TOWARD FIRE RESILIENCE IN CANADIAN BRIDGE INFRASTRUCTURE

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ABSTRACT

In Canada, bridge fires are becoming a growing concern due to the increasing urbanisation of major cities. Although bridges are designed to provide life safety for a range of extreme loads as prescribed by the relevant codes and standards, the economic losses associated with temporary or permanent critical bridge closure can be enormous and difficult to rationally quantify. The vulnerability of bridges to catastrophic events is amplified by the fact that the infrastructure is aging and provincial budgets can make even basic maintenance a challenge. The economic benefit associated with bridge operation can outweigh the cost of the structure itself and yet many Canadian bridges have not been fully assessed to understand their performance to fire loading, what the post-fire recovery looks like, and how this relates to the overall infrastructure resilience. Many bridges, particularly those made of complex materials and assemblies, may have unique and unidentified vulnerability associated with their operational fire resilience. This study aims to map the existing bridge fire research projects internationally and orient future research to help improve bridge fire design resilience in Canada. Challenges facing the design of resilient bridge infrastructure and knowledge gaps are presented.

INTRODUCTION

The international civil engineering industry is trending towards performance-based designs when considering significant projects. Specifically with regards to fire-resistance, performance-based fire design (PBFD) is the design that considers detailed and case-by-case analyses in order to meet requirements agreed upon in advance by all project stakeholders, and approved by the Authority Having Jurisdiction (AHJ). Although intensive, PBFD is becoming industry standard and, as structures become more complex and novel materials are introduced, prescriptive code designs may no longer be adequate in all situations.

With PBFD on the rise in Canada, new avenues for more optimized design are enabled. One important extension of PBFD is the concept of resilience, a measure of a structure's ability to not only resist but also recover from catastrophic damage and return to an operational state. Resilience involves designing for more than minimum code requirements and life safety; it requires an understanding of a structure's role in the economic and social fabric of the area it serves and designing to ensure these functions are maintained after significant damage. Bridges are particularly vulnerable to fires due to the lack of required fire protection on structural members based on the assumption life safety can be achieved rapidly due to the open nature of bridges. Current guidance does not consider the economic losses associated with fire and fails to ensure resilience in Canadian infrastructure. The rising number of aged and disrepaired bridges exacerbates the vulnerability of this critical infrastructure. This paper outlines the state of the art in bridge fire engineering to inform practitioners and researchers about available research to guide design and assessment as well as direct future study. Ultimately a framework for the cumulative assessment, repair, and analysis of bridges and their structural response to fire scenarios is proposed.

STATE OF THE ART

This section briefly summarizes some of the current research being undertaken domestically and internationally organised by topic area. Table 1 below includes an outline of the literature reviewed herein sorted by general topic. More detailed descriptions of individual studies follow Table 1.

