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RECTIFICATION OF “RESTRAINED VS. UNRESTRAINED”

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Keywords

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

Abstract

For furnace testing of fire resistant floor and roof assemblies in the U.S., 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 to an “unrestrained” classification.

The emerging standardization of structural fire engineering practice in the U.S. 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.

Introduction

For furnace testing of fire resistant floor and roof assemblies in the U.S., the ASTM E 119 standard[i] (*Standard Test Methods for Fire Tests of Building Construction and Materials*) (and similarly the UL 263 standard[ii]) permits two classifications for boundary conditions: “restrained” and "unrestrained." Many listings in the UL Fire Resistance Directory[iii] 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 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 and contractors routinely task structural engineers and/or fire protection engineers to judge what classification should be assigned, often with pressure to select the often less restrictive "restrained" classification. Unlike the U.S., individual fire resistance rated assembly listings used in other parts of the world (e.g., Europe[iv]) do not provide differing construction requirements for "restrained" and "unrestrained."

This paper serves as an exposé of the U.S. "restrained vs unrestrained" paradigm in terms of its paradoxical nature and its unintended and potentially harmful impact the industry. More importantly, this paper offers potential solutions toward industry rectification of this controversial paradigm for the first time in a contemporary study of this paradigm.

The Need for Rectification

A structural fire protection design is deemed as adequate if it adheres to prescriptive code requirements (referred to as *standard fire resistance design*), or less commonly if its performance is demonstrated by conducting structural analyses at elevated temperatures (referred to as *structural fire engineering*). These two design methods share no qualification metrics that can be cross-plotted for comparison purposes. When employing standard fire resistance design, the primary qualification metric is *fire resistance*, expressed in hours. This metric is an artifact of standard fire testing, which requires thermal exposure of a mock-up assembly to a standardized temperature history, and its rating is judged in accordance with specific acceptance criteria. The standardized time-temperature history does not equate to any specific real fire and the acceptance criteria are predominantly expressed in thermal, rather than structural, terms. Even in the cases where structural terms are used to define a failure condition in this context (e.g., deflection), such terms have a very limited relation to actual system structural behavior. Therefore, the metric of 'fire resistance' has little to no correlation to actual structural system performance at elevated temperatures. Conversely, evaluation of relevant structural limit states and/or simulation of structural system performance is 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, as discussed herein. Accordingly, the "restrained vs. unrestrained" paradigm within standard fire resistance design can be regarded as grossly oversimplified in the vast majority of cases, and the true implications of its form may not have been entirely contemplated when first introduced. Consequently, this paradigm causes confusion and conflict for designers and building authorities alike.

The "restrained vs. unrestrained" paradigm stipulates compatibility between standard fire resistance design and structural engineering by its procedural definition. However, there are many incompatible aspects as contemporarily examined herein. Standard fire resistance design is entirely based on furnace testing of isolated structural components and assemblies, relying almost exclusively on insulation (or concrete cover) for structural fire protection. Accordingly, the intrinsic fire safety of a given structural system is not explicitly evaluated. Also, the anticipated in-situ fire conditions are not explicitly evaluated. Rather, a single intense heating exposure (i.e., ASTM E119/UL 263 curve) is used to comparatively test isolated small-scale mock-ups to generalize the robustness of the protection scheme to severe fire exposure. This approach permits relative comparison between assemblies but is largely divorced from actual expected structural system performance. Ultimately, the primary intent of this approach is to reduce the heating of individual structural components, with the goal of mitigating the risk of structural system failure during an uncontrolled fire. In reality, understanding the primary mechanisms that can lead to structural failure requires a realistic definition of in-situ temperatures and temperature gradients. Thus, the link between the intensity of heating and structural behavior is neither direct nor simple[v].

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. Accordingly, structural fire engineering explicitly requires the participation of a structural engineer in all cases[vi]. Within this framework, the thermal demand on a fire-exposed structural system 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/continuity, increasing slab thickness and/or concrete cover, connection enhancements, increasing member size, 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" classifications 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[vii]. 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[viii]. 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[ix].

