STRUCTURAL FIRE DESIGN FOR COMPOSITE STEEL DECK CONSTRUCTION IN CANADA

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ABSTRACT

In Canada, there has been a dearth of research and design attention given to developing innovative fire design solutions for composite steel deck construction. This is despite the increasing number of these constructions in densely populated metropolitan centers in Canada. These structures are currently treated with classic prescriptive based fire designs. Isolated building components are designed based on implicit fire relations and as international practice has shown, prescriptive fire design may be viewed as restrictive, uneconomical, and is challenged in its representation of reality. Internationally, practice has been maturing towards Performance Based Fire Design (PBFD) for composite steel deck structures for the last several decades with significant research into the behavior of these structures occurring. Herein; the first objective is to examine the development of PBFD techniques used globally through relevant experiments, experiences, and applications. The second objective is to explore the state of fire design within Canada and what can be learned from global fire design and research experiences – the international state of the art. The goal is to promote best practice discussion on where structural fire design for composite steel deck construction in Canada, and internationally, could move towards.

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INTRODUCTION

In Canada, the treatment of fire protection is predominately prescription based. The National Building Code of Canada (NBCC), contains acceptable solutions that, when followed, are intended to provide adequate performance under fire conditions. These assemblies are tested individually under standard fire conditions and given fire ratings that indicate the time to failure, with failure being when the stability, integrity, or insulation criteria are met and exceeded. As far back as 1898, however, the importance of analyzing full building response to fire was understood when pioneering fire engineer Himmelwright stated, "the actual and relative expansion of the materials due to heat and the deflections caused by unequal heating must receive careful consideration...The limit of safety is in some cases dependent upon temperature and in other cases upon expansion" [1]. The objective of this paper is to investigate the development and application of Performance Based Fire Design (PBFD) in a global context, before shifting to an examination of the state of PBFD within Canada as it relates to the design of composite steel deck construction. Composite steel deck construction has been selected due to the abundance of the construction method in Canada, coupled with the advances seen globally as it relates to PBFD. The authors present a preliminary framework that builds on lessons learned to advance PBFD in Canada in a responsible and efficient manner.

DEVELOPMENT OF PBFD

Prior to the early 1990's, fire research, design, and construction focused on single member response to fire as made evident through the state-of-the-art design guidelines available. The guidelines, dating back to 1976 with Sweden adopting the "Rational Fire Engineering Method" proposed by Petterson in the 1960's, detailed how to calculate steel temperatures through a heat transfer analysis and related the elevated steel temperature back to a material strength for use in design [2]. In North America, approved fire solutions are related to ratings from the ASTM E119 fire test. This test includes a "steel failure temperature" that was to be met by the approved solution, but was also imposed by the Authority Having Jurisdiction (AHJ) on any performance-based solution with the structure not allowed to exceed it. Seigel proposed that the limiting temperatures were introduced by ASTM and Underwriters' Laboratories as an additional end-point criteria to the E119 standard since it was understood that the fire endurance tests were not representative of the assemblies in their as-built condition, both in terms of arrangement and loading [3]. It does not represent when steel fails as that has been shown to be dependent on arrangement, restraint, and loading [4]. It was not until 1990 that whole building response was demonstrated and testing started to evolve in this direction.

BROADGATE FIRE, 1990 [5]

In 1990, a 14 storey building under construction in Broadgate experienced a fire that lasted over 4 hours showing no sign of structural collapse. At the time of the fire, the sprinkler system and fire protection was incomplete. This was one of the first opportunities to analyze the effects of fire on a full-scale, contemporary steel building. An investigation into the building's response to the fire concluded that the structure performed well due to load redistribution. Even without fire protection measures in-place, the structural damage was only 6% of the total cost from the fire. The conclusion of the investigation stated "it would be worthwhile in the future to investigate the effects of major fires in significant structures to gain a better understanding of the most important mechanisms in practice". Indeed, the momentum towards contemporary PBFD started here.