Table 1: Summary of current bridge fire engineering literature by general topic

Study	Author (Year)	Focus	Conclusions
Bridge Fire Modelling and Determination			
Analysis of a Bridge Failure due to Fire Using Computational Fluid Dynamics and Finite Element Models	Alos-Moya et al. (2014)	Computational Fluid Dynamic (CFD) and structural analysis modelling of a case study with emphasis on various fire parameters	The model was consistent with the observed case study and made suggestions regarding the consistency of fire loading for given bridge spans. Application of the Eurocode standard and hydrocarbon fires were found to not accurately represent bridge fire scenarios.
A Streamlined Framework for Calculating the Response of Steel-Supported Bridges to Open-Air Tanker Truck Fires	Quiel et al. (2015)	Framework for modelling and analyzing bridge structural members applied to a case study	The proposed outline for modelling bridge fire responses proved efficient in recreating a wide variety of fire parameters and as a tool to inform design.
Performance-Based Prioritization of Fire Mitigation for Highway Bridges	Quiel et al. (2016)	Tool development to prioritize bridge fire protection	Proposed tool efficiently develops an envelope for a variety of fire exposures to identify areas that require fire protection.
Analysis of the Factors that Influence the Maximum Adiabatic Temperatures in I-girder Bridges	Peris-Sayol et al. (2016)	CFD modelling of bridge fires	Four geometric and two fire parameters are studied for influence on gas temperatures. Results show that fire load position, fuel type, and vertical clearance are the most influential.
New Design Fires for Performance Based Engineering of Highway Bridges	Hu et al. (2016)	Development of potential bridges fires to consider in design and a case study	Proposed bridge fire classes enable more realistic approximations of bridge response in fire.
Assessing the Fires on the Deck of Cable Stayed Bridges	Kotsovinos et. al (2016)	Framework for the assessment of cable-stayed bridge robustness	A variety of potential fire scenarios and the impact on structural and thermal responses are presented.
Bridge Fire Hazard Assessment, Repair, and Resilience Framework			
Fire Hazard in Bridges: Review, Assessment and Repair Strategies	Garlock et al. (2012)	Review of major bridge fires and repair & assessment strategies	Details of actual fire incidents are provided and assessment and repair techniques are discussed with respect to concrete, steel, and prestressed concrete bridges.
A Probabilistic Assessment for Classification of Bridges Against Fire Hazard	Naser and Kodur (2015)	Provides a probability-based framework for assessing bridge vulnerability to fire hazards	Proposed assessment provides a means to identify critically vulnerable bridges and suggests factors to inform design.
Re-testing of a Fire Damaged Bridge	Alexander Au (2016)	Assessment of post-fire strength of a concrete bridge	Repetition of original test methods found very few discrepancies between tests 6 years apart. Post-fire repair and retrofit techniques were successful with no mid-term strength loss.
Resilient Bridge Design Framework to Extreme Fire Loading	Mueller et al. (2016)	Framework for informing resilient and robust bridge fire design applied to a case study of a cable-stayed bridge	Framework successfully established the maximum fire exposure threat and informed hypothetical design decisions.
Detailed Analysis of the Causes of Bridge Fires and Their Associated Damage Levels	Peris-Sayol et al. (2017)	Collection and data analysis of over 150 bridge fire scenarios	Study found that tanker truck fires are the most damaging fire events a bridge can experience. Gasoline fueled fires were responsible for most damage; typical fuel volumes ranged from 30-35 m^3.

Study	Author (Year)	Focus	Conclusions
Steel Supported Bridges			
Behaviour of Steel Bridge Girders Under Fire Conditions	Aziz et al. (2014)	Numerical and experimental modelling of steel plate girders exposed to standard fire	The developed numerical model could accurately replicate experimental results. Emphasis placed on the critical nature of the shear-flexure interaction of fire exposed girders.
Numerical Simulation of Fire to a Long Span Truss Bridge	Gong and Agrawal (2015)	Numerical modelling of steel bridge stringers compared with a case study	Novel numerical modelling approach found good agreement with observed fire results.
Post-Tensioned Concrete			
Post Fire Guidance for the Critical Temperature of Prestressing Steel	Robertson and Gales (2016)	Experimental high temperature tests of prestressing steel for post-tensioned concrete	Residual strength tests over extended high temperature exposures show conventional guidance for pre-stressing steel may be non-conservative. Guidance revisions are suggested.
Structural Fire Performance of Contemporary Post-Tensioned Concrete Construction	Gales et al. (2016)	Thorough study involving the fire behaviour of post-tensioned concrete members	Document outlines methods for testing post-tensioned concrete in fire, results of structural fire tests, and recommendations for practitioners and future study.
Composite and Emerging Bridge Materials			
Numerical Study of FRP Reinforced Concrete Slabs at Elevated Temperature	Adelzadeh et al. (2014)	Numerical modelling of one-way slabs reinforced with GFRP rebar	Results show fire resistance increases proportionally with additional GFRP reinforcement layers.
Fire Test of FRP Members Applied to Railway Bridge	Cabova et al. (2016)	Experimental testing of FRP pultruded panels for use in railway bridges	FRP panel fire performance was competitive with traditional steel elements.
Performance of GFRP Stay-in-Place Formwork for Bridge Decks After Real and Simulated Fire Damage	Nicoletta et al. (2017)	Experimental study of the behaviour of glass fibre reinforced polymer (GFRP) stay-in-place formwork for bridge decks exposed to a hydrocarbon pool fire	Formwork provided good fire resistance for the fire scenario and potential heat-induced strengthening effects were hypothesized.

