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STRUCTURAL FIRE DESIGN IN CANADA USING ANNEX K

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Abstract: Performance-based design approaches are seeing increased adoption in structural design for a variety of loading conditions, this being a direct result of the operational value within buildings far exceeding the asset value in today's market, and the life safety goals of building codes not being sufficient for some building owners. This paper discusses fire as a load case to be considered during structural design, as described in Annex K of CSA S16-14. The Annex is a normative (mandatory) part of the steel design standard, which can be applied to the structural fire design of steel and composite-steel buildings. To perform a structural fire design, the engineer requires an understanding of the design fires, the material behaviour at elevated temperature, a load combination to apply the fire effects, tools to determine the loading and deformation imposed by the fire, and finally acceptance criteria to assess the structure. Annex K describes all of the above for the Canadian practitioner as provided in this study. The study introduces Canadian case studies that use Annex K for a structural fire design, which would be an "alternative solution" under Canada's objective-based building code. The novelty of the study is that the recently introduced Annex K has not been effectively communicated or demonstrated yet and as such has had only marginal impact on the fire safety of structures. Canadian practitioners and educators will benefit from this study's overview of possible structural fire designs and their benefits, while authorities will be introduced to performance-based approaches that are being proposed on contemporary Canadian structures with increasing frequency.

1 INTRODUCTION

Structural fire engineering in Canada is a young discipline, especially in the context of international practice where performance-based solutions see widespread implementation. However, with the introduction of Canada's objective-based code in 2005, increased education in fire safety engineering, and increased awareness of the benefits of a performance-based approach, it is maturing towards a profession (Quiquero et al., 2018). The advantages of a performance-based approach in steel and composite construction, in a Canadian context, have previously been discussed (Smith et al., 2015), as well as the implementation of fire engineering into current Canadian design practice (Smith and Gales, 2016) and the opportunities to leverage fire engineering to enable resilience (Smith and Gales, 2017). Building on these efforts, the following paper gives an overview of CSA S16 Annex K, which has been available to Canadian practitioners since 2009 but has seen little documented adoption in practice. The goal of this paper is to orient practitioners with the content of Annex K, draw attention to currently available supporting documents, and provide case studies that demonstrate the opportunities that exist when applying Annex K to structural fire engineering.

2 OVERVIEW OF ANNEX K

In the 2009 edition of CSA S16, Design of Steel Structures, Annex K was added to aid practitioners in the design and evaluation of structural steel elements for fire conditions (CSA, 2009). The Annex is normative meaning it is a mandatory part of the standard. Clause 6 of CSA S16, Design Requirements, states that fire resistance for steelwork in buildings shall be calculated using the qualification based test methods of CAN/ULC-S101 or, when permitted by the regulatory authority, the equations and methods provided in Annex K. In brevity, the main contents of Annex K are outlined below. Annex K has a commentary available online with further explanatory information on many of the clauses (Frater and Alfawakhiri, 2016).

2.1 Structural Fire Design

Where permitted by the regulatory authority, the provisions in Annex K can be used to demonstrate the performance of an alternative solution. In this scenario, an engineering analysis is done on a structural system to demonstrate stability and deformation performance goals are met as defined in Clause K.1.3 and agreed upon in advance with all stakeholders. Guidelines are available to guide engineers through this performance-based design process (SFPE, 2007), which have been applied successfully in past Canadian applications (Quiquero et al., 2018).

2.2 Design-Basis Fires

In a structural fire design, the fire protection engineer must determine the design-basis fire(s). Using the actual compartment geometry, ventilation, and fuel, heating conditions can be developed for the structure in terms of a heat flux or temperatures in the hot upper layer. The design fires outlined within Annex K are localized fires, post-flashover compartment fires, and exterior fires. Each fire will have a unique duration to be considered as described in Clause K.2.2.5. As well, active fire protection measures such as sprinklers, smoke vents, and heat vents are permitted to be used when describing the design-basis fire as outlined in Clause K.2.2.6. Reliability of these active measures are a key consideration when taking into account beneficial effects of them, as described in the commentary to Annex K.

