CASE STUDY

Battery Train Fire Risk on a Steel Warehouse Structure

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ARTICLE INFO	ABSTRACT
	Lithium ion battery fire hazard has been well-documented in a variety of applications. Recently, battery train technology has been introduced as a clean energy concept for railway. In the case of heavy locomotives such as trains, the massive collection of battery stacks required to meet energy demands may pose a significant hazard. The objective of this paper is to review the risk evaluation processes for train fires and investigate the propagation of lithium ion battery fire to a neighboring steel warehouse structure at a rail repair shop through a case study. The methodology of the analyses conducted include a Monte Carlo-based dynamic modeling of fire propagation potentials, an expert-based fire impact analysis, and a finite element (FE) nonlinear fire analysis on the structural frame. The case study is presented as a demonstration of a holistic fire risk analysis for the lithium ion battery fire and results indicate that significant battery fire mitigations strategies should be considered.

1. Introduction

With high energy density, lithium ion battery is quickly becoming the dominant rechargeable battery chemistry for electrified vehicles, which typically involves packaging lithium ion batteries in bulks. Studies on lithium ion battery fire are limited and design guidelines to prevent fire damage due to lithium ion battery fire are almost non-existent. Thermal runaway is one of the failure modes in batteries. It occurs when an exothermic reaction goes out of control, that is the reaction rate increases due to a temperature increase causing further increases in temperature and hence a further increase in the reaction rate, possibly resulting in an explosion. For the lithium ion battery runaway, it is caused by the exothermic reactions between the electrolyte, anode, and cathode – with the temperature and pressure increasing in the battery, the battery will rupture at last [1-2]. For bulk storage of lithium-ion batteries, the fire propagation can be initiated by battery pack deformation [3]. Hence, the packaging design of a battery pack plays an important role in preventing cell fire propagation [4].

The battery train concept was initially introduced as a clean energy technology which involves a train configuration that consists of two locomotives, one with a standard diesel-electric engine and another with a battery storage system – known as a zero-emission boost locomotive

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(ZEBL) [5]. Currently, battery train technology is rapidly being promoted in the US, Germany, China, South Korea and Japan. Implementation of this technology could reduce diesel engine use by approximately 40% during train operation which results in an equivalent drop in air pollution from the locomotive. Similar to energy storage solutions, conventional design of a battery train involves the stacking of multiple lithium ion battery packs. Hence, the fire scenario should include fire safety stacking design of the battery packs within the locomotive.

In 2017, a rail cargo car carrying lithium ion batteries caught fire and exploded in downtown Houston [6]. The incident damaged several residential structures due to the shock waves and burned down a nearby warehouse. This incident indicated the potential danger for the ZEBL locomotive or other lithium-ion battery electrified trains. The intent of this study is to determine the fire propagation scenario for a lithium-ion battery train assuming the rail car is completely loaded with lithium ion batteries.

The motivation behind this study is a research of the potential of Wireless Power Transfer (WPT) technology for an electrified train using lithium-ion battery racks as the propulsion method. Trains are typically electrified by overhead catenaries or by stand-alone diesel-electric powered engines. Overhead catenaries are often expensive to construct, and diesel-electric locomotives have inherent pollution problems. Lithium-ion powered trains have the same benefits as typical electrified vehicles that include zero emission problems. Similarly, lithium-ion powered locomotives need to be charged.

WPT is an emerging technology that is designed to transfer power from a transmitter on the primary side of a receiver or multiple receivers on the secondary side, wirelessly. The WPT technology requires an Inductive Power Transfer (IPT) to be applied in the battery charging application through the magnetic coupling to deliver the power. In the railway system, the conventional diesel-fueled locomotives produce severe air pollution, which makes the electric locomotive more popular in the industry [7]. The WPT concept under current consideration will include large scale use of Li-ion batteries and it is important to understand the potential fire hazard that these batteries may introduce to a rail system in order to properly develop an appropriate fire protection and mitigation strategy.

However, the current procedure of charging an electric locomotive is too complex because it involves the railroad locomotive parking adjacent to a trackside power station, then having a railroad worker physically attach large electrical cables by hand to the locomotive. The new IPT charging technology has huge potential for improving the railway industry by means of saving the charging time, increasing the worker safety, reducing the cost as well as increasing the robustness of the charging system.