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[x]. 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[xi]. Development of a varying degree of applied restraint against thermal expansion in standard fire tests was assumed to be the main reason for such variations[xii] . Additionally, during this time, there were debates about the feasibility of simulating realistic restraint within a test furnace[xiii]. The 1969 proposed revision received the greatest support from the committee members and was first adopted in the 1971 edition of ASTM E119[xiv]. 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 in the 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[xv].

The experimental program at Ohio State University involved fire tests of twelve 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 12WF27 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 ½ 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[xvi]. 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 to "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[xvii].

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 based on application of temperature limitations during restrained tests. Revealingly, this same proposal acknowledged that correlating restraint conditions of a furnace test to that present in actual building construction is a daunting task[xviii].

Table 1. Restrained Classification for Fire Resistance Ratings of Floor and Roof Assemblies and Individual Beams in the 1969 Proposal[xix]

Fire Endurance Classification For:	*Obtained or Derived From:*
1. Restrained individual beam	Loaded beam test (width 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 unrestrained)
4. Unrestrained assembly	Temperature limitations applied to restrained assembly test

Code Adoption of Restraint Classifications

At the time in which restraint classifications first appeared in ASTM E119, there were three predominant model building codes used regionally in the U.S.: (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 Code[xx], the 1970 edition of the UBC Code[xxi], and the 1969 edition of the Southern Standard Building Code[xxii] each adopt and reference ASTM E119. Beyond these externally pointing references, the adopted buildings codes at the time of the revision to ASTM E119 in 1971 offer no explicit guidance on restraint classification, thus effectively abdicating the classification. Although an interpretation by BOCA in 1993[xxiii] clarified the need to apply the ASTM E119 criteria to the end conditions (i.e., consideration of furnace boundaries), the model building codes remained silent on what specifically constitutes "restrained" or "unrestrained" boundary conditions when considering in-situ construction. Complacency regarding this issue throughout this time may have been based on a level of comfort with transferring the onus of resolving the specific issues onto designers. This became clear as further code commentary was developed.

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, now §X3, and the language remains largely unchanged. To date, ASTM E119 has not provided any precise method for defining "restrained" or "unrestrained" conditions for a given fire-rated assembly within in-situ construction. However, the standard offers some 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." Furthermore, §X3.5 describes restraint in actual building construction as occurring "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." "Unrestrained" conditions are essentially defined by 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)[xxiv] 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 similarly UL 263) in §703.2, and provides limited 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 to designers. Further confusion is then added by including a requirement that the registered design professional – typically a professional fire or structural engineer – be responsible for providing sufficient evidence to the building official in order to qualify an assembly as "restrained." Figure 1 below illustrates the full timeline of relevant code adoptions.

