

Prediction of the Structural Fire Performance of Buildings

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1 Background

The events of 11 September 2001 demonstrated the need for engineering methods to predict the structural fire performance of buildings when subjected to arbitrary design fires and to extreme events. Some capabilities exist but lack specific data such as material properties at elevated temperatures. Existing test methods like ISO 834 and ASTM E119 assess performance under a single, standard exposure that was developed long ago when fuel characteristics were quite different from today. These tests do not provide insight into the interaction of assemblies that were tested independently nor to the sensitivity of the assembly to variations in construction to the design specification that was tested.

A project is being organized as a cooperative, global effort through CIB W14: Fire and ISO TC92 Fire Safety with the support of the FORUM for International Cooperation in Fire Research and the NIST Building and Fire Research Laboratory. This wide cooperation is emblematic not only of the interest in the response of buildings to extreme events but also the worldwide interest in performance based building regulation.

The first task in the project will be to assemble a clear picture of the current ability to predict structural performance. The most current information is compiled in a recent, joint standard published by the American Society of Civil Engineers and the Society of Fire Protection Engineers, *Standard Calculation Methods for Structural Fire Protection*^[1], and a CIB W14 document, *Rational Fire Safety Engineering Approach to Fire Resistance of Buildings*^[2]. Additional information may be found in any of several Engineering Guideline (Code of Practice) documents published in several countries in support of their performance based building regulations. The purpose of this paper is to outline proposed objectives and scope for this effort.

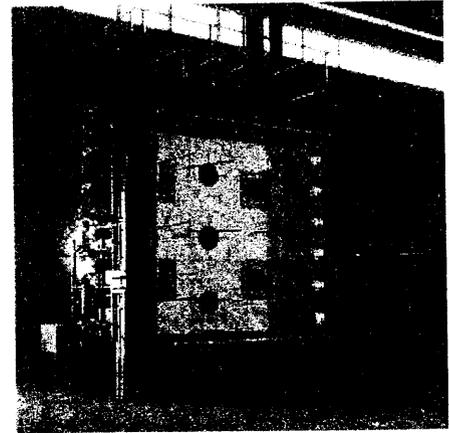


Figure 1—Fire resistance ratings are traditionally determined in wall (shown), floor, or column furnaces (courtesy SwRI)

2 Fire endurance tests

The concept of structures resisting the effects of fire for a set time was introduced in the early part of the 20th century. For example, the first edition of the U. S. fire endurance test (ASTM E119) was adopted in 1918 with the designation C-19-18 and was nearly identical to the test method, as it exists today^[3].

In the original test method, two samples were prepared. One was exposed to the standard time-temperature curve in order to determine the rating period based on the criteria of no passage of fire to, and not exceeding a limiting temperature on, the unexposed side. The second specimen was used for the hose stream test following exposure for half the rating period determined with the first specimen. Because of the expense of testing duplicate specimens the method allowed the hose stream test to be

performed on a single specimen following the full rating period exposure. Eventually this became the typical method of running the test.

The corresponding ISO test method is known as ISO 834^[4]. The furnace and time-temperature exposure is nearly identical but ISO 834 does not include a hose stream test. There is also a difference in the furnace pressures — ASTM E119 is operated at a negative pressure and ISO 834 at a positive pressure. This is the subject of some controversy relative to testing of fire doors.

The fire endurance concept was successful in the prevention of fire-induced collapse by protecting structural elements for sufficient time that manual or automatic suppression could occur. Further, spread of fire was limited to a maximum area by rated firewalls with these maximum areas determined by what could reasonably be handled by fire fighting forces. Finally, fire rated assemblies were used to protect means of egress for sufficient time to allow the evacuation of occupants and to provide a protected space from which to fight fires where an interior fire attack was necessary.

3 Limitations of fire endurance ratings

The system of fire endurance ratings has served well while the building regulatory system was largely prescriptive. Rating periods are specified and the inherent conservatism of this system results in buildings performing as expected. The problem comes when we try to predict the performance of these systems for exposures other than the standard time-temperature curve.