This paper investigates the fire safety of a neighboring structure due to fire propagation from a battery train. A literature review was first conducted to identify the literature that can best help structure a systematic study on the risks for a structure due to fire propagation from a battery train. A battery train fire propagation risk analysis is then performed using dynamic modeling technique. Finally, a case study on a steel structure is presented to demonstrate the risk evaluation from a battery train fire. An expert opinion approach is used in rationalizing the fire risks. The fire propagation risk on the steel structure is presented in a risk index matrix.

Fire Safety Regulations for Rail-Road Structures Review

Initial sources on train fire investigation can be found in several publications from the APTA (American Public Transportation Association). The APTA Recommended Practice for Transit Bus Fire/Thermal Incident Investigation [8] is the recommended practice for fire safety analysis of existing passenger rail equipment. Every effective system safety program has four essential elements:

(1) A means to identify and prioritize safety risk (a hazard analysis);

(2) An action plan that allocates resources to reduce the most severe risks;

(3) A means to monitor, measure, and document the effectiveness of the action plan;

(4) Assesses periodic adjustment of the action plan based on the measured effectiveness and as service or equipment characteristics change.

APTA outlines steps required for a thorough fire safety analysis. These steps have been summarized in Figure 1 and organized with respect to historical data, site survey of the location, risk assessment of the possible fire scenarios, and remediation plan for the assessment. Other relevant APTA guidelines including recommended practices for fire safety [9], for fire protection systems [10], fire safety analysis for existing passenger rail equipment [11] and fire detection technologies [12], should also be evaluated for the fire safety concerns for Li-ion battery trains.
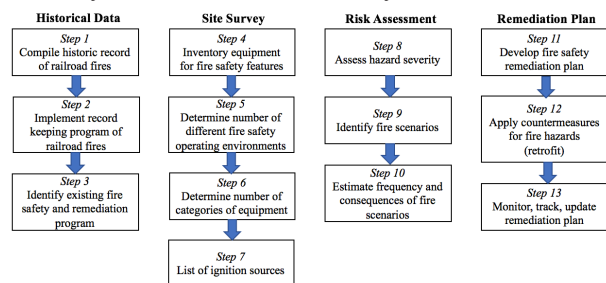

Figure 1. Fire Analysis Overview

The National Fire Protection Association (NFPA) also has specific standards for fire protection – the NFPA (National Fire Protection Association) 130 [13] is the standard for fixed guideway transit and passenger rail systems (both surface and underground systems). The main objective of NFPA 130 is to ensure occupant safety and structural integrity against runaway fires. NFPA represents a minimum requirement to provide a reasonable degree of safety from fire and its related hazards in fixed guideway transit and passenger rail systems. Life safety and fire protection requirements are specified for stations, trainways, emergency ventilation systems, vehicles, emergency procedures, communications, and control systems.

NFPA 130 [13] states that systems shall be designed, constructed, and maintained to protect occupants who are not intimate with the initial fire development for the time needed to evacuate or relocate them or to protect such occupants in place during a fire or fire-related emergency. The structural integrity of stations, train-ways, and vehicles is important to be maintained for the time needed to evacuate, relocate, or protect people who are not aware of the fire. NFPA 130 also states that there needs to be assumed possible fire scenarios that need to investigate while considering the location and size of a fire or a fire-related emergency.

Finally, the International Building Code (IBC) [14] defines required fire resistance ratings for buildings based on construction type and building element. IBC also presents several methods for establishing the fire resistance of components and assemblies to ensure that the required ratings are met including experimental fire testing as per ASTM E119 [15], prescriptive code adherence, or engineering calculation.

To develop a fire protection strategy, a fire risk analysis should be first conducted. The outcomes of the risk analysis should be a quantitative measure of the risk level and the potential spread scenarios that enables a performance-based fire protection design to minimize the risks. To assess the risk level, a risk index can be established to quantify the fire risk. For example, Salvati et al. [16] used a fire risk indexing method to study forest fire risks.

