REEXAMINATION OF ‘RESTRAINED VS. UNRESTRAINED’

Kevin LaMalva [1], Luke Bisby [2], John Gales [3], Thomas Gernay [4], Elie Hantouche [5], Cliff Jones [6], Ali Morovat [7], Robert Solomon [8] & Jose Torero [9]

Simpson Gumpertz & Heger Inc., USA, *corresponding author* [1]
University of Edinburgh, UK [2]
York University, CAN [3]
Johns Hopkins University, USA [4]
American University of Beirut, LBN [5]
Jensen Hughes, USA [6]
University of Texas at Austin, USA [7]
National Fire Protection Association, USA [8]
University of Maryland, USA [9]

Keywords

Structural fire protection, restrained, unrestrained, thermal restraint, structural fire engineering, prescriptive method, standard fire resistance design.

Summary

For furnace testing of fire-resistant floor and roof assemblies in the United States, the ASTM E 119 standard (and similarly the UL 263 standard) permits two classifications for boundary conditions: “restrained” and “unrestrained.” When incorporating tested assemblies into an actual structural system, the designer, oftentimes a fire protection or structural engineer, must judge whether a “restrained” or “unrestrained” classification is appropriate for the application. It is critical that this assumption be carefully considered and understood, as many qualified listings permit a lesser thickness of applied fire protection for steel structures (or less concrete cover for concrete structures) to achieve a certain fire resistance rating if a “restrained” classification is confirmed, as compared with an “unrestrained” classification. The emerging standardization of structural fire engineering practice in the United States will disrupt century-long norms in the manner to which structural behavior in fire is addressed. For instance, the current edition of the ASCE/SEI 7 standard will greatly impact how designers consider restraint. Accordingly, this paper serves as an exposé of the “restrained vs unrestrained” paradigm in terms of its paradoxical nature and its controversial impact on the industry. More importantly, potential solutions toward industry rectification are provided for the first time in a contemporary study of this paradigm.

KEYWORDS
prescriptive method, restrained, standard fire resistance design, structural fire engineering, structural fire protection, thermal restraint, unrestrained

1 | INTRODUCTION

For furnace testing of fire resistant assemblies, ASTM E 119 (and similarly UL 263) permits two boundary conditions: “restrained” and “unrestrained.” When incorporating tested systems into an actual structural system, the designer, oftentimes a fire protection or structural engineer, must judge whether a “restrained” or “unrestrained” classification is appropriate for the application. It is critical that this assumption be carefully considered and understood, as many qualified listings permit a lesser thickness of a given applied fire protection to achieve a certain fire resistance rating if a “restrained” classification is confirmed, as compared to an “unrestrained” classification.

The emerging standardization of structural fire engineering practice in the U.S. will disrupt the century-long norms in the manner in which structural behavior in fire is addressed. Notably, the current edition of the ASCE/SEI 7 standard (*Minimum Design Loads and Associated Criteria for Buildings and Other Structures*) has commenced a new industry-consensus standard of care for structural fire protection, which will greatly impact how designers consider Fire Resistance and in particular structural behavior such as restraint. Specifically, ASCE/SEI 7-16 explicitly addresses what designers have known for decades: there is no correlation between assembly structural performance in a furnace test and in-situ structural system performance under fire exposure. This fact is absolutely irrefutable. In light of this, the “restrained vs. unrestrained” paradigm may be regarded as paradoxical, and designers are rightfully concerned about the liability associated with making uncertain judgments in this regard. Hence, proper rectification of this paradigm is necessary as proposed herein.

Many listings in the UL Fire Resistance Directory[i] permit reduced fire protection thicknesses to achieve fire resistance ratings if the designer can demonstrate that the assembly will be “restrained” when it is constructed as part of an actual structural system. Otherwise, the assembly must be considered “unrestrained.” Architects routinely task structural engineers and/or fire protection engineers to judge what classification should be assigned, often with pressure to select the less restrictive ‘restrained’ classification. This paper will examine the paradoxical nature of this paradigm. Furthermore, this paper offers potential solutions toward industry rectification on this controversial issue.

The Need for Rectification

A structural solution is deemed to adequately perform in the event of a fire if it adheres to prescriptive code requirements (referred to as *standard fire resistance design*), or less commonly if performance is demonstrated by conducting structural analyses at elevated temperatures (referred to as *structural fire engineering*). These two design methods share little to no qualification metrics that can be cross-plotted for comparison purposes. For standard fire resistance design, the primary qualification metric is ‘fire resistance,’ expressed in hours. This metric is an artifact of standard fire testing, that requires thermal exposure to a standardized temperature history and a failure criterion. The standardized temperature history does not equate to any realistic fire and the failure criterion is generally expressed in thermal, not structural, terms. Even if structural terms are used to define a failure condition, this is generally not representative of system structural behavior. Therefore, ‘fire resistance’ has no correlation to actual structural system performance at elevated temperatures. Conversely, structural limit state qualification metrics are required for structural fire engineering. In essence, standard fire resistance design is an empirical indexing method and structural fire engineering is structural engineering for a specific loading case. Hence, cross-plotting their primary qualification metrics is not only inappropriate, but specifically prohibited by new industry standards. Due to these irrefutable facts, the paradigm known as ‘restrained vs. unrestrained’ within standard fire resistance design can be regarded oversimplified, and the true implications of its form may not have been entirely contemplated when first introduced. Consequently, this paradigm has perpetually perplexed designers and building authorities alike.