The standard curve was developed in an era when fuels were cellulosic and fuel loads quite different than today. Modern fuels can result in fires with significantly faster growth rates and higher radiative fractions that affect fire spread rates. Additionally, automatic sprinklers are far more common, resulting in limited fire growth potential. Thus the fire exposures in modern buildings can be far greater or far less than those represented by the standard curve employed in fire endurance tests. The results of the fire endurance test are of little value in predicting the performance of buildings to such arbitrary exposures and may result in significant over designs that are safe but far too costly, or in designs that may fail to perform as intended under some conditions. This limitation is recognized in the FEMA WTC Building Performance Study^[5], which states in 8.2.1 (b) “The ASTM E119 Standard Fire Test was developed as a comparative test, not a predictive one. In effect, the Standard Fire Test is used to evaluate the relative performance (fire endurance) of different construction assemblies under controlled laboratory conditions, not to predict performance in real, uncontrolled fires.”

Another limitation of the fire endurance rating system is that the physical limitations of the test furnaces result in components of the building being tested independently such that we do not know how they interact in the overall building design. That is, floors, walls, columns, and beams are all tested separately but will interact in the building in ways that may result in failures. For example, elongation or sagging of beams supported on walls may exert lateral forces on those walls that can cause them to topple (Fig 2^[6]). Restraint and loading conditions in use may not be reproduced adequately in the

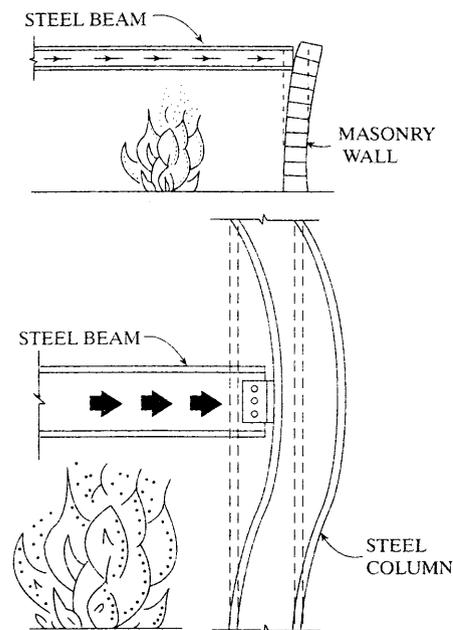


Figure 2—Fire exposure of restrained elements can result in lateral forces on other structural elements(ref5)

testing arrangement.

4 Performance-based regulations

Beginning in the mid-1980's the building regulatory systems of many countries are now partially or fully performance based. Under Performance Based Regulatory Systems (PBRS) end objectives representing society's expectations for the built environment are specified in terms of quantifiable performance requirements. Compliance is demonstrated either by meeting the former prescriptive requirements or by predicted performance in the specific context of use.

For fire endurance this means to design for the time needed and the fire severity expected rather than for a fixed time and standard fire.

The time needed may be as short as the time required for occupant evacuation, assuming the fire service can do an exterior attack. Protecting firefighters at least through any search and rescue, and interior fire fighting is now usually explicit. Prevention of progressive collapse is generally intended but may not be required for some unoccupied, agricultural buildings.

In this context the traditional fire endurance tests are of little value for predicting performance. Modern fuels and ventilation conditions would rarely be expected to produce the standard time-temperature curve in any space and extrapolating the fire endurance to another exposure condition is not possible.

Since even the failure mechanism is not reported, the test provides no clue as to the weakness of the assembly that might be useful in understanding the impact of construction quality on performance.

What PBRS demands is the ability to predict the performance of a specific assembly to an arbitrary fire exposure including the time to and specific mechanism(s) of failure. We further need the ability to account for the interaction(s) of assemblies and components that are traditionally tested independently but which can influence the performance of other components around them. The events of 11 September 2001 demonstrated a need to incorporate the impacts of an initiating event that may affect the configuration or initial conditions of building components at ignition.

5 State-of-the art of predicting fire endurance

Fortunately we are not starting from zero. The financial and time burdens of large scale testing motivated early methods of interpolating from test results and correlation methods that have some predictive capabilities. Building codes in a number of countries recognize specific calculation methods for determining fire endurance of some materials and simple assemblies.