Bridge Fire Modelling and Determination

Alos-Moya et al. (2014) investigate the use of numerical studies to model the response of bridges exposed to fire and make suggestions for creating models for use in bridge design. The authors apply a CFD fire model and a thermo-structural analysis in a parametric study to consider the influence of fire load discretization, fire curves suggested in codes, and live loading. The numerical study was conducted using the 2002 I-65 overpass fire in Alabama as a reference. Multiple conclusions were presented by the authors. Most notably, the use of a uniform fire load is not representative of a real fire for the case of medium to long span bridges, where large heat variations are found. Short span bridges do not experience significant temperature changes and may be more suited for modelling with uniform fire loads. The study found that the Eurocode hydrocarbon and standard fires are not well suited to represent typical bridge fires for medium and long span bridges. The CFD model was found to be accurate in replicating a fire scenario and could potentially be applied in PBFD. Additionally, it was determined that the presence of live loading has little effect on the overall response of the bridge.

Quiel et al. (2015) focus on creating a methodology to analyze steel supported bridges exposed open air hydrocarbon pool fires. This variety of fire is associated with collisions involving tanker trucks and is the most common scenario of bridge fires. The authors consider four general steps to determine the structural response of bridge exposed to fire:

1. Determine fire characteristics (or a set of possible design fires). If necessary, computational fluid dynamics (CFD) models can be used;
2. Calculate the heat transfer to structural elements;
3. Calculate structural member temperature increase based on heat exposure and duration; and
4. Apply material degradation factors at elevated temperatures and conduct structural analysis.

Quiel et al. (2015) note that many studies involving bridge fires make use of very simplified fire models like the standard hydrocarbon fire or parametric fires which are over-conservative worst-case scenarios and not representative of real fires. The most detailed solutions involve CFD models and are very intensive and often not practical due to the unavailability of input parameters, especially for forensic studies in which observations may not have been possible. Intermediate solutions may estimate a single peak parameter of a fire such as temperature or heat release rate (HRR) for use in a FEM to determine member temperature response. For large, open air, hydrocarbon fires, radiation is the dominant mode of heat transfer and the models used must be able to reflect this. The authors provide calculations to estimate the intensity, duration, and geometry of a hydrocarbon pool fire. The approach taken by Quiel et al. (2015) considers a pool fire as a solid vertical cylinder which outputs calculated radiation values. This solid model is then discretized twice, first into a luminous and smoke obscured region (each of which has different emissivity properties), and again into multiple rectangular elements that can be individually modified. This model is known as a modified discretized solid flame model (MDSF) and allows the consideration of non-uniformity in the fire due to geometry or environmental factors. The authors conclude with a case study of the 2007 MacArthur Maze overpass collapse to demonstrate the effectiveness of the proposed framework.

Bridge Fire Hazard Assessment, Repair, and Resilience Framework

Garlock et al. (2012) provide a comprehensive overview of the state of bridge fire hazards and presents reviews of actual incidents, post-fire assessment strategies, and repair considerations. The authors present a list of significant bridge fires from 1995 to 2010 as well as research efforts to analyze case studies to develop assessment and repair techniques. One difficulty cited in comparing studies is the method through which hydrocarbon fires are modelled. Many available hydrocarbon fire models have limitations and researchers are often required to develop their own iterations when examining particular case studies, creating inconsistencies between studies.

