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STRUCTURAL FIRE RESISTANCE AND BUILDING CODE REQUIREMENTS

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The Final Report on the investigation of the collapse of World Trade Center towers conducted by the National Institute of Standards and Technology (NIST) was released on October 26, 2005. Like the Draft Final Report issued on June 23, 2005, the Final Report includes 30 recommendations for improving the safety of high rise buildings. Four of the 30 recommendations, Recommendations 4, 5, 8 and 9, deal with structural fire resistance.

Recommendation 4 reads as follows:

> "*NIST recommends evaluating, and where needed improving, the technical basis for determining appropriate construction classification and fire rating requirements (especially for tall buildings)—and making related code changes now as much as possible—by explicitly considering factors including . . . .*"
>
> "*Adoption of this recommendation will allow building codes to distinguish the risks associated with different building heights, fuel concentrations, and fire protection systems. Research is needed to develop the data and evaluate alternative proposals for construction classifications and fire ratings.*"
>
> *"Model Building Codes: A comprehensive review of current construction classification and fire rating requirements and the establishment of a uniform set of revised thresholds with a firm technical basis that considers the factors identified above should be undertaken.*"

Recommendation 5 reads as follows:

> "*NIST recommends that the technical basis for the century-old standard for fire resistance testing of components, assemblies, and systems* [ASTM E119] *should be improved through a national effort. Necessary guidance also should be developed for extrapolating the results of tested assemblies to prototypical building systems. A key step in fulfilling this recommendation is to establish a capability for studying and testing the components, assemblies, and systems under realistic fire and load conditions."*

Recommendation 8 reads as follows:

> "*NIST recommends that the fire resistance of structures be enhanced by requiring a performance objective that uncontrolled building fires result in burnout without partial or global (total) collapse. Such a provision should recognize that sprinklers could be compromised, nonoperational or nonexistent*".

Recommendation 9 reads as follows:

> "*NIST recommends the development of: (1) performance-based standards and code provisions, as an alternative to prescriptive design methods, to enable the design and retrofit of structures to resist real building fire conditions, including their ability to achieve the performance objective of burnout without structural or local floor collapse; and (2) the tools, guidelines, and test methods necessary to evaluate the fire performance of the structure as a whole.*"

Recommendations 4, 8 and 9 imply that the construction type/fire resistance requirements pertaining to high rise buildings contained in the model building codes used in the United States, in particular the 2000 and 2003 editions of the International Building Code (and also the BOCA National Building Code), do not have a firm technical basis. Recommendations 5 and 9 suggest that ASTM E119 needs to be updated, at the very least, and probably should be scrapped in favor of a more rigorous engineering approach to determining structural fire resistance.

Given that the high rise building provisions presently contained in the model building codes were developed in the early 1970's and that ASTM E119 was developed in the early in the twentieth century, many in the fire protection field, including, apparently, some of the staff at NIST, lack a historical perspective on these two subjects. One of the only discussions of the history of the development of the structural fire protection provisions contained in our present model building codes which I have run across is contained in the 4th edition of a book titled ***Fire Protection Through Modern Building Codes*** published by the American Iron and Steel Institute (AISI) in 1974.

The following are a few excerpts from that book:

> "*Building-code regulations that deal with fire safety are of inestimable importance insofar as public safety is concerned. Yet they are perhaps the least understood of construction-code requirements.*" (Page 1)

“*Fire endurance, or the time period during which a material or assembly continues to exhibit fire resistance, is usually measured by the methods specified and according to the criteria defined in the American Society for Testing and Materials' publication (ASTM E119), titled "Standard Method of Fire Tests of Building Construction and Materials,". . . .The standard, first adopted in 1918, remains essentially in its original form despite frequent revisions made necessary by the changes in building materials and design concepts.*” (Page 11)

"*The Standard Method of Test has evolved from a standard first adopted in 1903 by the International Fire Prevention Congress, held under the auspices of the British Fire Prevention Committee.*" (Page 11)

"*Floor tests were also conducted at Columbia University, in the City of New York, between 1902 and 1912. Data generated by these tests were used in preparing a tentative standard proposed by ASTM Committee P (predecessor to Committee E05) in 1906.*" (Page 13)

