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ASSESSING STRUCTURAL VULNERABILITIES: ANALYZING THE EFFECTS OF WILDFIRES ON POWER INDUSTRY STEEL INFRASTRUCTURE

Mehrooz Zamanzadeh, George T. Bayer, Anil Kumar Chikkam, Peyman Taheri, Edward Larkin, and Clinton Char
Matergenics, Inc.
100 Business Center Drive
Pittsburgh, PA 15205

ABSTRACT

This paper focuses on the detrimental effects of wildfires on steel structures within the power industry, specifically examining the degradation of mechanical properties in structural materials and protective coatings due to high-temperature exposure. It discusses the impact on transmission and distribution structures, as well as the generation of gases and corrosive substances during wildfires. Furthermore, the paper investigates the influence of high temperatures on the mechanical properties of bare structural steel and the degradation of galvanized steel coating layers. Additionally, it explores the thermal degradation of organic coatings, changes in concrete mechanical properties, and the application of non-destructive techniques for condition assessment, including remote temperature monitoring, on structures exposed to wildfires. This research provides valuable insights into the effects of wildfires on power industry steel structures, enabling better understanding and the development of effective mitigation strategies to safeguard infrastructure and ensure its resilience in fire-prone areas.

Keywords: Wildfires, steel structures, power industry, mechanical properties, coatings, concrete, condition assessment.

INTRODUCTION

A wildfire, bushfire, wildland fire or rural fire is an unplanned, unwanted, uncontrolled event in an area of combustible vegetation starting in rural areas and urban areas. Climate change is responsible for a dramatic increase in wildfire events. By December 18, 2020, there were about 57,000 wildfires compared with 50,477 in 2019, according to the National Interagency Fire Center[1].[1] More than 10.3 million acres were burned in 2020, compared with 4.7 million acres in 2019. Five of the top 20 largest California wildfires fires occurred in 2020. Due to the extreme drought conditions in the West, the predictions are for increasingly worst fire events. The extreme temperatures of these wildfires can cause a reduction in structural strength and even melt the zinc based galvanized coatings on the steel. This can lead to accelerated corrosion, or even the collapse of lattice towers at some later time. Figure 1 is a photograph of one such wildfire approaching perilously close to power transmission structures.

[1] National Interagency Fire Center, 3833 S. Development Avenue, Boise, ID, 83705, USA.

Figure 1: Wildfire approaching close to power transmission structures.

WILDFIRES AND TRANSMISSION AND DISTRIBUTION STRUCTURES

Steel structures used in overhead transmission and distribution (T&D) lines can be divided into two generic groups:

- Lattice towers including masts in portal and H-frame structures, as shown in Figure 2.
- Poles and other type of structures with tubular design.

A variety of structural designs exist in each category which results in a wide range of structural features specific to different applications and service environments.

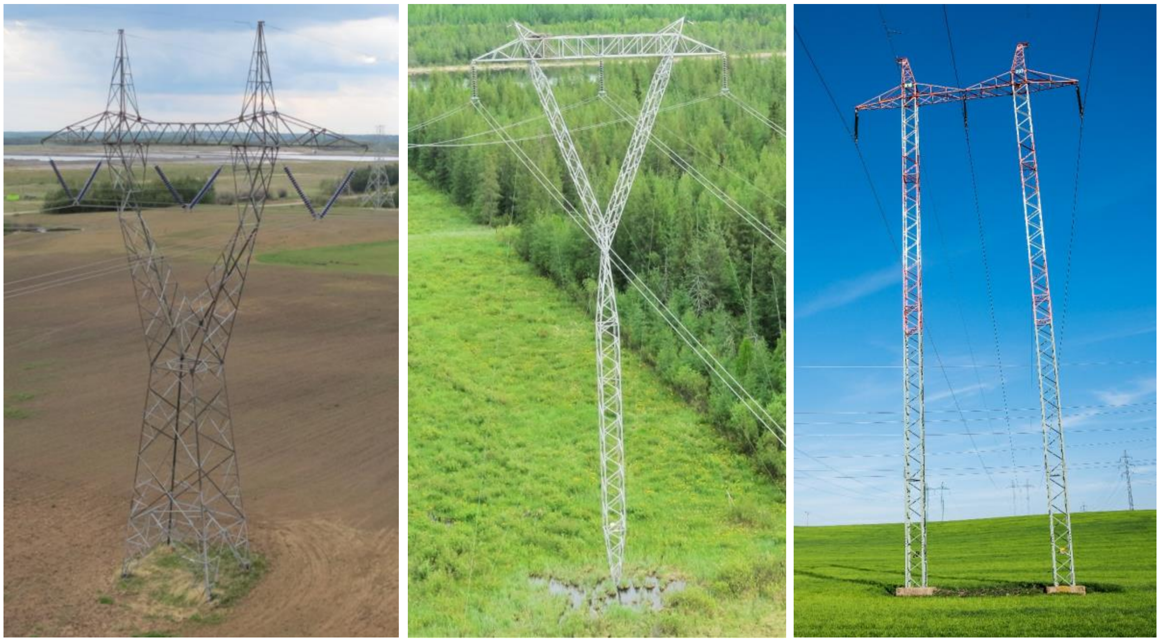

Figure 2: (Left) Lattice structure; (Middle) Portal structure; (Right) H-frame structure.

Despite design variations, all T&D structures are composed of two sections:

- Above-ground section, which supports the overhead conductor at a safe height from ground level.
- Below-ground section, referred to as the structure foundation, which supports the above-ground section.

