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# POLITICAL SCIENCE: STRUCTURAL DESIGN FOR FIRE

By Richard Schulte

In the wake of the collapse of the World Trade Center towers and the WTC 7 Building on September 11th, a renewed interest in structural fire protection for tall buildings has developed. This renewed interest is due in part to the development of fire models which can be used to predict the effects of fire (i.e. fire temperatures) and the development of the concept of "performance-based" building fire protection.

A paper which addresses the concept of the combination of structural engineering and fire modeling authored by Richard Bukowski prior to the release of the National Institute of Standards and Technology (NIST) WTC towers collapse investigation report in the Fall of 2005 titled "*Prediction of the Structural Fire Performance of Buildings*" includes the following excerpts:

> "*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.*" (Page 1)

> "*The first task in the project will be to assemble a clear picture of the current ability to predict structural performance. . . . The purpose of this paper is to outline proposed objectives and scope for this effort.*" (Page 1)

> "*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 E 119) was adopted in 1918 with the designation C-19-18 and was nearly identical to the test method, as it exists today.*" (Page 1)

> "*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.*" (Page 2)

"*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.*" (Page 2)

"*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, 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.*" (Page 2)

"*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 E 119) was adopted in 1918 with the designation C-19-18 and was nearly identical to the test method, as it exists today.*"

"*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.*" (Page 2)

"*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.*" (Page 3)

"*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.*" (Page 3)

"*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.*" (Page 3)

"*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.*" (Page 3)

"*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.*" (Page 3)

"*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.*"

(Page 4)

"*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). 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, Fire-T3) and the critical temperature for that steel.*" (Page 4)

> *"Here there exist some limited capabilities that should be used judiciously."*

"*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.*" (Page 4)

"*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.*" (Page 5)

"*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 11September 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.*" (Page 5)

“*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).*” (Page 5)

“*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. . . 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.*” (Page 6)

“*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. . . . 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.*” (Page 6)

“*Failure of restrained structural components can be triggered by forces and loads associated with the physical distortion of components. . . . Thus, this type of testing is likely to require full scale testing procedures as opposed to small-scale tests and models.*” (Page 6)

“*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 models that predict performance from extensible properties are available.*” (Page 6)

"*Design fire scenarios as applied to buildings generally have not included explosions or other extreme initiating events. . . .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.*" (Page 7)

"*. . . .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.*" (Page 7)

"*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.*" (Page 7)

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A report which also addresses "structural design for fire" was developed by Hughes Associates, Inc. after the NIST investigation report on the collapse of World Trade Center towers was issued is titled "*The Technical Basis of a Fire Resistance Test for Performance-Based Fire Design of Buildings*". Excerpts from this report include the following:

"*This approach requires engineering data that existing test methods, like ASTM E 119 (American Society for Testing and Materials), are not currently configured to provide (Grosshandler, 2002). The lack of engineering data from standard fire resistance test methods requires that performance-based design utilize data obtained from ad hoc test methods performed outside of the scope of standard test methodologies. This process is lacking in both standardization and efficiency.*" (Page 1)

"*In addition to other limitations with respect to test procedures, measurements, and reporting, reproducibility of standard furnace testing has always been a serious issue. Fire resistance tests are unique within the fire test world in that the apparatus is only generally specified in the test standard. Fuels, burners, furnace linings, furnace dimensions, loading levels, and loading mechanisms are either unspecified or only generally specified. This has led to the situation that test results cannot be reproduced from laboratory to laboratory. This situation causes significant problems in a performance-based design environment.*" (Page 1)

*"Fire resistance tests are unique within the fire test world in that the apparatus is only generally specified in the test standard."*

"*A test plan outline to develop and validate the proposed capabilities, procedures, and instrumentation has been developed and is included in this report.*" (Page 1)

"*The prescriptive approach has provided very satisfactory results in application. It is simply hoped that the performance-based system can provide similarly satisfactory or better results in a more cost-effective manner.*" (Page 2)

"*In the area of engineered structural fire protection, there are many ongoing organizational efforts to develop the required design method infrastructure. The Society of Fire Protection Engineers (SFPE) has a committee working on a standard for determination of the design fire exposure. SFPE is also in the process of constituting a committee to develop a standard on the thermal/heat-transfer portion of the design process. The National Fire Protection Association (NFPA), meanwhile, is developing a standard for fire loads for structural fire protection design. These committees are coordinating their efforts to produce a suite of documents that collectively support PBSFE.*" (Page 2)