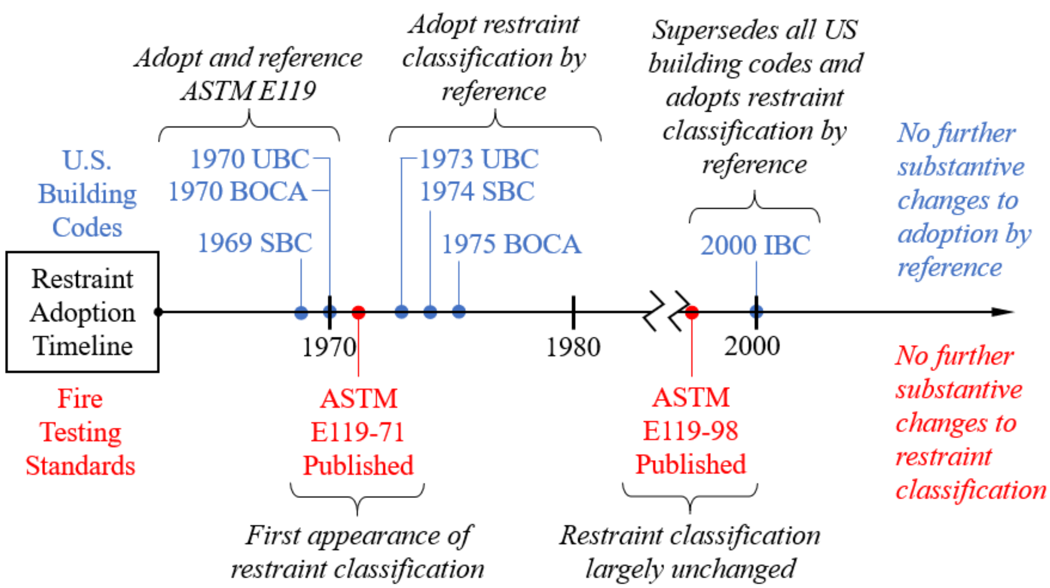

Figure 1: Code Adoption Timeline[xxv]

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 including judgment of restraint, entitled 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 relevant, the information above does not provide the explicit and quantifiable guidance necessary to adequately judge or justify restraint conditions in the context of the prescriptive method, no matter the skill or competence of the design professional. In fact, advanced knowledge of structural performance under fire exposure may leave a competent designer more confused and conflicted about this paradigm as compared to a designer with little or only basic knowledge in this respect[xxvi].

Furnace Testing versus In-Situ Restraint

Boundary Conditions

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. The flexural stiffness of furnace framing is very high, often much higher than would be expected in a typical structure, and this stiffness remains constant throughout the fire test, a condition that is often unrealistic in a fire-loaded structure. If the assembly is made of two components (e.g. 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. Furthermore, an assembly is considered "unrestrained" when it is free to thermally expand without contacting the furnace edges. By this definition, 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 the prescriptive definition of restraint 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 requirement 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. As a result, these conditions may provide any degree of restraint, with most offering intermediate levels that likely lie between "resisting substantial thermal expansion" and allowing free thermal expansion and rotation. Further, the restraint offered by an assembly's connections and surrounding framing may significantly change during the fire event. Finally, the restraint conditions may enhance, but also could degrade, the resulting structural performance in fire. Consequently, reliance on such an oversimplified classification system is at best misleading, and at worst, unsafe.

Failure Criteria

At the heart of the divergence between in-situ and furnace testing restraint is the definition of "failure." ASTM E119 (and similarly UL 263) establishes acceptance criteria used to determine failure of a test assembly. For the integrity of a floor assembly to resist flame passage, the standard states "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 "unrestrained" classifications. Furthermore, the standard specifies historically-based temperature thresholds of the structure that shall not be exceeded, and these temperature thresholds are also identical for "restrained" and "unrestrained" systems. For "unrestrained" floor and roof assemblies, ASTM E119 states that "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 acceptance criteria thresholds for "restrained" assemblies, but only changing the period from the "classification period" to the "first hour," the standard further states 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 with the period can only be interpreted and justified in terms of an undefined, but apparently expected, beneficial effect of restraint on structural performance during a fire. This 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 actual structural system behavior. There exists no clear evidence supporting either of these assumptions.

In addition to temperature thresholds, the confirmation of structural adequacy diverges between in-situ and furnace testing. In a furnace test, the test is typically halted when an arbitrary threshold is exceeded in deflection or rate of deflection. At that time, it is deemed that the system has failed, as the structural component is interpreted as no longer being able to sustain the load. The adopted deflection thresholds are essentially arbitrary, as they have no documented meaning outside the context of the furnace testing context, and the values selected for these thresholds may influence the fire rating[xxvii]; however, it is necessary to adopt a limit to define the "end point" of the test. Once these limits have been exceeded, there is little point in continuing the test because, on the one hand, continuation could endanger the safety of the test equipment and, on the other hand, no means of load redistribution is possible since the test is conducted on an isolated structural component or assembly. Conversely, in an actual structural system the end conditions of a structural component could affect the structural failure mode. While a simply supported beam with no restraint could exhibit a failure mode that is qualitatively similar to that of a furnace test, a restrained component or assembly part of a structural system may develop secondary load bearing or load redistribution mechanisms when undergoing large displacements under fire exposure that could dramatically affect its performance and the failure mode, rendering irrelevant the adoption of deflection threshold criteria in furnace testing. For instance, a restrained beam may develop catenary action provided the end restraints (i.e. connections and supporting framing) are capable of supporting the resulting tensile forces. This type of secondary load bearing and load redistribution behavior can be highly beneficial to fire performance. In fact, robust structures can be intentionally designed to take advantage of catenary action, tensile membrane action, and other secondary load redistribution mechanisms that build on structural system behavior to enhance performance under fire. The mobilization of these beneficial mechanisms is extremely dependent on the restraint conditions of in-situ structural systems; however, these effects are by no means realistically captured by "restrained" furnace tests.