Foundations are designed to stabilize the structure in the service environment (usually soil or concrete) and provide support and a path to ground to carry the dynamic and static forces imposed on the structure. During their service life, both above and below-ground portions of T&D structures are exposed to a variety of natural calamities and environmental conditions; thus, aging and material degradation are inevitable as a result of environmental and mechanical stresses.

Corrosion is the most common aging process that affects the integrity of any metallic structure, if it is not detected and properly monitored and controlled during service life of the structure. Corrosion occurs at both above and below-ground portions of T&D structures; however, in most cases the rate of below-ground corrosion is much higher than above-ground (atmospheric) corrosion.

Due to their high strength to weight ratios and relative low cost, ferrous-based alloys, steels, are the favored materials in construction of T&D structures. The three types of steels that are typically used include:

- Carbon steel, special alloys which generally are referred to as structural quality steel, specified by standards such as ASTM[2] A572: *Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*[2] or CSA[3] G40.20/G40.21: *General requirements for rolled or welded structural quality steel/Structural quality steel*[3].
- Galvanized steel – more details about galvanized steel are provided later in this report.
- Weathering steel; please refer to the following reference for more details about weathering steel.[4]

Steel lattice tower transmission and distribution structures exposed to wildfires may suffer damage from the heat and smoke which could affect their mechanical properties, structural strength and corrosion resistance. The lattice structures are assembled from constructional steel components that may be painted bare steel, weathering steel, hot dipped galvanized, and/or painted. Wildfire exposed transmission and distribution structures may experience degradation at low, mid, or high elevation, on overhead hardware, and on insulators.

GASES AND CORROSIVE SUBSTANCES GENERATED IN WILDFIRES

Wildfires are major sources of trace gases and aerosol. It is believed that these emissions significantly influence the chemical composition of the atmosphere and the earth's climate on both regional and global scales.[5] Over the past century, wildfires have accounted for 20 to 25 percent of global carbon emissions. The gaseous pollutants generated by wildfires include greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and photochemically reactive compounds such as carbon monoxide (CO), volatile organic carbon (VOC) compounds and nitrogen oxides (NO_x). Most important to the issue of structural materials corrosion are the fine and coarse particulate matter (PM), or soot, generated by wildfires. Figure 3 presents photographs of wildfires with apparently heavy soot content.

[2] American Society for Testing and Materials (ASTM), 100 Barr Harbor Drive, West Conshohocken, PA, 19428, USA.
[3] CSA Group (CSA), 178 Rexdale Boulevard, Toronto, ON, M9W 1R3, Canada.

Figure 3: Photographs of wildfires with heavy soot (particulate matter) content.

Wildfires produce soot containing chlorides and other water-soluble corrosive ions such as sulfates. The wind will carry the potentially corrosive soot and deposit the soot on galvanized steel and other metallic assets. After the passage of a wildfire, if the structures are not analyzed for contaminants such as chloride and subsequently cleaned free of them, this will cause accelerated corrosion of galvanized steel and weathering steel structures.

Additionally, soil foundations will become corrosive due to contamination by the corrosive soot. For example, deposition of the corrosive soot may change soil resistivity in a sandy non-corrosive soil from 200,000 to 300,000 ohm-cm to less than 1000 ohm-cm, which is very corrosive. Chloride levels in the soil may change from 10 to 20 parts per million to greater than 1000 parts per million. The same situation is true for the other water-soluble corrosive ions.

EFFECTS OF WILDFIRES ON STRUCTURAL STEEL

The mechanical properties of steel are temperature dependent. Mechanical properties such as tensile strength, yield strength, ductility, hardness and toughness could be negatively affected when exposed to the heat of a wildfire. A reduction in these properties could reduce the strength capacity of the structure to a level below a minimum factor of safety. Physical properties such as thermal conductivity, electrical conductivity, the coefficient of thermal expansion could also be affected by exposure to a wildfire. In addition, permanent changes in the microstructure of the steel could take place. These are all important factors in considering the effects of wildfires on structural steel.[6,7] Figure 4 illustrates the effect of mechanical deformation on a transmission structure caused by wildfire heating.

Temperature and Mechanical Properties of Steel

With increased temperature as experienced in a wildfire, the yield strength (>400°C = 752°F) and the modulus of elasticity (>200°C = 392°F) would decrease. If the temperature is above 600°C (1112°F) bainite phase forms, almost 50% of the strength will be lost. Table 1 summarizes these critical temperatures and their impacts.

Table 1: Impacts on structural steel of critical temperatures.

Temperature	Structural Impact
>200°C or 392°F	Decrease in modulus of elasticity.
>400°C or 752°F	Decrease in yield strength and zinc will begin to melt.
>600°C or 1112°F	50% loss in strength and oxidation will occur.

Please note that martensite can form due to rapid cooling from water by aerial water drops, fire hoses and extinguishers. Figure 5 illustrates the metallurgical microstructures of pearlite (top photomicrograph a) and bainite (bottom photomicrograph b); bainite being indicative of high temperature exposure.

If the temperature does not exceed 600℃ (1112°F) and there is no prolonged exposure, the mechanical properties return to their initial values after cooling down. If steel is exposed to temperatures above 600℃ for about 20 to 30 minutes, oxidation will appear on the surface, as well as pitting and a loss of cross-sectional thickness.

Above 715℃ (1320°F) steel experiences a crystalline phase transformation. If the steel is then quenched or cooled rapidly, a phase known as martensite can form. Untempered, or relatively untempered, martensite is brittle and prone to cracking when subject to mechanical stress. This will reduce the ductility of the steel which will reduce its impact resistance.