"*While the American Society of Civil Engineers (ASCE) had announced some time ago its intention to produce a document in the structural portion of the design process, it seems that this process has not yet materialized (ASCE Committee for Structural Design for Fire Conditions is charged with development of a Performance-Based Fire Design Standard). There is no doubt that the SFPE efforts on the heat-transfer portion and ASCE's efforts on the structural portion will require data that cannot be obtained using current test methods.*" (Page 2)

> *"The prescriptive approach has provided very satisfactory results in application. It is simply hoped that the performance-based system can provide similarly satisfactory or better results in a more cost-effective manner."*

"*While the field of Performance-Based Structural Fire Engineering is in the developmental stage, the overall structure of the process has been well defined for some time. . . .The process includes both design and analysis components. The analysis components involve the definition of the design fire exposure, the thermal/ mechanical response of the structural assembly (including any fireproofing materials), and structural response of the structural system.*" (Page 3)

"*It is significant to note that the time-temperature curves developed in compartment fires most often exceed the time-temperature curves used in the test methods like ASTM E 119. As noted by Drysdale (1999), this has been recognized but tacitly accepted since the 1920s in the setting of prescriptive fire resistance requirements for buildings.*" (Page 3)

"*It is significant that existing models cannot deal with the mechanical performance of the assembly in any substantive manner. Loss of physical integrity of a material or the assembly cannot be modeled at this time. The designer relies entirely upon the results of testing to assure that physical integrity is maintained over the design exposure period. In most cases, the engineer will seek to use materials and assemblies that can be relied upon to maintain integrity, or alternatively simple, and somewhat ad hoc, assumptions about material loss are made in the design calculations.*" (Page 5)

"*In addition, the current listing may not be directly supported by reported tests. Testing may have been performed with an old version of the protective material and the current material may be accepted under the listing based upon the listing agency's engineering judgment. While this may be satisfactory for prescriptive use of the product, it has serious limitations with respect to PBSFE.*" (Page 5)

"*The analysis methods employed in the design process may vary from special purpose software to general heat-transfer or structural analysis software. Some software is developed by the designer, some is developed by government laboratories, and some is commercial software. There is a specific need to address applicability, validation, and verification of these methods for use in specific Performance-Based Structural Fire Engineering (PBSFE) designs.*" (Page 5)

"*It is the vision of this report that a fire resistance test in support of PBSFE should be a part of the validation and verification (V&V) basis for the application of analysis tools to specific fire resistance designs.*" (Page 5)

"*The successful prediction of the test would form a partial basis for demonstrating the applicability of the models to the particular fire resistance design. The test would further identify any mechanical behaviors such as erosion, cracking, spalling, shrinkage, fastener failures, warpage, and other behaviors that need to be mitigated in the design or accommodated in the design calculations.*" (Page 6)

> *"It is significant that existing models cannot deal with the mechanical performance of the assembly in any substantive manner. Loss of physical integrity of a material or the assembly cannot be modeled at this time."*

"*It has been recognized for many decades that realistic fire exposures can exceed the exposure in ASTM E 119 and that the exposure conditions to the assembly vary among furnaces operated in a manner consistent with existing test methods. There is also a need to develop and validate thermal properties of insulating materials and the methods and instrumentation of standard test methods to support PBSFE. There are definite unresolved issues concerning the structural conduct of the test to assure that the results are applicable to longer spans and connections found in actual construction. This brings to the fore issues of structural scaling laws, and the use of structural rather than thermal endpoints for the test. Issues also exist with the conduct of the test with respect to failure criteria. Valuable failure mode data can be provided by the practice of "testing to failure." These and other issues have received varying levels of attention in the testing and research literature. There is no doubt that a new fire resistance test method can become a valuable tool in PBSFE design.*" (Page 6)

