Building Tomorrow's Society
Bâtir la Société de Demain

Fredericton, Canada
June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

EFFECT OF FIRE ON MSE HIGHWAY RETAINING WALLS AND BRIDGE ABUTMENTS

Rrokaj, Ertiana[1,2], Mirmirani, Shahriar[1]
[1] Reinforced Earth Company Ltd., Canada
[2] errokaj@recocanada.com (corresponding author email)

Abstract: In recent years, Mechanically Stabilized Earth (*MSE*) walls have gained wide acceptance among North American and international transportation jurisdictions as a versatile alternative to cast-in-place (*CIP*) retaining walls. While MSE structures are designed to fulfill a variety of retaining purposes, similarly to CIP walls, there exist fundamental differences with respect to their susceptibility to heat and fire. This paper will investigate how fire conditions can affect the performance of MSE structures for highway retaining walls and bridge abutments. The paper will (a) comment on relevant government regulations regarding the design of highway structures under fire conditions, (b) summarize and report on studies conducted on heat conductivity from fire on MSE walls, and (c) analyze the effect of fire on different types of soil reinforcements (geosynthetic, metal) and precast concrete panels. Finally, this paper will identify the consequences from potential failure modes of MSE structures under fire conditions and discuss solutions for prevention.

1 Introduction

The use of Mechanically Stabilized Earth (*MSE*) walls for retaining purposes is a popular alternative to conventional cast-in-place (*CIP*) walls. MSE walls are used in a variety of applications, including retaining walls and bridge abutments for highways and railways. With the frequency of transport of hazardous materials (*flammables and combustibles*) via highways and railways, fire has become a significant risk for infrastructure projects. Depending on the intensity and duration of these potential fires, the integrity of the structure can be compromised. Not many studies have investigated the effects of fire on MSE bridge abutments. Most literature references the material thermo-mechanical properties of the components under high temperature conditions, and most studies focus on the determination of an 'importance factor' to evaluate the risk of fire for a bridge or on the restorative strategies to be undertaken after a fire-event, (*Branco et al. 2000, Kodur et al. 2013, Pay_a-Zaforteza and Garlock 2012, Aziz and Kodur 2013, Dwaikat and Kodur 2011*). If the structure is evaluated with a 'high risk' factor, it is important that measures be taken to prevent fires. As well, after a fire, the long-term serviceability of the structure must be determined, which is challenging due to the lack of information regarding fire temperatures and affected components, and the complexity of the force interactions during and after such an event. The general assumption is that, while a significant hazard, fire-induced collapse of bridges is a rare occurrence, therefore there exists low economic incentive to design all bridges for such an event except for 'at high risk' structures. Nearly all studies investigating the topic recommend that preventive measures be taken to reduce the risk of fire. However, most literature confirms that, to date, there exist no specific fire prevention design specifications for bridge structures (*Garlock et al. 2012*). Furthermore, bridge design codes lack information on the recommended fire models that should be used in the design of bridges (*Wright et al. 2013*). Nevertheless, it is important to investigate these hazards and their effect on structures to better protect the public and the economic investment that bridges represent.

2 Risk of Fire in Bridges

The primary cause for fires that damage bridges are due to vehicle crashes (*Wright et al. 2013*), particularly heavy-goods trucks and tankers, which carry flammable materials. Fires involving hydrocarbon burning are more severe than building fires, as they are characterized by higher peak temperatures and faster heating rates. Therefore, within a few minutes, extremely high temperatures (*1000ºC*) can be reached that can affect the structural integrity of the bridge to the point of collapse (*Kodur and Naser 2013*). While there exist many fire provisions regarding the safety of buildings, there are no fire safety provisions for bridges (*Garlock et al. 2012*). In the United States, the NFPA 502 (*National Fire Protection Association*) standard states a mandate for protecting critical structural components from high-temperature exposure to prevent collapse of bridges, yet it lists no guidelines on the methods to be undertaken to prevent collapse due to fire (*NFPA 2011*). Many crash events have been reported to have been caused due to factors relating to highway safety features of bridges, such as piers close to the roadway and narrowing shoulders (*Wright et al. 2013*). Preventive measures for reducing the risk of fires can include the improvement of these highway safety features. The AASHTO Highway Safety Manual is a useful tool for assessing the risk of fire by determining the risk of vehicle crashes (*Wright et al. 2013*). Most data and specifications on fire-events in infrastructure originates from the U.S. In fact, a study was published by the Virginia Polytechnic Institute and State University (*Virginia Tech*) evaluating the problem of fire damage to bridges. This study will be referenced in this paper.

2.1 Statistics on Fire Events

Most bridges in North America are made of steel and concrete. Damage from fire events can occur by vehicle crashes, rail car fires, and arson. An investigation was carried out by Virginia Tech to assess the risk of fire in causing bridge collapses in the U.S. From the NY Department of Transportation (*DOT*) database, it was determined that from 1746 cases of bridge collapses in the U.S. between 1920-2008, only 52 collapses were caused by fire (*See Figure 1*). Half of these cases were timber bridges that collapsed due to wildfire damage in remote locations and the other half (*25 bridges*) were incapacitated for service by vehicle crashes. In the U.S. there have been only two (*2*) fire events to cause complete collapse of bridges that involved fully loaded trucks. In all cases, there has been no human loss-of-life, however, the service of the bridge was lost either temporarily or permanently.