In a joint project by the American Society of Civil Engineers (ASCE) and the Society of Fire Protection Engineers (SFPE) methods for the calculation of fire endurance times of "selected structural member and barrier assemblies using structural steel, plain concrete, reinforced concrete, timber and wood, concrete masonry, and clay masonry" were compiled in *Standard Calculation Methods for Structural Fire*

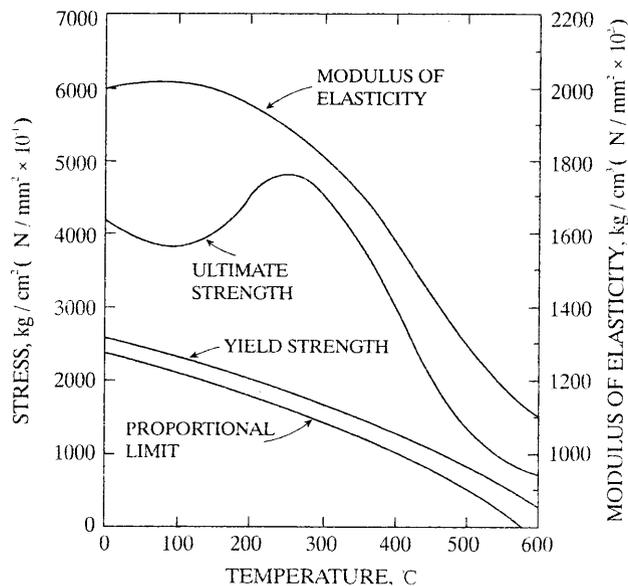


Figure 3—Strength of steel vs. temperature(ref6)

Protection, ASCE/SFPE 29-99. These methods allow the prediction of the performance of the member or assembly in the ASTM E119 test but not necessarily in a way that provides any insight into the performance in a building or to any other fire exposure.

More oriented to use in PBRS is a recent publication from CIB W14, Rational Fire Safety Engineering Approach to Fire Resistance of Buildings, CIB Publication 269. This document outlines the engineering design process including

- Identifying the fire safety objectives
- Developing a fire safety strategy
- Establishing the performance criteria
- Describing the design fire scenarios
- Determining the actions and loads
- Assessing the structural and thermal performance (by calculation or test)
 - Accounting for uncertainty, and
 - Documentation of the assessment.

Within the section, Assessing the structural and thermal performance, the document refers to the use of appropriate calculation or test methods. Here there exist some limited capabilities that should be used judiciously. For example, many structural members consist of steel beams or columns embedded in protective materials ranging from those spray-applied after assembly to concrete. These types of members tend to fail in fires when the temperature of the steel rises to the level that its mechanical strength begins to decline (Fig 3^[7]). This temperature is well known for common steel but there are some steels that maintain their strength to higher temperatures. The point is that the performance of these members is largely a heat transfer problem that can be analyzed with any of the (finite element) heat transfer models (e. g. , TASEF^[8], Fires-T3^[9]) and the critical temperature for that steel.

These analytical methods must be carefully applied when the performance can be affected by phenomena that are unpredictable. For example, reinforced concrete gains much of its strength from the steel reinforcing and that reinforcing is insulated by the concrete. Thus the performance of reinforced concrete in fire is strongly affected by the depth of concrete covering the steel. But concrete is subject to spalling in fires, where pieces of the surface concrete come off. It is currently impossible to predict the spalling process and thus the detailed performance of a reinforced concrete member subject to spalling. There is a parallel with spray-applied protection of steel that may be lost or reduced in thickness over time such that the conditions when exposed to fire are quite different than what was tested and originally installed.

Another area relative to the performance of structural frames is distortion due to the expansion of the frame members. In the early 1980's the American Iron and Steel Institute (AISI) developed a research model called FASBUS^[10]. The work was done at NIST and included experimental verification in a specially constructed, full-scale facility that simulated three (upper) floors of a tall building^[11]. The

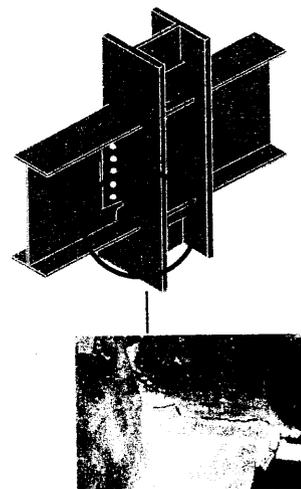


Figure 4—Performance of connections can be crucial to structural performance (ref NIST)

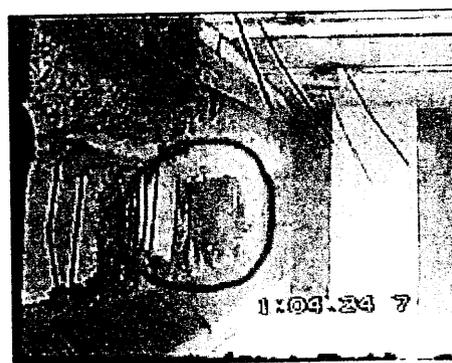


Figure 5—Spalling of concrete covering reinforcing steel during fire exposure results in structural failure (courtesy SP)

model predicts distortions produced by the differential expansion of members in the frame under arbitrary heating from a localized fire. It does not include the failure of connections within the frame nor interaction of the frame with other building elements. Steel beams exposed to fire are known to push over supporting walls when they expand or to pull over supporting walls as they sag.