The collection of carbon soot and ash can increase the corrosion rate of the metallic members that they settle upon.

Thus, while a structure may appear to have survived a wildfire unscathed, the potential loss of mechanical strength and ductility could reduce the strength of the structure to levels below its required factor of safety. This could lead to catastrophic failure in the future. To mitigate this possibility, a detailed investigation on the structural steel should be performed to determine if the steel has been negatively affected by exposure to a wildfire.

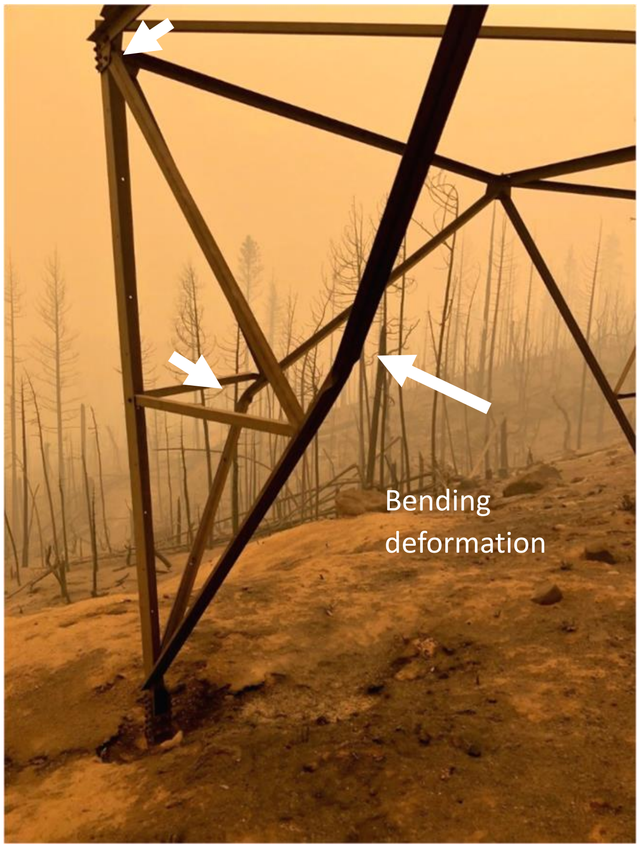

Figure 4: Photograph showing the deformation of two diagonal steel braces and one instance of a bolted joint pulling away from vertical structural member (upper left). The other arrows point to the inflection points of the deformed diagonals.

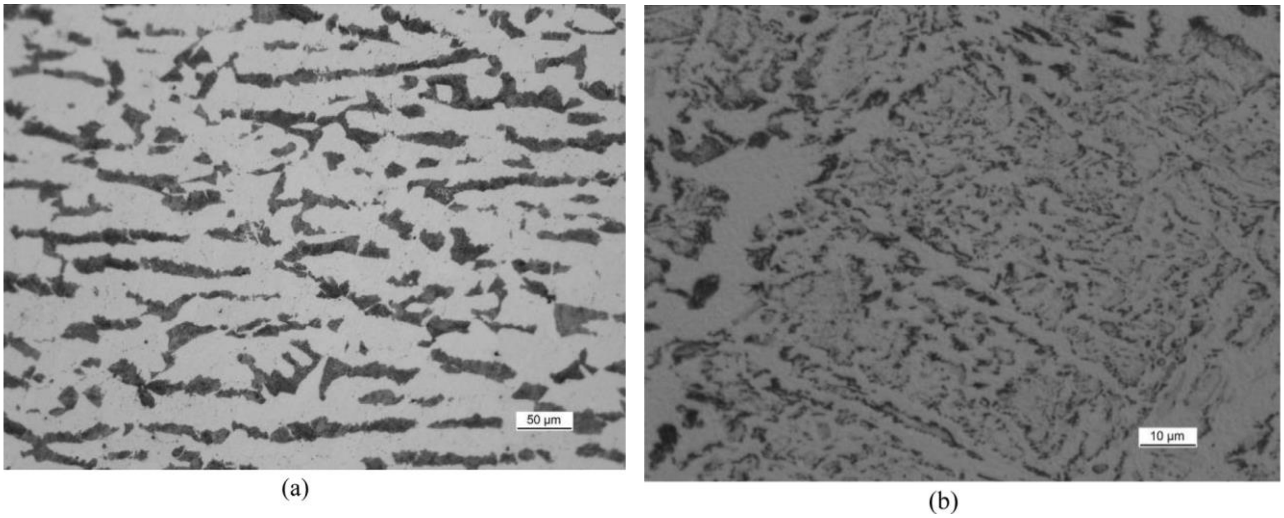

Figure 5: Cross section photomicrographs of pearlite (a) versus bainite (b); bainite being indicative of high-temperature exposure.

EFFECTS OF WILDFIRES ON GALVANIZED STEEL

Unlike paints and organic coatings used to protect steel structures, galvanized coatings are zinc-based metallic coatings applied to structural steel using a variety of processes. The performance of these zinc-based coatings when subjected to fires, depends on a number of factors, not the least of which is the characteristics of the galvanized coating arising from the process by which it is applied.[8] Pure zinc has a melting point of 419.5℃ (787℉). Therefore, a coating consisting primarily of pure eta phase zinc can be expected to start melting once this temperature is reached on the metal surface.