"*Heat-transfer analysis through an assembly exposed to fire conditions must be conducted using models that have been verified and validated (V&V) with data that is representative of the expected fire conditions. Guidance is provided in this section of the report to develop a furnace test that generates thermal response data that can be used to V&V heat-transfer models. Data collected will provide a means for engineers to V&V models for predicting the variables of potential concern in a fire resistance simulation including temperature profiles through the assembly, temperature rise of an item placed against the unexposed side of the assembly, and total heat flux off the unexposed side and/or through transparent portions of the assembly.*" (Page 6)

"*These procedures minimize furnace-to-furnace differences and provide a basis for validating the model performance with the furnace to be used to test the assembly to be used in PBFPE.*" (Page 7)

"*When extrapolating performance from one fire exposure to a more severe fire exposure, there are no assurances that the performance of materials or assemblies will be predictable. Some materials may perform well at elevated temperatures, while other materials may expand, contract, warp, spall, change phase, debond, or crack, and fasteners may fail. Materials may lose integrity and fall off from the surface. Many of these phenomena and failure modes cannot be predicted using the current state-of-the-art models. Therefore, testing products at the upper bound of temperature level expected is currently the only way to demonstrate the overall performance of a material.*" (Page 7)

"*A model that is validated against this upper-bound exposure data will also be demonstrated to be appropriate for predicting the thermal response of the assembly over the range of exposures. Temperature data can be used to demonstrate that the thermal properties being used in the heat transfer analysis are appropriate. In cases where material failures occur (i.e., fall off the exposed side), the through-thickness temperature data can be used to understand when such failures may occur and data could be used to assist in developing/validating constitutive models to predict these failures. Through model validation with the calibration test, as well as the test on the actual assembly, the heat-transfer model could be used with confidence to predict thermal response of the assembly during compartment fire exposures.*" (Page 7)

*"Fully-developed fires will always produce a positive pressure gradient across ceilings and a majority of the boundary height relative to ambient conditions. In these areas of positive pressure, hot gases are driven through small openings that develop in the assembly causing damage to the internal portions of the assembly. Hot gas migration through the assembly may also give rise to ignition on the unexposed side of the assembly in these local areas of weakness. As a result, it is recommended that furnace tests be performed with a positive furnace pressure so that the effects of hot gas transmission through the assembly can be observed."* (Page 9)

*"Predicting the correct temperature profile is a critical aspect of predicting heat transmission through the assembly as well as the structural response. Temperature data can be used to demonstrate that the thermal properties being used in the heat-transfer analysis are appropriate. In cases where materials may lose integrity (i.e., fall off the exposed side), the through-thickness temperature data can be used to understand when such failures may occur and could be used to assist in developing/validating constitutive models to predict these failures. The strength of materials is also strongly influenced by temperature; therefore, predicting the correct temperatures will affect the predicted structural response."* (Page 14)

*"When extrapolating performance from one fire exposure to a more severe fire exposure, there are no assurances that the performance of materials or assemblies will be predictable. . . Many of these phenomena and failure modes cannot be predicted using the current state-of-the-art models."*

*"Performance-based design analysis should be performed using models that have been shown to predict product performance over the expected temperature range. At high temperatures, material behavior can become unpredictable and material failures may occur that were not expected based on data trends at lower temperatures. As a result, using models to predict material behavior outside their validation temperature range is not acceptable engineering practice. . . .This curve can be used to evaluate the performance of products under higher temperatures that these products may be exposed to during compartment fires and can serve to validate model predictive capability for this product over the expected temperature range."* (Page 15)

"*Gas temperatures in compartment fires will be dependent on a number of variables including fuel type, compartment size, compartment boundary thermal properties, ventilation (i.e., door size), and fire stoichiometry.*" (Page 18)

"*The SFPE committee on Standard on Calculating Fire Exposures to Structures has compiled a database of 139 compartment fire tests. This database was used to evaluate the appropriate furnace exposure.*" (Page 19)

"*The use of a severe exposure condition to evaluate materials or assemblies will provide some assurance that for most materials, performance under a less severe exposure will not result in a degradation of performance. When extrapolating performance from one fire exposure to a more severe fire exposure, there are no assurances that the performance of materials or assemblies will be predictable. Some materials may perform well at elevated temperatures, while other materials may expand, contract, warp, spall, go through phase changes, debond, or crack; fasteners may fail, and lose integrity and fall off from the surface. Many of these types of phenomena and failure cannot be predicted using the current state-of-the-art models. Therefore, testing products at the highest temperature level expected is currently the only way to demonstrate the performance of a material.*" (Page 23)