"*The Standard Time-Temperature Curve (Fig. 3), which specifies the furnace temperature that must be maintained from beginning to conclusion of a fire test, was first incorporated in the 1918 edition of the present standard ASTM E119.*" (Page 14)

"*In 1922 the National Bureau of Standards* [now NIST] *began a series of burnout tests for the purpose of determining the relationship of the Standard Fire Test-specifically, its time-temperature curve-to the duration and intensity of uncontrolled fires involving the combustible contents of certain occupancies. The tests were conducted in specially constructed fire resistive buildings in which materials were placed to simulate the selected occupancy. The weight of the combustible contents in each test was carefully determined, and temperatures at many locations in the test rooms were recorded at frequent intervals throughout the burning period. The combustible materials used in these tests were assumed to have heat of combustion and rate of heat release similar to that of dry wood or paper (7000 to 8000 BTU per pound).*” (Pages 14 and 15)

"*From data developed from these tests, the assumption could be made that a fairly simple relationship existed between the weight of combustibles and the time-temperature curve that developed; and a time equivalent of fire severity, as measured by the Standard Time-Temperature Curve, was thus developed. This equivalence is summarized in Table 2.*” (Page 15)

“***Table 2-Relation of Amount of Combustibles to Fire Duration***

Average weight of Combustibles* *(psf)*	***Equivalent Fire Duration*** *(hours)*
5 psf	*1/2*
7-1/2 psf	*3/4*
10 psf	*1*
15 psf	*1-1/2*
20 psf	*2*
30 psf	*3*
40 psf	*4-1/2*
50 psf	*6*
60 psf	*7-1/2*

***** *Combustibles reduced to wood equivalent to 8000 BTU per pound.*”
(Page 15)

“*Recognition should be given to the fact that the burnout tests were conducted in small buildings with a limited number of windows and therefore fires in larger buildings with adequate ventilation could have considerable different characteristics.*” (Page 15)

“*The relationship in Table 2 has been a means by which fire-resistive requirements, based on the total amount of combustible materials in the building and occupancy, can be established for structural building components (Fig. 5).*" (Page 15)

"*Fire loading, i.e., the quantity of combustibles in a given fire space, divided by the area of the space, has a direct correlation to the severity of any fire within a building under conditions of controlled air supply. A correlation can thus be made between fire loading and recommended fire resistance of structures.*" (Pages 17 and 18)

"*While the test* [ASTM E119] *is useful only for comparison, it can serve as an acceptable guide for many building-code fire-safety requirements.*" (Page 18)

"*Therefore, knowing the kind and amount of fuel likely to be present in any given occupancy and in the particular structure that houses it is extremely important for making a realistic evaluation of the total fire hazard in a building.*" (Page 19)

"*Supporting the logic of this approach for estimating comparative fire severities, the following statement appears in the Bureau of Standards Report BMS 92*:

> *. . . it has been indicated that there is a fairly definite relation between the amount of combustible contents and the resulting fire severity. This is applicable for building having the main structural elements of incombustible* [noncombustible] *materials of fire resistance sufficient to preserve their integrity in a fire consuming all the combustible contents. Considering the wide range in weight of the combustible contents to be found in buildings, it appears logical to proportion the fire resistance of structural members with reference to the severity of fires that can occur within them."* (Page 28)

"*Results of surveys conducted for residential, educational, institutional, assembly, storage and business occupancies were reported in "Fire Resistance Classifications of Buildings," BMS 92 (1942) and for mercantile, industrial, and storage occupancies in "Combustible Contents of Buildings," BMS 149 (1957). In the Bureau report "Techniques for the Survey and Evaluation of Live Floor Loads and Fire Loads in Modern Office Buildings, BSS 16 (1967), additional information relating to business or office occupancies has been reported and evaluated.*" (Page 28)