In-Situ Restraint Effects

The effects of in-situ restraint on structural components depend on, amongst other things, the position of the supports. 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 (throughout the fire). Axial restraint in horizontal concrete members can also enable compressive membrane action (or compression arching) to develop. This secondary load-bearing and load redistribution mechanism can enhance the performance of such members, although the efficiency of this secondary action, again, depends on the magnitude and location of the restraint to the edges of the member[xxviii].

In an actual composite floor beam and concrete slab assembly, unlike in furnace testing where both components would be restrained equally, the beam and slab will generally experience varying degrees of axial restraint. This can result in differential longitudinal movement under fire exposure, particularly if the structural components are not acting compositely, resulting in potentially significant differences in overall performance. Figure 2 illustrates the difference in boundary conditions (i.e., restraining spring stiffness) between furnace and in-situ conditions for a composite steel beam and slab.

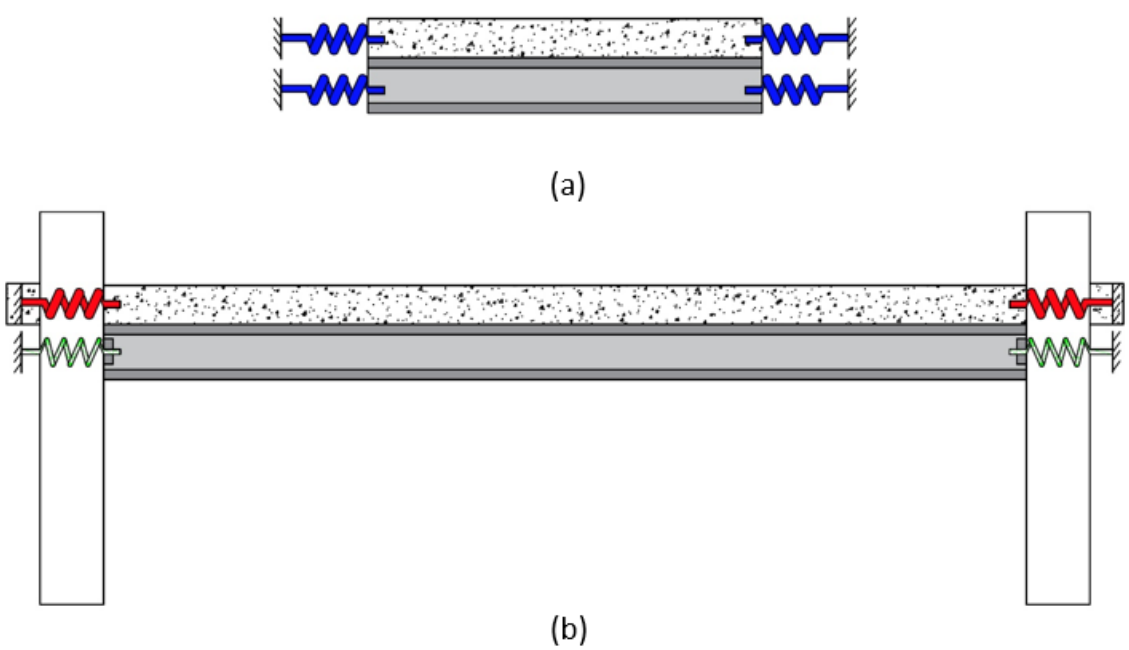

Figure 2: Furnace (a) vs. In-Situ (b) Boundary Conditions[xxix]

[*Each Spring Color Represents a Different Stiffness*]