The authors outline three requirements to better develop assessment and repair strategies:

1. More accurate methods to evaluate fire damage;
2. More accurate and consistent models to determine post-fire bridge serviceability; and
3. Development and testing of repair techniques

Garlock et al. (2012) continue to provide some established methods for determining the extent of fire damage in steel, concrete, and prestressed concrete bridge members as well as potential repair strategies for all three.

Naser and Kodur (2015) propose one of the most comprehensive tools currently available for assessing fire hazards in bridges. It is well known that, despite increasing occurrence, bridge fires are low probability events. As such, it may not be economically reasonable to design all bridges for fire scenarios. Only the bridges most critically vulnerable to fire hazards should be protected on the basis of first, protecting life safety, and second, minimizing economic disruptions. The authors have developed a framework for assessing the vulnerability of bridges to fire hazards which calculates importance factors to be applied during bridge design, similarly to snow and wind loading. The authors first use statistical data to estimate the probability of bridge fires occurring due to a traffic collision, then consider multiple bridge parameters on a case-by-case basis to establish the total vulnerability of a given bridge to fire. Although this study is based on American statistics and infrastructure, a similar framework could foreseeably be developed from the ground up or modified from this existing study for application in Canada or elsewhere.

Despite limited available statistical data, Naser and Kodur (2015) estimate the probability of a traffic fire occurring on a bridge in the United States in one year is 2.27%. This high enough to be considered a probable risk by the National Fire Protection Association (NFPA) but is still less frequent than that of multi-storey buildings. The discrepancy between bridge and building fire probability is a main factor as to why building structural members are designed with fire resistance requirements while bridge members are not. Occupant safety is less of a concern in bridges because they are open structures, but no value is placed on the economic continuity of the bridge's service.

Critical bridges must be identified based on a high risk of fire hazard such that infrastructure can be more accurately designed or retrofitted for fire resistance. To develop the basis of bridge classification, Naser and Kodur (2015) describe two important areas of consideration when determining the hazard level for a bridge. The first consideration to determine fire hazard is the structural vulnerability of a bridge to fire. This focuses on specific structural members which can be divided into two separate types, super-structural members (slabs and decks) and sub-structural members (girders, piers, and abutments). The second main consideration is the critical nature of the bridge which is mainly influenced by traffic density and location. A bridge in a major highway or transit route with large volume is more critical than a rural operating bridge with low traffic.

To inform bridge fire design, Naser and Kodur (2015) propose importance factors that can be applied to each member type to account for fire scenarios. These importance factors consider the bridge vulnerability and critical nature by giving a weight to five classes, considered briefly in Table 2 below.

Table 2. Weighted classes considered to assess bridge fire hazard (adapted from Naser and Kodur 2015)

Class		Parameters Considered	Weight in Determining Importance Factor
1	Geometric Features, Material Properties, Design Characteristics	Structural system; material type; span; structural component; lanes; current condition	0.47
2	Fire Hazard Likelihood	Firefighter response time; historical/architectural significance; potential fire scenario	0.22
3	Traffic Demands	Average daily traffic; location	0.11
4	Economic Impact	Vicinity to alternate routes; predicted repair time; predicted repair cost	0.12
5	Expected Fire Losses	Potential life and property loss; potential environmental damage	0.08

When considering the weighted score of all classes, the sum of all values will equal unity for the most critically vulnerable bridge. Based on the total score, Naser and Kodur (2015) assign importance factors similar to snow or wind loading which can better account for the fire limit state.

Peris-Sayol et al. (2017) compile critical data from over 150 bridge fire cases and present statistical analyses based on the influence of bridge and fire characteristics on damage levels. The authors propose a consistent methodology for collecting and analyzing information relating to bridge fires. Based on the cases studied, it was found that fires from tanker truck collisions cause the most damage and that gasoline is the most damaging of hydrocarbon fuels (however it is also the most common). Typical tanker fuel volumes were found to be between 30-35 m3. The authors also distinguish that the bridge site, structural system, and dimensions do not significantly affect the damage level from a statistical perspective. It is noted that bridges supported with plate girders represented the majority that collapsed as a result of fuel tanker collisions but were also featured more frequently than other bridge types. Peris-Sayol et al. (2017) conclude with recommendations to ensure adequate fuel drainage from the bridge deck and to limit storing flammable materials under bridges especially with low overheard clearance.