"*Residential occupancies have combustible contents with a low average weight. . . . .The surveys reported in Bureau Report BMS 92 show that movable combustible furnishings or contents of residential buildings average only 3.4 psf of floor area. The total combustibles represented by the furnishings plus floor finish, doors, windows, trim, frames, mouldings, shelving, etc., average 8.8 psf. Modern residential buildings may have less combustible contents than older structures, particularly where noncombustible materials have replaced trim, windows, doors, floors, etc. Some years ago, a major hotel chain undertook a study of the total design load requirements for hotel buildings. This research showed that the furniture (combustible and noncombustible) in a typical hotel guest room weighed 812 pounds, or about 4.1 psf of room area.*" (Page 29 and 30)

"*The following summary appears in the Bureau Report:*

> *In apartment and residences, even with combustible floors and other woodwork, the amount of combustible contents was found to be relatively light, with the average below 10 pounds per square foot of floor area."* (Page 30)

"*The data indicate that combustible content, i.e., schoolroom furnishings, usually range from a little below 3 psf of floor area for classrooms and lecture rooms, up to about 7 psf for rooms used for special instruction purposes.*" (Page 31)

"*In almost 90 percent of the floor area* [of hospitals]*, it was found that the weight of combustible contents averaged less than 5 psf. A density of greater than 10 psf was shown to exist in only 4 percent of the total floor area.*" (Page 33)

"*The widespread use of noncombustible floors in modern assembly buildings has reduced to an even greater extent the low combustible content averages cited, from 2 to 4 psf.*" (Page 35)

"*From the available data it would seem reasonable to conclude that auditoriums, theaters, churches, gymnasiums, passenger terminals, and similar occupancies considered to be within the assembly classification have a fire load (as represented by the combustible contents) that is much less than 5 psf of floor area.*" (Page 35)

"*Surveys published by the National Bureau of Standards suggest that business occupancies of the office building type have a uniformly low combustible content. This is true with all areas except those used predominantly for filing of storage purposes. Papers in metal filing cabinets do not burn at the same rate as those in the open. To recognize this characteristic, a reduction in the weight of combustibles so stored is warranted.*" (Page 36)

"*In survey data of Bureau Report BMS 92, the total weight of the combustible contents of metal filing cabinets, metal lockers, etc, has been adjusted to allow for the effective contribution of the combustible contents. According to this report, "where combustibles are stored in steel or equivalent incombustible* [noncombustible] *containers, a corresponding corrected weight should be used in determining expected fire severity" to compensate for the lower fire hazard of combustible protected in such manner.*" (Pages 36 and 37)

"*Both the intensity and duration of a fire depend on the amount of fuel contributed by the building's occupancy and its construction materials. . . . In the context of fire safety, a proper specification of construction materials calls for a clear and unequivocal definition of the term noncombustible. Once this definition is established, the fire loads of different occupancies and the protection requirements for structures that house them can be located on a fixed scale. Fire-load data is derived from surveys made during three separate periods. Earlier data are believed to be conservative by present occupancy standards, but they are used for want of more recent figures.*" (Page 47)

"*A general correlation among fire load, fire duration, and intensity has long been accepted and is the criterion for many basic fire-protection requirements in building codes. However, full-scale burnout tests, where air supply is varied have shown different time-temperature curves than that defined in the Standard Fire Test.*" (Page 147)

"*Underwriters' Laboratories, Inc. conducted a series of tests in 1967 for the purpose of determining fire exposure to exterior steel members from uncontrolled fire in a building. A considerable amount of information was obtained on time-temperature curves during burnout tests in rooms. During testing, fire loads varying from 5 to 20 pounds per square foot were used, and different quantities of air were introduced into th test chamber at each fire-loading level. Data obtained from this test series included time-temperature curves both within and outside the test enclosure.*" (Page 147)

"*In general, if a fire has an ample quantity of combustion air, the rate of temperature rise and maximum temperature attained in an enclosure may appreciably exceed the Standard Time-Temperature Curve. Moreover, the duration of the fire may be quite limited.*" (Page 151)

"*This test information does not necessarily invalidate the Standard Time-Temperature Curve. Some burnout tests that showed abrupt, short-duration peaking were conducted with fuel arrangements that were deliberately designed to burn rapidly. The Standard Fire Test Curve represents only one set of conditions of fuel and air supply by which the performance of constructions and materials during fire exposure are compared. It is based on the rate of combustion of fuel represented solely by the contents of an occupancy. However, in the development of the test curve the influence of fuel provided by combustible structural materials was not considered.*" (Page 151)

Analysis

The information contained in the 4th edition of ***Fire Protection Through Modern Building Codes*** provides the technical basis for the construction type/height limitations (and many of the passive fire protection requirements) contained in the model building codes presently used in the United States. While most of the information presented above is more than a half century old and may be considered to be crude by today's standards, the information is still extremely useful due to its simplicity.