"*Thus, it is very clear that materials and their performance can change when the fire exposure conditions change.*" (Page 24)

"*The higher gas temperatures in the compartment fire tests had an impact not only on the time to failure but also on the mode of failure.*" (Page 24)

"*Intumescent materials are another type of material used to provide acceptable fire resistance performance for structural elements; however, the performance of these materials may be highly variable from product to product. Two broad classes of intumescent materials have been specifically developed for distinctly different markets. Both are used for the protection of structural steel, however, the exposure conditions for which they have been designed are significantly different. Thin-film intumescent materials have been specifically designed for use in the less-severe ASTM E 119 fire exposure conditions. Epoxy-based intumescents were designed to withstand the more severe UL 1709 fire exposure. Many epoxy-based intumescents that are listed under UL 1709 , also have ASTM E 119 listings. However, there are numerous other intumescent coatings that have ASTM E 119 listings but do not have UL 1709 ratings. Though some of these coatings may not be capable of achieving a UL 1709 rating due to the environmental exposure requirements, many ASTM E 119 listed intumescents (not listed in UL 1709) may not produce durable chars or have adhesion properties sufficient to survive the UL 1709 fire exposure. The formation and degradation of these chars as well as the adhesion of the intumescent are not readily modeled and predicted performance is only recommended over the range of conditions at which it has been tested.*" (Page 27)

"*Modeling the heat-transfer through a test article exposed to furnace conditions requires an understanding of the exposure provided by the furnace to the test article.*" (Page 27)

*"Fire resistance furnaces have traditionally been lined with high temperature refractory brick materials commonly used in commercial furnaces. These refractory bricks are a low-density material (approximately 50 lbs/ft$^3$ (775 kg/m$^3$) and have a maximum operating temperature of approximately 2600°F (1425°C). . . . The furnace environment within the furnace transitions to a highly radiative environment once the brick temperature equalizes with the furnace air temperature.*" (Page 29)

"*The major conclusion from the work reported by Harada et al.(1997), indicated that the wall lining material was the dominant factor that influenced the heat impact on the exposed surface of the test specimen. Wall lining materials with a low thermal inertia, such as ceramic fiber insulating material, will result in improved furnace environment uniformity*." (Page 29)

"*Maintaining a minimum oxygen concentration within the test furnace is desired to produce conditions that could be obtained in compartment fires and to support the combustion and char oxidation of combustible test samples such as wood.*" (Page 31)

"*The accuracy in predicting the heat-transfer through the test article assembly during the test, as well as other exposure conditions will be dependent on knowledge of thermal properties of materials in the assembly. Thermal properties should be known over the temperature range at which the materials are expected to be exposed.*" (Page 32)

"*Thermal properties for noncombustible materials can be obtained as a function of temperature. However, thermal properties are more difficult to obtain for materials that lose mass through either moisture-loss or degradation or materials that are deformable or not dimensionally stable.*" (Page 32)

"*Structural modeling of the test results requires the inclusion of boundary conditions. Without these, no meaningful predictions of the test can be performed and as such, validation of the model through comparison with the results of furnace fire testing is not possible.*" (Page 33)

"*The default assembly support condition is just simple bearing on the furnace boundary. For the default bearing or end-connected assembly support condition, a complete description and quantitative characterization of the actual physical restraint provided during the fire test is very pertinent to the fire response of the assembly. Use of load cells at the restrained assembly boundaries to measure the thermally-induced forces that develop during the test would be quite illuminating in recording the assembly-to-frame interface conditions. A minimum of three load cells at a beam or stud end location within the assembly interior is recommended to measure both the total axial thrust and bending moments that occur from the thermal restraint. Additional such instrumentation for other beam or stud ends would serve to confirm similar restraint in other parts of the assembly or to demonstrate its variability. This information will provide quantitative structural data that can be converted for use in PBSFE relative to actual connections and assembly support stiffness.*" (Page 33)

"*Besides strength, the stiffness of a fire-resistive assembly is an important performance factor. Assembly deflections are not only a lead indicator of structural distress in the element tested, but large deflections also can lead to damage of its fire protection materials as well as damage to adjacent construction. Even without failure of the tested assembly, large fire-induced deflections can cause breaches of adjacent horizontal and/or vertical fire barriers, thereby leading to fire propagation into additional compartments.*" (Page 34)