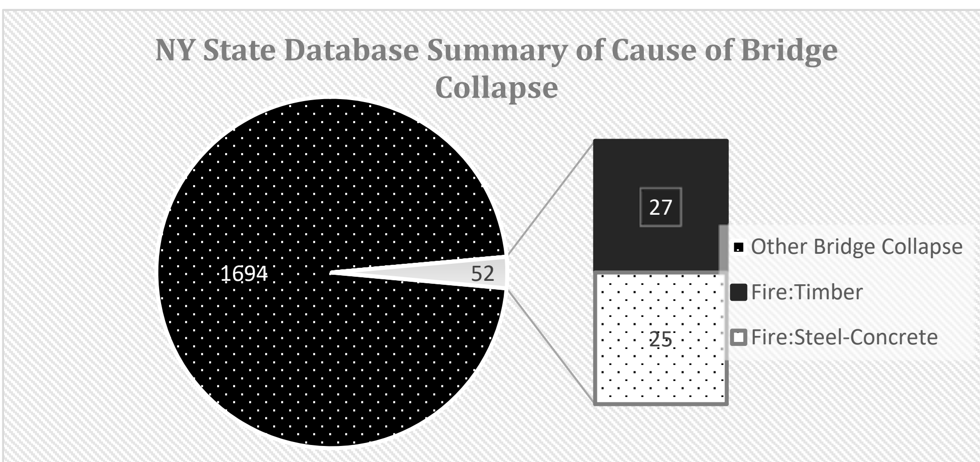

Figure 1: NY State Database Summary of Cause of Bridge Collapse (*1920-2008*)

Another database from the National Highway Traffic Safety Administration (*NHTSA*) Fatal Accident Reporting Service Encyclopedia (*FARS*) reported that from 5209 bridge collisions, only 536 had a fire occurrence and only 82 events involved large vehicles (*Class 7 truck, e.g. fuel trucks*) between the period of 1994-2008. Most bridge collisions occurred with the abutment or pier (*52%*).

In Canada, there exist no databases that provide detailed information on the types of accidents involving fuel trucks and bridge collisions. However, Transport Canada publishes a National Collision Database (*NCDB*) with all police-reported motor vehicle collisions on Canadian roads. The data spans 1999 to 2015. From this database, the authors collected information regarding accidents involving heavy unit trucks and road tractors (*with and without semi-trailers*) that occur either on bridges, overpasses, or viaducts, and tunnels or underpasses. The results are presented in the following Figure 2 and Figure 3.

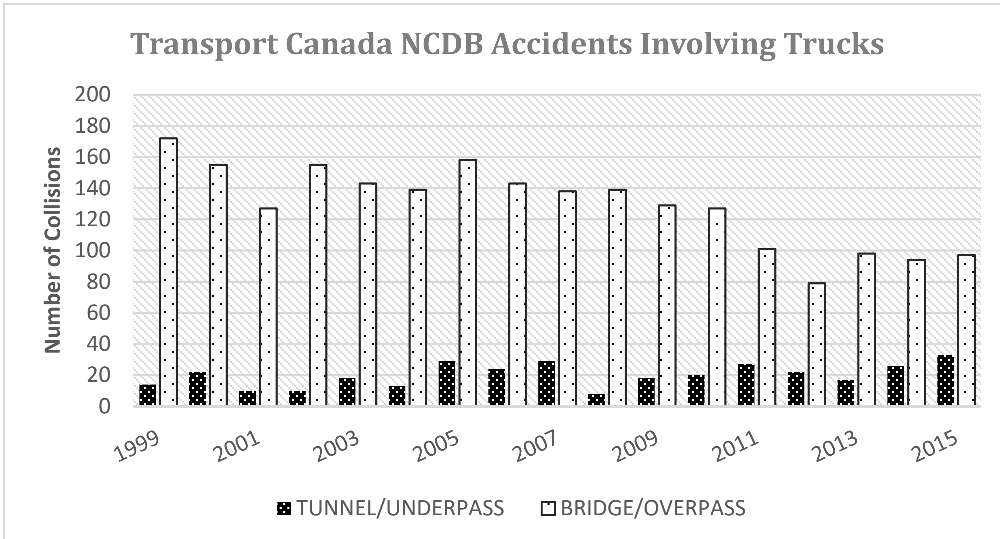

Figure 2: Transport Canada National Collision Database Accidents involving Trucks (*1999-2015*)