Steel Supported Bridges

Aziz et al. (2014) offer excellent insight into the performance of steel bridge girders during fire exposure. The research program considers both experimental and numerical studies involving three composite concrete-steel bridge girders heated and loaded transiently in accordance with the ASTM standard fire. All girders failed within 30-35 minutes, largely due to the interaction between shear and flexural stresses. Observed failure modes include flexural yielding, flexural yielding with shear web buckling, and shear web buckling.

Gong and Agrawal (2015) performed a numerical simulation of a real fire scenario that took place in the United States. The goal of this case study was to replicate the fire observed on the Ed Koch Queensboro Bridge in New York in August of 2013 through numerical modelling and aspects of forensic PBFD. Construction related scaffolding and netting caught fire on the lower level of the bridge and exposed several steel stringers on the upper deck to extreme heating. The general methodology presented by the authors consists of establishing observed fire characteristics, developing a dynamic fire model to replicate the known parameters, conducting a thermal analysis of the structural members based on the heat exposure from the developed fire model, reducing material properties according to temperature, and performing a structural analysis. Observed fire damage such as warping and deflection values were replicated with good agreement. The authors used Fire Dynamics Simulator (FDS) 5 and ABAQUS for the analysis.

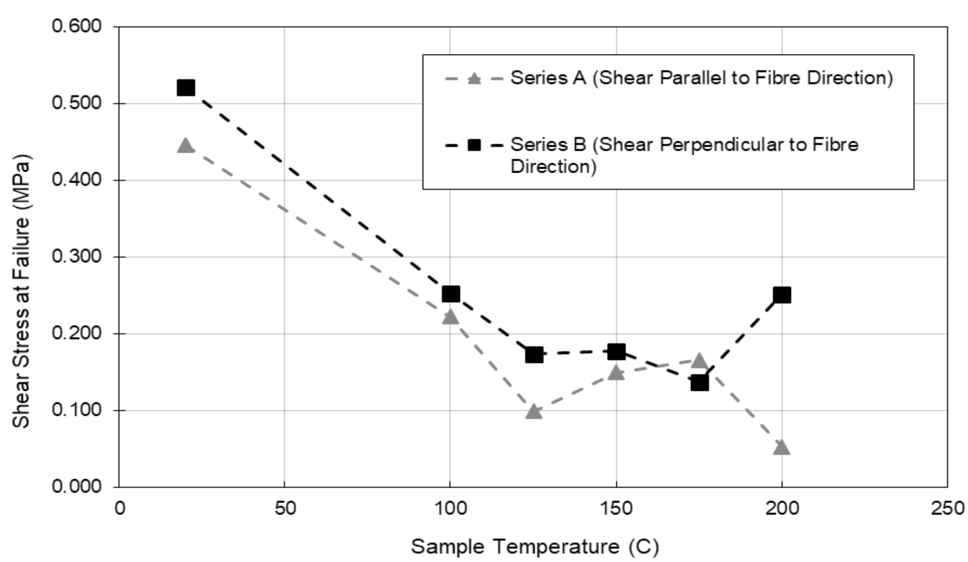
Post-Tensioned Concrete

Gales et al. (2016) provides a thorough outline of the problems facing post-tensioned concrete in fire, especially with reference to the behaviour of pre-stressing steel at elevated temperatures. The authors introduce a suggested test program for analyzing fire behaviour and present novel test results. A summary of the known behaviour of post-tensioned concrete structural members is also included. Guidelines for practitioners in assessing post-tensioned concrete after fires are discussed. The work includes a compilation of known case studies and repair requirements that itemizes literature available on that subject that include the MTO and the Concrete Society.