CARDINGTON STEEL TESTS, 1996 [6]

Following the Broadgate fire of 1990, a series of large-scale, non-standard, full structure tests were performed in Cardington, UK. The structure considered was an 8 storey, composite steel building. In total, 7 separate tests were performed at different times, with different combinations of protected primary members and unprotected secondary members. Bisby et al., provide a succinct summary of each of the tests and the key observations as taken from the available literature. Across the 7 tests, all of the studied members showed significant deflection ranging from 180 mm to 1200 mm with "no signs of collapse". The test members had experienced local failures, including beam buckling, shear-plate fracture (upon cooling), and cracking of the concrete slab. Despite the local failures observed, a global structural failure was not observed. The observations related to PBFD were:

- Load redistribution of a real structure is possible with tensile membrane action. In this condition, the secondary beams are allowed to fail and the load support mechanism is tensile forces in the floor plate resisting gravity loads and supported by protected primary members;
- With tension membrane action, additional forces are imposed on the beam-to-column connections, as well as within the plane of the composite floor deck at the primary beams. This was shown through beam-to-column failures and significant cracking of the concrete over the supporting beams where reinforcing mesh had been missed in the construction of the test assembly; and
- The importance of cooling was demonstrated in Tests 1 and 2 as connection failure was observed through increased load from structural contraction.

The fire resistance of the floor plate was shown to be much different than, in this case greater than, the fire resistance predicted from single member standard furnace tests [6]. The proposed methodology for unprotected secondary beams in a composite steel-framed building formed the basis for further testing [6] and has now permitted model verifications to help apply PBFD for real structures.

APPLICATIONS OF PBFD IN AVAILABLE LITERATURE

Load carrying mechanisms exist in real structures that cannot be demonstrated by the single member fire tests. Successful applications of PBFD will be discussed briefly. The first case study uses single member analysis and subsequent testing to verify reserve member capacity, the second refers to whole building response made possible by the test data from Cardington, potential advances are then discussed.

CASE STUDY #1: 600 GRANT STREET, 1971 [7]

This 64 storey office tower in Pittsburgh contained exposed structural steel columns filled with water to keep temperatures below a certain threshold in a fire. The fire design of this time period revolved around single member analysis and did not take into account the global behavior of the structure. The design was "based on performance" and used heat-transfer rate equations to determine the temperature on the surface of the exposed structural steel. It was rationalized that the internal surface of the steel would not exceed the boiling point of water, and thus an average temperature across the cross section of the steel could be calculated. The maximum computed temperature of the steel columns with 4 hour standard fire exposure was 337C, which was compared to the 538C maximum temperature permitted by E119 [7]. Seigel states that structural integrity is assumed to be maintained as long as the steel is not heated to a level that reduces its strength below design loads [3]. This case study demonstrates how PBFD had previously been applied to steel columns, however they are just a single element in an entire composite steel-framed structure.

CASE STUDY #2: MINCING LANE 2006 [8]

An Arup case study of a composite steel deck system structure provides a stark difference in design approach. The first advance in design methodology in this case study demonstrates the extent of analysis. Using Abaqus, the entire floor plate was analyzed for two different fire protection approaches. First, the building was analyzed using fire protection that met typical prescriptive code requirements. Next, secondary beams were left unprotected and the analyses were run again. The goal of this was to demonstrate analytically that the protection of secondary members was redundant. The second advance in design methodology was the design fires. Three fire scenarios were designed for: a "short-hot" fire where most of the glazing is assumed removed from the structure, a "long-cool" fire which is assumed ventilation controlled, and 90 minutes of standard fire exposure [8]. The 90 minutes of standard fire is actually not representative of a real fire, however many are accustomed to its use from its longevity, including AHJs. Its use to compare a prescriptive design to a PBFD gives a frame of reference for those familiar with it. The acceptance criteria used was to avoid structural failure (identified by runaway deflections, as opposed to a limiting steel temperature) and to maintain horizontal and vertical compartmentation (by ensuring connections at the vertical shaft wall did not fail). A direct relation to the stability and integrity criteria can be seen, albeit adjusted in practice to accommodate a whole-floor analysis in lieu of a single member. The results of the global analysis with secondary beams left unprotected were that runaway deflections did not occur, however strains in the rebar of the concrete directly over supporting beams were around 2%. As a result, a connection model was developed to ensure the support had adequate capacity to allow the development of membrane action. The resulting deflections of the floor plate for the PBFD were shown to be similar to the model with prescriptive fire protection throughout. Having these models, and being able to show that the PBFD behaved quite similar to approved methods, helped in the approval of the design by the AHJ.

LOOKING FORWARD

A further observation made during the Cardington tests was a spatial evolution in time of the compartment temperature [9]. This behavior was further demonstrated in the Dalmarnock test series where the increased instrumentation density allowed for spatial vertical distribution of the temperature profile to be analyzed [9]. Moving forward, the design of structures for fire can take into account actual flame travel within the compartments. This may be of considerable importance for large open office plans where uneven heating of the structure across bays with time, caused by travelling fires, could have detrimental effects on the performance of the structure [13][14]. An international research program has been initiated, which at the time of writing has demonstrated shortcomings of the traditional compartment fire framework where the range of validity is exceeded [9]. Advancing a framework that considers large enclosures with nonhomogeneous conditions to a stage that it can be used more efficiently in practice with test verification may be a next step for advancing PBFD internationally.

