Fire Hazards in Bridges – A Current Review

Author

Kenny Luu, Manager - Structures ANZ, SMEC
Laura Roberts, Associate Engineer Structures, SMEC

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The last two decades have seen a significant increase in fire incidents of bridges worldwide. Many of these fires have caused significant damage or total collapse of the structure. Based on recent studies, the biggest cause of fires in most of the bridges that collapsed or failed due to fire was from fuel leakage resulting from collision or spillage.

Bridge collapses often lead to life and significant economic losses which need to factor in loss due to connectivity. In the US alone, the average annual fire loss for bridges is estimated to be $1.28bn. Despite the increasing significance of fire hazards in bridges, current engineering practices lack comprehensive guidance for addressing fire hazards in the bridge structures, especially for existing bridges. This gap in knowledge poses significant challenges for ensuring the resilience and longevity of critical infrastructure which has the potential to significantly impact the safety of communities and result in significant economic impacts.

This paper aims to provide a critical review of the current design standards and practices to deal with fire hazards in bridges in Australia. Through this review, the authors aim to identify the critical gaps in the current approach and provide recommendations to better enhance fire resilience in bridges in Australia.

1.0 Introduction

Bridges are crucial components of modern transportation networks due to their high capital value, strategic significance and operational importance. Any failure or service restriction of a bridge can have far reaching consequences including substantial economic losses, community disruptions and potential loss of life.

Over the past two decades, fire incidents on bridges have increased significantly, often due to fuel leakages following vehicle collisions or spillages which can result in high intensity fires where peak temperatures can exceed 1200°C. These fires have resulted in extensive damage and, in some cases, total structural collapse. The occurrence of bridges collapsing due to fire surpasses the incidences due to wind and earthquake with a 2013 assessment in the United States revealing that 2.8% of all bridge failures was as a result of fire, surpassing the incidence of collapse caused by wind (1.6%) and earthquakes (1.9%) [1]. Fire was also identified as able to compromise the structural integrity of bridges regardless of the materials used, affecting timber, steel, and concrete [2].

It is worth noting that the probability of a fire occurring on a bridge is low. A recent study demonstrated the annual prospect of fire occurring in a bridge is approximately 5%, which is higher than that in tunnels (approximately 3%) but lower than that in buildings (approximately 12%) [4]. Despite this small probability of occurrence, fire incidents on bridges can cause significant structural damage, network disruptions and economic losses. In the US alone, the estimated annual economic loss due to bridge fires is $1.28 billion [4], reflecting both direct repair costs and long-term disruptions to transportation networks, which can significantly impact local and regional economies.

Whilst there has been increasing awareness around fire hazards and their associated impact on bridges, design provisions and guidelines to deal with fire risks in bridges is currently insufficient. In many bridge design standards worldwide, design requirements for fires are lacking when compared against the design provisions for wind and earthquakes. Furthermore, these provisions are lacking when compared against the design requirements for fires in buildings and tunnels which are inherently different to bridges due to the contrasting physical, environmental and human conditions of each.

Table 1 shows a comparison of the key differences between these types of structures.

Criteria	**Bridges**	**Buildings**	**Tunnels**
Exposure	Open-air space	Enclosed space	Enclosed, confined space
Fire spread	Wind and continuous oxygen supply can spread and fuel fire	Initial slow spread Once established, can spread rapidly with flammable contents	Limited airflow leads to rapid smoke and heat buildup
Materials	Structure is typically heat resistant. Cause of fire is external factors e.g. fuel	Structure is typically heat resistant. Interior contents can be flammable and produce toxic fumes	Structure is typically heat resistant Cause of fire is external factors e.g. fuel
Evacuation	Time and access is typically favourable allowing timely evacuation.	Multiple exits available. Purposebuilt evacuation stairs.	Limited evacuation routes. Purposebuilt evacuation stairs at increments along a tunnel.
Risk to life	Lowest risk to human life	Moderate-high risk to human life	Highest risk to human life

Table 1. Comparison of key differences between bridges, buildings and tunnel fires

In Australia, the current standard for bridge design is AS5100-2017 which includes provision for fire design but lacks the depth and specificity necessary to address modern fire hazards comprehensively. This gap highlights a critical vulnerability in current bridge design practices, which may not adequately safeguard against modern fire risks.

This paper aims to provide an informative background of fire effects on bridge structures by providing an overview of the material effects of fire followed by a number of case studies to illustrate the impacts of bridge fires across a range of structure types and fire types. This is then followed by a critical review of the current design standards and practices to deal with fire hazards in bridges in Australia and proposed recommendations to enhance fire design of bridges in Australia. Through this paper, the authors aim to identify the critical gaps in the current approach and provide recommendations to better enhance fire resilience of bridges in Australia which is essential for ensuring the longevity and safety of infrastructure, thereby protecting communities and mitigating the social and economic losses associated with bridge fires.

2.0 Overview Of The Effects Of Fires On A Bridge Structure

While fire can occur on or under a bridge, fires directly underneath the structure are typically the most critical. When a fire occurs, the high temperatures will generally have two main effects on the bridge structure which are (1) degradation of material properties and (2) thermal-induced design actions. The following section presents an overview of the effects of fire on bridge structures for these effects for common bridge material types.

2.1 Degradation of material properties

2.1.1 Structural Steel

Fire-induced temperatures can cause significant degradation in the mechanical properties of materials. The effect of elevated temperatures on the properties of structural steel has been thoroughly researched and documented in literature and local and international design standards. Amongst the most important parameters in the analysis and design of steel bridges is the yield stress and elastic modulus of steel. Depending on the design standards adopted for design and analysis e.g. Australian Design Standard AS4100-2020 or Eurocode 3-2005, the yield stress of steel starts to decrease at temperatures between 215°C degrees (AS4100) and 400°C (Eurocode 3). These design standards suggest that the yield stress at a temperature T=550°C is approximately 50% yield stress of steel at ambient temperature. When the temperature reaches to approximately 900°C, steel retains less than 10% of its yield strength at the ambient temperature.