In the current study, a risk indexing matrix is established based on two perspectives, probability and severity. An analysis is conducted using a combination of how likely an event is to happen and how severe it would be if it did, to create a risk rating for the particular event. The probability aspect is scaled from 1 to 5, 1 being frequent and 5 being improbable to occur. The severity aspect is scaled 1 to 4 where 1 being catastrophic and 4 negligible.

In this paper, we described the use of the risk indexing method for the evaluation of a steel warehouse structure for potential battery train fire. The risk indexing method helped in prioritizing the fire risks for the building, which helps in dictating the structural evaluation procedure for the building. The results of structural fire analysis using finite element method (FEM) are then conducted and used to establish the fire protection strategy.

Rail Car Battery Stack Fire Monte Carlo Simulation

To determine how battery train fire propagates towards a neighboring structure, a Monte Carlo simulation is first conducted to determine the severity and likelihood of battery fire propagation.

The risk simulation is established by performing a limited Monte Carlo-based dynamic modeling of the fire propagation. The dynamic modeling, originated from cellular automaton [17], simulates the discrete state, space and time for fire propagation where each cell unit is assumed to be identical in properties and fire processes.

In the current study, the battery train fire propagation model is a two-dimensional battery stack represented by a 50 X 10 rectangular grid. The battery stacks are closely spaced, and fire is assumed to start from a single battery and propagate randomly (with an assigned probability of spreading) from the single cell to the neighboring cells. The transition at each time step is dependent on the state for the cell and the neighboring cell. Figure 2 shows the relationship between each cell and its neighbors. The cells are labelled by its index (i, j). Each cell is also identified by its state and is influenced by the state of its neighboring cells – the propagation of fire is determined at each time step by checking the states of neighboring cells [18]. The diagonal neighboring cells have no impact to the cell of interest. Also, at the boundary of the battery stack, empty cells are assumed. Hence, the actual matrix in calculation is (n+2, n+2).
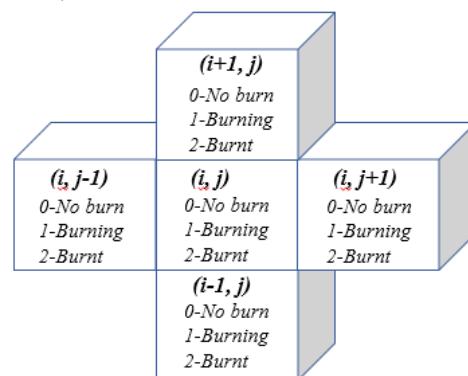

Figure 2. Coordinate System for the Battery Stack Using Cellular Automation

In the simulation for the spread of fire, a cell can contain one of three values: 0 to indicate an empty cell with no battery or a burnt battery, 1 to indicate a cell with a non-burning battery, or 2 to indicate a cell with a burning battery. All batteries are initialized as not burnt nor burning. But once the cell is on fire, it is identified as burning. A battery always burnt down in one-time step. Hence, the cell is identified as empty during the next time step.

During each iteration (time step), the cell (i, j) is checked against its neighboring cells and its state is updated by determining if the neighboring cell is on fire. If a cell's neighbor cell is burning, the cell may or may not catch on fire, the assigned probability determines if the cell will catch on fire. The boundary of burnt cells is similar to a fire break and no fire propagation will occur to such a boundary. This insulating boundary helps to dictate the direction of fire propagation based on the stochastic process. To propagate fire, a number (between 0.0 and 1.0) is randomly generated and compared to the assigned probability value. If the number if greater than the assigned probability value, then fire will start at the cell, or else, fire will not start. Furthermore, a burnt cell will not cause the neighboring cells to burn.

The rule of propagation is summarized in the following:

$$if\ (random(0\ to\ 1) < probability_{assigned})\ then$$

$$battery_{t+1}(i, j) = burning \qquad (1)$$

else

$$battery_{t+1}(i, j) = unburnt \qquad (2)$$

end if

Time in the simulation does not represent any real time unit and is defined by the number of computing time steps. This is also due to the fact the actual fire chemistry is not considered in the model. At each discrete time step, the simulation determines the state of each cell at the next time step based on the state of each cell at the current time. Thus, by counting time steps, the simulation was able to generate a new grid for the next time step. The goal of the dynamic modeling simulation is to gain insight into the likelihood of fire spread and the speed of fire spread (in relative time). The model also allows visualization of the fire propagation through animation of the simulated fire event.