2.3 Material Properties

With the design-basis fires developed, resulting material temperatures and properties can be determined for the structural fire analysis. Guidance for simple and advanced methods of thermal analysis are outlined in the commentary (Frater and Alfawakhiri, 2016). Material mechanical properties at elevated temperature are provided in Clause K.2.4 of Annex K, and are generally derived from the Eurocode (CEN, 2005a). This includes the coefficient of thermal expansion for structural steel and concrete, and the degradation of elastic modulus, yield strength, and tensile strength with elevated temperature.

3 CANADIAN PRACTICE

Current Canadian practice relies on prescriptive code clauses to assign fire-resistance ratings. From a structural perspective, the building code dictates which members within a building require a fire-resistance rating, and that these ratings shall be determined from assemblies tested to CAN/ULC-S101 or matching the approved solutions provided in Appendix D, Division B (Fire Performance Rating) of the National Building Code. As of 2005, the code has transitioned to an “objective-based” format, where each prescriptive clause is assigned functional and objective statements that outline the specific intent of that clause. Through the objective-based code, designers can also propose “alternative solutions” if it can be shown they meet the functional and objective statements of the relative code provisions.

Although not a true performance-based building code, it was observed at the time that there was a trend towards performance-based designs and that the objective-based code could help guide designers along that path (Bergeron, 2008). With regards to alternative solutions, Annex K is a necessary document as it provides engineers the information necessary to examine structural steel assemblies under fire scenarios and demonstrate the objective and functional statements are met. Currently there is a lack of literature and case studies available that demonstrate the applicability of Annex K to innovative alternative solutions.

4 DESIGN REFERENCES

Annex K provides the information necessary to orient a structural engineer in performance-based fire engineering as outlined above. It is expected that structural engineers applying the provisions of Annex K to the structural fire design of buildings will have some formal education in fire safety engineering. Current fire safety engineering education available to the Canadian practitioner is limited and includes York University, University of Waterloo, and Carleton University. Each institution specializes in particular subsections of fire safety engineering, while students are typically able to take courses from other institutions as desired. The available offerings should mature as the field of fire safety engineering itself grows.

Several references are available to assist engineers in applying the provisions of Annex K to develop performance-based solutions. These include:

- SFPE Engineering Guide to Performance-Based Fire Protection (SFPE, 2007)
- Guidelines for Peer Review in the Fire Protection Design Process (SFPE, 2009)
- NBC 2015, Part 1 Clause 1.2.1.1, Alternative Solutions (CCBFC, 2015)

Complimentary literature to be used in conjunction with Annex K also includes:

- Eurocode 1: Actions on structures – Part 1-2: General Actions – Actions on structures exposed to fire (CEN, 2002)
- Eurocode 3: Design of steel structures – Part 1-2: General rules – Structural fire design (CEN, 2005a)
- Eurocode 4: Design of composite steel and concrete structures – Part 1-2: General rules – Structural fire design (CEN, 2005b)
- SFPE Handbook of Fire Protection Engineering, 5th edition (SFPE 2016)

Lastly, the ASCE Fire Protection Committee is currently writing a Manual of Practice for ASCE/SEI 7-16 Appendix E, Performance-Based Design Procedures for Fire Effects on Structures. This manual, once published in the near future, will complement Appendix E by providing information on available data, current analysis techniques, and ongoing developments. It also addresses key knowledge gaps. While useful in its current form to Canadian practitioners, the authors believe a Canadian adaptation of this document would greatly benefit structural fire engineering in Canada and in particular applications of Annex K.

5 DESIGN EXAMPLES

The following section provides brief case studies that demonstrate possible applications of Annex K. The methods of analysis presented in Annex K include advanced methods of analysis, and simple methods of analysis. A simple analysis is performed on individual members using the resistance equations provided in Annex K, while the advanced analyses will generally extend beyond a single member and consider system response. Three simple case studies are presented followed by an introductory advanced analysis. While hypothetical, they have been derived from actual applications of structural fire engineering. The results of these case studies should be treated as illustrative examples and not relied on for actual design decisions without independent calculations using Annex K or an alternative acceptable reference.