Steel has been suggested by the current design standards to start softening i.e., experience a reduction in its Elastic Modulus at relatively low temperatures. Both AS4100 and Eurocode 3 suggest steel will retain 50% of its Elastic Modulus when temperatures reach 550-600°C. However, after this point, the two codes differ in the rate of reduction in the Elastic Modulus of steel versus temperatures. The Eurocode 3 predicts a higher reduction rate but suggests steel retains a small residual (less than 10% of the Elastic Modulus) after the temperature has reached 1000°C while AS4100 considers steel to have lost all of its stiffness at 1000°C. Figure 1 (left) shows the impact of temperatures on the Yield Stress and Figure 1 (right) shows the Elastic Modulus of structural steel as predicted in AS4100 and Eurocode 3.

It must also be noted that fireinduced temperatures have a profound effect on the stress-strain relation of structural steel. In design, the behaviour of steel at room temperature is often idealised to be close to elasticperfectly plastic. As the temperature increases, literature has suggested the shape of the steel stress-strain curve becomes more rounded with a large decrease in the proportional limit. This decrease in the proportional limit, combined with the reduction of the yield stress results in an overall drop in the stress-strain curve and could surpass the members elastic limit in which case permanent deformation will be experienced by the steel component. Despite this, our research to date has revealed that the impact of fires on the stress-strain relation of structural steel is currently not covered in AS4100, or any of the current Australian Design Standards.

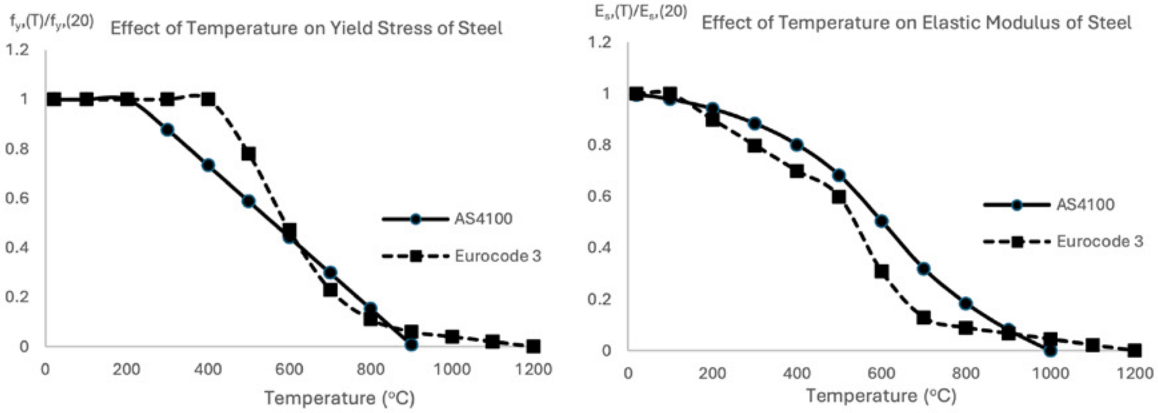

Figure 1. Effect of temperature on steel according to AS4100 and Eurocode 3. (Left) Yield stress, (Right) Elastic Modulus

2.1.2 Concrete, reinforcement and prestressing steel

Available test data suggests concrete experiences a minor degradation in compressive strength as temperature rises to 200°C. Beyond this point, a prominent reduction occurs with both AS5100.5 and Eurocode 2 assuming a linear reduction in concrete compressive strength to a temperature of 900°C. Figure 2 shows the effect of temperature on concrete compressive strength. The degradation mechanism of concrete due to fire exposure is influenced by the material's low thermal conductivity, which can result in substantial thermal gradients between the surface and the inner concrete. When exposed to high temperatures, the outer layer of concrete heats, while the interior remains relatively cool. This temperature differential can lead to the surface concrete spalling, whereby fragments of the concrete surface break away. Spalling of concrete then further advances the degradation of the section with reinforcement and/or prestressing strands becoming more exposed to elevated temperatures.

Steel reinforcement also undergoes significant changes at elevated temperatures. At around 600°C, steel reinforcement can lose up to 50% of its yield strength. However, it can fully recover its yield strength on cooling from temperatures of up to 450°C for cold worked steel and up to 600°C for hot rolled steel. At temperatures higher than these, the loss in yield strength is permanent, reducing to levels characteristic of mild steel. The modulus of elasticity of steel is also significantly reduced while steel is at elevated temperatures. Furthermore, the material bond between reinforcing steel and concrete can be adversely affected at temperatures higher than 300°C. This is due to differences in thermal conductivity between steel and concrete, as well as their differing rates of thermal expansion. This temperature differential can weaken the material bond, further compromising the structures' integrity.

Prestressing steel is vulnerable to fire, with the heating and subsequent cooling of strands able to result in substantial strength loss and property changes. When considering the residual strength of prestressing steel in accordance with the Eurocode General (without considering the effects of temperature on concrete or the bond strength between steel and concrete), prestressing strands maintain their strength up to 400°C, then linearly lose approximately 80% of its strength from 400°C to 700°C. As presented in [6], practical testing of prestressing strands resulted in a loss of strength at lower temperature, with strands heated to above 200°C noted as having some reduction in strength, refer Figure 3.

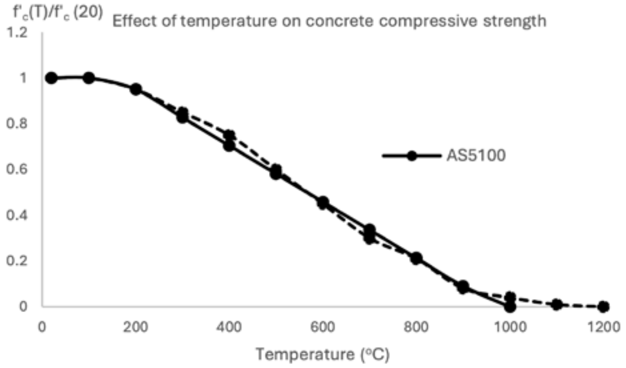

Figure 2. Effect of temperature on concrete compressive strength according to AS5100.5 and Eurocode 2