"*The accuracy in predicting the heat-transfer through the test article assembly during the test, as well as other exposure conditions will be dependent on knowledge of thermal properties of materials in the assembly.*"

"*Measured strains can also be related by compatibility to thermally-induced elongations and assembly restraint to better quantify these test assembly variables. Such localized and detailed structural response information cannot be deduced solely from measured deflections that are more representative of the overall gross response.*" (Page 34)

"*Inconsistencies and differences in the load application methodology alone may lead to discrepancies between tests and/or laboratories.*" (Page 37)

"*As with the thermal aspects of the test, it is necessary to provide loads that create the maximum allowable structural conditions so that potential serious failure modes can be realized in the test. Lesser loading would not provide full expression of assembly response potentials, leading to the potential for unanticipated failure modes in the field.*" (Page 37)

"*Only rather large increases of at least 2–3 times the current limits* [for minimum furnace size] *would enable more fully capturing the nature of continuous building construction.*" (Page 38)

"*Given the clear value of larger test specimens, it is desirable to create a number of furnace size classes so that the construction and use of larger furnaces can be recognized and the enhanced value of larger-scale testing can be reflected in the V&V requirements for models to be employed in PBSFE.*" (Pages 38 and 39)

"*In order to observe the full possible range of structural fire behavior, effects of longer spans and/or the larger assembly depths, which are actually used in construction, should be evaluated, since these could be more critical than shorter assembly spans and smaller depths. This approach would involve fire testing scaled specimens under load, which better represent reality. These geometric variables can be tested in practical furnace size and laboratory facility constraints using reduced-scale loaded assemblies and scaling laws to represent deeper trusses, bigger or taller columns and walls.*" (Page 39)

"*Criteria for how and when large geometric changes in assembly span and depth can affect their fire resistance should be formulated, along with requirements for when assemblies must undergo additional scaled tests to account for these possible size effects in their fire resistance rating in lieu of extrapolation. Floor systems and columns appear to be the most likely candidates for such reduced scale testing. However, it is recognized that consistent scaling of concrete floor slabs may be problematic due to lack of sufficient control over aggregate size and internal moisture/humidity content. Furnace-scaled specimens can be considered to be about approximately ½ to ¼ size of the real prototype.*" (Page 40)

"*Some adaptation of full-scale to reduced, furnace-scaled fire testing of assemblies (in particular for beams, roofs, and composite steel-concrete floors) should be accomplished in the relative short-term. It would provide much needed supporting data to supplement or replace the current extrapolation of results of larger and heavier construction.*" (Page 41)

"*The importance of continuing fire tests to structural failure, despite any rating time considerations, lies in gaining a fuller understanding of the actual structural limit states that can be encountered as the assembly reaches its failure time. These ultimate fire performance facts are not at all evident when the test is prematurely stopped, sometimes well in advance of even any visible structural distress. All loaded fire tests should continue until an imminent or actual structural limit state (failure condition) is reached.*" (Page 41)

"*Typical structural testing requires knowledge of the actual stress-strain properties and dimensions of the specimen material(s) at ambient temperatures. This mechanical property data is needed to accurately correlate the experimental results to predictor equations or analyses that utilize the material's yield or ultimate strength. Simple use of the minimum specified strength gradation of the structural material for this purpose is inadequate and could be grossly misleading for interpretation of the results, especially if the actual strength is substantially different (either more or less) from its nominal value.*" (Page 42)

"*However, the real steel, wood, or masonry properties of test assemblies commonly are not more precisely documented other than their nominal size and grade designation. Yet, it is possible, even currently probable for some lower grade, mild structural steels such as ASTM A 36, that their actual material strength may be 50% higher than its minimum nominal value. (ANSI/AISC 341-05).*" (Page 42)

"*The major mechanical properties needed for structural fire resistance engineering are yield and ultimate strength, Young's (elastic) modulus, and stress-strain curves. The first two strength and stiffness parameters as a function of temperature, may be deduced from a series of stress-strain data. All materials exhibit degradation of their ambient mechanical properties with higher temperatures, and this representation, often depicted as a percentage of ambient, or so called retention ratio, is crucial to an accurate modeling of fire resistance, and ultimately any fire-induced collapse prediction.*" (Page 43)