NIST is correct in its assessment that ASTM E119 fire resistance test standard provides little information on how a structural element will actually perform in a real fire environment. However, the NIST investigation into the WTC towers collapse clearly demonstrated the extreme complexity of structural analysis under constantly changing fire conditions. In presentations on the investigation, NIST indicated that computer runs of the structural analysis under fire conditions even with today's powerful computers took months to complete and this was for just a single scenario. Given this, the practicality of structural analysis under fire conditions during the course of building design would seem to be questionable, at least at present, particularly when the cruder methodology developed by the National Bureau of Standards in the first half of the twentieth century has yielded more than satisfactory results.

Interestingly enough, the NIST investigation appears to have confirmed the relationship between fire loading and fire duration. The following are a few excerpts from the NIST Final Report:

> "*The differences in the fire behavior under the different* [work station] *experimental conditions was profound in these roughly hour-long tests. The jet fuel greatly accelerated the fire growth. Only about 60 percent of the combustible mass of the rubblized workstations was consumed. The near-ceiling temperatures varied between 800°C* [1,472°F] *and 1,100°C* [2,012°F]." (Pages 125 and 126, NCSTAR 1)

> "*A number of preliminary simulations had been performed to gain insight into factors having most influence on the severity of fires. The most influential was the mass of combustible per unit of floor area (fuel load); second was the extent of core wall damage, which affected the air supply for the fires. The aforementioned workstation fire tests had also indicated that the damage conditions of the furnishings also played a key role.*" (Page 126, NCSTAR 1)

> "*Combined with the results above, this suggested that the overall combustible load of 4 lb/ft² was reasonable.*" (Page 129, NCSTAR 1)

> "*At any given location* [in WTC 1]*, the duration of the temperature near 1,000°C* [1,832°F] *was about 15 min to 20 min. The rest of the time, the calculated temperatures were near 500°C* [932°F] *or below.*" (Page 129, NCSTAR 1)

> "*Even in the vicinity of the fires* [in both WTC 1 and WTC 2]*, the columns and trusses for which the insulation was intact did not heat to temperatures where significant loss of strength occurred.*" (Page 141, NCSTAR 1)

"*Both the results of the multiple workstation experiments and the simulations of the WTC fires showed that the combustibles in a given location, if undisturbed by aircraft impact, would have been almost fully burned in 20 min.*" (Page 147, NCSTAR 1)

"*In the simulations of Cases A through D, none of the columns and trusses for which thermal insulation was intact reached temperatures at which significant loss of strength occurred. Thermal analysis showed that steel temperatures in areas where the insulation remained intact rarely exceeded 400°C* [752°F] *in WTC 1 and 500°C* [932°F] *in WTC 2.*" (Page 147, NCSTAR 1)

"*In WTC 1, if fires had been allowed to continue past the time of building collapse, complete burnout would likely have occurred within a short time since the fires had already traversed around the entire floor and most of the combustibles would already have been consumed (see Figure 6-38). During the extended time from collapse to burnout, the steel temperatures would likely not have increased very much. The installed insulation in the fire-affected floors of this building had been upgraded to an average of 2.5 in.*" (Page 147, NCSTAR 1)