Composite and Emerging Materials

Nicoletta et al. (2017) present experimental results of exploratory fire testing conducted on novel glass fibre reinforced polymer (GFRP) stay-in-place (SIP) formwork. GFRP SIP formwork is an application of pultruded composites intended to provide a form for concrete bridge decks while simultaneously acting as tensile reinforcement through pultruded shapes in the GFRP cross section. The rapid implementation of this material has outpaced fire safety research with respect to use in bridge decks. This study exposes several beams intended to replicate strips of a GFRP reinforced concrete bridge deck to a hydrocarbon pool fire. Results indicate that GFRP SIP offers good fire resistance and was comparable to an ambient control test for a 15-minute heptane pool fire. The authors provide evidence of a potential strengthening of the composite system as a result of heating and cooling. However, novel direct shear tests of the GFRP-concrete interface have shown no apparent chemical bond enhancement has a result of heating and cooling. Cast concrete-GFRP bonded samples were heated at incremental temperatures for 2 hours, allowed to cool, and tested in a direct shear apparatus. Figure 1 shows the shear stress developed by a GFRP-concrete interface in direct shear with respect to heated temperature and fibre direction relative to loading based on slip shear tests described below.

Figure 1: Direct bond shear tests of heated GFRP-concrete interface



There is little distinction of a bond-strengthening effect as a result of heating. The opposite is apparent with a visible non-linear degradation of bond shear strength with higher temperatures. It should be noted that the direct shear tests used in this experiment would only indicate a chemical bond enhancement, possibly related to post-curing of the GFRP resin. The bond enhancement hypothesized by Nicoletta et al. (2017) may still be related to some degree of concrete post-tensioning as a result of thermal expansion of the GFRP rib if not experimental inconsistency. The authors intend to pursue larger scale structural testing in order to further investigate the high temperature behaviour of GFRP stay-in-place formwork.

THE CASE FOR BRIDGE RESILIENCE AND FRAMEWORK DEVELOPMENT

The basis for a framework to establish bridge fire resilience in Canada is rooted in the concept of operational resiliency. Operational resilience can be defined as the ability for an operation to respond to shocks or stresses and to recover to a required level of performance within a required amount of time (Hay 2016). In the context of buildings, it can be seen that this operational resilience is partly enabled by the structure itself in terms of how it responds to various hazards and is able to be repaired in a timely manner to restore occupancy (Smith and Gales 2017). This point of view considers two economic factors associated with fire hazards: direct losses and indirect losses. Direct losses consider the cost of repair and/or rebuilding while indirect losses consider the lost economic potential associated with operational downtime (Smith and Gales 2017). While both losses can be minimized through resilient design, the impact of indirect losses can substantially outweigh direct losses depending on the structure and function. In 2016, the resilience of the Trans-Canada highway was tested. The Nipigon River bridge northeast of Thunder Bay was heaved off of its abutment due to strong winds and was closed to vehicle traffic. The bridge cost a total of $106 million – the most expensive bridge project in Ontario to date - and was the only connection along the Trans-Canada highway between the east and west sides of the country (CBC 2016). It was reported that on average 1300 commercial vehicles carrying over $100 million worth of goods crossed the Nipigon River daily. Moreover, as a result of the closure, drivers from Toronto would have to take a 350 km detour through the United States to drive to Thunder Bay (CBC 2016). While it is difficult to express the delayed volume of commercial goods in terms of an indirect loss, this case study gives an indication of the vital economic service bridges provide and the vulnerability of certain transportation links to extreme events. Elsewhere in North America, Chung et al. (2008) reported that the daily indirect traffic losses associated with the MacArthur Maze overpass fire and collapse in California were about $6 million USD. It took 26 days for the MacArthur Maze interchange to reopen to traffic (Chung et al. 2008).