"*In contrast to long-standing test standards for determination of ambient material strength, such as A370-06 tensile testing for steel, none exists for such applications at high temperatures.*" (Page 43)

"*A more efficient alternative is central development within a separate program the standard procedures for such testing of these properties to conduct sufficient high temperature experiments of the common construction materials and grades, compile and publish the results for engineering applications. . . .As the common construction materials and grades are likely to change over time, this high temperature material testing and official documentation should be periodically repeated, perhaps every 10–20 years, for validation and/or recalibration. If modern material property data is not available, it will be necessary for the materials to be tested in conjunction with the furnace testing.*" (Page 44)

"*Most of the structural column fire resistance ratings have been derived from tests on unloaded, nominally straight specimens that are fully engulfed (uniformly heated) in the fire, and that are subject only to temperature endpoints. Use of this type of critical steel temperature test obscures a great deal of real fire response information for the member. Effects of accidental load eccentricity, initial column curvature or imperfections, column mechanical strength properties, length slenderness ratio, and type of structural failure (squash or stability/buckling) under fire exposures are relatively unknown.*" (Page 44)

*"All materials exhibit degradation of their ambient mechanical properties with higher temperatures, and this representation, often depicted as a percentage of ambient, or so called retention ratio, is crucial to an accurate modeling of fire resistance, and ultimately any fire-induced collapse prediction."*

"*In addition, compression members can potentially experience non-uniform heating in real fires (for example, in perimeter framing or tall columns subjected to lower, partial height heating), which will cause bowing curvatures (Cooke, 1988) due to thermal gradients through the section depth (see Figure 17). These induced thermal curvatures reduce the strength of the members due to P-delta effects, and hence, influence the stability of the columns. Such thermal effects will depend on whether the fire totally engulfs a given structural column, in which case similar thermal exposures on all sides can be expected, (uniform heating) or if not, gives rise to the non-uniform heating cases.*" (Page 44)

"*This behavior at elevated temperatures, as well as the adherence of the fire protection material under lateral column deflections, will only become manifest when columns are tested until actual/incipient failure under maximum design load and without temperature limits. The benefit of using different strength grades of column materials for fire resistance will also become better established.*" (Pages 44 and 45)

"*Loaded column tests with non-uniform heating are expected to show asymmetric structural response and failure mechanisms that are not obviated from the currently unloaded, uniformly-critical E 119 temperature tests with their idealized conditions. Similar performance differences can exist for some wall assemblies due to non-uniform heating, applied load and deformation, even for non-loadbearing elements such as those that may be used as fire separations for large record storage compartments (Beyler and Iwankiw, 2005).*" (Page 45)

"*Provision for investigating loaded column and wall response under non-uniform fire exposure should be studied, as this may be a more severe condition than uniform heating. In the interim, a surrogate approach for simulation of wall and column assembly strength degradation due to geometric imperfections and additional non-uniform heating effects is the imposition of a minimum eccentricity for compressive loads.*" (Page 46)

"*The ambient, post-test (cold) condition of the assembly should be well-documented, in particular all the fire protection and structural damage, and final displaced configuration of the assembly. This information would reveal any changes and additional damage from thermal contraction after the fire and during the cooling stage.*" (Page 48)

"*Very few fire tests have been conducted on assemblies with real end connections, in place of the common insertion of the assembly frame into the furnace. Most assemblies typically have simple bearing supports butted against the test frame for floors and roofs, or to the load device for walls. While the current prescriptive code provisions in the U.S. requiring fire protection of connections to be at the same level as for the most highly rated adjoining structural member have generally been considered adequate, the fire response of connections, of its constitutive elements and details (bolts, welds, reinforcing bars and development lengths, ties, etc.) is not well understood or developed. Moreover, the ductility, or lack thereof, of connections under potentially very high strain demands and reduced strength at elevated temperatures could be a critical factor in the integrity assessment of adjacent structural member(s) and framing, as well as for development of any secondary load redistribution paths. The Cardington building tests amply demonstrated this aspect of real structural fire performance (University of Edinburgh, 2000 and BRE 215-741).*" (Page 51)