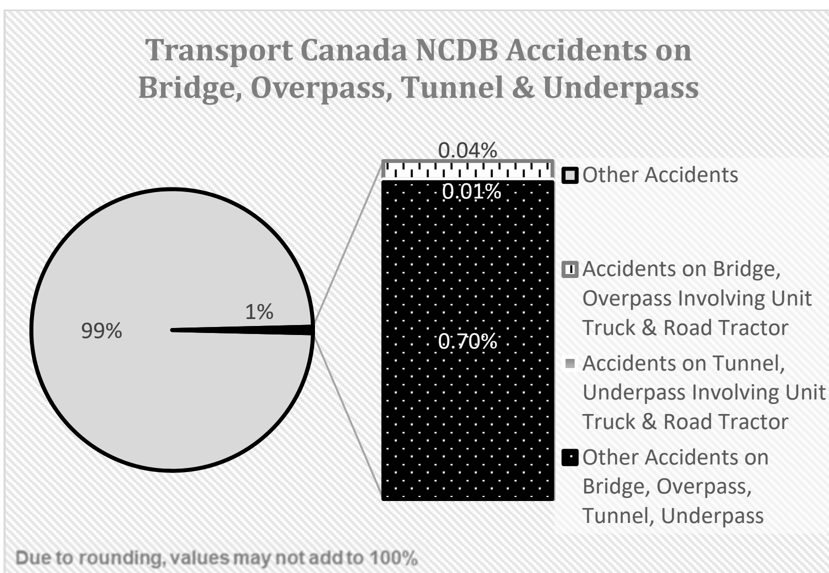

Figure 3: Transport Canada National Collision Database Accidents on Structures (*1999-2015*)

The general observation is that most collisions in Canada do not involve structures that are within the scope of this paper. Accidents that occur on bridges and overpasses consist mainly of collisions with parapets, similarly to the conclusions from the U.S. database, while accidents on underpasses involve collisions with piers and abutments. However, according to the Transport Canada NCDB, less than 0.01% of accidents between 1999 and 2015 occurred in underpasses and involved heavy unit trucks. It cannot be discerned from this data how many trucks were carrying flammable material and there exists no information on the damage, if any, of the bridges, abutments, and other structural components involved in the collision.

Extracting information from another database published by Transport Canada, we can determine the number of spills and emergencies reported each year for Class 3 Dangerous Goods (*Flammable Liquids*) from the calls received by the Canadian Transport Emergency Centre (*CANUTEC*). The data in Figure 4 represents calls received for Class 3 spills and accidents via road transportation.

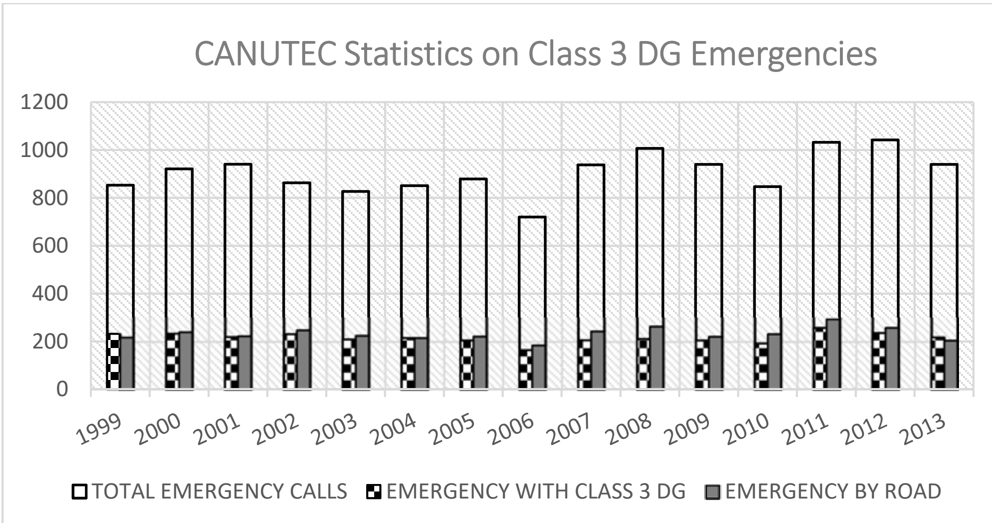

Figure 4: Transport Canada Canadian Transport Emergency Centre Statistics for Class 3 Dangerous Goods by Road Transportation Mode (*1999-2013*)

The data suggests that Class 3 DG-related emergencies occur almost exclusively on roads, however, this is not for certain because sometimes the number of emergencies with Class 3 DG exceeds the number for those by Road. It can only be determined that between 1999 and 2013, 23.4% of all emergency calls received by CANUTEC were regarding Class 3 Dangerous Goods spills and accidents, and that 25.6% of all emergencies occurred with material transported via Road. The data provides no information to determine if a fire resulted from those spills and if the spills were near bridges. By comparison, from a survey conducted by Kodur et al. (*2010*) it was determined that in the U.S. only 2% of heavy vehicles utilizing major traffic routes and major bridges carried flammable liquids (*Class 3 DG*).

Overall, the data from all databases indicates that due to the rare occurrence of these accidents, it is not economically feasible to design all structures to perform against this hazard, but instead focus should be made to ‘at risk’ or ‘important’ structures.