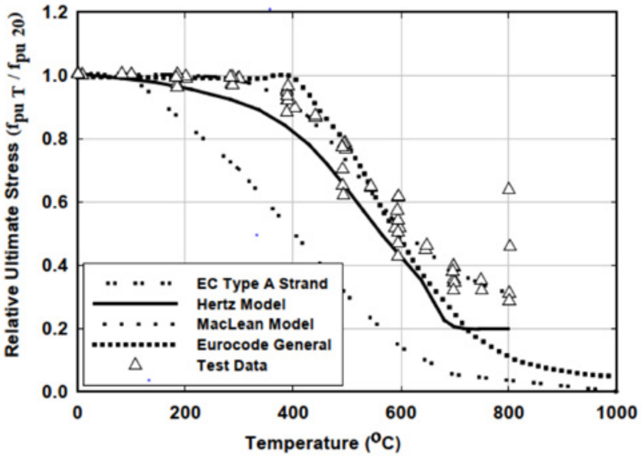

Figure 3. Extract from Figure 46, Highway Bridge Fire Hazard Assessment Draft Final Report Prepared for the NCHRP Program Transportation Research Board of The National Academies [6]

2.1.3 Timber

As described in AS5100.8-2017, wood itself does not burn, the effect of heat is to firstly decompose the wood in a process known as pyrolysis, and it is some of the products of this decomposition that burn if conditions are suitable. Typically, timber bridges are comprised of large sections which have good resistance to fire, and except during a severe bush fire, are usually resilient to fire. Temperature ranges and the associated effects as defined in the TMR Structures Inspection Manual is given below and shown visually in Figure 4.

Zone A: Water vapour is given off and wood eventually becomes charred
Zone B: Water vapour, formic and acetic acids and glyoxal are given off, ignition is possible but difficult
Zone C: Combustible gasses, diluted with carbon dioxide and water vapour are given off
Zone D: Char develops, glowing occurs and the char is gradually consumed
Zone E: Char is consumed as fast as it can form

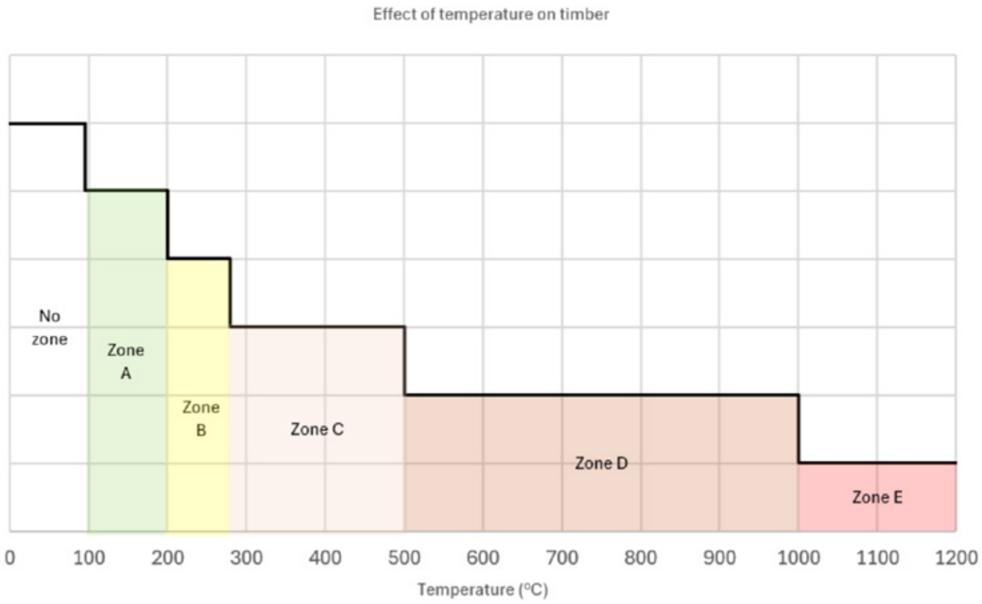

Figure 4. Effect of temperature on timber according to TMR Structures Inspection Manual –2016 [13]

2.2 Thermal-induced design actions

When a bridge is subjected to elevated temperatures as a result of fire, its structural members will experience deformation. The deformation of structural members subjected to fire generally includes the following two actions:

Extension of members: An extension based on the average temperature increase at the neutral axis of the member; and

Bowing: A bowing towards the hot surface (generally surface exposed to the heat source) if a thermal gradient is formed.

If the above deformation is not restrained, additional temperatureinduced design actions will not occur. However, as the temperature continues to rise, the stiffness of the member is reducing as its material modulus is decreasing. Therefore, the temperature induced deformation and the deflection due to the service loading on the bridge deck will increase accordingly, and if heating is not stopped, this will lead to excessive deflection and eventually a collapse of the bridge.

In many cases, the temperature induced deformation of the structural member is restrained, which will result in additional forces and moments in the member. These design actions must be fully understood and accounted for in the structural fire design and assessment.

If the restraint is internal e.g. cool part of the bridges restraining the heated part of the bridge or in a steel concrete composite beam, the structural capacity of the interfaces must be assessed to ensure it has sufficient capacity to accommodate the developed internal forces to prevent structural collapse.

3.0 Case Study: Introduction

The following section presents a number of case studies to illustrate the impacts of bridge fires across a range of bridge types and range of fire sources. These case studies highlight the vulnerability of bridges to fire.

3.1 Case Study 1: MacArthur Maze Interchange

On April 29 2007, a catastrophic incident occurred at the MacArthur Maze interchange in Oakland, California, when a tanker truck carrying 32,000 litres of fuel overturned and ignited. This accident, which took place on the I-80/880 Highway bridge, became one of the most significant bridge fire incidents in recent history due to its impact on infrastructure and public safety, refer Figure 5 for the bridge post collapse.

This incident is summarised as follows:

- The fire occurred at the MacArthur Maze interchange in Oakland, California, where highways I-80, I-580, and I-880 converge.
- The incident was caused by a fuel tanker truck carrying 32,000 litres of fuel that overturned and ignited, leading to a massive fire.
- The fire spread across the deck, with fuel flowing through the scupper drains which then spread the fire down to the ground around an I-880 pier. Temperatures reached up to 1100°C, which weakened the steel girders of the I-580 overpass above and caused a portion of the I-580 overpass to collapse onto the I-880 roadway about 22 minutes after the fire started. A second section of the I-580 sagged heavily and partially collapsed about 37 minutes after the fire started. [3]
- The driver of the truck was injured, with no further injuries or fatalities reported.
- The reconstruction of the damaged sections of the MacArthur Maze interchange cost approximately $16 million USD, with the estimated economic loss due to the disruption to the network estimated to be 17 times the rebuild cost at $272 million USD.
- The bridge was rebuilt and reopened 26 days after the incident, following a rapid reconstruction effort.