The current “restrained vs. unrestrained” paradigm requires compatibility between standard fire resistance design and structural engineering in order to be viable. However, there are many incompatible aspects as examined herein. Standard fire resistance design is entirely based on furnace testing of isolated structural components/assemblies, and relies almost exclusively on insulation for structural fire protection. Accordingly, the intrinsic fire endurance (or weakness) of a given structural system is not quantified or explicitly contemplated. Also, the anticipated in-situ fire conditions are not quantified or explicitly contemplated. Rather, a single intense heating exposure (i.e., ASTM E119[ii]/UL 263[iii] curve) is used to comparatively test isolated small-scale mock-ups against specified acceptance criteria that are meant to generalize the robustness of the protection scheme to severe fire exposure. The primary intent of this approach is to reduce the heating of individual structural components, with the intent of mitigating the risk of structural system failure during an uncontrolled fire. The primary mechanisms leading to structural failure require an adequate definition of temperatures and temperature gradients, thus the link between the intensity of heating and structural behavior is not direct or simple[5].

As an alternative to standard fire resistance design, structural fire engineering explicitly evaluates the demand and capacity of structural systems under in-situ fire conditions, in a similar manner as other design loads are treated in structural engineering practice. Within this framework, the demand on a structural system under fire exposure can be reduced by means of rationally-allocated structural insulation (i.e., membrane protection or direct application methods) or control of fuel loads. Also, the capacity of a structural system to endure fire effects can be increased by means of reinforcement strengthening/placement/detailing, slab thickening, connection enhancements, member sizing, geometric layout modifications, and/or other measures to enhance structural robustness with respect to explicit performance objectives. As opposed to the binary “restrained vs. unrestrained” classification system in standard fire resistance design, the analysis of structural system response required for this alternative approach inherently considers the degree and condition of restraint.

Origin of Restraint Classifications

The origin of the “restrained vs unrestrained” paradigm can be traced to the time period spanning from 1966 to 1971, although the industry seems to have been aware of restraint effects since at least 1899.[7]

The concept of restraint classifications originated when it was formally observed and documented that the behavior of structural members and assemblies during a standard fire test can be significantly influenced by the end restraint provided by the testing furnace frame. In this context, restraint was identified as the combination of reactive moments and forces generated by the dead and live loads plus the forces generated by temperature variations in structural members during the fire test.8 Restraint was perceived to be generated at the perimeter of the test assembly as the result of the method of framing and tolerance of fit in the test furnace.[9]

To address the impact of end restraint on the results of standard fire tests of floor and roof assemblies, several revisions were proposed to the governing ASTM committee in 1964, 1965, 1967, 1968, and 1969 for adoption in the ASTM E119 standard.[10] These proposals stemmed from the observation that the results from fire tests on structural assemblies tested under identical configurations, protection schemes, and temperature conditions varied considerably from test to test.[11] Development of a varying degree of applied restraint against thermal expansion in standard fire tests was assumed to be the mainreason for such variations[12] .

Additionally, during this time, there were debates about the feasibility of simulating realistic restraint within a test furnace.13 The 1969 proposed revision received the greatest support from the committee members and was first adopted in the 1971 edition of ASTM E119.14 Apparently, results and observations from fire tests performed at Ohio State University with sponsorship from the American Iron and Steel Institute (AISI) played a significant role inthe success of the 1969 proposal. The Ohio State tests were conducted on protected steel beams with both "restrained" and "unrestrained" end conditions under the standard time-temperature exposure.[15]

The experimental program at Ohio State University involved fire tests of 12 beam-slab assemblies with different degrees of composite action (non-composite to fully composite) subjected to varying levels of end restraint. The range of end restraint varied from zero to full end-fixity. Each beam-slab assembly consisted of a 4-in. concrete slab (36 in. wide) cast over a 22-gage steel deck and supported by a 12 WF27 ASTM A36 steel beam. The steel beam was protected with spray-applied insulation. The beam-slab assemblies had a length of approximately 15 ft ("restrained" assemblies were about ó in. shorter). Sliding- and fixed-hinge bearings were used to model the end supports of the "unrestrained" assemblies. For "restrained" assemblies, the end conditions were modeled using the standard AISC B-Series bolted clip angle connections and fully welded end plate connections.[9]

Prior to each fire test, point loads were applied at outer quarter points of the beam span for each beam-slab assembly. The magnitude of the applied loads was calculated to impose design allowable stresses to the beam-slab assemblies.Several observations were made from the fire tests conducted at Ohio State University that later served as the basis for the 1969 proposed revisions to the ASTM E119 standard. The most pertinent observation was on the effect of end restraint on the performance of beam-slab assemblies during the fire tests. On average, a 25% increase in the level of fire resistance was observed for the "restrained" beam-slab assemblies, as compared with "unrestrained" assemblies. This increase was attributed to the negative bending moments induced at the beam-ends in the "restrained" beam-slab assemblies. Specifically, the generated negative bending moments at the beam-ends resulted in smaller effective positive bending moments at the mid-span of each assembly.15 The 1969 proposed revisions to the ASTM E119 standard are summarized in Table 1. As indicated in Table 1 (left column), restrained classifications were proposed to be defined for two classes of structural systems: individual beams and floor/roof assemblies. Also shown in Table 1 (right column) are proposals on how to obtain the. level of fire resistance for each assembly type. Essentially, the 1969 proposed revisions recommend that beam and floor/roof assembly tests be performed under restrained conditions and unrestrained classifications be derived on the basis of application of temperature limitations during restrained tests. Revealingly, this same proposal acknowledged that correlating restraint conditions of a furnace test tothat present in actual building construction is a daunting task.[10]