By assigning the probability of fire propagation (from 0 to 1), the analysis can generate the burning time and percentage of battery racks burned. The probabilistic analysis is not based on actual fire physics but estimates the probability of directional propagation from a random fire starter in a 2-D dense battery rack. The battery burning time for each cell is constant, but the propagation rate is dependent on propagation path and the remaining unburned batteries.

1,000 randomly generated simulations were performed and the results are shown as the probability of propagation and the normalized duration and percentage of the battery burnt in Figures 3 and 4. Each figure presents the average of the data collected, as well as the range of all the data points recorded (limits of range shown with black circles). As shown in Figure 3, the percentage of the battery being burned reaches almost a constant 100 percent at a probability of 0.6 of a single cell fire propagation. On the other hand, the single cell fire will not reach the entire bulk if the probability of propagation is equal to or less than 0.4. In Figure 4, the time step takes for the battery being burned varies significantly, meaning that the percentage of the battery being burned should be directly correlated to the possible fire scenarios. In general, it would take 40 timesteps to burn the entire stack.
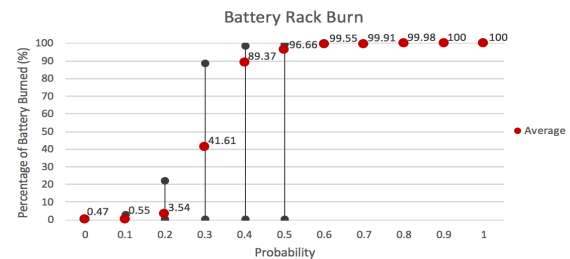

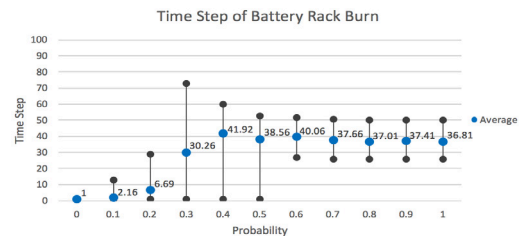**Figure 3.** Probability vs Percentage of Battery Burned

Figure 4. Probability vs Time Step of Battery Burned

The simulation process is known as a Monte Carlo simulation and it is conducted to determine the probabilistic distribution of the fire propagation scenarios. The results give a first-order indication of the likelihood of a fire propagation in the battery stack. Once the likelihood of fire propagation and the time of propagation are established, then the fire scenarios at the selected site should be identified and more detailed fire risk evaluation should be performed.

For the battery train fire study, the latter processes are illustrated using an actual warehouse and is presented as follows:

Case Study: North Carolina Capital Railyard Warehouse

To demonstrate the fire propagation risk analysis, a

study has been performed on the North Carolina Department of Transportation (NCDOT) Capital Yard train maintenance warehouse. The study evaluates the building structure for fire using finite element modeling and a fire risk analysis using an expert opinion approach to establish the risk indices for different fire scenarios, so that the critical aspects of the building fire can be unpacked for better understanding.

Building Description

The 483 m^2 building is an open-span steel structure. The eave height of the warehouse is 7.3 m and the roof is at 9.3 m from the floor slab. Figure 5 shows the steel structure that sits within the NCDOT Capital Yard. The bay width for the floor plan is 7.3 m by 7.9 m. Figure 6 shows the plan view of the train warehouse. The building is composed of six rigid frames connected with beams and purlins on each roof side between the rigid frames [19-21]. The rigid frame is composed of tapered beams of W18x40's [22-23]. The purlins are made of C10x25 beams.