CANADIAN MOMENTUM FOR PBFD

In 1994, the Canadian Commission on Building and Fire Codes (CCBFC) formed a task group to develop a long-term strategy for Canada's building and fire codes [10]. At that time, Canadian codes were prescriptive, and one goal of the task group was to evolve them. What resulted was Canada's introduction of the world's first objective-based codes in September 2005. The reason for an objective-based approach as opposed to performance-based is because the CCBFC feared that performance-based might create an "anything goes" situation as had been seen globally where poor regulation and implementation accompanied PBFD [11].

Canada's objective based codes contain three divisions within them: Division A provides the scope and definitions, Division B lists acceptable solutions, and Division C is for administrative requirements. The acceptable solutions in Division B automatically satisfy all requirements of Division A, however an 'alternative solution' requires the builder, designer, or building owner to show that it will perform the functional statements of Division A as well as the 'acceptable solution' it replaces. Where it becomes difficult, is in showing equivalence since not all acceptable solutions in Division B have their level of performance in quantitative terms. Objective-based codes are hence "benchmarking" and it must be shown that the alternate solution performs at least "as well as" an acceptable solution according to the functional and objective statements for that structural assembly.

In Canada, there is currently a trend towards PBFD solutions, but for now the objective-based solutions are guiding designers and decision makers in that direction with a few key differences. At this stage, not all acceptable solutions frame their performance in precise terms; but they all contain an inherent level of performance within them that represents society's expectations of building performance to fire [11]. The critical next step in Canada towards full performance-based fire solutions is to develop verifiable performance criteria for the acceptable solutions of Division B. This could be dependent or independent of the acceptable solutions. The National Research Council (NRC) currently has research projects aimed at quantifying the level of performance current acceptable solutions provide with the aim of using this approved performance as the criteria for true performance-based solutions [11].

An eventual shift could have benefits to the building community at-large as objective-based solutions are based on showing equivalency to approved solutions, many of which were tested individually under unrealistic standard fire conditions to meet the requirements of E119 (or equivalent). With objective-based codes, the benefits of analyzing whole building performance, as demonstrated globally and successfully implemented to real building through PBFD, cannot be realized.

FIRE SAFETY DESIGN PRACTICE TODAY IN CANADA

In Canada, most building fire design follows the prescriptive based approach from NBCC. We are, however, beginning to see PBFD solutions in the area of building egress. Referring to Division B, we see for example that the travel distance to an exit cannot be more than 40m for a business occupancy. The objective of this clause is to limit the risk of delayed movement (OS3.7), with the function being to facilitate timely movement during an emergency (F10). Instead of meeting the prescriptive travel distance of 40m that the acceptable solution states, practitioners have begun to calculate ASET and RSET to show that the available time is greater than the required time for evacuation. In doing so, the objective and functional statements of the approved solution are met and the alternate solution is shown to perform as well as the approved solution.

With regards to composite steel deck construction, it can be seen that existing practice already lends itself to the PBFD approaches being used in practice elsewhere. Typical good construction practice of composite steel deck calls for additional steel mesh to be placed over primary supporting beams. This mesh was shown to be crucial in the Cardington tests [6]. Further, computer analysis has shown the importance of this mesh in developing and maintaining tensile membrane action when and if the secondary beams 'shed' their load [8]. When looking at current floor plans of modern construction, a recurring pattern of primary beams with secondary beams on roughly 3 m centers are typical for an economical design. This same arrangement is what the case studies have shown, since aspect ratios of 1 to 2 for each bay may allow for tensile membrane action to develop provided the primary beams and columns are protected.

The mentioned egress example was for a case where the prescriptive approach is stated in quantifiable terms. The difficulty in Canada for composite steel decks is that the acceptable solutions do not have their performance quantified. To help new solutions be incorporated into construction, the Canadian Construction Materials Centre, offers an evaluation service that will assess a product's performance and compare it to a minimum acceptable solution from Division B. This does not guarantee that the product will be approved, but it does support the objective-based approach by showing equivalence and could help the AHJ, specification writers, design professionals, and builders determine approval or acceptability [11]. It is unclear if this approach can extend to an entire building, for example to show if unprotected steel members in composite steel deck construction can demonstrate as equivalent to an entire floor of steel beams protected with an acceptable solution, however this is an approach put forth by the timber community to show equivalence between timber construction and current prescriptive solutions.