TABLE 1 Restrained classification for fire resistance ratings of floor and roof assemblies and individual beams in the 1969 proposal[10]

Fire Endurance Classification For:	Obtained or Derived From:
1. Restrained individual beam	Loaded beam test (no temperature limitations)
2. Unrestrained individual beam	Temperature limitations applied to loaded beam or restrained assembly test
3. Restrained assembly	Restrained floor or roof and ceiling assembly test (also, main structural members to qualify on basis of temperature limitations for at least one hour)
4. Unrestrained assembly	Temperature limitations applied to restrained assembly test

Code Adoption and Application of Restraint Classifications

Restraint classification first appeared in ASTM E119-71[iv]. At this time, there were three predominant model building codes used regionally in the United States: (1) the Basic National Building Code published by the Building Officials and Code Administrators, International (BOCA), in the northeast, (2) the Standard Building Code published by the Southern Building Code Congress, International, in the southeast, and (3) the Uniform Building Code (UBC) published by the International Conference of Building Officials, in the west. Investigating the history of these building codes reveals that the 1970 edition of the BOCA[v], the 1970 edition of the UBC[vi], and the 1969 edition of the Southern Standard Building Code[vii] each adopt and reference ASTM E119 for fire-resistant construction. Beyond these externally pointing references, the adopted buildings codes at the time of the revision to ASTM E119 in 1971 do not offer guidance on restraint classification, thus abdicating the classification indistinctly. Although an interpretation by BOCA in 1993 in essence clarified the need to apply the ASTM E119 criteria to the end conditions (i.e., consideration of furnace boundaries), the codes remained silent on what specifically constitutes "restrained" or "unrestrained"[viii] in in-situ construction. Complacency with this conundrum at the time may have been based on a level of comfort with pushing the onus of resolving the specific issues onto designers. This became clear as further code commentary was developed on this paradigm.

In its first appearance in ASTM E119-71, guidance on restraint classification was provided in an appendix to the standard, §A4. This restraint classification guidance remains in an appendix to this date, now §X3, and the language remains largely unchanged. To date, ASTM E119 provides no precise way to define "restrained" and "unrestrained" conditions for a given fire-rated assembly. However, the standard offers the following limited guidance on restraint classifications. In the context of testing, §X3.3 notes that "a restrained condition is one in which expansion and rotation at the ends and supports of a load carrying test specimen resulting from the effects of the fire are resisted by forces external to the test specimen." Later §X3.5 describes restraint in actual building construction as "floor and roof assemblies and individual beams in buildings are considered restrained when the surroundings or supporting structure is capable of resisting substantial thermal expansion and rotation throughout the range of anticipated elevated temperatures caused by a fire." In contrast, "unrestrained" conditions are essentially defined through a diagnosis of exclusion.

Namely, all conditions that are not considered to be "restrained" are considered to be "unrestrained."

Through the close of the 20th century, the three regional model building codes were abandoned and the International Building Code (IBC)[ix] was developed as an amalgamation of the three regional codes. Like it's legacy model building code predecessors, the IBC also references ASTM E119 (and UL 263) for fire-resistance ratings of building elements, components, or assemblies in §703.2, and provides guidance on restraint classification in §703.2.3 where it states that "fire-resistance-rated assemblies tested under ASTM E119 or UL 263 shall not be considered to be restrained unless evidence satisfactory to the *building official* is furnished by the *registered design professional* showing that the construction qualifies for a restrained classification in accordance with ASTM E119 or UL 263." Thus, the IBC, like its legacy model codes, abdicates responsibility for defining restraint for in-situ conditions. Also, further confusion is added by including the requirement that the registered design professional – typically a professional engineer – be responsible for providing sufficient evidence to the building official – the authority having jurisdiction (AHJ) – to qualify a material, assembly, or system as "restrained."

To help fill the void of guidance/prescription in building codes, Underwriter Laboratories (UL) publishes a companion guide to UL 263 that provides additional information for fire resistance ratings, UL 263 (BXUV) *Guide Information for Fire Resistance Ratings*. In §III.15, the guide specifies that restrained conditions in 14-ft by 17-ft fire test frames built from composite steel and concrete offer an approximate flexural stiffness of 850,000 kip-in and 700,000 kip-in along their short and long sides, respectively, which is significantly higher than that provided by most structural systems. This stiffness remains essentially constant throughout a typical fire test because the test frame is insulated from the fire environment. Also, in a somewhat circular reference, guide states the following:

> *It is up to the designer and code authority to determine if an assembly is being used in a restrained or unrestrained application, as required by the building code being enforced.*

While helpful, the information above does not provide the explicit guidance necessary to adequately judge restraint conditions in the context of the prescriptive method, no matter the skill/competence of the designer.