Figure 5. The I-80/880 Highway bridge collapse, MacArthur Maze Interchange, Source: New York Times, 2007 [31]

3.2 Case Study 2: Interstate I-85

On March 30 2017, a significant incident occurred on Interstate 85 (I-85) in Atlanta, Georgia, when a fire started beneath the bridge where construction materials were stored. The fire resulted in an intense blaze which severely damaged the bridge, leading to the collapse of one span, refer Figure 6 for the bridge during the fire and Figure 7 for the bridge during the reconstruction works. This incident is significant as the bridge is comprised of prestressed concrete girders, which are typically considered more resilient when considering the impacts of fire, however this incident demonstrates concrete bridges are also vulnerable to high-temperature fires.

This incident is summarised as follows:

- The fire began at around 6PM under the bridge which contained highdensity polyethylene (HDPE) and fibreglass tubing.
- The blaze quickly spread through the storage area, reaching high temperatures that weakened and lead to the collapse of one section of the northbound bridge, as well as significant damage to the adjacent spans and southbound section. Ultimately, 3 spans of the northbound and southbound bridges were replaced
- The impact to the community was significant, with the bridges forming a vital component of the Atlanta transport network, carrying over 250,000 vehicles per day.
- The cost to rebuild the damaged sections of the I-85 bridge was estimated at $16.6 million USD.
- The disruption led to significant logistical and economic challenges in the region, with the cost of shipping estimated to have increased by up to 20%.
- The bridge was rebuilt and reopened to traffic in 43 days.
- No injuries or fatalities were reported.

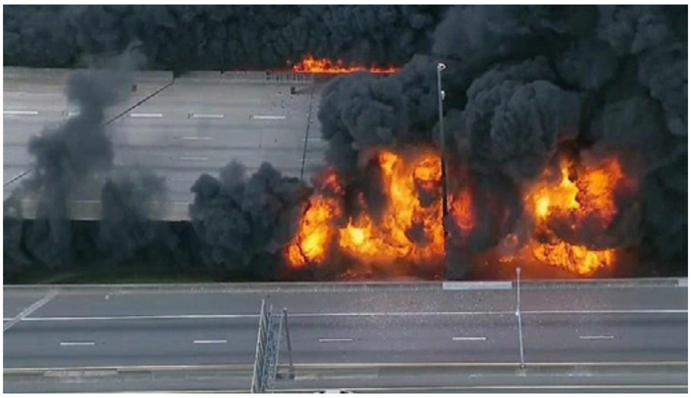

Figure 6. Fire under the I-85 bridge caused by material storage, Source: NBC News, 2017 [32]

Figure 7. I-85 during reconstruction, Source: Youtube, 2017 [34]

3.3 Case Study 3: Bush Fires – Eurobodalla Shire Council

Eurobodalla Shire Council in New South Wales, Australia was significantly affected by bushfires in 2019-2020, with 80% of the shire impacted, refer Figure 8 showing a schematic of impacted bridge locations. The impact to the shires' infrastructure was extensive, with 18 timber bridges destroyed or significantly damaged resulting in 17 full replacements and 1 repair [14]. The destruction to the road network severely impacted residents, farmers and businesses as well as emergency services and subsequent construction access.

The replacement structures included culverts and modular bridge systems where possible. Figure 9 (left) shows Murphy's Bridge during the bushfires and Figure 9 (right) post replacement.

The replacement of timber bridges with concrete structures significantly improves the resilience of the network for future bushfire (and floods). The estimated cost of replacing the timber bridges according to Eurobodalla Shire Council was $8M AUD and the economic impact was estimated at $130M AUD.

Figure 8. Schematic showing bushfire (and flood) impacts to timber bridges, Source Eurobodalla Shire Council [14]

Figure 9. Left: Murphys bridge 31 December 2019 during the bushfires, Right: Murphy's Bridge concrete replacement, Source Eurobodalla Shire Council [14]

3.4 Case Study 4: Future Vehicles – Electric Vehicles

Given the established risks of bridge fires from fuel leakage, highly combustible storage materials, and bush fires demonstrated in the previous case studies, it is advisable to also consider emerging and future vehicle trends to best provide resilient transportation networks. Of note, electric vehicles are increasing in size and prevalence and therefore their unique fire risks should be incorporated into fire safety and infrastructure planning.

EV fires can burn up to 1,200°C, hotter than combustion engines which range from 800- 1,000°C [12]. The complex nature of lithiumion batteries means that they can pose ongoing risks by reigniting hours or even days after the initial fire. This risk is due to the phenomenon known as thermal runaway, where the batteries continue to generate heat and potentially catch fire again even after being extinguished. This means EV's present additional challenges in firefighting compared to combustion engine fire, requiring specialised training and equipment.

One incident of note occurred off the Westgate Bridge in Melbourne Australia on November 28, 2023, when an electric truck experienced a battery fault resulting in a "thermal runaway" fire which took 80 minutes to extinguish. Refer Figure 10 for location of the incident relative to the Westgate Bridge and Melbourne CBD. Fortunately, the driver was able to coast the cement truck off the bridge, stopping near the inbound exit to Todd Road before the fire took hold, resulting in no injuries. Refer Figure 11 (left) and (right) for images of the EV truck fire.