5.1 Simple Analysis: Tension Hanger

A common question that arises in structural engineering is how to fire protect hangers supporting floors, and if these hangers require fire protection in the first place. The national building code and provincial buildings codes all have clauses regarding “rating of supporting construction”. This clause states that if a roof or floor assembly requires a fire-resistance rating, the supporting structure below shall have the same fire-resistance rating. Common interpretation of this clause is that hangers supporting a fire-rated floor also need the same fire-resistance rating of that floor.

In this example, a hollow structural section is supporting a cantilevered floor that is required to have a fire-resistance rating. The cantilevered floor is in a large, open atrium, with the hanger being supported 35 feet up from the roof. Fire protection strategies for the hanger are spray-applied fire-resistive materials, or intumescent coatings. While intumescent coatings is the clear choice for this exposed and accessible application, the fuel load in the atrium is minimal and it is not expected that the hanger would actually see any severe fire situations (this may not always be the case for atriums). As such, the engineer has determined that a structural fire engineering approach will be used to demonstrate the hanger has sufficient capacity for a range of design fires and to eliminate the need for intumescent coatings. The hanger is shown in Figure 1.

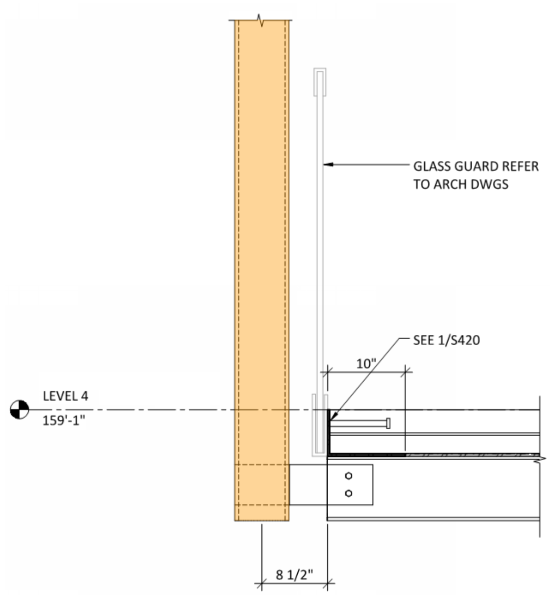

Figure 1: HSS Hanger

The shear tab connection shown has been designed to resolve the vertical load at the centreline of the hanger, with the moment induced from this lever arm being resolved in the bolts and welds where the shear tab is connected to the supporting floor beams. This means the hanger is in pure tension. First, the design fires are evaluated as described in Clause K.2.2.1 of Annex K. Due to the size of the atrium, a post-flashover compartment fire is ruled out. The design fires considered are:

a) Localized fire immediately adjacent to the hanger
b) Localized fire at the base of the atrium, causing hot gases to accumulate at the roof where the hanger is supported
c) Localized fire at lower levels in the atrium, causing hot gases to accumulate at the roof where the hanger is supported

Due to the separation between the hanger and the level it is supporting, the governing design fire was (b). The fuel load at the base of the atrium consisted of the box office structure and its contents, surrounding vendor displays, and surrounding furniture. The maximum temperature throughout the duration of the fire at the roof level was found to be 650°C. A one-dimensional heat-transfer analysis of the HSS hanger revealed the peak steel temperature to also be 650°C.

First, the factored load is calculated under fire conditions. The ambient factored load is 1000 kN (63% tension utilization). Applying the fire load combination from Section K.1.5 gives a factored load of 535 kN.

The hanger is an HSS 178 x 9.5. Although a Canadian project, the material specified for the HSS is ASTM A500 Grade C. This has a lower ambient yield stress of 317 MPa and a lower design wall thickness using CSA S16. Clause K.2.5.3.2 of Annex K states the factored resistance of a tension member is determined using Clause 13.2, with the steel properties specified in Clause K.2.4. The factored tension resistance of the hanger is shown in Figure 2, as well as an increased wall thickness.