2.2 Effects from Fire Events

It is generally assumed that fire safety is not a significant factor for bridges, compared to tunnels and buildings. This is because bridge fires are open-air flames and ventilation is not an issue. However, loss of service is a significant factor that needs to be considered in the design. The main concern for bridges under fire is large deflection of the span and total collapse. Modeling studies suggest that this occurs when bridges are exposed to large fires, which are usually caused by large fuel tank truck crashes. Smaller damage from other collisions can be repaired. Damage examples include concrete cracking and spalling, damage to joints and bearings, and some localized buckling. In terms of MSE walls, damage can consist of cracking of precast concrete panels, burning of filter fabric, or reduction in strength of reinforcement. More severe damage might include complete failure of geosynthetic reinforcement. For events that do not produce permanent deflection of the bridge, there exists a low probability that the steel strength has been significantly compromised. As well, if the collision and fire occur near the abutments, i.e. the region of lowest positive moment, the smallest deflections are observed. However, collisions with abutments are cause for fires in the vicinity of MSE walls. Depending on the design considerations and materials utilized, a fire can have either negligible or significant effects on the structural integrity of the MSE wall bridge abutment.

2.3 Evaluation of Fire Risk Factors

Since there exist very few to no specific fire prevention design specifications, studies have been conducted to evaluate the risk of fire on bridges to develop bridge fire protection standards (*Kodur et al. 2010, Han and Weng 2010*). For example, Kodur and Naser (*2013*) developed a fire risk evaluation indicator system based on bridge fire-resistance-design vulnerability. Wang and Elhag (*2007*) published a method to assess the fire risk of bridges based on fuzzy group theory mathematics, and Fabiano et al. (*2002, 2005*) proposed a risk assessment method for the transport of dangerous goods. A study developed an approach for mitigating fire hazards in bridges by assigning a fire-based importance factor to categorize bridge fire risk and then implementing mitigation approaches (*Kodur et al. 2017*). The factor is calculated by analyzing data on the geometric features of the bridge, which include material, structural geometry, and loading conditions, as well as other factors like predicted fire intensity, geographic location of the bridge, traffic density, cost of bridge, etc., all of which are sub-categorized into other sub-factors that are assigned numerical values between 1 to 5 based on a fire hazard risk. The importance factor is then determined by applying another approach that was proposed from Kodur and Naser (*2013*), which categorizes bridges into four categories with risk grades 0.8, 1.0, 1.2, and 1.5. Measures for fire hazard mitigation are recommended for bridges that fall under the 'high' and 'critical' (*1.2 and 1.5*) categories. The mitigation strategies are applied to lower the risk grade of the bridge to 'low' or 'medium' (*0.8 and 1.0*) through fire insulation protection measures that are implemented on structural members and other components. Other methods include limiting access to fuel-carrying tanker trucks on 'high' risk bridges. The main conclusion from these studies is that bridges need to be assessed for their potential to undergo fire-related damage and if that risk is high then it must be ensured that mitigating factors are applied to existing bridges or implemented in the design considerations for new constructions.

3 Material Properties in Fire

Material properties play a significant factor in the failure mechanisms of the structural components. Concrete is more durable than steel due to its lower thermal conductivity properties. Compared to steel, concrete experiences strength loss at a slower rate. Most case studies reporting on this phenomenon indicate that for severe fires lasting less than one-hour, there is minimal internal damage observed in concrete, but that after the one-hour mark, concrete begins to lose its strength. The loss in strength under high temperature conditions is recoverable for steel once it has cooled, but concrete does not regain its pre-fire strength. Since the through-thickness temperature gradient for concrete is high, damage and strength loss occurs primarily near the surface.

3.1 Steel Properties

Steel is a material used for soil reinforcing strip in construction of many MSE walls due to its high strength, ductility, and cost. However, due to its high thermal conductivity and low specific heat, it is susceptible to temperature increases. At elevated temperatures, steel can lose its strength. It needs to be mentioned that soil reinforcing steel attached to the backside of a panel is insulated by concrete and therefore the rebars are relatively protected.

Regarding thermal properties, thermal conductivity decreases for steel when temperature increases, whereas specific heat capacity increases. The coefficient of thermal expansion increases at elevated temperatures for steel, and this factor increases the rate of thermal strain experienced by the material (*Figure 5*). Strain is the main factor for global deflection and localized damage in steel (*Wright et al. 2013*). Thermal expansion can cause stress to develop if the steel is restrained either by surrounding cooler material or physical boundaries. This stress causes buckling of steel and damage to concrete.

Regarding mechanical properties, yield strength and the modulus of elasticity decrease for steel with rising temperatures (*Figure 6*). As well, the stress-strain curve changes for steel under high temperatures, which introduces difficulties in predicting structural deformation under high temperature conditions. At temperatures above 400ºC, strain effects due to creep become more pronounced. While these effects have been shown to be of minimal consequence to the deflection of steel for regular vehicle fires, they become significant for fires that last longer than one hour (*Wright et al. 2013*).