The targeted level of performance must be determined by the stakeholders, with the impacts of these performance levels articulated by the design team. Smith and Gales (2017) propose three levels of post-fire performance (LOP) that can be targeted in resilient design for buildings, each of which are based on a minimum economic disruption requirement specified by the client. A low LOP ensures only life safety, the extent of operational downtime and repair scope is unknown. A medium LOP ensures life safety and yields a short-term operational disruption. The affected region will require repair but will be limited in scope. A high LOP ensures life safety and minimizes operational downtime.

It is clearly not economical to design every bridge for a high LOP. A framework is required for both the determination of critical bridges in Canadian road networks and the assessment of bridge vulnerability. Current bridge inspections in Ontario are focused on the condition of individual bridges and using this to determine a bridge condition index (MTO 2015). From a resilience perspective, it is proposed that bridge assessments also take into account the importance of the bridge to the transportation network and the hazards to which the bridge is exposed. This includes considering nearby bridges that add redundancy to the system, proximities to fire hazards, and the estimated down time following a range of fire events. This can be extended beyond fire to include all hazards. By evolving bridge review frameworks to also consider the context of the bridge, it allows a weighted scheme similar to that proposed by Naser and Kodur (2015) to be applied. A more holistic assessment of bridge conditions and vulnerabilities would allow limited maintenance budget and resources to be applied more efficiently. Once vulnerable bridges are able to be identified, a set of a guidelines must be available for practitioners to use to inform repairs, retrofits, and designs.

A proposed framework for improving the resilience of bridge infrastructure to fires is as follows:

1. Increase the scope of current bridge reviews to also determine the importance of individual bridges to the overall network. This should be done at a system level and not on a bridge-by-bridge basis

2. As part of bridge reviews, determine bridge vulnerability to specific types of fires and what parts of the bridge are expected to be impacted.

3. Identify critical bridges vulnerable to fire and potential risks associated with not upgrading their fire resistance

4. Make available to practitioners practical guidance on retrofitting specific bridge structural systems for improved fire resistance and post-fire review requirements to safely re-open bridges

Research to further develop and bridge fire resilience framework in Canada is needed. Some common research needs identified in the aforementioned studies and suggested by the authors are presented in Table 3.

Table 3: Research needs for the development of bridge fire resilience framework in Canada

Topic	Research Needs and Suggestions
Bridge Fire Modelling and Determination	• Experimental data is needed for the validation and development of more comprehensive bridge fire models especially with regards to fuel types, volumes, and environmental factors • A general framework is needed to identify the most critical fire threats to a bridge based on traffic type and bridge geometry
Bridge Fire Hazard Assessment, Repair, and Resilience Framework	• There is a lack of statistical data on all aspects of bridge fires. Statistical data is needed to develop models for categorizing bridges as demonstrated by Naser and Kodur (2015) • Post-fire repair strength assessment and repair strategies are not well developed. Many tests rely on qualitative observations • A study from the economic perspective of bridge fire resilience considering all effects would be enlightening
Steel Supported Bridges	• Many models do not adequately account for steel-concrete composite action which can be problematic in fires due to the rapid degradation of steel properties • Critical effects such as shear-flexure interaction in steel plate girders are not included in many models but frequently govern the fire load case
Composite and Emerging Materials	• High temperature interactions between novel GFRP applications like stay-in-place formwork and concrete are not well understood. Tests are required to assess structural integrity during and post-fire.

PRELIMINARY CONCLUSIONS

This paper provides an overview of current international bridge fire research and the state of bridge fire resiliency frameworks outside of Canada. Little public domain Canadian research has been published on bridge fire resilience despite significant potential for severe interruptions to traffic networks in parts of the country. This paper aims to outline current research gaps in the international resilience framework in order to stimulate Canadian research to provide both international and domestic guidelines. Ultimately, a Canadian-centric framework for bridge fire resiliency needs to be developed and applied to domestic case studies. Such a development can be initiated by reviewing the information herein.

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