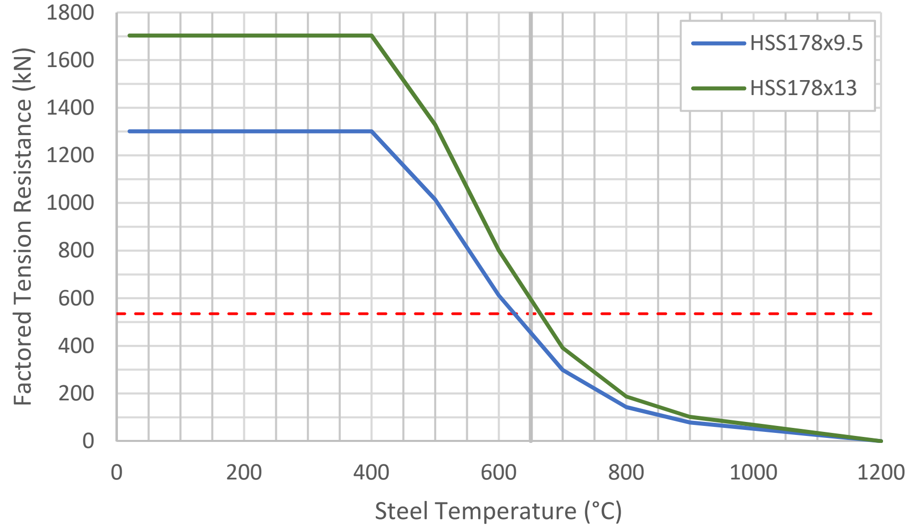

Figure 2: Factored tension resistance as a function of temperature

Based on the above, the original HSS178 x 9.5 hanger did not have sufficient resistance at 650°C. By increasing the wall thickness to 13mm from 9.5mm, it was found that the factored resistance increased to 596 kN at 650°C, which exceeds the factored tension force of 535kN. The increase in wall thickness is much more cost effective than applying intumescent paint over the whole height of the hanger.

5.2 Simple Analysis: Column

In this next example, an existing exterior HSS column is assessed to determine if it must be fire protected due to supporting a new addition that requires a specified fire-resistance rating. As mentioned in Section 5.1, the fire-resistance rating of a column must match the required fire-resistance rating of the supported floor assembly. Originally the HSS column supported a roof that was not fire rated, and hence the column was left unprotected, however the addition of an occupied space above the column with a one-hour fire-resistance rating has prompted the designers to look into options for the column.

The column is an HSS 152 x152 x 6.4 originally supporting an intensive green roof, and there is ample capacity for the column to support the new occupied office space above (Figure 3). As this is an interior courtyard, the design fires considered are an adjacent localized fire. An additional design fire to consider is a post-flashover compartment fire in the interior compartment that heats the column through flame projection and radiation. This latter design fire is described in Clause K.2.2.4 of Annex K, with an accepted approach for calculating external fire exposure described in the SFPE Handbook of Fire Engineering (SFPE, 2016) as well as the Eurocode (CEN, 2002).

Based on the two design fires described above, the maximum column temperature was found to be 700°C. The existing column is an HSS 152 x 152 x 6.4, supporting a factored load of 510 kN under ambient conditions. At the fire limit state, the factored load is 260 kN using the load combination of Clause K.1.5.

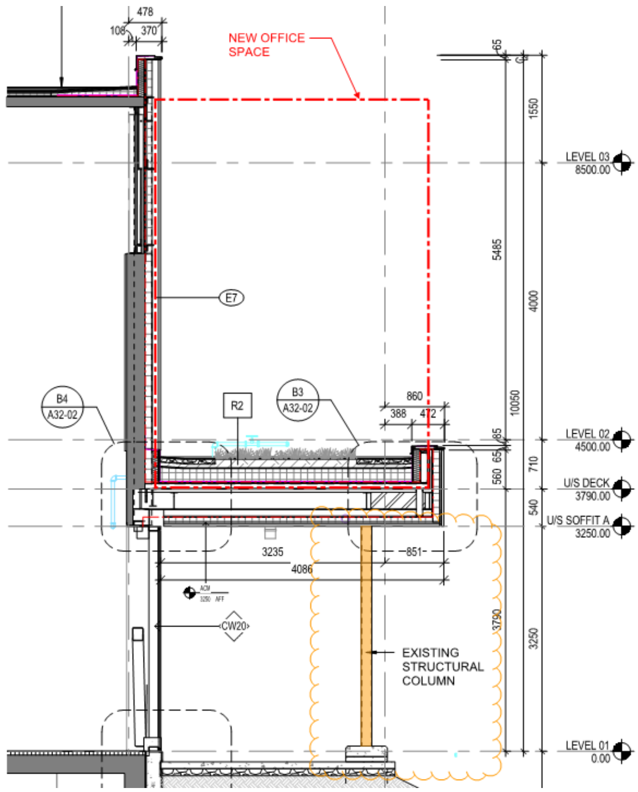

Figure 3: Existing column supporting new office space above

The factored compressive resistance of the column is calculated as per Clause K.2.5.3.2(b),