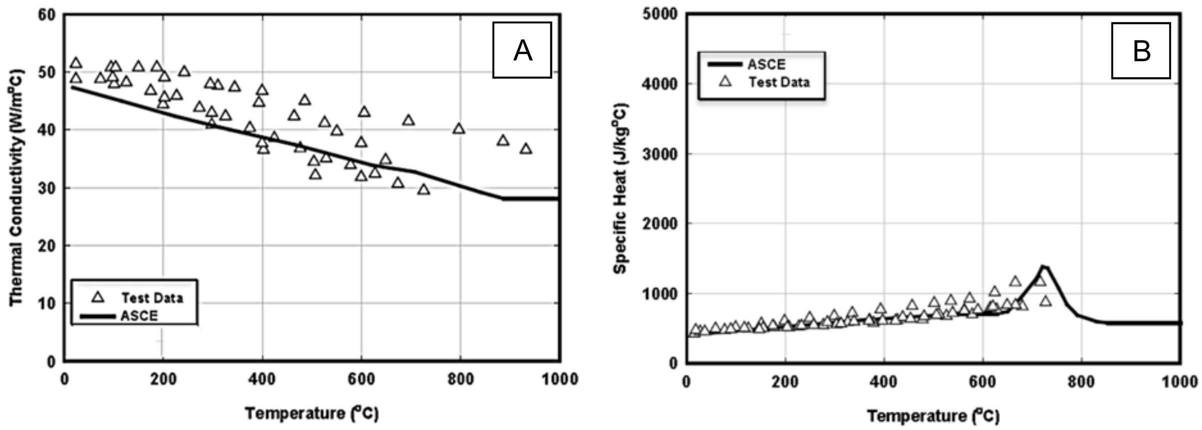

Figure 5: (A) ASCE Model of Thermal Conductivity of Steel as a Function of Temperature (B) ASCE Model of Specific Heat of Steel as a Function of Temperature (*Wright et al. 2013*)

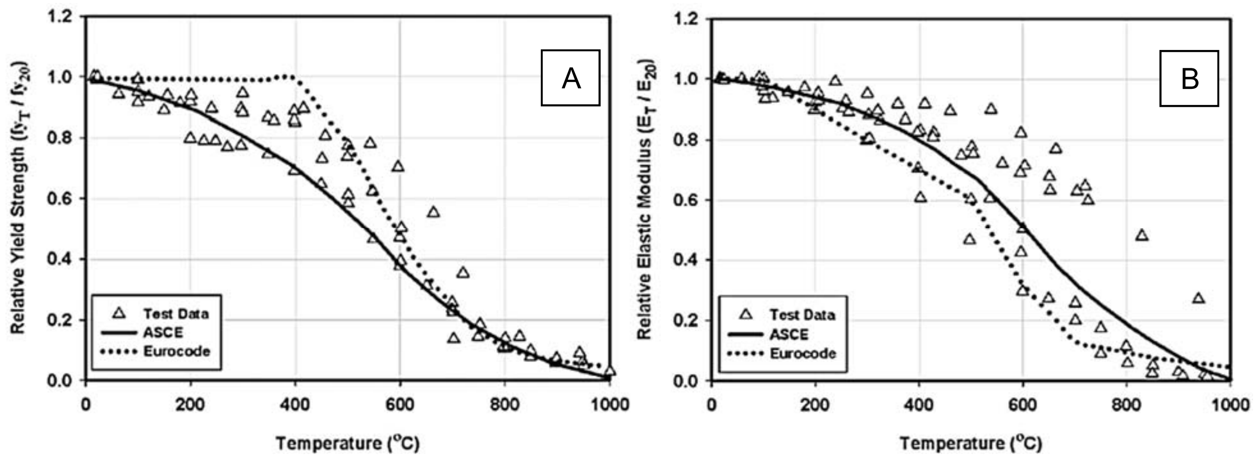

Figure 6: (A) Reduction in Yield Strength of Structural Steel as Function of Temperature (B) Reduction in Elastic Modulus of Structural Steel as a Function of Temperature (*Wright et al. 2013*)

It is apparent that fire greatly affects steel properties, but these effects vary by the temperature and duration of the fire, as well as the steel grade used for construction. For example, a study by Aziz and Kodur (*2016*) tested the effect of temperature on high-strength low-alloy ASTM A572 Grade 50 steel, which is commonly used in structural members of bridges. The study determined that A572 steel behaves similarly to carbon steel in the degradation of strength and stiffness under high temperature conditions. In addition, A572 steel recovers almost all its room-temperature yield strength when heated to temperatures up to 600°C, regardless of whether it is air-cooled or water-quenched. This study was also significant in recommending methods for determining residual strength of steel after a fire event and assessing the serviceability of bridges after experiencing extreme temperature conditions. The steel grade that is commonly used as soil reinforcement for MSE walls is generally ASTM A572 Grade 65.

3.2 Concrete Properties

Concrete properties are also affected by temperature changes; however, they vary more unpredictably than steel properties due to factors like moisture content, aggregates, and material composition. Regarding thermal properties, variations exist based on the moisture content and aggregate composition (*siliceous vs. carbonate*) of concrete. The general conclusion is that the thermal conductivity of steel is greater than concrete and therefore, concrete heats up at a slower rate than steel. The heat capacity of concrete does not vary significantly with temperature, except for carbonate aggregate concrete, whose aggregates undergo an endothermic reaction with other cement materials at temperatures between 600°C and 800°C.

