel Construction Institute and the University of Sheffield. Results from these tests show that designing structural frames based on single element behavior does not give a realistic idea of what frame behavior will occur in fire conditions (British Steel 1998). Normal office fuel loads were used in the compartment tests and though temperatures in excess of the traditional 1000°F were experienced by steel elements, structural collapse and/or breaching of compartments did not occur; a new design guide due this year by the Steel Construction Institute will take account of these newly understood behaviors when designing for steel structures in fire.

There will always need to be a relationship between the standard fire test and real fire analysis because of the wealth of component knowledge available to designers from years of use of the test. However, fire engineers now investigate the relationship with a view to improving efficiency and, even in the case of steel structures, proving that added fire protection material can sometimes be unnecessary.

Performance-based design solutions

A more rational approach to fire resistance is based on a "t-equivalent" analysis. This determines the heating effects of the actual fire load on a given compartment's construction. The term "t-equivalent" means the exposure time in the standard fire resistance test that gives the same heating effect on a structure as a given real compartment fire (Law 1991). Such features as fire load, ventilation and compartment dimensions characterize the compartment fire.

The typical fuel load is considered, and therefore, the temperatures from an agreed design fire rather than the standard furnace test can be used. The ventilation provision is calculated along with the volume of the compartment. The construction type of the compartment is determined and a factor incorporated based on its insulating properties.

This method is now part of the *European Building Codes*. Other factors can also be determined to take account of the consequence of an uncontrolled fire, such as the probability of fire occurrence and the benefits of sprinklers.

A factor was determined to address the consequence of an uncontrolled fire based on the following:

- Ease of evacuation (stair and perimeter evacuation, stairs only, evacuation time and simultaneous or phased evacuation) and
- Ease of fire fighting (internal and perimeter, internal only and fire spread to adjacent compartments)

The comparative ease of evacuation and firefighting has traditionally been related to depth below grade and building height.

Probability of occurrence factors have been derived based on the number of fires reported to the fire service (BSI 1997).


(photo by Esto Photographics, Jeff Goldberg)

The Gathering Space at the Mashantucket Pequot Museum and Research Center, Ledyard, Connecticut. This museum is a significant public building and has been designed to reflect the culture of the Pequot Indians. The building contains one very large sprinklered gathering space, 48 feet.

The benefits of sprinklers are incorporated by applying a factor of 0.6 to the final fire resistance calculated (Magnusson, Pettersson, and Thor 1976).

An "equivalent" fire resistance can then be calculated taking these parameters into account. The t-equivalent method has a recognized scientific basis and correlates well with compartment fire test results (Eurocode 1995)

This design method ensures real fire behaviour and its effect on structures are addressed as well as providing a useful link back to the familiar benchmark of the standard fire test.

Benefits of performance-based design solutions

By using performance-based design methods, real fire effects are addressed based on credible 'worst case' design scenarios. This can lead to increased design freedom from prescriptive code restrictions whilst maintaining safety. Appropriate and cost-effective fire safety measures are derived. Practically, it can mean that intumescent coatings can be specified rather than a cementitious spray or board protection due to the reduced fire resistance required. Other fire protection systems can be utilized; for example, using a sprinkler system to give an integrated sprinkler/water cooling system that keeps steel temperatures below the temperature required to cause failure. It can also mean that steel elements can be left completely unprotected in large open spaces with low fire load areas: open-sided car parks, stadia, transportation terminals, high atrium spaces and so forth.

These design solutions have been proposed, accepted and integrated throughout Europe and are increasingly being proposed for the US.

Completed performance-based designs

Arup Fire has used a performance-based design approach on projects throughout the world, and local authorities throughout Europe, Australia and the US have approved it. The following provide a brief description of some of the projects where Arup Fire has implemented these techniques.

Alfred Lerner Student Center, Columbia University, NY

This 240,000 sq. ft, $68 million project includes: a dual theater and cinema, a black box theater, student clubs, 6000 student mailboxes, computer labs, a bookstore, the campus radio station and administrative offices.

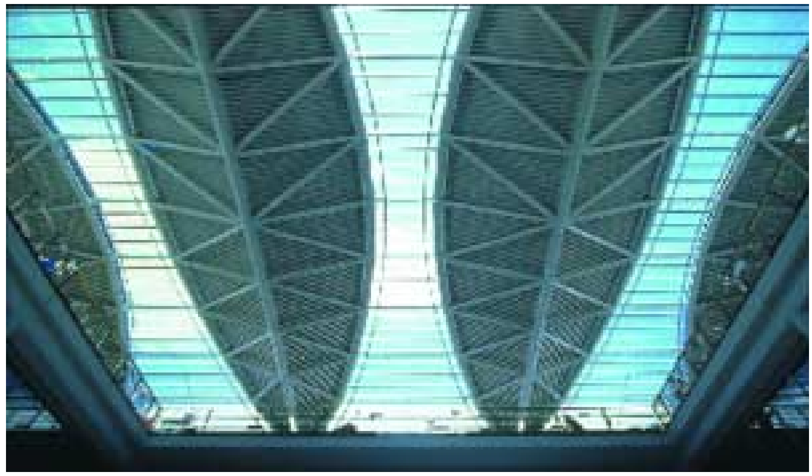
Arup Fire examined the need for fire protection to the exposed steelwork supporting the north façade atrium enclosure. By adopting a performance-based design approach, combining hazard analysis with real fire behavior modeling and then using this to analyze the structural response in a fire, additional passive fire protection was not required for the design fires analyzed.