$C_r(T) = (1+\lambda(T)^{2dn})^{-1/dn} A F_y(T)$

Where λ(T) is the column slenderness evaluated at temperature T, Fy(T) is the yield strength at temperature T, n is as specified in Clause 13.3.1, and d is 0.6. The derivation and validation of the reduction factor, d, of 0.6 is described by Takagi and Deierlein (2009).

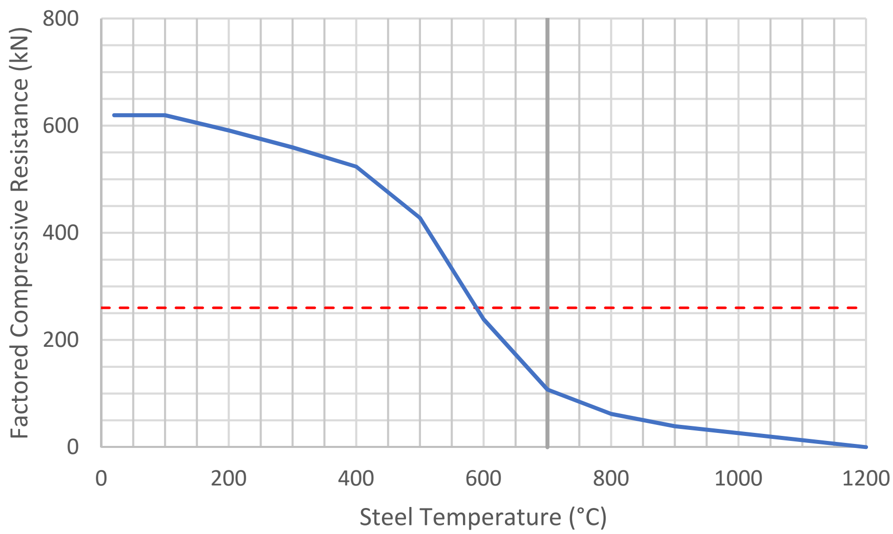

Figure 4: Factored compressive resistance as a function of temperature

As seen in Figure 4, the column does not have sufficient capacity when left unprotected for the expected fire exposure. However, if the structural steel could be kept at 580°C or lower, the factored compressive resistance would exceed the factored load under fire conditions. This temperature can be achieved through the application of spray-applied fire-resistive materials and a subsequent thermal analysis performed to demonstrate the structural steel temperature.

5.3 Simple Analysis: Truss

By combining the tensile and compressive examples of Sections 5.1 and 5.2, a truss is analyzed. In this example, the same atrium from Section 5.1 is used. A large roof truss supporting hangers from fire-rated floors below required fire protection according to the code. However, it is known that the actual fire temperatures at the roof of the atrium will be relatively low.

The truss presented herein has a continuous top and bottom chord, the diagonals are all pin connected, and the truss supports do not provide axial restraint (i.e. the top chord does not develop thermal expansion forces). The truss spans 34.4 m, has a maximum depth of 5.6 m, and has W530 x 219 top and bottom chords. The factored tension and compression force in the bottom and top chords, respectively, is 5400 kN under ambient conditions. At the fire limit state, this factored load is 2950 kN.