At this range the concrete absorbs energy, which increases its heat capacity. Regarding mechanical properties, compressive strength is constant for temperatures up to 400ºC, at which point, beyond this threshold, a steady decrease in strength is observed. For high-strength concrete, another pattern is observed. There is a sudden drop at around 100ºC, steady strength up to 400ºC, and then a continuous drop for higher temperatures. All models that fit experimental data studying the effect of temperature on concrete compressive strength, predict higher strength loses for high-strength concrete. This is attributed to the formation of micro-cracking and increased pore-pressure in high-strength concrete due to the presence of a denser cement matrix.

3.3 Geosynthetic Properties

Geosynthetics are synthetic polymers that are used as soil reinforcement in MSE walls. Examples include geotextiles, geogrids, and geosynthetic straps. Due to their polymeric condition, geosynthetic properties are highly dependent on increasing temperature conditions. Many studies have demonstrated the effects of temperature on the properties of the material. They include reduction in tensile strength and increase in creep effects, reduction in the modulus of elasticity and increase in failure strain, and reduction in surface hardness and increase of physical degradation (*Yarivand et al 2017*). Since the 1980s, the effect of temperature variation on geosynthetic reinforcement has been investigated. Segrestin and Jailloux (*1988*) conducted a study in France to determine the effect of temperature variation on the degradation of geosynthetic reinforcement used in MSE walls. The mechanisms studied included the effect of solar radiation and seasonal temperature change. They observed that soil temperatures were constant at a depth of 10m from the facing of the MSE Wall, reaching the average atmospheric temperature of the geographic location. At a depth of 0.5m from the facing, high temperature variations were observed due to solar radiation and daily temperature variations. These temperature changes were noted to cause creep and ageing of the geosynthetics at a higher rate than assumed when considering only *the average* annual temperature of the location. Their calculations determined that, considering that temperature affects creep and ageing of geosynthetics at an exponential rate, for a temperature variation from 10ºC to 20ºC, polyester terephthalate (*PET*) hydrolysis increases by a factor of 4.5 and for a variation from 10ºC to 30ºC, the factor jumps to 20. Similarly, the time to rupture due to creep for polyethylene (*HDPE*) is reduced by a factor of 10 and 100, for each respective temperature variation. All studies suggest that geosynthetics are more susceptible to temperature-induced degradation, experiencing often non-linear behavior compared to steel. This effect is even more severe with fire-induced temperatures.

3.3.1 Study of MSE wall under Fire Scenario

A recent study was conducted at the University of Tehran to investigate the effect of fire hazards on MSE bridge abutments with geosynthetic soil reinforcements. Experiments were conducted to observe the temperature variation in the soil backfill of the MSE wall and the effect of the temperature variation on the tensile strength and elastic modulus of PET and HDPE geosynthetic reinforcements. Experimental results were verified using finite element model (*FEM*) analysis (*ABAQUS software*). The tensile strength results were used to evaluate the efficiency of the model; the model was in agreement with the experimental results of the PET, up to T=80ºC, and HDPE, for all tested temperatures. The limitation of the model was the inability to simulate post peak-point behavior. The elastic-plastic temperature-dependent model (*defined in ABAQUS as a 'isotropic elasto-plasticity constitutive model*) used to simulate the geosynthetic reinforcement behavior incorporated non-linear stress-strain behavior, where the mechanical strain rate of the material exhibited elastic behavior at strains less than 1%, followed by plastic behavior for strains up to 12% for the PET and 30% for the HDPE (*Tensile tests at temperatures of 100ºC*). The model was used to simulate the temperature change of the soil backfill for different distances from the facing. While the modeling results from the study (*Yarivand et al. 2017*) cannot be reproduced in this paper, the following was concluded: simulations were in agreement for distances beyond 0.04m from the facing, with simulations for a distance 0.0m, having the highest discrepancy. The study determined that the effect of fire on geosynthetic reinforcement used in bridge abutments was severe for fire durations exceeding one hour and that the depth of the affected backfill was approximately 0.5m. The furnace temperature reached 1100ºC, which is consistent with hydrocarbon fires, and, while the melting point of PET is 245-260ºC and HDPE is 120-180ºC, the maximum fire temperature that was recorded in the experiments was 177ºC for PET and 166ºC for HDPE. The authors concluded that most of the energy was absorbed by the soil and concrete. This conclusion is consistent with Murray and Farrar (*1988*), who stated that due to their small cross-sectional area, compared to the entire soil backfill zone, geosynthetics play no significant role in the transfer of heat in the backfill. Finally, since the highest temperature was recorded behind the facing 184min after the fire event was complete, it was concluded that the backfill absorbed most of the energy and continued to release it over time. The recorded temperature for thermocouples located behind the concrete facings were lower than for those placed facing joints where blocks meet, indicating that concrete absorbs heat, and joints can accelerate thermal flow into the backfill. It should be noted that this experiment was conducted on an MSE wall with concrete facing thicknesses of 0.15m, 0.20m, and 0.28m. The temperature variations were measured at a distance behind the back surface of the facing. It was also determined that the thickness of the concrete facing affected the temperature variations observed in the soil backfill, but that for thicknesses up to 0.28m (*as was investigated in this study*) the mitigating effect was not significant for soil backfill depths beyond 0.5m. Tests showed that HDPE geosynthetic reinforcement was more sensitive to temperature elevations for tensile strength tests.