Due to the degree and variability of in-situ restraint during a fire event, nonlinearities in the response of the structural system at the ends of the component can result, especially when considering the behavior of materials at elevated temperatures. For instance, yielding of connections in a moment resisting frame would modify the rotational restraint provided at the ends of the beam, reducing the overall stiffness significantly and limiting the restraining strength. Similarly, geometric nonlinearities (e.g., local and global instabilities, large displacements) can affect the stiffness of an assembly's restraints. For example, considering a floor beam undergoing thermal expansion within a structural system, the beam may impose lateral loading on the girder and column support points. Depending on the detailing of the support points, thermal expansion may or may not be resisted. In fact, the thermally-induced lateral loading may exceed either the beam or support capacities resulting in a significant change in restraint. Accordingly, the possibility that the restraint thermal forces may jeopardize the surrounding structure must clearly be taken into account, as the potential effects could greatly influence the level of performance. For instance, in the 2010 fire in the Tour d'Ivoire in Montreux, Switzerland, thermal expansion of concrete slabs subjected to the action of two burning cars led to the shear failure of a supporting column that was several meters away from the fire source, resulting in collapse[xxx]. Finally, other components framing and supporting a given floor or roof assembly (e.g. girders, column supports, surrounding framing beams and/or floor and roof assemblies, etc.) may themselves be subjected to heating from the fire, in which case their strength, stiffness, and other physical properties may be affected, which, in turn, may generate complex transient interactions at the boundaries of the different components and assemblies.

Non-Standard Fire Exposure

The simplification of the fire exposure into a monotonically increasing time-temperature history as used for standard furnace testing represents another limitation in the way that restraint is considered in standard fire resistance design. Actual building fires consist of a heating phase followed by a cooling phase. During the heating phase, heat from the fire increases the temperature of the structural elements in a manner that can produce temperature gradients within these elements. The increase in bulk temperature corresponds to thermal expansion, while thermal gradients can lead to curvature and overall contraction of the element[xxxi]. The performance of the structural element when restrained is, therefore, captured by the coupled effect of bulk heating and temperature gradients. Given that a furnace follows a predefined temperature history, it cannot reproduce the variety of fire related temperature gradients. Similarly, cooling is likely to generate a reversal of thermal strains (shift from thermal expansion to contraction) that can affect connections between components[xxxii] and dramatically redistribute forces in a structural system[xxxiii]. This effect is also not approximated in the standard furnace test. To resist cooling, supports may need to resist thermal contraction forces that aggregate in the structural system and through connections. The restraint forces at the end of a structural component under realistic temperature histories differ substantially from those experienced during a furnace test. Thus, the standard fire test is an ineffective means by which to consider boundary effects given the potential complexities generated in a realistic fire.

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. The American Institute of Steel Construction (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[xxxiv]. This testing resulted in modifications to a specific UL listing (D982). The National Institute of Standards and Technology (NIST) performed furnace testing of steel trusses typical of the World Trade Center (WTC) 1&2 floor construction[xxxv]. Contrary to expectations, it was found that an "unrestrained" assembly achieved a higher fire resistance rating when compared to an equivalent "restrained" assembly. These 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[xxxvi]. These results demonstrate that the effect of restraint can vary considerably among different structural systems and restraint conditions, and cannot be easily simplified in practice, particularly in a binary fashion as is currently predominant practice in the U.S.

Incompatibility

Similar to the previously cited and discussed component-level performance testing and research, the importance of restraint conditions on the fire performance of building structures has also been established by full-scale fire tests such as the Cardington test[xxxvii], as well as by analysis of real failures, such as the NIST investigation on the WTC 7 collapse[xxxviii]. These studies, and many subsequent analyses, have undoubtedly demonstrated that structural system behavior can differ dramatically from isolated member behavior, and that thermal restraint effects often govern much of the response of structural systems in fire. However, it is not within the purview of standard fire resistance design to consider such behaviors, as declared in 1967[xxxix]:

> *If we attempt to develop the fire endurance of a construction system in actual buildings under fire conditions we would not obtain a single-valued answer, but rather we would have to measure a range of performance levels depending upon methods of structural framing existing in a single building as well as the methods of structural framing of any and all buildings into which the construction system under consideration could be incorporated…*