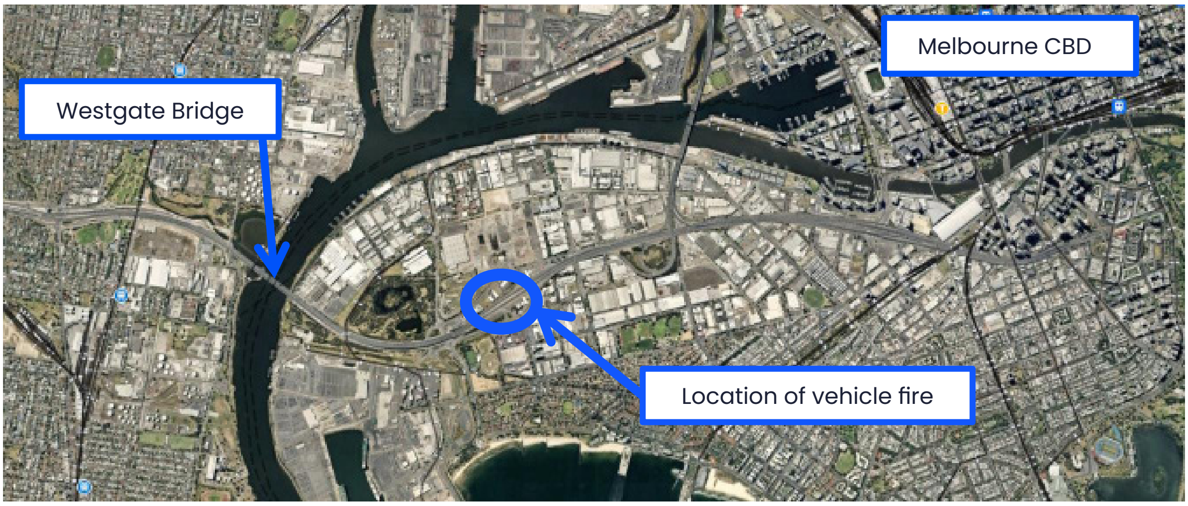

Figure 10. Location of EV fire in Melbourne Australia, November 2023, Source: GoogleMaps

Figure 11. EV truck fire Westgate Freeway, Source 7News, 2023 [33]

4.0 Review Of AS5100

Australia's AS5100-2017 standard for bridge design, provides guidelines for the design of new bridges and the evaluation, and maintenance of existing bridge structures. AS5100-2017 shows notable improvement in addressing fire design compared to its predecessors AS5100-2004 and the earlier Austroads Bridge Design Code 1992. Notable inclusions in AS5100-2017 include:

- AS5100.2 Clause 26, acknowledges and considers fires as a ULS load case for bridges and specifies fire characteristics (timetemperature curves). The associated load combination is described by AS5100.2 Clause 23.3 and Appendix D, Table D3.
- AS5100.5 Section 5, provides guidance for Design for Fire Resistance against hydrocarbon fires, which includes guidance on the impact of fires on the material properties of concrete, reinforcement and prestressing. This section refers to AS3600 for design guidance on non-hydrocarbon fires.
- AS5100.5 Section 16.6, provides guidance on how to calculate the impact of fires on the residual tensile strength of Fibre Reinforced Concrete.
- AS5100.6 Section 3.8, refers to AS/NZS2327 Composite Structures – Composite SteelConcrete construction in buildings in addition to AS4100. It is worth noting that significant updates of fire design requirements have been added to AS/NZS2327-2017.
- AS5100.8 Section 3.4, provides comprehensive guidance on the visual inspection and assessment of fire-affected concrete bridges, however this guidance is limited to concrete material and does not address the impacts to reinforcement and prestress within concrete sections.
- AS5100.8 Section 3.4, provides guidance on how to repair fire-affected concrete and as per the above point, it limited to concrete material and does not address reinforcement and prestress within concrete.
- AS5100.8 Section 4.4.1 and 4.4.2, provides some guidance on post-fire properties of structural steel and advice on reuse of steel bridges; and
- AS5100.8 Section 6.3, provides guidance on assessment of fire-affected masonry bridges.

Despite the notable improvements, there are critical gaps in the current approach. The following points are not exhaustive, however represent critical gaps within AS5100-2017 identified by the authors in their review:

- AS5100 delegates entirely to 'the relevant authority' to specify if a bridge structure is required to be designed for fire. Even after the 'relevant authority' specifies that fire design is required, the 'relevant authority' is also responsible for specifying the fire design requirements i.e. the duration which a bridge structure must standup and the fire loads i.e. the timetemperature curves.
- In the case a bridge is required to be designed for fire, AS5100.2 does not provide any guidance to the bridge designer on the load combination to be adopted. Table D3, Appendix D of AS5100.2 essentially refers the designer to 'specialist literature' but stops short of specifying the 'specialist literature'. The ULS load combination detailed in Clause 23.3, AS5100.2 associated with fires is therefore not determined.
- AS5100.2 Clause 23.3, specifies the ULS Load combination as:
    - Permanent effect (PE) + Fire effects.
- If the fire occurs on the bridge deck, the above load combination should also include a live load provision, which is to account for fire fighting vehicles including fully loaded fire trucks on the bridge deck at the time of the fire.
- AS5100 makes references to fire design provisions in AS3600 and AS4100, which are written for building structures. It has been suggested in recent studies that the fire design provisions developed and included in design standards for building structures are not readily transferable to bridges due to the markedly different fire load characteristics, as was demonstrated in the comparison table presented in Section 1 of this paper.
- Whilst AS4100 and AS/NZS2327 provide guidance on the change of the yield stress and elastic modulus of structural steel subject to fires, and AS5100 refers to these provisions, neither code provides any guidance on the stress-strain curves of steel at elevated temperatures. This information is required to predict the behaviour of steel elements, particularly to predict if these elements will experience plastic behaviour/permanent deformation.
- AS5100 does not provide sufficient guidance on the structural analysis and design provisions of new bridges (Parts 5 and 6) or assessment and strengthening of existing bridges subject to a fire event (Parts 7 and 8). Notably, the code does not specify the calculations for structural capacity of both concrete and steel members which have been subjected to fire.
- AS5100 frequently refers to specific international/specialist references but stops short of specifying the 'specialist literature'.
- Given the limited guidance in AS5100-2017 on fire design for bridges, Australian bridge designers may need to

reference international standards, such as the Eurocode and other literature for fire design. This reliance on external sources may result in variability in design practices and increased costs, posing challenges in ensuring compliance with client and project specific requirements.

The authors’ recommendation for key improvements to AS5100-2017 is given in Section 8.2.

5.0 Review Of ‘Relevant Authority’ Requirements

As discussed in Section 4, in accordance with AS5100, a ‘relevant authority’ will need to specify if fire design is required to “activate” the provisions of fire design in accordance with AS5100. A review of the current fire design requirements from a number of ‘relevant authorities’ was undertaken. Within the timeframe of this study, the authors’ review includes a selection of core technical requirements, directions, and specifications from a number of relevant authorities, and while not exhaustive of all relevant authorities within Australia, is representative of typical authority requirements. Relevant authorities considered in this study include:

- State road authorities:
  - Transport for New South Wales (TfNSW)
  - Department of Transport and Main Road (DTMR)
  - VicRoads
- Rail authorities:
  - ARTC
- Local councils:
  - Nil specific references identified within this study.