4 Discussion

Regarding MSE wall bridge abutments, studies indicate that high temperatures degrade the strength of the soil reinforcing elements. Structural steel (*ASTM A572 Gr. 50*) lost half its yield strength by 600°C (*Aziz and Kodur 2016*). From Yarivand et. al. (*2017*) geosynthetic soil reinforcement (PET) lost half its peak tensile strength by 140°C and HDPE did by 80°C. Most severe fire events consist of hydrocarbon fires that reach temperatures of over 1000°C. Depending on the location of the fire and thickness of the concrete facing, soil reinforcements can be severely damaged from exposure to high temperatures. Consequences of failure and prevention measures must be considered in the design of MSE walls.

While it was concluded from Wright et al. (*2013*) that the fire hazards should occur near abutments, where moments are lowest, this arrangement compromises the MSE wall. Although it has a very low probability for occurrence, a fire-event would likely affect the lower half of the wall. From Figure 7 it is observed that when designing for the internal stability of an MSE wall, tensional resistance governs the lower part of the wall and frictional resistance governs the top. Therefore, if a fire occurs and heat is propagated through the panels and into the backfill, the tensile capacity of the soil reinforcements will be compromised because high temperatures will reduce the tensile strength of the reinforcements. The literature review indicated that geosynthetic reinforcements are more susceptible to tensile strength loss at rising temperatures. A preventive measure for the abutment failure in tension would be to utilize steel reinforcements for ‘at risk’ structures, which is recommended by some Highway Departments. Regardless of the choice of reinforcement, after a fire-event a thorough assessment of the capacity of the MSE wall abutment must be determined by sampling and analyzing embedded reinforcements.

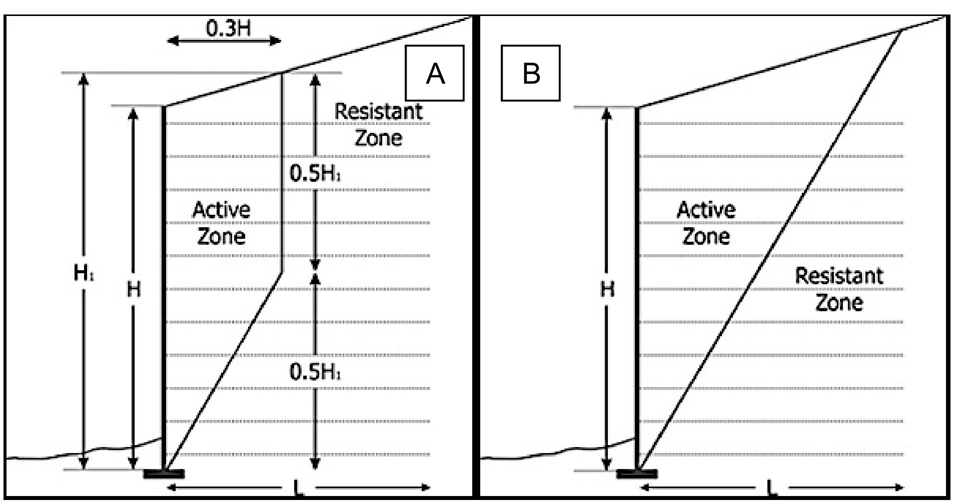

Figure 7: (A) Resistance Zone for Steel Reinforcement (*Inextensible*) (B) Resistance Zone for Geosynthetic Reinforcement (*Extensible*)

The concrete facing is the first line of defence for the reinforced soil mass that supports the overbearing structure. From Yarivand et al. (*2017*) it was concluded that thicker concrete facing decreased the internal temperature of the soil backfill. Another preventive measure to mitigate the reduction of tensile strength is to install thicker panels on 'at risk' structures to prevent fire from penetrating into the soil backfill. After a fire event, the extent of the damage on the concrete facing may need to be assessed. The concrete may crack and spall on the surface, which would require replacement of the affected panels post-fire.

Although the panels are not a major structural component of the MSE wall, in combination with the geotextile, they prevent backfill erosion. During a fire, the geotextile might burn. Regardless of the temperature effects on the soil reinforcements, if the geotextile is compromised then the backfill can be washed out. Loss of backfill is a significant risk for MSE wall stability because the reinforcements lose their frictional capacity and the MSE system no longer supports overbearing pressures, like bridge loads.

Finally, it is often assumed that the weakest point of the MSE wall is the panel-soil reinforcement connection. Considering the proximity of the connection to the surface of the fire hazard, designers must prevent failure at the connection by either utilizing a stronger steel alloy that maintains its strength at high temperatures or provide a protective coating. The Yarivand et al. (*2017*) study indicated that the soil and concrete are very effective in absorbing most of the heat from a fire-event and that the soil reinforcements are protected from the 1000°C fire temperatures observed on the facing surface. In most MSE wall systems, the connection is very near the face of the precast concrete facing. In some instances, that distance can be as close as 30mm. For plastic connections (geosynthetic reinforcement), the consequences of heating are catastrophic. Mitigating or preventive measures should be considered and implemented where necessary if the structure is deemed 'at risk' because the consequences of an MSE wall abutment failure are as destructive as a total bridge collapse.