It is the objective of structural fire engineering to quantify structural fire effects by the application of scientific and engineering methods. Currently, advanced analysis based on first principles and numerical methods is the best option to predict the behavior of structural systems under fire exposure. Accordingly, advanced analysis techniques, like finite element analysis (FEA), can be used to capture the complex interactions between structural components, including the effects of thermal expansion and contraction, the nonlinearities resulting from thermal effects as well as large displacements and the effect of realistic fire exposures including heat transfer and the different stages of fire development (e.g. heating and cooling). Hence, advanced analysis can be used to explicitly account for the transient effect of restraint for the near endless variety of structural systems and restraint conditions in their as-built condition. The last two decades have seen major advances in the development of advanced analysis software for structural fire engineering along with parallel improvements in computational speed and power, making these computational and analytical tools instrumental to supporting the emerging practice of structural fire engineering in the U.S.[xl] and elsewhere.

Examination of the Ongoing Justification

Realization that the prescriptive method does not – and theoretically cannot – provide adequate justification to design professionals to make rational judgments with regard to the “restrained vs. unrestrained” paradigm is not new to the building design community. Indeed, both government and industry commentators have repeatedly advocated for more comprehensive guidance/prescription on the “restrained vs. unrestrained” classification of fire resistant assemblies. In the final report on the WTC Investigation[xli], NIST recommended (in 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[xlii]. A group recommendation from the workshop dealing with steel structures provided a specific 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 Structural Engineering Institute’s (SEI) flagship magazine echoes the above concern[xliii]. Also, an official straw poll found that a near unanimous consensus of the ASCE/SEI Fire Protection Committee objects to the current paradigm, and the membership advocates for designers to make conservative “unrestrained” judgements, eliminating the need for restraint evaluation, until the paradigm is fully rectified[xliv]. Lastly, during a recent workshop on the “restrained vs. unrestrained” paradigm[xlv], the following points were expressed in a majority consensus (>70% attendee approval):

- From the code authority perspective, furnace testing standards only provide examples/guidance for restraint classifications, so the designer is ultimately responsible for such judgments in all cases and circumstances.

- From the fire testing standards authority perspective, the boundary conditions of the test furnace should be clearly described and considered when making a judgment on restraint within the prescriptive method.

- From the academic perspective, restraint conditions of a furnace test can virtually always be expected to differ from those of the in-situ structural system.

- From the design professional perspective, although consideration of restraint is a common task in the industry, designers are concerned about the potential liability associated with making these judgments in the absence of clear and quantifiable guidance.

Historically and currently, restraint classification in U.S. building codes and their referenced standards remains, in both theory and practice, essentially undefined. Some guidance is provided; however, this is insufficient to ensure uniform application across a range of assemblies and in-situ conditions. The need for additional guidance thus remains.

In light of this ongoing dilemma, some American industry interest groups such as AISI and AISC, continue to advocate that *all* typical steel construction should be rated as restrained[xlvi] based on limited supporting research[xlvii] for this rationale, in the opinion of the authors of this paper. The justification appears to be primarily based on the observance of (typically) beneficial compressive membrane action during furnace testing, which can act to limit member deflections and achieve higher fire resistance ratings. 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 that floors are more likely to act as tensile membranes thereafter, assuming adequate support and continuity is provided by the surrounding framing[xlviii]. This is particularly pertinent for floors with realistic structural spans, as compared with the comparatively short typical spans of 14 ft. or 17 ft. used in furnace testing. This declarative rationale also extends to the consideration of concrete structures in which all spans and conditions are routinely considered to be "restrained" and corresponding lower concrete cover requirements are applied. In terms of prestressed concrete, this can be particularly problematic, especially for assemblies that are susceptible to heat-induced explosive cover spalling. Consequently, the level of applied fire protection (or concrete cover) provided to components and assemblies is routinely reduced based upon these declarations, and not upon actual judgement of the registered design professional. Giving the dearth of full-scale concrete tests available to support this rational, it appears difficult to defend full reliance on the presumed beneficial effects of restraint in real construction. However, many design professionals routinely follow such declarations without protest for convenience and expediency. Unfortunately, those designers that choose not to (e.g., those with more advanced knowledge of structural behavior under fire exposure) are easily subject to perceptions by other project stakeholders as being obstructionist or over-conservative. Hence, many well-informed designers are often placed in a quite precarious position in this respect.