This approach was presented to the New York City Building Department who granted a waiver from the requirements of the NYC Building Code.

Mashantucket Pequot Museum and Research Center, Ledyard, CT

This museum, a significant public building, has been designed to reflect the culture of the Pequot Indians. The building contains one very large sprinklered gathering space, 48' high, which can be used as an auditorium, exhibition space or for receptions. Arup Fire examined the need for fire protection to the exposed steelwork supporting the glazed wall and the roof. Two hours of fire resistance was required by code for this steelwork.

A flashover fire was not a concern due to the height of the space and the provision of a smoke control system. The study concluded that the fire scenario of interest was a fire local to the glazed wall. Of particular interest were the members, which tie the wall to the horizontal arch. For the analysis, it was assumed the members forming this truss were engulfed in flame. It was also assumed that the inclined steel ties were fully engulfed.



(photo courtesy Ove Arup & Partners)

Hong Kong Air Cargo Terminals Ltd. (HACTL). Butterfly wing truss concept for the steel roof system over the container storage system. Sprinklers were provided in the steel tubular structure ensuring that surrounding steelwork remained well below the calculated failure temperature.

(Photo courtesy Photo Poteau)

The support structure for the Credit Lyonnaise, above the station, on the left. The station structure beneath is strengthened to survive a fire but without introducing cladding.

The fire load analysis demonstrated that the fire load in the gathering space was enough to support an unsprinklered fire local to the wall for 15 minutes. The heat transfer to the unprotected elements engulfed in flame was calculated for this period. This demonstrated that the temperature increase in the steel elements was not enough to cause failure.

By using performance-based design techniques, it was shown that the intent of the code was being met without the need for additional structural fire protection.

HACTL SuperTerminal 1, Chep Lap Kok, Hong Kong

The photo of HACTL SuperTerminal 1 shows the delicate butterfly wing truss concept for the steel roofing systems over the container storage system at Chep Lap Kok airport, Hong Kong. The Hong Kong Fire Services Department agreed to a two-hour fire rating for the roof structure after prolonged negotiations. Intumescent paint on the relatively slender members clearly could not provide the necessary rating, and cladding them with fire-rated board would be unattractive; a water-filled tubular system was proposed. However, the thermal capacity was inadequate unless the water was circulating. Sprinklers were provided in the steel tubular structure itself, and it was connected to the fire service drencher system. In the event of a fire, any activated sprinkler would activate receiving cold water, ensuring that surrounding steelwork remained well below the critical temperature. The Loss Prevention Council carried out full-scale tests, and Arup Fire and the Hong Kong Authorities witnessed them to prove this concept worked as calculated. Steel temperatures did not exceed 40°C even with a full propane gas fire load.12

Lille TGV Station, France

The Lille TGV Station extends along Quai Londres at Lille TGV with the support structure for the Credit Lyonnaise on one side. French regulations require two hours fire resistance for structures adjacent to high-rise buildings to prevent fire spread. Therefore, the roof and structure supporting the roof at Lille TGV station lying underneath the World Trade Center and Credit Lyonnaise towers required two hours fire protection.

Rather than use a cladding system, a fire engineering study was carried out and design fires were developed. An analysis of the effect of these fires on individual steel elements then determined which elements would fail. An analysis of the total structure in the fire load case then occurred, assuming the failed members. It was assumed the steel members forming the arches failed and that the arch carried no load.

The subsequent fire-engineering analysis showed the columns supporting the roof structure required additional fire protection to withstand the design fires but for a period of 30 minutes. Applied fire protection was not desirable to the design so the thickness of the steel in the columns was increased by 5 to 10mm where the additional fire protection was needed.

In this way the standards required were achieved in that the structure would survive the fire but without compromising the architectural uniformity of the column lines.

Performance-based design techniques are increasingly being accepted as a rational approach to fire safety. During the past few years a number of unique structures have been the subject of fire resistance analyses and have not required added fire protection. For other structures, reduced levels of fire protection are acceptable. These specific analyses, as well as background data used to develop the current codes, have been considered, plus data from fire tests and real fire incidents, resulting in a revised approach to required periods of fire resistance. Now it is possible to propose a performance-based definition of fire resistance that relates to fire load, compartment size and ventilation, as well as the ease of evacuation and firefighting rather than relying solely on the standard fire resistance test.

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