"*In a fire simulation of WTC 2, that was extended beyond Case D and with all windows broken during this period, the temperatures in the truss steel on the west side of the building (where the insulation was undamaged) increased for about 40 min before falling off rapidly as the combustibles were consumed. Results for a typical floor (floor 81) showed that temperatures of 700°C* [1,292°F] *and 760°C* [1,400°F] *were reached over approximately 15 percent of the west floor area for less than 10 min. Approximately 60 percent of floor steel had temperatures that between 600°C* [1,112°F] *and 700°C* [1,292°F] *for about 15 min. Approximately 70 percent of the floor steel had temperatures that exceeded 500°C* [932°F] *for about 45 min. At these temperatures, the floors would be expected to sag and then recover a portion of the sag as the steel began to cool. Based on the results of Cases C and D, the temperatures of the insulated exterior and core columns would not have increased to the point where significant loss of strength or stiffness would occur during these additional 2 hours. With intact, cool core columns, any inward bowing of the west exterior wall that might occur would be readily supported by the adjacent exterior walls and core columns.*" (Page 147, NCSTAR 1)

"*Computer simulations, supported by the results of large-scale fire tests and furnace testing of floor subsystems, showed that insulated structural steel, when coated with the average installed thickness of insulation thickness of 3/4 in., would not have reached high temperatures (i.e. greater than 650°C* [1,382°F]*) from nearby fires for a longer time period than the burnout time of the combustibles (approximately 20 min for 4 lb/ft^2 of combusted material). Simulations also showed that variations in thickness resulting from normal application, even with occasion gaps in coverage, would not have changed this result.*" (Page 148, NCSTAR 1)

"*WTC 1 did not collapse during the major fire in 1975, which engulfed a large area (about one-fourth of the floor area or 9,000 ft^2) on the southeast quadrant of the 11th floor. At that time, office spaces in the towers were not sprinklered. The fire caused minimal damage to the floor systems with the 1/2 in. specified insulation thickness applied on the trusses (four trusses were slightly distorted), and at no time was the load-carrying capacity compromised for the floor system or the structural as a whole.*" (Page 149, NCSTAR 1)

"*Four standard fire resistance tests of floor assemblies like those in the WTC towers conducted as part of this Investigation showed that (a) it took about 90 min of sustained heating in the furnace for temperatures to exceed 600°C* [1,112°F] *on the steel truss members with either 1/2 in. or 3/4 in. insulation thickness, and (b) in no case was the load-carrying capacity compromised by heating of the floor system for 2 hours at furnace temperatures, with applied loads exceeding those on September 11 by a factor of two.*" (Page 149, NCSTAR 1)

"*In absence of structural and insulation damage, a conventional fire substantially similar to or less intense than the fires encountered on September 11, 2001, likely would not have led to the collapse of a WTC tower.*" (Page 149, NCSTAR 1)

"*The towers likely would not have collapsed under the combined effects of aircraft impact and subsequent multi-floor fires encountered on September 11 if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.*" (Page 149, NCSTAR 1)

"*These findings apply to fires that are substantially similar to or less intense than those encountered on September 11, 2001. These do not apply to a standard fire or an assumed fire which has (a) uniform high temperatures over an entire floor or most of a floor (note that the WTC floors were extremely large) and concurrently over multiple floors, (b) high temperatures which are sustained indefinitely or for long periods of time (greater than about 20 minutes at any location, and (c) combusted [combustible] fire loads that are significantly greater than those considered in the analysis. They also do not apply if the capacity of the undamaged structure to redistribute loads via the spandrels, hat truss and floors is not accounted for adequately in a full 3-dimensional simulation model of the structure.*"

In summary, the NIST investigation indicates that the contents of the offices on the fire floors in the WTC produced fires which consumed all of the combustibles in an area in roughly 20 minutes as predicted by the NBS research in the 1920's. The above also indicates that the ASTM E119 standard time-temperature curve is an extremely conservative fire exposure when compared to the fire exposure which actually occurs in fires in typical office occupancies. Although the temperatures generated by a fire in a typical office occupancy may be higher than the standard time-temperature for a brief period of time, the temperatures generated in an actual fire rapidly peak and then decrease, while the temperatures on the standard time-temperature curve continuously rise.

Given our present building design, construction and inspection capabilities, utilizing a cruder, but simpler method of determining adequate structural fire resistance may be just as reliable as a more complex method of determining structural fire resistance. After all, despite all of our sophistication, building designers, fireproofing contractors and code enforcement personnel have yet to master the simpler method of determining structural fire resistance using ASTM E119. In other words, the adage "keep it simple, stupid" is probably applicable in the case of structural fire resistance.

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