Furnace Testing vs. In-Situ Restraint

Failure Criteria

At the heart of the divergence between in-situ and furnace testing restraint is the definition of failure. UL 263/ASTM E 119 establish different criteria for failure being the main criterion is a load bearing criterion that states that: "The test specimen shall have sustained the applied load during its classification period without developing unexposed surface conditions which will ignite cotton waste." This criterion is identical for restrained and un-restrained. ASTM E 119 will further specify temperature thresholds that shall not be exceeded and these temperature thresholds are identical between restrained and unrestrained systems.

For example ASTM E 119[1] indicates for un-restrained systems: "For test specimens employing steel structural members (beams, open-web steel joists, etc.) spaced more than 4 ft (1.2 m) on centers, the temperature of the steel structural members shall not have exceeded 1300°F (704°C) at any location during the classification period nor shall the average temperature recorded by four thermocouples at any section have exceeded 1100°F (593°C) during the classification period." Repeating the exact language and thresholds for restrained systems only changing the period from the "classification period" to the "first hour." ASTM E 119 further adds that: "For restrained assembly classifications greater than 1 h, these temperature criteria shall apply for a period of one half the classification period of the floor or roof construction or 1 h, whichever is the greater." The change associated to the period can only be justified in terms of an expected beneficial effect of restraint on structural performance which implies, not only a quantification of the benefit in terms of tolerable temperatures but also that structural behavior within a furnace is representative of the structural system behavior. No clear evidence supporting either requirement is currently available.

A final difference occurs during the interpretation of "The test specimen shall have sustained the applied load." In a furnace test, the test is stopped when an arbitrary threshold is exceeded in deflection or rate of deflection. At that time, it is deemed that failure is reached, as the structural component can no longer sustain the load. The adopted thresholds are arbitrary, as they have no particular meaning outside of the furnace testing context, and the values selected for these thresholds may influence the fire rating[x], but it is necessary to adopt a limit to define the "end point" of the test. There is no point in continuing the test because, on the one hand, that would endanger the integrity of the equipment and, on the other hand, no redistribution of load is possible since the test is conducted on an isolated structural component. In an actual structure, on the contrary, the end conditions of a structural component affect the structural failure mode. While a simply supported beam with no restraint will exhibit a failure mode that is qualitatively similar to that of a furnace test, a restrained component part of a structural assembly may develop second order load bearing mechanisms when undergoing large displacements under fire exposure that dramatically change the failure mode and that render irrelevant the adoption of deflection threshold criteria. For instance, a restrained beam may develop catenary action (i.e., a transition from predominantly bending forces to tensile forces) provided the end conditions support the resulting tensile forces. This type of behavior can be highly beneficial to the fire performance. Robust structures can be designed to take advantage of catenary action, tensile membrane action, and other second order and load redistribution mechanisms that build on structural system behavior to enhance performance under fire (and under other extreme structural loading as well). The mobilization of these potentially beneficial mechanisms depends on the restraint conditions in in-situ structures; however, these effects are by no means captured by the "restrained" furnace tests.

Adequacy of the Furnace Restrain

In a standard furnace test, an assembly is considered "restrained" if it bears directly against the edges of the furnace at the outset of the test. As mentioned, the flexural stiffness of furnace framing is very high, and this stiffness remains constant throughout the fire test because the test frame is insulated from the fire environment. Further, if the assembly is made of two components (e.g. in a composite floor beam and concrete slab assembly), both components would be in contact with the edges and restrained equally by the furnace framing during a "restrained" furnace test. In contrast, an assembly in a standard test is considered "unrestrained" when it is free to thermally expand without contacting the furnace edges.

The prescriptive definition of “restrained” fails extraordinarily to capture the complexity and variety of actual restraint conditions observed in-situ during a fire. To provide tentative guidance about mapping this prescriptive definition to actual building construction, UL 263 specifies that "floor-ceiling and roof-ceiling assemblies and individual beams in buildings should be considered restrained when the surrounding or supporting structure is capable of resisting substantial thermal expansion throughout the range of anticipated elevated temperatures." However, there is an acknowledged need for engineering judgment in assessing what constitutes “substantial thermal expansion”. With in-situ construction, the restraint conditions of structural components during a fire may be affected by many factors. These conditions may provide any degree of restraint intermediate between “resisting substantial thermal expansion” and allowing free thermal expansion and rotation, and further, they may significantly change during the fire event. Finally, the restraint conditions eventually may enhance or decrease the resulting structural performance.

The effects of restraint provided on a structural component by an actually-constructed assembly depend, amongst others, on the position of the support. For instance, for reinforced or prestressed concrete slabs or beams, a horizontal axial restraint force may have a positive effect on the fire behavior, provided that the line of thrust is below the resultant of the compressive stress block. Axial restraint in horizontal concrete members can also enable compressive membrane action (or arching effect) to develop, which enhances the load-carrying capacity of these members, but the efficiency of this effect again depends on the location of the restraint on the edges of the member[xi]. In a composite floor beam and concrete slab assembly, unlike in furnace testing where both components would be restrained equally, the beam and slab may experience varying degrees of restraint. This can result in differential longitudinal movement under fire exposure, particularly if the structural components are not acting compositely.