WOOD

Due to limitations within the Canadian building code, the authors of "Technical Guide for the Design and Construction of Tall Wood Buildings in Canada" [12] have proposed using the objective based-codes on the basis of equivalent risk for tall timber structures. This rationale is a risk-based approach for a building of combustible construction that could demonstrate the overall level of safety and risk that a noncombustible structure of acceptable solutions would have. This equivalent risk level would translate into equivalent performance allowing the alternative solution to meet the objective and functional statements of the acceptable solutions. The objective-based approach would extend to the entire building such that equivalent performance is shown for the complete timber structure that would be provided by the group of acceptable solutions compiling the entire noncombustible, code compliant structure [12]. The proposed tall timber structure would be a partially encapsulated solution, meaning that the timber is partially protected from the effects of fire. The goal of this is to ensure that the structure itself does not contribute to the fuel load of the room until flashover. Once flashover has occurred, the fire typically shifts to a ventilation controlled condition where available oxygen controls burning. Once this occurs, the effect of a timber structure contributing to the fuel load is thought not to be as pronounced [12]. However, this means that the fire may have prolonged burning. To compensate, additional fire protection measures would be implemented so that performance is unaffected, such as improved sprinkling. The end goal is for the overall risk to be equivalent to an acceptable solution structure using a risk analysis under different fire scenarios. The risk assessment could be qualitative or quantitative so long as it demonstrates equivalency using accepted methods. If the steel composite deck industry could learn from the timber industry proposals, the overall risk of the structure due to fire could be considered without the focus being on single member behavior as the current application of the objective-based codes have trended. Additionally, there would be a need to compromise to ensure equivalent performance of the overall structure. In the case of timber construction, sprinkling demands increased. In the case of steel composite construction, connections will face increased loads to allow tensile membrane action to develop, sprinkling requirements may be increased, and additional reinforcing of the concrete floor may be required.

DISCUSSION TOWARDS A FRAMEWORK IN CANADA

The authors suggest three main aspects necessary for a proposed framework in Canada to move towards a viable PBFD implementation for composite steel decks. The proposed framework herein must be: responsible; mindful of the Canadian regulatory landscape; and draw successfully from international lessons.

To advance PBFD in Canada, competency must be shown to ensure the practitioners are experienced in the fields of structural engineering and fire engineering. This competency must also extend to the AHJ who is reviewing the designs. In particular, the interaction of fire with the structure must be understood. Current fire education offerings in Canada appear limited. In particular, Fire Resistance – not Fire Design – is prevalent. Confidence of the AHJ should be increased by ensuring designers are competently trained in both structural and fire engineering. When undertaking a PBFD, the structural engineer must be prepared to accept responsibility for the design since it will be integral with the stamped structural drawings. This accountability can help ensure structures are fire designed in a responsible manner, as is currently standard practice in ambient design.

As PBFD strategies begin to be implemented in Canada, it is expected that the AHJ will initially have understandable reservations. It is proposed that incremental advances in PBFD be implemented as level of comfort increases. The first steel concrete composite designs are expected to optimize fire protection placement on secondary members (though not omit). The mesh reinforcement that is necessary for tensile membrane action of composite structures is already best practice, but its importance will be highlighted in a fire design. The NBCC currently contains a plethora of acceptable solutions which can be used to benchmark whole building performance with the aim of providing a reference point for the AHJ. Multiple design fires can be rationalized, however eliminating the standard fire completely from the discussion will be difficult given how engrained it has become in current fire testing, approval, and implementation.

Lastly, Canada has the unique advantage of being able to learn from previous international experience as well as other international efforts underway to further develop PBFD practice. In Canada, the regulation of PBFD must be thorough and consistent from the beginning. A minimum acceptable level of peer review, both by the AHJ itself and third parties, must be agreed upon by all stakeholders to ensure no engineered fire design receives less due diligence than any other. As competency in structural fire engineering grows and is demonstrated within Canada, the pool of qualified, local peer reviewers will grow. Canada, as with all countries, will also benefit from increased testing, test data for model verification, and published case studies to spread knowledge and lessons learned.

Any application of PBFD must be done in the pursuit of improved building performance and best practice. It is well documented in the literature that the standard fire is not representative of reality: PBFD could aim to improve this. Although economic and sustainability benefits may be realized, these should not be the only drivers for deviation from the approved solutions which have historically proven satisfactory. As qualified engineers begin to assess a building for fire more realistically, building performance measures can be improved and Canada will see increased resilience of its structures.

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