5 Conclusion

The information presented in this paper consists of a general investigation into the effects of fire on MSE bridge abutments. From the literature review that was included, it can be determined that bridges have a low chance of collapse due to fire events. Efforts should be taken to evaluate the 'risk factor' of every bridge and overpass to be damaged by a fire-related hazard. Many studies have dedicated their efforts on developing methodologies for determining this factor. Most preventative measures have been focused on material protection against fire. Preventative measures for MSE walls include increasing the concrete facing thickness for 'at risk' structures, utilizing steel reinforcement instead of geosynthetics for 'at risk' structures, and strengthening the panel-soil reinforcement connection. Through the implementation of these methods, and others, the risk factor for fire-induced damage can be reduced for MSE walls.

References

Aziz, E.M. and Kodur, V.K.R. 2016. Effect of Temperature and Cooling Regime on Mechanical Properties of High-Strength Low-Alloy Steel. *Fire and Materials,* **40**(7): 926–39.

Aziz, E.M., and Kodur, V.K.R. 2013. An Approach for Evaluating the Residual Strength of Fire Exposed Bridge Girders. *Journal of Constructional Steel Research,* **88**: 34–42.

Branco, F.A. Mendes, P.M. and Guerreiro, L.M.C. 2000. Special Studies for Vasco Da Gama Bridge. *Journal of Bridge Engineering,* **5**(3): 233–39.

Dwaikat, M.M.S. and Kodur, V.K.R. 2011. A Performance Based Methodology for Fire Design of Restrained Steel Beams. *Journal of Constructional Steel Research,* **67**(3): 510–24.

Fabiano, B. Currò, F. Reverberi, A.P. and Pastorino, R. 2005. Dangerous Good Transportation by Road: From Risk Analysis to Emergency Planning. *Journal of Loss Prevention in the Process Industries*, **18**(4–6): 403–413.

Fabiano, B. Currò, F. Palazzi, E. and Pastorino, R. 2002. A Framework for Risk Assessment and Decision-Making Strategies in Dangerous Good Transportation. *Journal of Hazardous Materials,* **93**(1): 1–15.

Garlock, M. Paya-Zaforteza, I. Kodur, V.K.R. and Li G. 2012. Fire Hazard in Bridges: Review, Assessment and Repair Strategies. *Engineering Structures,* **35**: 89–98.

Han, Z.Y. and Weng, W.G. 2010. An Integrated Quantitative Risk Analysis Method for Natural Gas Pipeline Network. *Journal of Loss Prevention in the Process Industries*, **23**(3): 428–36.
Kodur, V.K.R. Aziz, E.M. and Naser, M.Z. 2017. Strategies for Enhancing Fire Performance of Steel Bridges. *Engineering Structures,* **131**: 446–58.
Kodur, V.K.R. Aziz, E.M. and Dwaikat, M. 2013. Evaluating Fire Resistance of Steel Girders in Bridges. *Journal of Bridge Engineering,* **18**(7): 633–43.
Kodur, V.K.R. Li, G. and Garlock, M.E.M. 2010. Review and Assessment of Fire Hazard in Bridges. *Transportation Research Record: Journal of the Transportation Research Board,* **2172**: 23–29.
Liu, X. Zhang, L. Guo, S. and Fu, M. 2017. A Simplified Method to Evaluate the Fire Risk of Liquid Dangerous Chemical Transport Vehicles Passing a Highway Bridge. *Journal of Loss Prevention in the Process Industries,* **48**: 111–17.
Murray, R.T. and Farrar, D.M. 1988. Temperature Distribution in Reinforced Soil Retaining Walls. *Geotextiles and Geomembranes,* **7**: 33–50.
National Fire Protection Association. 2011. NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways. Quncy, MA.
Payá-Zaforteza, I. and Garlock, M.E.M. 2012. A Numerical Investigation on the Fire Response of a Steel Girder Bridge. *Journal of Constructional Steel Research,* **75**: 93–103.
Segrestin, P. and Jailloux, J.M. 1988. Temperature in Soils and Its Effect on the Ageing of Synthetic Materials. *Geotextiles and Geomembranes,* **7**(1–2): 51–69.
Wang, Y.M. and Elhag, T.M.S. 2007. A Fuzzy Group Decision Making Approach for Bridge Risk Assessment. *Computers & Industrial Engineering,* **53**(1): 137–48.
Wright, W. Lattimer, B. Woodworth, M. Nahid, M. and Sotelino, E. 2013. Highway Bridge Fire Hazard Assessment Draft-Guide Specification for Fire Damage Evaluation in Steel Bridges. Blacksburg, VA.
Yarivand, A. Behnia, C. Bakhtiyari, S. and Ghalandarzadeh, A. 2017. Performance of Geosynthetic Reinforced Soil Bridge Abutments with Modular Block Facing under Fire Scenarios. *Computers and Geotechnics,* **85**: 28–40.