The "restrained vs. unrestrained" paradigm is deeply entrenched in standard fire resistance design due, in part, to the evolution of the ASTM committee that maintains the contemporary ASTM E119 standard. When ASTM as a body began, changes to standards were relatively straight-forward, and transparent within the public record (all meeting minutes can be readily obtained in historical transactions). In the early days, the committee membership overseeing the ASTM E119 standard consisted of less than 20 representatives, primarily of professional societal and insurance background. In general, few material manufactures were represented on the committee when it began. In fact, at its formation, those from the material industries in association with the society were largely from the concrete industry and expressed that the committee could be at risk of being regarded as a trade organization. For example, Robert Lesley (arguably the founder of the Portland Cement Association (PCA)) advocated the following at the committee's first attempt to standardize fire resistance testing[xlix]:

> *…The American Society for Testing Materials with its committees stands for fair play for all materials having common use and a common purpose, and we do not want the specifications that go to the public to be questioned as being influenced by cement men, by concrete men, or by men in any other form of industry or trade. This is a broad scientific body, and not a trade organization.*

As the standard fire test became enforced and listings began to be codified, the make-up of the committee evolved and changed. Various material representatives from across the construction industry joined the committee with what appears to be commercial interests as a key motivator. For example, the following was proclaimed at the time[l]:

> *Manufacturers (need to) know the resistance periods of their materials and increase them if possible. [Financial] Competition must be met on the basis of performance in tests.*

Presently, the materials industries are well represented in the ASTM committee that maintains the ASTM E119 standard.

Contrary Industry Advances

The current edition of the ASCE/SEI 7 standard[li] (*Minimum Design Loads and Associated Criteria for Buildings and Other Structures*) permits designers to use 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 in accordance with 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 crystallizes the fact that there is little or 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 warns 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 also addresses thermal restraint more directly/explicitly than preceding U.S. codes/standards. 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 in some cases exhibit worse behavior than a relatively unrestrained condition with all else being equal, and that thermal restraint conditions encompass many more than two distinct scenarios (i.e., "restrained" or "unrestrained").

Effectively, Appendix E brings structural engineers into the fold of structural fire protection design as integral participants 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 required to be considered explicitly as a design load condition in a U.S. structural engineering standard[lii]. As a supplement to Appendix E, ASCE/SEI has recently released a new Manual of Practice No. 138[liii] (MOP-138: *Structural Fire Engineering*). Similar to ASCE/SEI 7, MOP-138 prohibits designers from intermingling aspects of the standard fire resistance design (prescriptive method) with structural fire engineering[liv]. 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.*

MOP-138 Section 7.2.1 further 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 little open to interpretation in terms of consensus from designers. However, building codes continue to make reference to the "restrained" and "unrestrained" qualifications included in the UL Directory and other similar sources for fire resistant assemblies since such provisions are generally reliant on these references.

ASCE/SEI guidance supports structural engineers who wish to undertake rational design in the field of structural fire protection. Furthermore, building officials now have tools to comprehensively evaluate structural fire protection variances[lv]. It is the authors' joint opinion that the new ASCE/SEI guidance should influence building officials' interpretation and enforcement of restraint classifications within standard fire resistance design. Also, it is the authors' hope that advanced knowledge of structural system performance under fire exposure will no longer be penalized by project stakeholders in this respect.