As mentioned, the degree of restraint provided on a structural component by an actually-constructed assembly may vary during the fire event. Nonlinearities in the response of the structural system at the ends of the component can result from the behavior of materials at elevated temperatures. For instance, yielding of connections in a moment resisting frame modifies the rotational restraint at the ends of the beam. Similarly, geometric nonlinearities (i.e., instabilities, large displacements) can change the stiffness of an assembly. Considering a floor beam undergoing thermal expansion as part of a structural system, this beam may impose lateral loading on the girder and column support points. Depending on the characteristics of the support points, the thermal expansion may be resisted or the thermally-induced lateral loading may exceed either the beam or support capacity. Indeed, the possibility that the restraint thermal forces may jeopardize the surrounding structure must be taken into account. For instance, in the 2010 fire in the Tour d’Ivoire in Montreux, Switzerland, thermal elongation of concrete slabs subjected to the action of two burning cars led to the collapse in shear of a column that was several meters away from the fire source[xii]. Finally, the other components in the assembly (girders, column support points, surrounding beams and floor) may also be subjected to heating due to the fire, in which case their stiffness is affected by temperature and subject to thermal expansion, which may generate complex transient force interactions at the boundaries of the different components.

The simplification of the fire exposure into a monotonously increasing gas temperature evolution as used for standard furnace testing represents another limitation in the way that restraint is considered by the prescriptive approach. It is fundamental that actual building fires consist of a heating phase followed by a cooling phase. During the heating phase, the fire will increase the temperature of the structural element in a manner that temperature gradients form within these elements. The increase in bulk temperature corresponds to thermal expansion while the gradients lead to curvature and overall contraction of the element[27]. The performance of the structural element when restrained is therefore defined by the integrated effect of bulk heating and temperature gradients. Given that a furnace follows a predefined temperature history, it cannot reproduce fire related temperature gradients. Cooling generates a reversal of thermal strains (shift from thermal expansion to contraction) that can affect connections between components[xiii] and dramatically redistribute forces in a structural system[xiv]. Supports may need to resist thermal contraction as tensile forces build up in the structural system and through the connections. Under realistic temperature histories, it is clear that the restraint forces at the end of a structural component completely differ from those experienced during a furnace test where the component expands against the edges of a frame of constant stiffness.

Experimental Evidence

Aside from first principles of structural mechanics, a number of published furnace test results demonstrate the inadequacy of the prescriptive method's treatment of restraint conditions. AISC and AISI funded furnace testing of steel floor assemblies, which demonstrated that restraint from the furnace frame provided no fire resistance benefit in the specific cases tested[xv]. This testing resulted in modifications to a specific UL listing (D982). NIST performed furnace testing of steel trusses typical of the WTC floor construction[xvi]. They found that an unrestrained assembly achieved a higher fire resistance rating when compared to an equivalent restrained assembly. The NIST tests also raised concern about whether furnace tests are "scalable" to larger floor systems. More recently, NIST performed localized fire tests on steel beams with differing end restraints and found that the presence of restraint, provided through double-angle connections, decreased the fire resistance of the beam when compared to the unrestrained configuration[xvii]. These test results demonstrate that the effect of restraint varies among different structural systems and restraint conditions, and cannot be easily simplified in practice, especially in a binary fashion.

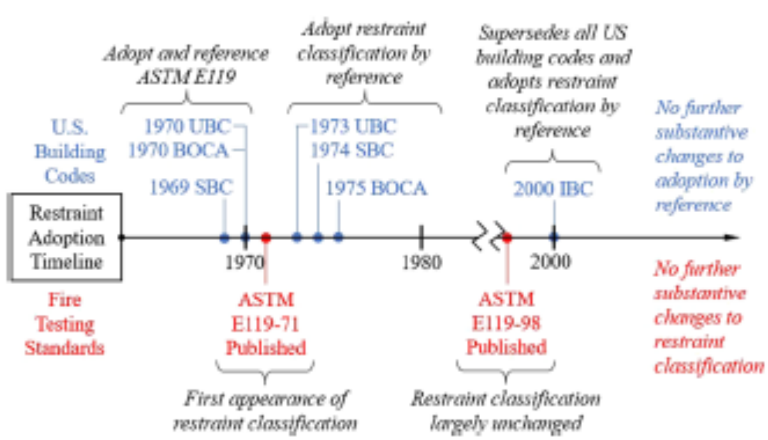

FIGURE 1 Code adoption timeline[21]

Proper evaluation of restraint effects requires consideration of the in-situ structural system, which is not represented in standard furnace testing used for the prescriptive method. The corollary is that testing of isolated structural components with simplified and constant boundary conditions does not properly evaluate in-situ restraint effects. In-situ restraint is complex to evaluate, and it plays a paramount role in structural fire response. The importance of restrained conditions on the fire performance of building structures has been established by full-scale fire tests such as the Cardington test[xviiixixxx] as well as by analysis of real failures such as the NIST investigation on the WTC 7 collapse[xxi]. These studies, and many subsequent analyses, showed that system behavior differs dramatically from isolated member behavior, and that thermal expansion effects govern much of the response of structures in fire. It is the objective of structural fire engineering to quantify these effects, amongst others, by the application of scientific and engineering methods. Currently, advanced analysis based on first principles and numerical methods is the only option to fully address the behavior of structural system under fire. It allows capturing the complex interactions between structural components, including the effects of thermal expansion/contraction, the nonlinearities and large displacement effects, as well as capturing the effect of realistic fire exposures including the different stages of fire development. As a result, advanced analysis can account for the transient effect of restraint for different structural systems and restraint conditions. The last two decades have seen major advances in the development of advanced analysis software for structural fire engineering, with these tools being instrumental in supporting structural fire engineering.