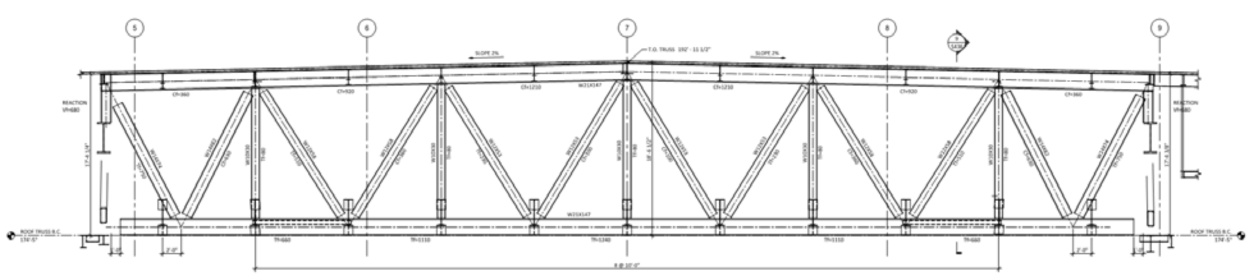

Figure 5: Truss geometry

Using the procedures of Section 5.1 and 5.2, the factored resistance of the top and bottom chord is shown in Figure 6.

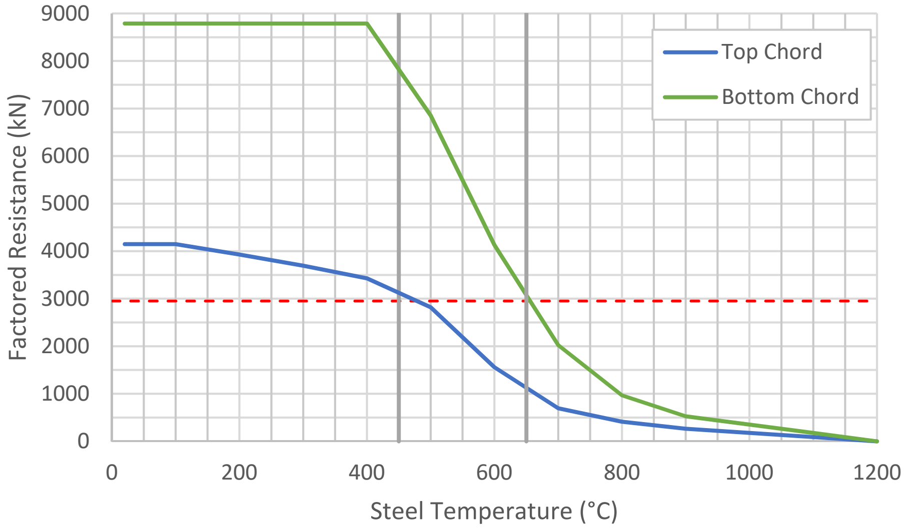

Figure 6: Factored resistances of top and bottom truss chords

At 650°C, the top chord of the truss does not have sufficient capacity to resist the factored compression load. Figure 6 demonstrates how much more drastic the effect of fire on compression members is than on tensile members. This is due to the fact that the elastic modulus decreases with temperature at a faster rate than the yield strength as shown in Table K.1 of Annex K. This in turn lowers the Euler buckling stress of the member, which increases the slenderness and reduces the factored compression resistance.

Figure 6 also demonstrates design options for leaving the truss unprotected. By providing increased mechanical ventilation, more reliable sprinkler, or a reduced fuel load in the atrium, the calculated temperature at the roof can be reduced. If the roof temperature can be kept at around 450°C for all design fires, the truss has sufficient capacity to remain unprotected. This drastically reduces the amount of expensive fire protection required and shortens the construction schedule.

5.4 Advanced Analysis: Composite floor

The last example presented used an “advanced method of analysis”, as defined in Annex K Clause K.2.5.3.1. For these analyses, Annex K does not provide specific equations to follow but rather lays out the framework for what the advanced analysis must include. For this reason, an advanced analysis using Annex K must ensure the regulatory authority is consulted early in the process to ensure the methods, criteria, and assumptions used are appropriate. This early consultation and involvement in the design process serves to reduce approval risk in the performance-based design process.

In this example, a composite floor is considered. Equipment and storage loads throughout have resulted in a heavily reinforced concrete slab with composite steel beams supporting it. Due to the already heavy reinforcement in the slab, it is proposed to optimize the fire protection by removing it from the secondary beams.