To date, limited fire design requirements for the design of new bridges from the “relevant authority” have been identified, with the following points summarising the key requirements identified from the authors’ review:

- TfNSW has included project specific fire design requirements in the project Scope of Works and Technical Criteria (SWTC) for a number of recent projects (circa 2022 onwards) as follows:
  - The bridge superstructure, except for shared user path bridge superstructure must provide a level of fire resistance not less than 90/-/- i.e., 90 minutes for the structural adequacy but nil for insulation and integrity
  - Shared User Path bridge superstructure is to be provided with a fire resistance of 60/30/30
  - The above requirements are applicable for the standard (cellulosic) fire curve given in AS1530.4

It is worth noting the above SWTC requirements apply to all bridges on the project, which can be located in very different locations and have very different functions which could result in over-design in lowrisk areas.

- TfNSW, NSW Transport Asset Standard Authority (ASA) Standard T HR CI 12030 ST Version 4.0 for Overbridges and Footbridges includes fire safety objectives for overbridges which are deemed to be satisfied if the bridge design meets specific fire resistance requirements. This standard also details the deemed to comply specific fire resistance requirements for footbridges at station locations and includes passive fire protection as a provision to achieve the necessary fire resistance. In the authors’ review, this standard includes the most prescriptive fire design requirements by an authority.
- TfNSW, NSW Transport Asset Standard Authority (ASA) Standard T HR CI 12020 ST Version 1.0 for Underbridges states ‘requirements for new underbridges are designed for fire resistance do not exist, however, project requirements, as determined from site-specific risk assessment, or as nominated by the RIM (Rail Infrastructure Manager) can apply’. No detail or further guidance of the site-specific risk assessment is then provided in this standard.
- DTMR’s Design Criteria for Bridges and Other Structures dated February 2024 delegates the determination of if a bridge is required to be designed for fire, as well as the fire curves to the Project requirements and SWTC or as directed by the Director (Planning and Delivery). To date, the authors have not been aware of such requirements being specified on recent projects.
- VicRoads Technical Note TN67 “Fire retardant chemicals for use in the protection of road and bridge assets from bushfires” permits the use of fire-retardant chemicals on ‘valuable assets such as heritage timber bridges or key structural links to local areas’ which are prone to bushfires.

- No fire design requirements for bridges have been identified in our review of ARTC and local council technical requirements.

Considering the limited fire design requirements of relevant authorities identified above, it is apparent the framework established by AS5100 when combined with relevant authority's supplementary design requirements leaves critical gaps for designers when designing for fire design.

Furthermore, in contrast to the sparse fire design requirements for bridges, fire design requirements for tunnels and other infrastructures such as stations have been extensively documented in technical documents of various authorities.

6.0 Fire Risks In Aging Bridges

Literature suggests fire hazards can pose a greater threat to bridges which are older than 50 years. This heightened vulnerability is often the result of one or more factors which reduce the structural strength of these bridges [5]. These factors may include the gradual accumulation of defects over time, overloading, inadequate maintenance and material fatigue due to loading and unloading cycles. As the structural strength decreases, the ability of these bridges to withstand the effects of fire weakens, making older bridges more vulnerable to fire.

It has been reported that as high as 70% (depending on literature source) of bridges in Australia are more than 50 years old. According to the Australian Local Government Association 2024 National Stage of the Assets Report [11], local councils are responsible for operating and maintaining approximately 22,000 bridges (42% of all Australia bridges). Many of these bridges have been classified as being in fair to poor conditions. This suggests a substantial portion of Australia's existing bridges may be vulnerable to fire hazards, potentially leading to significant replacement or repair costs.

Despite growing awareness of fire risks, particularly from bushfires, there is currently no mitigation strategy or guidelines from relevant authorities or asset owners to address these hazards identified by the authors research to date. This highlights the need to develop an overarching and risk-based framework to manage fire risks in bridges and enhance the resilience of transport infrastructure in Australia. The authors' recommendations for this framework is given in Section 8.1.

7.0 Post-fire Assessment Of Bridges

When a bridge is subjected to fire, a post-fire assessment is required to determine if the bridge can safely be retained, if any repair/strengthening is required to ensure it can continue its operation safely or if replacement is required. Given the significant direct costs of bridge replacement as well as the significant indirect social and economic costs due to the loss of connectivity and network disruptions, the post-fire assessment must be realistic (without too much conservatism) whilst ensuring public safety is maintained. For bridges which have either collapsed or undergone excessive permanent deformation, permanent loss of service is obvious, and replacement is therefore required. The focus of the post-fire assessment strategy should therefore be directed towards bridges which have not collapsed or exhibited excessive permanent deformation. Key to informing the post-fire assessment is determining the maximum temperature that structural members were likely exposed to during the fire event.

7.1 Steel

For steel bridges, visual inspection can identify signs of overstressing such as buckling, distortion and excessive deformations, which often indicate the member has been exposed to high temperatures. However, there is limited literature which provides good correlation between steel discolouration/visual signs and the temperatures which the steel members were exposed to.

AS5100.8, Clause 4.4.1 stipulates that ‘Fire-affected structural steel shall be assessed by initial inspection and, where damage is suspected, supplemented with hardness testing in situ and tensile testing of samples to establish the full extent of damage and the residual quality of the material, including connections. Clause 4.4.1 further stipulates ‘The initial inspection shall estimate the range of fire temperature and the temperature effects of fire damage on steel by assessing the damage on surrounding material and by comparison with nonfire-affected steel’. This appears to suggest the temperature which the steel element has been exposed to can be estimated by comparing the residual strength of fire-affected steel against that of nonfire affected steel. Additionally, the Australian Steel Institute outlines detailed methods to assess the residual strength of fire-affected structural steel on their website[34].

Depending on the intensity and the temperature of the fire, steel members can have permanent loss in strength on cooling [6],[8],[34]. The residual strength must be understood to facilitate the determination of the structural capacity of a bridge post-fire. It has been suggested in literature that steel will recover most of its strength at ambient temperature after cooling if it has not been subjected to a temperature greater than 600°C during the fire [6],[34]. Even if the temperature has reached higher than 600°C, it is expected that normal strength steel (yield strength between 250-275 MPa) still retains about 90% of its strength at ambient temperature after cooling [34]. For higher strength steel, which is commonly used in bridges, a decrease in the strength of steel will occur after cooling if it has been subjected to high temperatures. In this case, testing is necessary to determine the residual strength of fire-affected steel.