Loss of galvanizing without loss of strength may occur at lower temperatures and not be obvious, since such a pole/tower would still be standing. It would, however, be subject to accelerated corrosion and weakening over time. To inspect for melted zinc galvanizing a close-up visual examination would be required, preferably under moderate magnification. The melting point of zinc is 419.5℃ (787℉). The iron-zinc intermetallic phases will melt between 530℃ (986℉) and 730℃ (1346℉). When the zinc melts liquid droplets would form followed by the collection and formation of small pools of zinc. In addition, the surface of the liquid zinc metal could oxidize. Areas to be examined must be free of dust and ash.

Most galvanized steel products produced by a continuous galvanizing process (sheet, coil and some tube) have a coating that is largely pure eta phase zinc and is typically 15 – 25 microns (0.6 – 1.0 mil) in thickness.

Hot dip galvanized coatings are for T&D applications, applied by immersing batches of fabricated structural steel in a bath of molten zinc, are made up of zinc-iron intermetallic alloy crystals with a thin layer of pure zinc on the surface. These zinc-iron intermetallic alloys constitute between 50 to 100% of the coating, depending upon steel chemistry and processing techniques. These zinc-iron intermetallic alloys are not only much harder than pure zinc, being about four to five times harder, but they also have a much higher melting point ranging from 530℃ to 780℃ (986℉ to 1436℉).

Peeling of Outer Free Zinc Layer Above 200℃ (390℉)

Although not often considered, excessive heating of galvanized coating caused by wildfires and other heat sources may induce peeling of the outer free zinc layer, which is caused by metallurgical changes that create a series of closely spaced voids at the free zinc – zinc-iron alloy interface.[9] These voids are produced by the diffusion of zinc from the outer free zinc layer into the inner zinc-iron alloy layer. When these voids expand and form a gap, it causes the outer free zinc layer to physically separate from the underlying zinc-iron alloy layers. This solid-state physical process is known in metallurgy and materials science as the Kirkendall effect. At or below the industry-recommended limiting service temperature of 200℃ (390℉), the coating resists zinc layer peeling.

However, the remaining zinc-iron alloy layers may still provide a level of corrosion protection for an indeterminate duration. Exactly how long depends on the time/temperature conditions and the rate of the deterioration process is influenced by coating thickness, the relative thickness of outer zinc and iron-zinc alloy, and by the uniformity of the individual layers. At exposure temperatures ranging from 200℃ (390℉) to 250℃ (480℉), the zinc-iron alloy layers may continue to protect the steel from corrosion. Exposure temperatures above 250℃ (480℉) will accelerate peeling and continued exposure can result in the zinc-iron alloy layers cracking and separating from the steel.

Figure 6 presents cross section microscopic evidence of this peeling phenomenon as documented by the authors.

Some investigators have found that the peeling effect is greatly reduced when the galvanized coating contained very low levels of lead, less than 0.001 percent.[9] These investigators also found that brief temperatures excursion up to 300℃ (572℉) can be handled with no coating problems.

Galvanized Coating Exposures Above 538℃ (1000℉)

Although temperatures in fires can easily exceed 538℃ (1000℉), they do not often last for durations which might compromise the integrity of a hot-dip galvanized steel structure.[10] Therefore, the potential for coating damage exists, however, prior experience has typically found minimal fire damage on galvanized structural steel parts exposed to fires. Fire exposure usually results in some orange and/or rust color staining, with a layer of black carbon dust, while the underlying galvanizing is intact. The steel members in Figure 4, exhibit the orange and/or rust color after exposure to a wildfire.

According to testing performed the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO)[4] Manufacturing and Infrastructure Technology Bushfire CRC, typical bushfire conditions may expose steel structures to air temperature of 800℃ (1472℉) for periods of up to 120 seconds.[11] Depending on section thickness of the steel, the actual steel surface temperatures do not exceed 350℃ (662℉) for a Level II bushfire event.

In another study conducted by the Galvanizers Association of Australia (GAA), an assessment was made of the performance of hot dip galvanized utility poles exposed to brushfires.[8] Small scale burn testing was employed to simulate bushfire flame characteristics. It was found that even though surface temperatures of 520℃ (968℉) were achieved, the hot dip galvanized coating remained intact, but it did experience some staining.

Zinc-based coatings will vaporize at relatively low (about 950℃ or 1742℉) temperatures and re-condense as zinc oxide fume below that temperature. This vaporization phenomenon is typically seen when galvanized coatings are flame-cut or welded.

The advantages of hot dip galvanized steel over bare steel under conditions of fire exposure have been documented in a nationally funded research project in Germany.[12] During a wildfire, while the galvanizing may be compromised, it acts as a sacrificial layer which protects the base steel from mechanical property degradation. The results of the fire test show better behavior of hot dip galvanized steel structural members compared to steel members having bare or rusted surfaces. This is particularly true with regard to a smaller value of emissivity, slower heating development, and a longer duration until the critical

[4] Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), Canberra, Australia.

temperature of the structural steel members is reached.

At higher temperatures (420℃ or 788℉) and longer wildfire durations, galvanized layer may be completely removed, and accelerated oxidation takes place! At the temperature of molten zinc (420℃ or 788℉), proof stress of the structural steel is reduced to 70 percent of its original value. At a temperature of 650℃ (1202℉), the structural steel will suffer a significant reduction in proof stress.