"*Columns typically carry only compression loads, but may experience uplift for some braced frame conditions. Ordinary structural design for beams and floors does not regularly include the secondary effects of larger axial tension forces and strains from catenary action (see Figure 18) that are likely to become manifest only under the final strength limit states of fire exposure, blast, or impacts.*" (Page 52)

"*One approach to acquire fire performance data on connections is to require every assembly to be detailed and tested with real connections. However, development of standard provisions for such would be rather difficult, given the wide variety of alternative connection types and details, and it would regularly encumber every test.*" (Page 52)

"*A seemingly more viable alternative is to develop in a special research study a unique set of fire test criteria and results for a suite of typical steel connectors (mechanical fasteners, welds, shear studs), connections and steel reinforcing details (longitudinal rebar, shear stirrups, ties, etc.) for steel, concrete and masonry that form typical simple (shear only) and rigid (moment-resisting) connections, composed of different base materials in beam-to-beam and beam-to-column designs. This could be done within or separate from the standard review. Given suitable instrumentation and loading, important new information on connection ductility, force transfer mechanisms, and their ultimate failure limit states under load and high temperature exposures would be thereby obtained, including effects from cooling after the fire. These connection results could supplement the conventional assembly ratings, and form a basic set of input properties for modeling of connections in PBSFE.*" (Pages 52 and 53)

"*Thermal properties (conductivity, specific heat capacity, heat of decomposition) need to be measured at temperatures as close to the highest temperature the material is expected to reach. Physical properties (density, moisture content, expansion/contraction, decomposition kinetics) also need to be measured as a function of temperature up to temperatures the material is expected to reach. Material strength tests need to be performed on materials used in the primary structural assembly members to determine their actual mechanical properties at high temperatures (including yield and ultimate strength, and elastic modulus.*" (Page 53)

"*Research is needed to develop and evaluate the available methods. This will support the selection of the best methods that can then be subjected to V&V and ultimately become accepted standard test methods for this application.*" (Page 53)

"*Fire resistance data and rating results from any fire test can differ, sometimes quite markedly from one identical test to another, both in terms of recorded thermal and structural performance. This is due to the many random experimental variables and inaccuracies (laboratory facilities and practices, furnace temperatures and pressures, loading, instrumentation, test frame boundary conditions), combined with differences in actual material properties and workmanship quality of the individual assembly construction. At times, multiple fire resistance tests have been conducted for an assembly to achieve a desired rating outcome, and only the single best "passing" test is used as the benchmark for the fire resistance listing.*" (Page 53)

"*A rigorous statistical study of the random variations in standard fire tests (as compiled in the database) should be performed to determine the expected probability distribution of experimental results for identical or similar assemblies. To the extent possible, the variability of all the experimental and assembly-specific factors should be established. Such rationally assigned statistics of the published test data could be used to improve interpolation of existing test results and to assess validation accuracy of analytical models, whose solutions otherwise may not exactly match the output of any single test.*" (Pages 53 and 54 )

"*Based upon this investigation it is indeed possible for fire resistance testing to provide critical data for use in performance-based structural fire engineering. The needs of PBSFE differ from the prescriptive design approach. . . . A number of general research areas that would serve the development of PBSFE were identified. Collectively, the recommendations and research areas identified provide a way forward to the achievement of PBSFE.*" (Page 71)

**Analysis**

The paper authored by Richard Bukowski excerpted above is from 2003, while the report authored by Hughes Associates, Inc. is dated June 18, 2007. Bukowski's paper clearly states that additional work is required before engineers can meld structural engineering and fire protection engineering so that building structural systems can be specifically designed to withstand fires which could potentially occur in a building. The report by Hughes Associates' provides more detail on the "pieces of the puzzle" which are still missing for structural design of buildings under fire conditions.

Perhaps one of the most interesting statements made in these two documents is Bukowski's statement addressing "*society's expectations for the built environment*". While Bukowski mentions "societal expectations", his paper does not provide any elaboration on how to determine these "expectations". Just exactly how do the engineering professions determine "*society's expectations for the built environment*"? That seems like a fair enough question to ask.

We know that Americans tolerate around 40,000 fatalities on our nation's highways each year. We also know that lightning kills around 50 Americans each year.