Proposed Rectification

There exists an unavoidable conflict between the boundary conditions and general limitations of standard furnace testing and the ability of such a method to represent realistic structural system behavior under fire exposure. ASCE/SEI 7 and ASCE/SEI Manual of Practice No. 138 highlight this conflict, and both express that "restrained" as stipulated by the "restrained vs. unrestrained" paradigm in the U.S. is a condition that does not practically exist outside of a test furnace[lvi]. Hence, the pressure that design professionals routinely experience from stakeholders to judge an assembly as “restrained” is not based on applying the scientific method or on their engineering knowledge and understanding, but rather on endorsing a demonstrated fallacy – troublingly with the backing of their professional credentials/stamp. This is unfair to design professionals, especially those who understand the relevant aspects discussed above. Consequently, the “restrained vs. unrestrained” paradigm continues to frustrate some design professionals, and many remain conflicted between their ethical duties as a registered and licensed professional to base their judgments on code prescriptions or engineering principles, and stakeholder pressures to reduce cost and avoid deviation from “normal practice,” which actually varies based on jurisdiction in the U.S. The “restrained vs. unrestrained” paradigm sets design professionals up for failure by definition and does not necessarily improve the fire safety of buildings as compared to an environment in which such a requirement for classification does not exist.

In the authors’ opinion, the current prescriptive provision in the U.S. permitting a lesser amount of applied fire protection for steel structures (or concrete cover for concrete structures) for a “restrained” assembly should be discarded. At a practical level, the “restrained vs. unrestrained” paradigm’s reliance on a design professional’s judgment is highly problematic. At a scientific level, the prescriptive provision is not supported by relevant experimental evidence or analytical reasoning. Fundamentally, the paradigm conflicts with the overarching philosophy clearly conveyed by new industry standardization, which prohibits the selective adoption and/or intermingling of aspects of the prescriptive method and structural fire engineering.

Similar to most other aspects of the prescriptive approach, an industry-consensus prescription on the matter within the building code and the ASTM E119 standard (and similarly UL 263) would relieve design professionals of an unrealistic obligation to assess in-situ restraint in the absence of an actionable, quantifiable, documented definition. However, it should be noted that, even if defined, such a prescription would be entirely arbitrary and not based upon any postulation of actual structural system performance under fire exposure. In essence, it would serve as an another empirical indexing measure that designers could uniformly reference and apply, solving the issue of consistent application, but being otherwise divorced from realistic expectations of structural system performance.

As an alternative to an explicit prescription, the “restrained vs. unrestrained” paradigm could be entirely abandoned. In this case, the industry would need to obtain a consensus on whether fire resistance listings, which are dependent upon this paradigm, would default to current “restrained” specifications (typically less insulation thickness for steel structures or concrete cover for concrete structures), current “unrestrained” specifications, or some type of compromise between the two. If a compromise is proposed, competing interest groups should be included in the discussion (e.g., the steel industry and the applied fire protection industry) to promote a balanced approach. Such measures would require the next edition of the UL Directory to be comprehensively revised in this respect.

At an absolute minimum and in the short term, it is the authors’ opinion that a specific statement should be added to the next edition of the ASTM E119 standard (and similarly UL 263) that explicitly warns users of the limitations of the “restrained” interpretation and the lack of an industry consensus definition for what constitutes a “restrained” in-situ condition. Such a disclaimer has been implemented for the standard fire time-temperature curve in the past, so it is a reasonable short-term goal founded upon past precedent. A statement of this kind would likely catalyze dialogue within ASTM and the wider fire safety industry. However, the authors do not believe this measure alone would properly rectify the paradigm since it would have minimal impact on industry practice without enforcing efforts or an official change in the standard's procedure. Nonetheless, it would mark a clear start toward proper rectification.

As evidenced above, there is a demonstrated need for ASTM (and similarly UL) to take an active role in explicitly defining what specifically constitutes an in-situ "restrained" condition or abolishing the interpretation entirely. The authors' joint preference would be for the latter. In the absence of their action, it is the position of the authors that designers should refrain from specifying "restrained" listings entirely. In this unfortunate case, the design community would need to self-regulate in the midst of inaction from the originating party of this paradigm and hold its peers accountable (e.g. by means of third-party review). Accordingly, designers would default to specification of "unrestrained" listings which is deemed as conservative by building codes. Promisingly, the conditions for reform are improving as industry advancements and education in structural fire safety continue to accelerate in the U.S.[lvii].

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