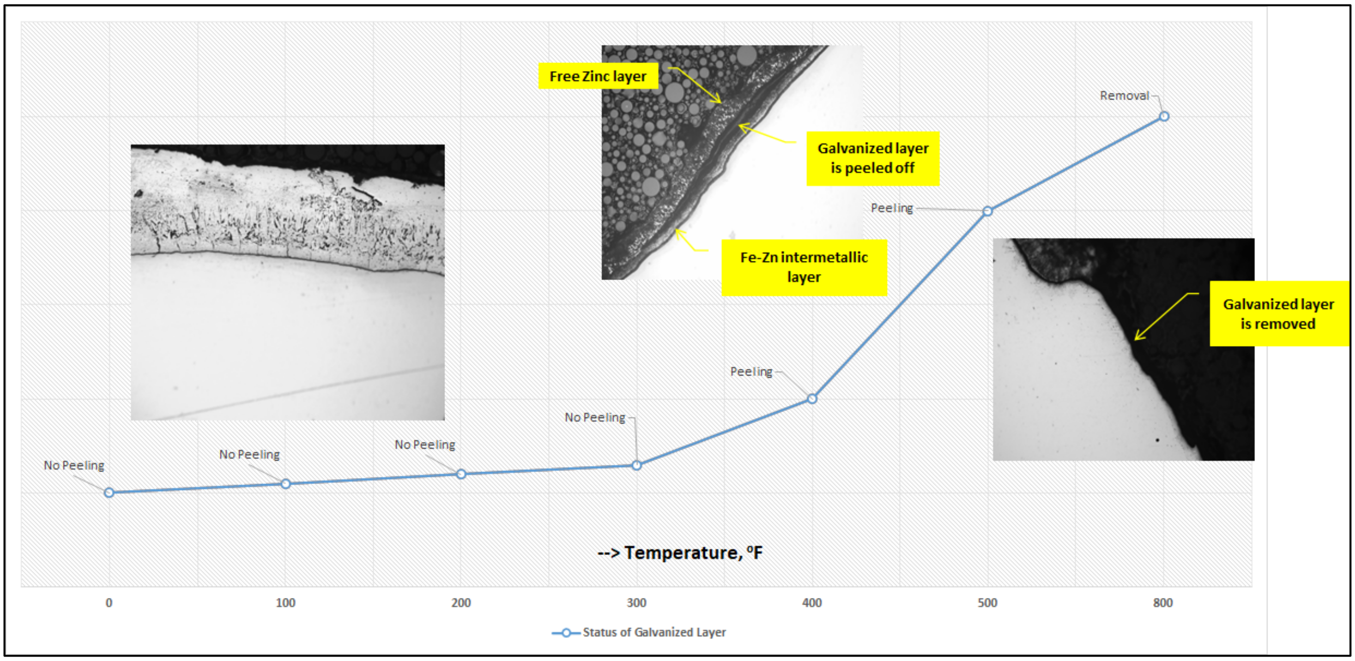

Figure 6: Cross section microscopic evidence of this peeling phenomenon as documented by the authors.

EFFECTS OF WILDFIRES ON CONCRETE

Concrete exposed to high temperatures such as fires has a complex behavior due to the differences in coefficient of thermal expansion of the concrete constituents.[13] The proportioning of concrete mixtures to achieve high strength and durability requirements in service has led to the production of dense mixtures with lower water to cementitious material ratios. The mechanical properties of high strength concrete at elevated temperatures are different than conventional concrete, particularly with regard to strength loss in the intermediate temperature range 100℃ – 400℃ (212℉ – 752℉) and with the occurrence of explosive spalling in high strength concrete. The foundation engineer should consider this strength loss in design and code specifications. Explosive spalling during a fire may lead to the direct heat exposure of steel reinforcement, causing a loss of structural capacity.[14] There will be significant differences in fire performance between high strength and normal strength concrete. Several factors may affect the fire resistance of concrete. These factors include concrete strength, moisture content, concrete density, and aggregate type.[15]

Figure 7 is a photograph of a tower leg foundation which has been exposed to wildfire. Note that the high temperature of the wildfire has caused spalling of the concrete. If left unmitigated, this could lead to further foundation degradation when exposed to the various environmental conditions.

Figure 7: Photograph of a tower leg foundation after exposure to a wildfire. Note spalling of the concrete foundation.

Moisture Content

The resistance to fire of concrete is affected by the presence of free moisture and exposure to varying levels of relative humidity. If the relative humidity is above 80%, the concrete may experience major spalling during a fire. The ability of free moisture in the concrete structure to move from the fire side to the colder side will reduce the internal pressure and the occurrence of spalling. In high strength concrete, the high-density structure limits the movement of moisture, and it is more susceptible to spalling.[16]

Concrete Density

High strength concrete is comprised of a dense paste, a low water to cement ratio, and other materials such as silica fume. The dense paste in high strength concrete makes it prone to spalling during fire exposure. The transmission of the high fire temperature is rapidly transmitted to the concrete core, leading to rapid loss of the concrete surface layers.[17]

Type of Aggregate

Concrete mixtures are usually 60% to 70% by volume of aggregate. Therefore, the properties of the concrete are determined by the type of coarse aggregate used in the mixture. The following three types of aggregates are used in construction, and their high temperature compressive strength and modulus of elasticity properties are presented in Table 2.[13]

Table 2: Effect of high temperature on concrete properties.[13]

Aggregate Type	Compressive Strength	Modulus of Elasticity
Carbonate (limestone, dolomite)	Maintain strength up to 649℃ (1200℉)	Reduction up to 50% at 427℃ (800℉)
Siliceous (granite and sandstone)	Reduction up to 50% at 649℃ (1200℉)	Reduction up to 50% at 427℃ (800℉)
Lightweight (natural or manufactured)	Maintain strength up to 649℃ (1200℉)	Reduction up to 40% at 427℃ (800℉)