We know that Americans tolerate around 40,000 fatalities on our nation's highways each year. We also know that lightning kills around 50 Americans each year. Based upon statistics collected by the National Fire Protection Association, the average annual number of Americans who die in fires in office buildings, both high rise and low rise buildings, is 1. If 50 Americans die annually as a result of being struck by lightning, is one death caused by fire in office buildings each year too many?

I'm sure that unemployed construction workers appreciate NIST's efforts to make the construction of new tall buildings impractical.

Just how NIST determined that the level of safety in high rise office buildings and high rise hotel and apartment buildings needed to be improved based upon the NFPA fire fatality statistics has yet to be explained by NIST. Are existing high rise office buildings, hotels and apartment buildings "safe" even if the buildings do not comply with the NIST WTC recommendations? I'm quite confident that most Americans would believe that to be the case if they actually knew about the fire safety statistics for high rise buildings.

To avoid any public disagreement about the level of safety necessary for high rise buildings, NIST simply neglected to include a discussion of the statistics on high rise building safety in their WTC investigation reports, but this has already been said many times. What's really interesting about being a member of the NIST Building and Fire Research Laboratory (BFRL) team of researchers is that facts don't seem to matter much.

What does matter at NIST, however, is funding for the Laboratory. So if Congress insists on a report which concludes that tall building are not "safe" in order to keep special interests, such as the Skyscraper Safety Campaign, quiet, just give Congress and the Skyscraper Safety Campaign what they want. It doesn't matter if the implementation of the NIST recommendations will put a damper on the construction of new tall buildings in the United States and put thousands of construction professionals out of work during a severe economic recession. After all, the jobs at NIST BFRL are secure and that's far more important than thousands of construction jobs anyway, isn't it? But onto an even more crucial point regarding the Bukowski paper and the Hughes Associates' report.

Clearly both the Bukowski paper and the Hughes Associates' report indicate that we still do not yet have an adequate level of knowledge to properly and accurately perform structural analysis under fire conditions. In particular, the Hughes Associates' report indicates that the models used in structural analysis under fire conditions have yet to be "verified and validated". In other words, the engineering methodology has not yet been perfected.

If this is indeed the case, and the Bukowski paper was written before NIST issued its investigation report on the collapse of the WTC towers and the Hughes Associates' report was written after NIST issued its WTC towers investigation report, how did NIST do a properly "validated" structural analysis under fire conditions for the WTC towers (and also the WTC 7 Building)? The answer to that question appears to be obvious.

## Conclusion

Are the NIST investigation reports into the collapse of the WTC towers and the WTC 7 building "fatally flawed"? If the answer to that question is yes, then it is highly probable that the NIST recommendations for making tall buildings "safer" are also flawed.

The question which should have been answered before NIST developed its recommendations for making tall building "safer" is: what are "*society's expectations for the built environment*"? Should tall buildings be designed to resist a "military-style" attack, or should society simply accept the risk of another disaster in the event of such an attack?

It is my opinion that NIST has already provided the answer to that question. NIST has yet to forcefully push for making its recommendations for tall buildings retroactive to existing tall buildings. By its failure to push to make its recommendations retroactive, NIST is tacitly suggesting that we simply accept the risk for existing tall buildings. If the risk of a collapse of an existing tall building is acceptable, shouldn't the risk of a collapse of a new tall building also be considered to be acceptable? After all, requiring only new tall buildings to meet more restrictive construction safety standards won't eliminate the risk of another disaster in an existing tall building.

It is my opinion that the WTC towers performed well above expectations on 9/11 and if NIST had simply made the effort to explain that tall buildings are not designed to withstand missile attacks (the aircraft were used as missiles), the American public, including New Yorkers and the Congress of the United States, would have been capable of understanding this fact.

Also in my opinion, the NIST investigations into the collapse of the WTC towers and WTC 7 Building weren't really about the WTC towers and WTC 7 Building at all. The investigations were mainly about procuring continuing funding for NIST's Building and Fire Research Laboratory.

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Eighteen million tax dollars wasted for two "flawed" investigation reports and potentially billions of dollars more wasted for unnecessary code compliance costs for tall buildings-the safest buildings that we build. Imagine that? I'm sure that unemployed construction workers appreciate NIST's efforts to make the construction of new tall buildings impractical.

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