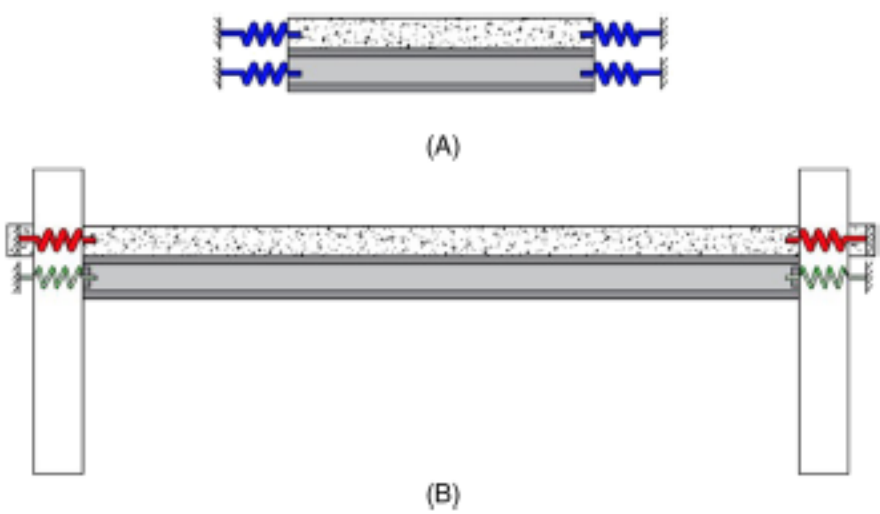

FIGURE 2 Furnace A, vs in situ B, boundary conditions.[25] Each spring color represents a different stiffness

Examination of the Ongoing Justification

Realization that the prescriptive method does not –and theoretically cannot– position designers to make coherent/accurate judgments with regard to the "restrained vs. unrestrained" paradigm is not new to the building design community. In fact, both government and industry have repeatedly advocated for more comprehensive guidance/prescription on the "restrained vs. unrestrained" paradigm. However, these recommendations have yet to be acted on. In the final report on the World Trade Center Investigation[xxii], NIST recommended (Group 2, Enhanced Fire Endurance of Structures, Recommendation 5) that improvements to the methods for fire resistance testing should be evaluated including the "effect of restraining thermal expansion (end-restraint conditions) on test results." A related recommendation was put forth in 2011 as part of a workshop that was organized to establish an agenda for the National Fire Research Laboratory[xxiii]. A group recommendation from the workshop dealing with steel structures provides a rather blunt view of the issue as follows:

> *Research should be undertaken to properly characterize the catenary and membrane action behavior that currently is poorly captured by the restrained vs. unrestrained argument. The group believes that the [paradigm] is meaningless when one looks at the system behavior.*

A recent article in a structural engineering magazine echoes the above concern[xxiv]. Also, during a recent workshop on the "restrained vs. unrestrained" paradigm[xxv], the following salient points were expressed:

- From the code authority perspective, furnace testing standards only provide examples/guidance for restraint classifications, so the designer is ultimately responsible for such judgments.
- From the fire testing standards authority perspective, the boundary conditions of the test furnace should be referenced when making a judgment on restraint within the prescriptive method.
- From the academic perspective, restraint conditions of a furnace test differ from those of the in-situ structural system.
- From the designer perspective, although consideration of restraint is a common task in the industry, designers are concerned about the liability associated with making uncertain judgments.

Historically and currently, restraint classification in U.S. building codes and their referenced standards remains essentially undefined. Limited guidance is provided; however, it is insufficient to ensure uniform application across a range of materials, components, assemblies and building construction types. As a result, the need for further guidance remains in 2019. Amidst the confusion, industry groups such as the American Iron and Steel Institute (AISI), and American Institute of Steel Construction (AISC), advocate that *all* typical steel construction should be rated as restrained[xxvi] based on recommendations provided in limited research[xxvii]. Such justification is primarily based on the observance of beneficial compressive membrane action during furnace testing, which acts to limit member deflections and achieve a higher fire resistance rating. However, it is known that any compressive membrane action achieved by in-situ structural systems tends to break down during the early stages of heating, and floors are more likely to act as tensile membranes thereafter, assuming that adequate support/continuity is provided. Hence, it is clear need that building codes and fire testing standards need to take an active role in explicitly defining in-situ "restrained" conditions and regulating the interpretation to ensure uniformity in application across all materials, constructing types, and geographic regions. In essence, a line needs to be "drawn in sand" for it is paradoxical for a designer to do so based on first principles of structural mechanics.

Contrary Industry Advances

ASCE/SEI 7-16[xxviii] permits designers to utilize structural fire engineering as an alternative to the code-default prescriptive method. Specifically, Section 1.3.7 states that structural fire protection shall be provided per prescriptive requirements of the applicable building code, or by employing a performance-based approach in accordance with the new Appendix E section per building authority approval. This standard reiterates/reaffirms/crystallizes the irrefutable fact that there is no correlation between assembly performance in a furnace test and in-situ structural system performance under fire exposure. Accordingly, the standard prohibits designers from intermingling aspects of the prescriptive method with structural fire engineering. For instance, Section CE.2 states that standard fire testing does "not provide the information needed to predict the actual performance of a structural system during structural design fires."