Fiber Reinforced Concrete

In order to improve plastic cracking characteristics, tensile and flexural strength, impact strength, and control cracking, steel fibers are often added to concrete mixtures. This is not an ideal situation from the perspective of design for fire exposure. At elevated temperatures characteristic of fire exposures, the steel fibers may in fact reduce the fire resistance of the concrete structures. To reduce the elevated temperature adverse effect of the steel fibers, it may be beneficial to use polypropylene fibers, or a mix of polypropylene fibers with steel fibers.[18]

The actual mechanism of structural concrete failure during a fire event will vary depending on the nature of the fire, the mechanical loading and the structure type.[25] Failure mechanisms include loss of bending or tensile strength, loss of bond strength, loss of shear or torsional, loss of compressive strength, and concrete spalling. The design of concrete structural elements should take into account their separating and load-bearing functions without failure for a required period of time under a given fire scenario. Fire resistance design of concrete structures should ensure sufficient overall dimensions of a structural element section to keep heat transfer through the element within an acceptable limit. There should also be a concrete cover over reinforcement sufficient to keep the reinforcement temperature below critical values for a sufficient duration for the required fire resistance.[19]

CONDITION ASSESSMENT AFTER WILDFIRE EXPOSURE BY NON-DESTRUCTIVE TECHNIQUES

VISUAL INSPECTION:

The lattice structures should be visually examined for evidence of sagging and distortion. Galvanized zinc coatings will melt at temperatures of approximately 419.5℃ (787℉). At lower, but still elevated temperatures, diffusion between the galvanized zinc coating and the steel substrate will occur changing the thickness and composition of the iron-zinc alloy layers beneath the outer free zinc eta layer. The free zinc eta layer itself could be converted to an iron-zinc alloy layer. Depending upon the cooling rate the brittle iron-zinc alloy layers may crack and/or spall.

In most cases the loss of mechanical properties cannot be determined or quantified by visual examination. This may have critical consequences for structures which are exposed to high wind and conductor loads.

Here are some thoughts to consider for condition assessment and wildfire materials assessment of transmission and distribution structures.

- Site documentation at the top of the structure, mid elevation and ground level by a metallurgist and drone pilot.
- Thermal imaging at the top of the structure and at a low elevation by drone.
- Dimensional measurement by drone pilot to determine presence or absence of deformation, corrosion products and risk analysis.
- On-site NDT measurements to determine mechanical integrity.
- On-site metallurgical inspection and surface potential measurements to determine any possible microstructure and corrosion issues.
- If feasible, sample collection (oxide, galvanized coating, etc.) at different elevations on the structure for metallurgical evaluation.
- Evaluation of fire exposed galvanized anchors (if any) and risk of liquid metal embrittlement (LME) fracture.

- Special attention to thermal damages to structural joints and hardware such as bolts and nuts. These are much smaller items than the members of a tower and can quickly fail and compromise the tower integrity.
- Compressive strength determination of concrete.

The American Institute of Steel Construction (AISC)[5] recommends the structure to be assessed into three categories.[6] On-site hardness measurements will confirm if the members exhibit softening. embrittlement, hardening or loss of ductility.

- **Category 1** – Straight members that appear to be unaffected by the fire, including those that have slight distortions that are not easily visually observable. These members are typically unaffected by the fire or require minor repairs.
- **Category 2** – Members that are noticeably deformed but that could be heat straightened, if economically justified.
- **Category 3** – Members that are so severely deformed that repair would be economically unfeasible when compared to the cost of replacement.

The AISC standard does not address embrittlement, loss of ductility during fast cooling by extinguishing liquids, galvanized steel and corrosion risks.

The following non-destructive techniques and condition assessments can be used to determine strength reductions or galvanizing damage due to wildfires.

- Dimensional check.
- Zinc coating thickness at visually affected areas.
- Wall thickness measurements at visually affected areas.
- On-site non-destructive hardness measurements.
- On-site non-destructive corrosion potential measurements.
- On-site non-destructive metallographic analysis.
- On-site non-destructive compressive strength hammer impact measurements of concrete and petrographic analysis.

PORTABLE AND NON-DESTRUCTIVE HARDNESS TESTING:

As the heat from a wildfire can affect the tensile strength of steel it is recommended that on-site hardness testing be performed using portable hardness testing equipment. Some models of portable hardness testers can convert measured values directly to approximate tensile strengths. If not, measured hardness values can be converted to Brinell hardness using the hardness conversion tables found in ASTM E140 – 12B(2019)e1.[20] Brinell hardness values have a known correlation with ultimate tensile strength which can then be calculated. Figure 8 shows a hardness and tensile strength correlation between Vickers (HV) microhardness and tensile strength (KSI).

ON-SITE POTENTIAL MEASUREMENTS:

On site corrosion potential measurements will identify if the galvanized layer or barrier paint is compromised due to wildfire exposure. A potential of -0.30 to -0.40 Volt indicates there is no corrosion protection due to galvanic action and structural corrosion will occur in service.

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[5] American Institute of Steel Construction (AISC), 130 East Randolph, Suite 2000, Chicago, IL, 60601, USA.