6 Limitations in understanding the details

While the fire performance of the primary structural members can be calculated as described above the limitations of understanding the fire performance of the entire structural system are primarily in the details of that system. First are the connections that join the members. The mechanical performance of these connections such as ductility under load is generally understood but when exposed to fire they may fail in any number of ways. These issues are raised in the FEMA report with regard to the structural response of WTC 1 and 2 to the fire^[12]. The ASTM has a standard for joints in fire resistive assemblies^[13] that details furnace testing procedures. This appears to be intended for joints within floor or wall assemblies and not necessarily for joints connecting structural members.

Another detail not well understood is what happens where assemblies come together—walls and ceilings or curtain walls and slabs are common examples. Just how should the junctions of assemblies be protected to prevent passage of fire or smoke, or failure of structural components protected by these assemblies?

A final example is the robustness of protection systems over the life of the building. Problems of compromise of fire resistive barriers by improperly sealed penetrations have long been debated. The events of 11 September highlighted issues of spray-applied fireproofing that may become damaged during tenant fitout or renovation. Added to these issues of normal use are the issues of impact or blast damage that may precede the fire in some extreme events and the effects on performance in a following fire^[14].



Figure 6—Fireproofing on steel columns can be lost over the life of the building (Roger Morse)

7 Research needs

At a joint meeting in March of 2002, CIB W14 (Fire) and ISO TC92 (Fire Safety) identified a preliminary list of issues that should be explored toward the development of engineering analysis methods for structural fire resistance determination. That list along with some limited explanation is provided below.

7.1 Dynamic exposure to arbitrary, transient conditions

Arguably the most important issue and limitation of the current classification methods is the use of a single, time-temperature exposure. This exposure may or may not be appropriate for any given application, and provides no guidance on performance under any other condition(s). A parametric set of exposures is needed that would allow extrapolation to any exposure condition. Considerable work has been done in Europe on such fire curves for the Eurocode system and this could provide a starting point. The result should be a set of design basis fires that could be specified for certain classes of buildings as representative of the range of events for which the design is expected to meet the performance objectives. If these design fires could be used to specify design performance criteria in terms of building loads the fire and structural engineers would be able to coordinate the design process^[15].

7.2 Performance metrics (data) linked to calculations

Another, crucial philosophical change is to develop a methodology that is based in the ability to predict performance in actual use rather than to certify or classify materials and assemblies for general use. This will require the development of engineering analysis methods and models supported by methods to measure extensible properties and performance metrics required by these calculation methods. An excellent discussion of this topic can be found in a position paper by Croce^[16] for the FORUM for International Cooperation in Fire Research.

Materials producers and product manufacturers often express concerns with this approach because

their products would no longer be approved for general use but rather must be evaluated for performance in specific designs. However, if the end uses are categorized into sets of design basis fires it should be possible to determine if performance is acceptable for these events and to provide a class approval for most applications.

7.3 Small furnaces measuring real properties of materials as a function of temperature

A concern is that the furnaces in which fire resistance determinations are carried out have a high degree of thermal inertia and may not be suitable for use with exposure conditions that change rapidly. This may necessitate a new concept in furnace design that would likely involve smaller scale furnaces that could be more responsive to rapidly changing exposure conditions. This would also involve testing of smaller samples with the overall advantage of lower testing costs. The enabling technology would be the ability to predict the performance in the context of end use of the full-scale assembly with at least equal uncertainty to full scale testing methods.

7.4 Physical distortion of materials and assemblies (need to test in full scale, restrained)

Failure of restrained structural components can be triggered by forces and loads associated with the physical distortion of components. Twisting, sagging, bending or other distortions can occur due to exposure to high thermal gradients or to residual stresses in components that are unlikely to be present in smaller samples or without representative restraint conditions. Thus, this type of testing is likely to require full scale testing procedures as opposed to small-scale tests and models.