7.2 Concrete

Due to its low thermal conductivity, heat transfer through concrete elements tends to occur at a much slower rate than in steel. As a result, most of the fire damage tends to occur near the surface, which is exposed to fire while the inner concrete can remain at a low temperature relative to the surface temperature. In current practice, assessing the temperature of fire event for a concrete bridge is often done by a visual inspection of the impacted bridge. Australian references including the VicRoads Technical Note TN102 (April 2011): Fire Damaged Reinforced Concrete – Investigation, Assessment and Repair and AS5100.8 provide excellent correlation between discolouration and visual signs and the temperatures the structural members may have been exposed to. However, visual inspection is limited to visible and accessible elements and can only detect surface damage. To assess the quality of concrete beyond the surface, non-destructive testings and scanning can be used in conjunction with the visual inspection. It is critical to identify and appropriately repair or replace fire-damaged concrete.

As discussed in Section 2.1.2, considerable research has been directed at the post-fire strength of reinforcement and the effects of fire on the concrete/reinforcement bond strength. It is generally accepted that hot rolled steel reinforcement will be impacted by fires in a similar manner with structural steel. It will tend to recover most of its strength after cooling. The impact of fires on prestressing steel is more profound and more complex than that for steel. Although recent years have seen a number of studies on the impact of fires on the strength reduction, prestress losses, bond strength between concrete and prestressing strands, this is an area, which still requires further research work.

7.3 Timber

Timber bridges are widely accepted to be the most vulnerable to fire and often collapse or suffer irreparable damaged from fire threats such as bushfires. As a result, the majority of existing available literature on post-fire bridge assessments focuses on concrete and steel bridges.

7.4 Post-fire Assessment (Desktop)

After the visual and initial inspection, including the necessary testing to ascertain the conditions and post-fire material residual strength of the bridge members, structural analysis and assessment is often required to ensure the structural adequacy of the bridge under its operating loads.

The followings should be considered during a post-fire assessment of a bridge:

- While the visual inspection should be focused on the areas/surfaces of the bridge which were exposed to the fire as these areas are the most likely to have material damage, the entire bridge should be carefully inspected for sign of overstress due to thermal-induced forces.
- Compare the post-fire inspection against any past inspection records of the bridge.
- Mapping of areas of the bridge which are likely to have experienced high temperatures can give an indication of the fire source location and how the fire spread.
- Fire modelling should be undertaken to validate the estimated fire temperatures and areas of impact from the visual inspection findings.
- Structural analysis of the bridge during the fire event should be undertaken in addition to the post-fire structural analysis. This is to obtain a complete history of the bridge response to the fire. This is particularly important for bridges with a high degree of restraint against thermal induced deformation as this restraint can generate additional complex and significant forces on the members.

In addition to the strength assessment of a bridge post-fire, it is important that the serviceability, including the residual service life of the bridge is determined. This information is critical to enable the asset owner/operator to develop an asset management strategy for the bridge. However, our research has revealed significant gaps in this area. Further research is needed in the following key areas to enable an accurate assessment of the post-fire serviceability and the residual life of bridges:

- Fatigue issues in both steel and concrete bridges (and other construction materials)
- Long-term behaviour of concrete, which was subjected to heating during a fire
- Long-term behaviour of reinforcing steel, prestressing steel and their bonding with concrete
- Steel connection behaviour under and post fires

Due to the gaps in the current literature on the residual service life of bridges, which have been subject to fires but are retained in services, an inspection regime may need to be implemented, at least for a short duration post rehabilitation to ensure these bridges can continue their operations safely. The authors' recommendation for post-fire assessment is given in Section 8.3.

8.0 Recommendations Of Strategies To Enhance Fire Resilience

Based on the identified gaps from this study, there are a number of recommended strategies that can be implemented to better enhance fire resilience of bridges in Australia. The following section includes a selection of key strategies, and while not exhaustive, represents core strategies that will significantly enhance fire resilience of bridges in Australia which is essential for ensuring the longevity and safety of infrastructure, thereby protecting communities and mitigating the social and economic losses associated with bridge fires. This paper recommends the following core key strategies:

1. Relevant authorities to develop and implement an overarching fire risk management framework for fire design
2. Improvements to AS5100 for the design of new bridges
3. Development of comprehensive post-fire inspection and assessment processes in AS5100 and by relevant authorities.

8.1 Strategy 1: Overarching Framework

Implementation of an overarching framework is recommended to be instigated by the relevant authorities (rather than included as part of AS5100). This approach allows the relevant authorities to customise the framework to suit their specific regional or project requirements and can be tailored to assess new or existing bridges. The advantage of a framework approach includes allowing asset owners to take a proactive approach to assess the vulnerability of their existing network as part of their asset management strategy as well as better inform the design requirements for new bridges on a sites-pecific basis, therefore providing both safe and economical fire-resilient bridge designs for the community.

Furthermore, as bridge collapse due to fire is considered low probability but high consequence event, it is not economically viable to implement uniform fire resistance requirement on all bridges in Australia. Instead, it is more efficient to focus resources on existing or new bridges that are higher risk of fire exposure. A risk assessment framework quantifies the fire risk of bridges which can then inform the relevant authorities to implement cost-effective fire mitigation strategies that focus on protecting their most at risk infrastructure.

Fire Risk Assessment of Bridges

Recent studies recommend the implementation of an overarching framework to deal with fire hazards [4],[5],[7],[10], with two main methods to quantify fire risks as follows:

1. Assessment of a fire importance factor (IF)
2. Analytical Hierarchy Process (AHP)

Fire importance factor assessment

Determination of a Bridge Fire Importance Factor (IF) is similar to earthquake design in AS5100 whereby a Bridge Earthquake Design Category (BEDC) is determined based on the classification of the bridge relative to its function. A Bridge Fire Importance Factor reflects the vulnerability and impact of a bridge to fire and can be scaled according to a fire risk category such as low, medium, high and critical risk.