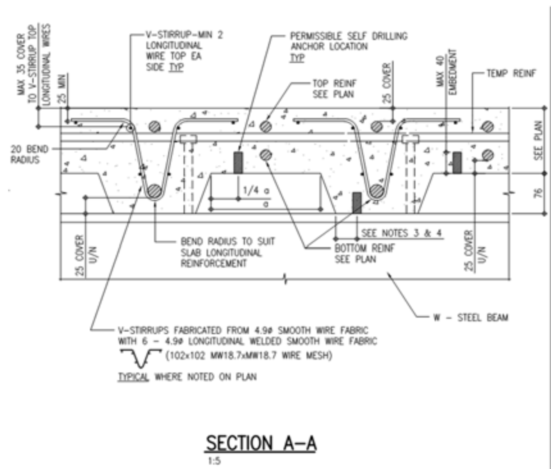

Figure 7: Heavily reinforced concrete slab

The method of analysis proposed for this is the Slab Panel Method (SPM) (Clifton, 2006). This method uses yield line theory to demonstrate resistance in the slab at the fire limit state through tensile membrane action. As the secondary beams supporting the floor slab rise in temperature and lose strength, the floor experiences increasing deflections. Large floor deflections induce in-plane forces in the panels which is used to amplify the flexural capacities calculated with a yield-line approach. A feature of SPM that differentiates it from other membrane calculation methods is that the capacity of the secondary beams is accounted for in addition to the slab capacity. In the case of unprotected secondary beams, this contribution will diminish as the fire temperature increases. Failure criteria using the SPM is tensile rupture of the slab reinforcement and concrete crushing.

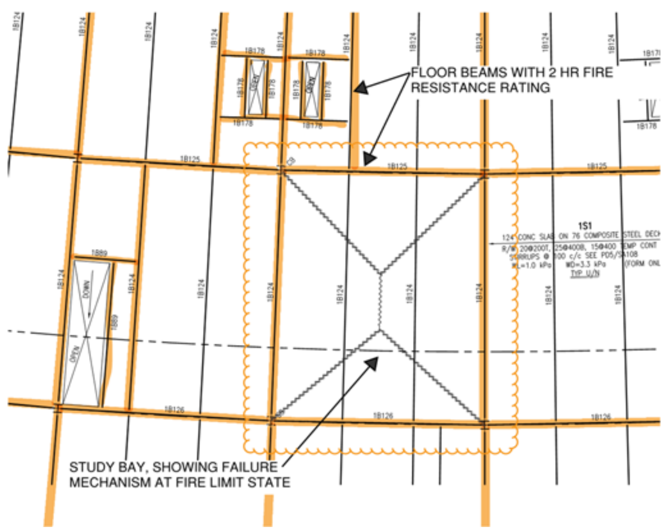

Figure 8: Study bay for whole floor response

Below the composite floor considered is a large open space. The most applicable design fire for this scenario is a localized fire, as the compartment can be shown to not reach flashover. Specifically, it is proposed to consider a moving localized fire within this large open space. This is referred to as a travelling fire, with the methodology for calculating the resulting time-temperature histories documented by Rackauskaite et al. (2015), as well as Stern-Gottfriend and Rein (2012).

While the specifics of the Slab Panel Method and the travelling fire methodology are beyond the scope of this initial paper on the applications of Annex K, the annex does contain all relevant information to guide practitioners towards advanced analyses such as this for the optimization and safe design of structural steel for fire scenarios. In the above case study, for example, it was found that fire protection on the secondary beams could be removed without needing to add additional reinforcement in the slab. The Slab Panel Method is just one example of an analysis method that can be used to demonstrate structural stability without fire protection on the secondary beams, while a more complex finite element analysis on the floor could also be performed to demonstrate structural stability and falls within the scope of Annex K's Advanced Methods of Analysis clause.

6 CONCLUSION

This paper has outlined the contents of Annex K that make structural fire design a possibility for the Canadian practitioner. It has then shown how the provisions of Annex K can be used to demonstrate structural stability at the fire limit state, optimize fire protection and material use, and quantitatively demonstrate performance goals beyond life safety to enable resilience within a building. The results of this are safer buildings, increased structural and architectural design options, and financial savings. Annex K is still a relatively young document, having just been introduced in 2009 and currently undergoing revisions for the 2019 edition of CSA S16. As the field of fire safety grows in Canada and the pool of competent structural fire engineers grows, it is expected that Annex K will also grow in scope and novelty to be a leading document in the field of structural fire engineering.

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