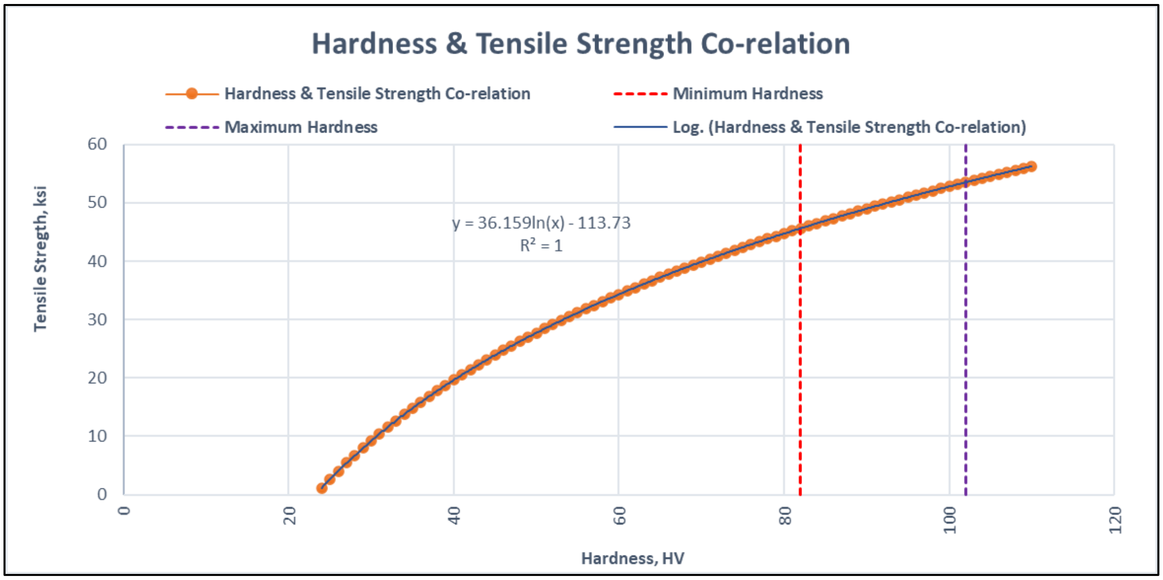

Figure 8: Hardness and tensile strength correlation between Vickers (HV) microhardness and tensile strength (KSI).

ON-SITE METALLOGRAPHIC EXAMINATION:

If it is suspected that the heat from a wildfire has exceeded 715℃ (1320℉) then on-site metallography can be performed to look for the formation of martensite. The procedure requires localized removal of any coating and shallow grinding of the steel surface followed by polishing and etching. Direct visual observation and/or replicas of the etched surface can be evaluated for martensite. Hardness measurements in the polished and etched areas would help confirm the presence of martensite and high temperature creep.

EXAMINATION OF CONCRETE FOUNDATIONS:

Visual examination should be performed to look for evidence of cracking and spalling. Both of these conditions can permit the ingress of water and possibly other contaminants that would accelerate the corrosion of embedded steel. Hammer impact sounding can be performed to evaluate soundness. Rebound hardness can indicate the compressive strength of the concrete. Table 3 presents nondestructive testing (NDT) sample reads and associated risks prior and after exposure to a wildfire.

Table 3: Sample NDT reads and associated risks prior and after exposure to wildfire.

Test	Readings
Corrosion Resistance Loss	-0.80 Volts (Acceptable) vs -0.40 Volts (Not Acceptable)
Concrete Strength Loss	4000 PSI (Acceptable) vs 1,500 PSI (Not Accptable)
Metallography	Pearlite (Accptable) vs Martensitic Structure (Not Acceptable)
Hardness and Strength	90 HV (Accptable) vs 70 HV (Not Accptable)

TEMPERATURE MONITORING:

As the temperature of steel increases above 204.4°C (400°F) especially during a wildfire, it will reduce the strength of a structure. Since the properties of steel, such as the Young's modulus and yielding strength, drop rapidly with increasing temperature, during a fire the load capacity of such structures will decline dramatically.

Wildfire temperature monitoring is the best way to determine the temperatures to which a structure has been exposed to. Based on this data, decisions can be made as to the level of investigation which will be required to determine the steel properties and stability of the structures. From this, remediation actions can be implemented. These actions could include repair, replacement or no action. There is a critical need to install sensors to ascertain any temperature and corrosion risks.

A wildfire temperature sensor should be able to transmit by satellite the temperature and corrosion potential in real time prior, during and after a wildfire. This will provide important information and identifies specific towers that have been exposed to wildfire and quantifies the risk by transmitting exposure temperature, time of exposure and corrosion potential. Figure 9 presents one such wildfire temperature sensor system configuration proposed by the authors.

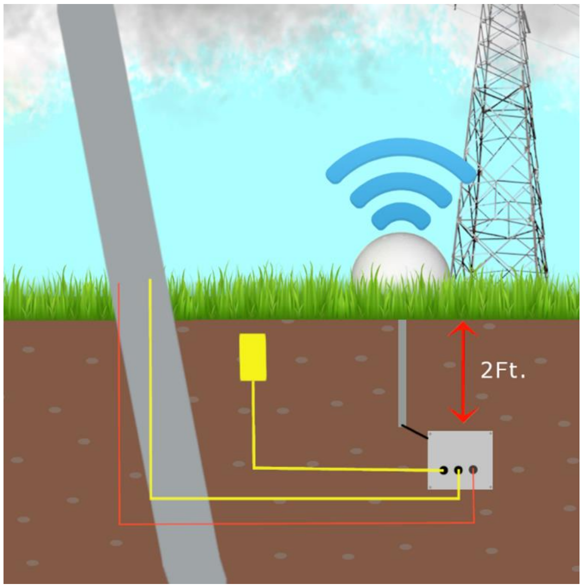

Figure 9: Wildfire temperature sensor system configuration for transmission and distribution structures including buried controller unit (gray), temperature sensors (yellow), corrosion sensors (red), and a helical satellite antenna with heat resistant dome (at ground level).