ASCE/SEI 7-16 also addresses thermal restraint more directly/explicitly than preceding U.S. codes/standards to date. Notably, Sections E.2 and CE.6 state that the "level of restraint depends on the adjacent framing and connection details," which are excluded from standard fire testing, and that "thermal restraint may dominate the behavior of framing systems, particularly floor systems, with degradation of stiffness and strength a secondary factor." Further, it is stated that thermal restraint "may generate forces sufficient to cause yielding or fracture, depending on the temperature reached and the degree of restraint provided by the surrounding structural system to the thermally-induced actions." Hence, this standard clarifies that a restrained condition can be worse than a relatively unrestrained condition with all else equal, and that thermal restraint conditions encompass infinitely more than two distinct scenarios (i.e., "restrained" and "unrestrained").

Effectively, Appendix E brings structural engineers into the fold of structural fire protection design when alternatives to the prescriptive method are sought by project stakeholders. Notably, the inclusion of Appendix E in ASCE/SEI 7 marks the first time that fire effects are considered as an explicit design load condition in a U.S. structural engineering standard[xxix]. Overall, ASCE/SEI guidance should validate structural engineers whom wish to engage and lead in the field of structural fire protection. Also, building officials now have tools to comprehensively evaluate structural fire protection variances[xxx]. It is the authors' opinion that such guidance will also influence building officials' interpretation and enforcement of "restrained" within standard fire resistance design.

As a supplement to Appendix E, ASCE/SEI has recently released a new Manual of Practice No. 138 (Structural Fire Engineering)[xxxi]. Similar to ASCE/SEI 7-16, MOP-138 prohibits designers from intermingling aspects of the prescriptive method with structural fire engineering. Notably, Section 7.2.1 states that "designers should analyze the level of restraint from adjacent structural framing that would resist the thermal expansion of a heated assembly or subsystem and not extrapolate standard fire test results to evaluate the restraint condition of a structural system." Further, Section 2.2.1 states that "binary restraint classification may be difficult (or even paradoxical) for a designer to judge with relation to in-situ conditions considering the incompatible aspects of standard fire resistance design and structural fire engineering." Even more directly, Section 7.2.1 states that "designers should not use standard fire test results for evaluating the restraint condition" of an assembly as part of a structural system. If design industry consensus is sought on the "restrained vs. unrestrained" paradigm, the standardized language above should leave nothing open to interpretation. However, building codes are still held to the "restrained" and "unrestrained" qualifications inherent in the UL Directory and other similar sources for fire resistant assemblies.

Proposed Rectification

There is an unavoidable conflict between the boundary conditions and general limitations of standard furnace testing to represent realistic mechanical behavior, and the understanding of how structural systems actually perform under fire exposure. ASCE/SEI 7-16 and ASCE/SEI MOP-138 highlight this conflict, for they both express that "restrained" is a condition that does not exist outside of a test furnace[xxxii]. Hence, the pressure that designers routinely experience from stakeholders to make a "restrained" judgment is not to apply the scientific method and their innate engineering knowledge, but rather to endorse a fallacy within a paradox with the backing of their credentials/stamp. This is truly unfair to designers, especially those that fully contemplate the relevant aspects discussed herein. For this reason, the "restrained vs. unrestrained" paradigm continues to frustrate designers, and many remain conflicted between their ethical duty as a registered design professional to base their judgments on code prescriptions or engineering factuality, and stakeholder pressures to not deviate from the "norm," which actually varies geographically. The current paradigm sets designers up for failure by its definition, and does not even incrementally raise the fire safety of buildings as compared to an environment in which it does not exist.

In the authors' opinion, the current prescriptive provision permitting reduced fire protection thicknesses for a "restrained" assembly is in need of proper rectification. At the practical level, the current paradigm's reliance on a designer's judgment is highly problematic. At the scientific level, the prescriptive provision is challenged by experimental evidence and analytical reasoning that must not be ignored for convenience. Fundamentally, the current paradigm directly conflicts with the philosophy of new standardization which explicitly prohibits the selective adoption of aspects of the prescriptive method and structural fire engineering. The prescriptive method is not performance-based in any way, and so the "restrained vs. unrestrained" paradigm should not be construed as such.

Similar to most other aspects of the prescriptive approach, an industry-consensus prescription on the matter within the building code and/or the ASTM E119 standard (and similarly UL 263) would relieve designers of an unrealistic obligation of assessing what/when constitutes an in-situ "restrained" condition. However, it should be noted such a prescription would be entirely arbitrary and not based upon any postulation of actual structural system performance under fire exposure. As an alternative, the entire "restrained vs. unrestrained" paradigm could be abolished. In this case, the industry would need to obtain a consensus on whether fire resistance listings dependent upon this paradigm would default to current "restrained" (typically less insulation thickness) or "unrestrained." This would require the next edition of the UL Directory to be reformatted in this respect.

In summary, either an explicit and arbitrary prescription on what "restrained" is should be enacted, or the entire paradigm be should deleted entirely from applicable codes and standards with proper adjustment to fire resistance directories. Paralysis on this matter is not an option, for the calls for reform will continue as industry advancement accelerates in the U.S.[xxxiii].

---

[i] UL Fire Resistance Directory, Underwriters Laboratories, Northbrook, IL, 2015

[ii] ASTM E119 (2016). E119-16a Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA.