7.5 Quality control issues and effects (as built vs. as designed or tested)

Construction specifications for fire resistive assemblies are highly detailed yet most people recognize that there are often variations in the way that they are constructed in actual buildings. There is little or no information on the performance impacts of these variations that would be useful in guiding the establishment of quality control procedures or regulatory inspections. What is needed here is a sensitivity analysis to the range of expected variation in the application to identify those critical aspects of the design and the acceptable variability that maintains allowable performance. This type of sensitivity determination would be prohibitively expensive to do by test but simple and economical where

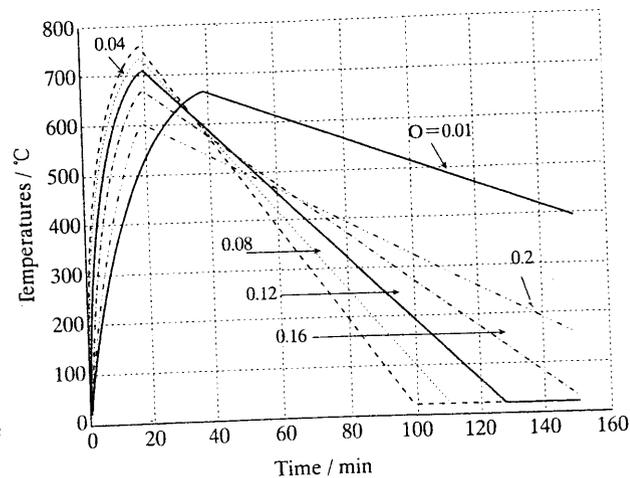


Figure 7—Eurocode parametric fires(ref2)

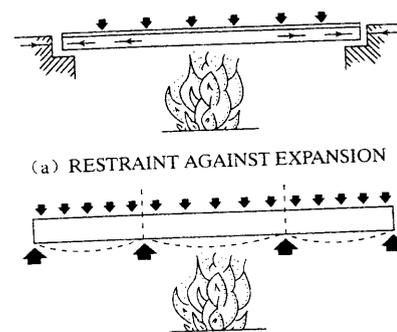


Figure 8—Restraint conditions may need to be evaluated in full scale (rdf5)

models that predict performance from extensible properties are available.

7.6 Impact loads and overpressures

Design fire scenarios as applied to buildings generally have not included explosions or other extreme initiating events. The exceptions are military sites that may be attacked in war and to a limited extent, fires following earthquakes. The events of September 11 will likely change this. Designing to fully resist extreme loads is likely to be unacceptably expensive. Here a concept that is included in the performance-based design option in NFPA's Life Safety Code (NFPA 101) and Building Code (NFPA 5000) may provide the answer. For low probability conditions it is acceptable for the design to fail to meet fully the performance objectives, but the resulting consequences should be examined and deemed acceptable relative to the probability of occurrence of the event. In this way policy makers can agree to accept significant losses for extreme, low probability events while requiring less than total failure. In the nuclear power business this is called *risk-informed regulation*.

7.7 Cooling phase performance

Other than the sometimes—controversial hose stream test included in the ASTM fire resistance testing protocol the performance of structural components in the cooling phase are not evaluated. However, cooling phase performance may be important in preventing progressive collapse and thus needs to be addressed. It is possible that this can be evaluated in the same apparatus that would be needed for physical distortion testing as discussed above.

8 Organization of the project

Initial discussions were held between CIB W14 and ISO TC92 in March 2002 and interest in the work was expressed by both groups. Within TC92 the work would be performed within SC2 (Fire Containment) and SC4 (Fire Safety Engineering). Discussions were held in June 2002 with ASTM E05 and many of their members were equally interested, with the work largely within the scope of E05.11. In each case, the subcommittee chairs will serve as the focal point for communication.

CIB W14 held a meeting in September 2002 to begin the planning process as they are taking the lead for organization and coordination of the overall effort. At this meeting a plan was developed in which thirteen fire laboratories worldwide will collaborate in a major effort of modeling and experiments to advance the ability to predict structural fire response. This effort is being coordinated with NIST's work on the World Trade Center collapse and may also help in the detailed understanding of the mechanisms of that incident. Appropriate international conferences will be identified at which technical papers related to the work can be presented to promote discussion. A technical session on the topic will be organized for the CIB World Congress scheduled for May 2004 in Toronto, Canada.

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