SUMMARY AND CONCLUSIONS

The key points concerning adverse effects of wildfires on power industry steel structures are summarized below.

- The mechanical properties of galvanized steel towers/poles are temperature dependent. With increasing temperature, the yield strength (>400°C = 752℉) and the modulus of elasticity (>200°C = 392℉) would decrease.
- If the wildfire temperature is above 600°C (1112ºF), almost 50% of the strength will be lost and load capacity of such member towers will decline dramatically.
- In most cases the loss of mechanical properties cannot be determined or quantified by visual examination. This may have important implications for high-voltage structures and in high consequence areas. Fast colling (quenching) of wildfire exposed towers by extinguishing liquids and chemicals may result in formation of martensite and embrittlement (loss of ductility) that cannot be detected by visual examination and may have serious consequences upon impacts.
- Sensors transmitting real time wildfire temperature and corrosion potential will provide specific information on the mechanical integrity and corrosion risk to towers during and after a wildfire.

Use of temperature sensors that can monitor temperature greater than 700 - 1400℉ is required.

- Life limiting mechanisms: corrosion, fatigue and embrittlement should be considered in condition assessment and inspection of transmission and distribution structures exposed to wildfires and fire extinguishing liquids.

REFERENCES

1. National Interagency Fire Center, *Statistics*, accessed June 3, 2021, from https://www.nifc.gov/fire-information/statistics.

2. ASTM A572 – 18, *Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*, West Conshohocken, PA: ASTM International, 2018.

3. GSA G40.20/G40.21, *General requirements for rolled or welded structural quality steel / Structural quality steel,* Mississauga, ON: Canadian Standards Association, 2018.

4. *Assessment, Prevention and Remediation of Corrosion in Weathering Steel Transmission Line Poles.* Montreal, QC: CEATI International, 2017.

5. S.P. Urbanski, W.M. Hao and S. Baker, "Chemical Composition of Wildland Fire Emission." In *Developments in Environmental Science, Volume 8.* A. Bytnerowicz, M. Arbaugh, A. Riebau and C. Anderson (Editors). Amsterdam, Netherlands, 2009, pages 79-107.

6. R.H.R. Tide, "Integrity of Structural Steel After Exposure to Fire." *Engineering Journal*, First Quarter, Volume 35, American Institute of Steel Construction, 1998, pages 26-38.

7. V. Kodur, M. Dwaikat and R. Fike, "High-Temperature Properties of Steel for Fire Resistance Modeling of Structures." *Journal of Materials in Civil Engineering*, May 2010, pages 423-434.

8. J. Robinson, "Industrial Galvanizers Specifiers Manual, 3rd Edition" Industrial Galvanizers Corporation Pty. Ltd., Carole Park, Queensland, Australia, 2013, page 145.

9. B.A. Duran, "Galvanized Steels Performance in Extreme Temperatures," American Galvanizers Association, Centennial, Colorado, accessed August 10, 2021, from https://galvanizeit.org/knowledgebase/article/galvanized-steel-s-performance-in-extreme-temperatures.

10. A. Fossa, "Performance and Inspection of HDG Exposed to Extreme Temperatures," American Galvanizers Association, Centennial, Colorado, accessed February 4, 2021 from https://galvanizeit.org/knowledgebase/article/performance-and-inspection-of-hdg-exposed-to-extreme-temperatures.

11. W.I.K. McLean, P.J. Golding, and A.M. Sheehan, "Performance of Protective Coatings on Small Steel Bridges Subject to Bushfires," presented at 8th Australian Small Bridges Conference, Surfers Paradise Marriott, Queensland, Australia, November 2017.

12. C. Gaigl and M. Mensinger, "Hot Dip Galvanized Steel Constructions Under Fire Exposure," presented at 2nd International Fire Safety Symposium, Naples, Italy, June 2017.

13. S. Yehia and G. Kashwani, "Performance of Structures Exposed to Extreme High Temperature – An Overview," *Open Journal of Civil Engineering*, Vol. 3, 2013, pages 154-161.

14. C. Castillo and A.J. Durrani, “Effect of Transient High Temperature on High-Strength Concrete,” *ACI Materials Journal*, Vol.87, No. 1, 1990, pp. 47-53.

15. “Fire Safety of Concrete Buildings,” Cement Concrete & Aggregates Australia, 2010.

16. V. Kodur, “Fire Performance of High-Strength Concrete Structural Member,” Institute for Research in Construction, Ottawa, Canada, 1999.

17. E. Ashley, “Fire Resistance of Concrete Structure,” National Ready Mixed Concrete Association, 2007, pp. 67-70.

18. J.P. Rodrigues, L. Laim and A.M. Correia, “Behavior of Fiber Reinforced Concrete Columns in Fire,” *Composite Structures*, Vol. 92, No. 5, 2010, pp. 1263-1268.

19. G.A. Khoury, “Effect of fire on concrete and concrete structures,” *Progress in Structural and Engineering Materials*, Vol. 2, 2000, pp. 429-447.

20. ASTM E140 – 12B(2019)e1, *Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness.* West Conshohocken, Pennsylvania: American Society for Testing and Materials (ASTM) International, 2015.