[iii] ANSI/UL 263 (2011) Standard for Fire Tests of Building Construction and Materials, Underwriters Laboratories, Northbrook, IL.

[iv] ASTM E119 (1971). E119-71 Standard Test Methods of Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA.

[v] The BOCA Basic Building Code, Building Officials & Code Administrators International, Inc., Chicago, IL, 1970.

[vi] Uniform Building Code (UBC), International Conference of Building Officials, Whittier, CA, 1970.

[vii] Southern Standard Building Code, Southern Building Code Congress, Birmingham, AL, 1969.

[viii] The BOCA Basic Building Code, Building Officials & Code Administrators International, Inc., Chicago, IL, 1993

[ix] International Building Code (IBC), International Code Council (ICC), Washington, DC, 2018.

[x] Dumont, F., Wellens, E., Gernay, T., Franssen, J.M. (2016). Loadbearing capacity criteria in fire resistance testing. *Materials and Structures*, *49*(11), 4565-4581.

[xi] Moss, P. J., Dhakal, R. P., Wang, G., & Buchanan, A. H. (2008). The fire behaviour of multi-bay, two-way reinforced concrete slabs. Engineering Structures, 30(12), 3566-3573.

[xii] Burnier, O. (2011). Reconstitution de l'incendie de deux voitures dans le parking de la Tour d'Ivoire à Montreux, le 9 décembre 2010, Travail de diplôme, heig-vd ed., Yverdon-les-Bains.

[xiii] Garlock, M. E., Selamet, S. (2010). Modeling and behavior of steel plate connections subject to various fire scenarios. Journal of Structural Engineering, 136(7), 897-906.

[xiv] Gernay, T., Gamba, A. (2018). Progressive collapse triggered by fire induced column loss: Detrimental effect of thermal forces. Engineering Structures, 172, 483-496.

[xv] C.J. Carter, F. Alfawakhiri, "Restrained or Unrestrained?" Modern Steel Construction, Chicago, IL, September 2013

[xvi] Gross, J., Hervey, F., Izydorek, M., Mammoser, J., Treadway, J. (2005). Fire Resistance Tests of Floor Truss Systems. Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR.

[xvii] Ramesh, S., Seif, M., & Choe, L. (2017, November). Localized fire tests on steel beams with different end restraints. In The 9th International Symposium on Steel Structures.

[xviii] Lennon, T., Moore, D. B., Bailey, C. (1999). The behaviour of full-scale steel-framed buildings subjected to compartment fires. The Structural Engineer, 77(8), 15-21.

[xix] Gillie, M., Usmani, A. S., Rotter, J. M. (2001). A structural analysis of the first Cardington test. Journal of Constructional Steel Research, 57(6), 581-601.

[xx] Gillie, M., Usmani, A. S., Rotter, J. M. (2002). A structural analysis of the Cardington British steel corner test. Journal of Constructional Steel Research, 58(4), 427-442.

[xxi] Gann, Richard G. (2008). Final Report on the Collapse of World Trade Center Building 7, Federal Building and Fire Safety Investigation of the World Trade Center Disaster (NIST NCSTAR 1A). No. National Construction Safety Team Act Reports (NIST NCSTAR).

[xxii] NIST NCSTAR 1, "Final Report of the National Construction Safety Team on the Collapse of the World Trade Center Towers", Recommendation 5, September 2005.

[xxiii] Almand, K.H, "Structural Fire Resistance Experimental Research – Priority Needs of U.S. Industry", Prepared for the Engineering Laboratory National Institute of Standards and Technology.

[xxiv] LaMalva, K.; McAllister, T.; Bisby, L., "Restrained vs. Unrestrained: Within the Context of New Industry Guidance," STRUCTURE Magazine, September 2018

[xxv] LaMalva, K., “Reexamination of Restrained vs. Unrestrained,” FPE Extra, Issue #20, Society of Fire Protection Engineers, August 2017.
[xxvi] Carter, Charles J.; Alfawakhiri, Farid, “Restrained or Unrestrained?” Modern Steel Construction, September 2013.
[xxvii] Gewain, Richard G.; Troup, Emile W., “Restrained Fire Resistance Ratings in Structural Steel Buidlings,” Engineering Journal, Second Quarter, 2001.
[xxviii] ASCE/SEI 7: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers: Structural Engineering Institute, Reston, VA, 2016
[xxix] Post, N. “Guidance for Structural Fire Engineering Making Its Debut,” Engineering New Record, New York, NY, February 2017
[xxx] Post, N. “Fanning the Flames for Structural Fire Engineering,” Engineering News Record, New York, NY, January 2018.
[xxxi] ASCE/SEI Manual of Practice No. 138: Structural Fire Engineering, American Society of Civil Engineers: Structural Engineering Institute, Reston, VA, 2018
[xxxii] LaMalva, K.J.; McAllister, T.; Bisby, L., “Restrained vs. Unrestrained: Within the Context of New Industry Guidance,” STRUCTURE Magazine, September 2018.
[xxxiii] CPF Grant #04-18. Advancing Performance-Based Structural Fire Engineering Design in the U.S. through Exemplar Procedural Guidance, Charles Pankow Foundation, Vancouver, WA, 2018 < https://www.pankowfoundation.org/projects/advancing-performance-based-structural-fire-engineering-design-in-the-u-s-through-exemplar-procedural-guidance/>