The impact of fire according to each fire risk category can then be used to inform whether or not fireproofing is recommended and could be considered to apply to both existing and new bridges. The description and recommendations for the fire risk category, as defined by [4], includes:

Fire risk category: Low

- IF = 0.8
- Negligible impact on integrity of bridges or operation facility with no human losses
- No need for fireproofing

Fire risk category: Medium

- IF = 1.0
- Minor impact on structural member of bridge and operation with no human losses.
- No investments are necessary to restore bridge following fire incident.
- No need for fireproofing

Fire risk category: High

- IF = 1.2
- Significant impact on structural members of bridge with partial/complete collapse of main structural elements, partial shutdown of operation with possible human injuries/losses
- At least 1 hour fireproofing should be provided to main structural elements

Fire risk category: Critical

- IF = 1.5
- Immediate/severe impact on bridge (loss of carrying load capacity and total collapse) and complete loss of operation.
- Expected human casualties and permanent closure of highway bridge.
- At least 1–2 hours fireproofing should be provided to main structural elements

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a multi-criteria decision making method which can be used for a wide range of applications. The AHP approach assigns weights to each variable, allowing for many variables to be taken into account simultaneously, compared to the more simplified Importance Factor approach. Similar methods are commonly used by road authorities when assessing the provision of throw screens and antijump screens on bridges. The advantage of this method is it offers a balanced decision-making approach which readily allows for assessment of bridges where fire damage would have the most significant impact, such as in terms of safety, economic disruption, and recovery time, preventing under-design in high-risk environments and over-design in low risk areas. Furthermore, this approach applies to both new and existing bridges.

[5] proposes 3 core criteria with a number of sub criteria. Below is a summary of the criteria and key consideration:

Social and economic impact

Bridge Location:

- Road type classification
- (e.g. rural, suburban, urban)
- Availability of alternate routes

Time and Cost to Repair:

- Direct costs to repair or replace a structure
- Indirect costs due to economic impacts

Closeness to a Major City:

- High traffic volumes
- Social and economic impact to communities

Vulnerability

Material:

- Types of materials used
- (e.g. concrete, steel, timber)

Age:

- Condition of the bridge.

Distance from Fire Station:

- Proximity to fire response services

Fire Protection:

- Existing fireproofing methods

Structural System:

- Type of structure (e.g. arch, truss, suspension)

Support Conditions:

- Support (e.g. simply supported, continuous)

Likelihood of Fire

Annual Traffic:

- Traffic volume
- % heavy vehicles

Distance to Chemical Plant/Oil Refinery:

- % dangerous good and flammable substances
- Number of previous accidents
- Number of accidents

Once each criteria has been assigned a value and is weighted, an overall risk score can be calculated which aligns with an associated risk level and damage level informing the required level of fire design,

8.2 Strategy 2: Improvements to AS5100 for the Design of New Bridges

Fire design in AS5100-2017 has been demonstrated throughout this paper to have a number of limitations. Currently, AS5100-2017 provides a foundation for fire design however it lacks the depth and specificity necessary to address modern fire hazards comprehensively. This gap highlights a critical vulnerability in current bridge design practices, which may not adequately safeguard against modern fire risks. The authors propose the following key improvements, noting this is not an exhaustive list:

1. Define the ULS load combination and the structural effects or make reference to the specific specialist literature
2. Include a clear fire design process
3. Include specific fire design provisions (or if the intent is for the designers to consult other literature, specify the specific literature /international standards to refer to)

Improvement to AS5100-2017 to include the above points is required to develop better guidance on the application of fire effects and the subsequent analysis and design of bridge structures.

8.3 Strategy 3: Development of Comprehensive Post-fire Inspection and Assessment Processes

The inspection and assessment of fire affected bridges is contained within AS5100.8. This Standard has the most extensive sections relating to fire effects, with sections dedicated specifically to fire assessment and repair of concrete, steel and masonry structures. Furthermore, a number of relevant authorities have supplementary guidance within their structural inspection manuals for inspections post-fire.

Despite this, there are aspects of both the Standard and relevant authority requirements which may be considered as oversimplified, leaving designers with gaps in sufficiently undertaking the inspection and analysis of bridges for the effects of fire. Key points of note include:

- **Lack of detailed guidelines for assessing non-visible damage:** The assessment must evaluate not only the visible, external damage but also the internal material degradation. As discussed earlier in this paper, the effects of fire at the material level extend beyond superficial damage and are critical to the performance of the structure post fire. For concrete, this includes the impact to the strength of steel reinforcement, strength of prestressing tendons and the bond between steel and concrete. For steel, this includes the impact to the microstructure of the steel and impact to welded and bolted connections.
- **Methodology to estimate fire temperature:** The Standard includes guidelines on the visual characteristics of fire at different temperatures for concrete (i.e. changes to colour). While colour changes provide a good visual estimate, it is subjective which may lead to under/over estimation of the fire temperature and therefore inaccuracy in the assessment. For steel, a similar subjective inspection approach is recommended, advising to undertake visual inspection of the surrounding material to compare nonfire affected steel. This approach may also lead to under/over estimation of the fire temperature and therefore inaccuracy in the assessment.
- **Limited focus on long-term effects:** The Standard addresses immediate damage but does not consider the long-term effects to the structure such as progressive cracking, ongoing material degradation, or corrosion of reinforcement over time. Failure to adequately consider long-term effects post fire potentially overlooks future risks which could be catastrophic.
- **Assessment of structure post fire:** As identified in Strategy 2, there are numerous gaps in the structural analysis of a bridge for the effects of fire and by extension post fire.

  While AS5100.7 and AS5100.8 provide guidance for the assessment and inspection of fire-affected bridges respectively, it is recommended that these Standards are further development to address their limitations to better enhance fire safety of bridges in Australia.

9.0 Conclusion

In conclusion, bridge fires, though rare, pose a significant risk to transport infrastructure, community safety and the economy. By examining case studies and reviewing current design practices, it is evident there is a need for the development of a more comprehensive and holistic framework or strategy to mitigate fire hazards in bridges. It is imperative that the first step in the framework includes an assessment to identify the bridges at high risks of fire threats, which require enhanced fire resistance.

Improvements of the limitations of the current standards, in conjunction with the development of comprehensive post-fire assessment inspection and assessment guidelines will be critical in improving the fire resilience of bridges, ultimately safeguarding communities and reducing the economic and operational impacts associated with bridge fires.

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Author

Kenny Luu, Manager - Structures ANZ, SMEC
Laura Roberts, Associate Engineer Structures, SMEC

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