Figure 5. The NCDOT Capital Yard Maintenance Warehouse

Since the case study is on an existing structure, to determine the exact design of the structure, original shop drawings were retrieved from NCDOT. In addition, a laser scan was performed onsite to generate 3D pointcloud imageries of the steel structure and the surrounding environment [21]. Figure 6 shows the scanned structures and its surroundings. The 3D imagery allows for precision measurements of the member dimensions and track locations to establish likely closest distance of any battery train may be approaching the structure. All the dimensions and measurements of structural elements in this study were validated using the LiDAR scan results.
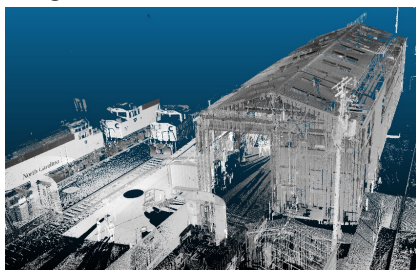
a) LiDAR Scan of Warehouse Exterior

b) LiDAR Scan of Warehouse Interior

Figure 6. LiDAR Scans of the NCDOT Capital Yard Maintenance Warehouse: a) LiDAR Scan of Warehouse Exterior and b) LiDAR Scan of Warehouse Interior

2. Fire Risk Analysis

The purpose for adding fire protection to a structure is to prevent the building from collapsing during the event of a fire, controlling damage, and allowing for safe evacuation. This needs to be performed along with a detailed fire risk evaluation. The warehouse that is being analyzed in this case study contains fuel, oxygen, and heat source, which are three elements needed in order to ignite a fire. Fire behavior is dependent on the fire temperature, the heat transferred to the surface of the structure, and corresponding rise of temperature occurring within the structure. Because the warehouse has open space and possible workers within, fire safety will be provided by selecting a way to control and extinguish the fire at an early stage and allow time for people to exit.

To analyze the fire risk, an expert opinion-based approach that involved multiple participants is performed. The following section describes the compartmentation of the warehouse and the different fire scenarios considered.

Warehouse Building Compartment Designation and Fire Scenarios

The warehouse building was partitioned in exterior and interior compartments, which have been assigned a numeric number as illustrated in Figure 7 and summarized in Table 1. Some of the compartments have different conditions for consideration: at compartment 9, there is a standalone office with glass frames, a railroad track extended all the way into compartments 11 and 12 for sheltered repair works, and electric controls have been installed on the interior wall of compartment 10. Furthermore, chemicals were stalled closely to the structure in tanks next to compartments 13 and 14. These special considerations make the compartments behave differently during fire.

Figure 7. Warehouse Building Compartment Designation

Table 1. Compartment Designations in the Fire Risk Evaluation

Compartment No.	Description
Exterior	
1	Top left exterior wall
2	Top right exterior wall
3	Middle left exterior wall
4	Middle right exterior wall
5	Bottom left exterior wall
6	Bottom right exterior wall
Interior	
7	Top left interior structural elements
8	Middle top left interior structural elements
9	Middle top right interior structural elements
10	Top right interior structural elements
11	Bottom left interior structural elements
12	Middle bottom left interior structural elements
13	Middle bottom right interior structural elements
14	Bottom right interior structural element

Another consideration in fire risk analysis is where and how ignition occurs. Even though this study focused on the battery train fire, other critical elements that may induce fire to the building have also been considered. These include fire induced by electric power transformers, chemical tanks outside of compartment 13 and 14, and a large gas tank behind the building. Thus, for this investigation, a total of six specific fire scenarios were considered and used for the fire risk analysis of the warehouse. These scenarios were chosen due to their high probability of occurrence. The six chosen scenarios are shown in Figure 8. Each scenario is further identified by a numeric number and the detailed description for each scenario is shown in Figure 9.

Risk Index Matrix

The fire risk matrix shown in Table 2 is recommended for use by the APTA when conducting fire risk analysis and was the basis of the risk analysis described in this pa-

per. Each of the six fire scenarios was individually applied to each compartment of the warehouse, giving a total of 84 scenarios. The expert opinion approach involved seven expert members with backgrounds in fire protection engineering, structural engineering, and railway engineering. Each participant ranked the risks independently, and then the average risks from the collected opinions of the seven participants were calculated. The calculated averages are then used to rank the different scenarios. The most and least critical areas of the warehouse were then identified. The outcomes are then mapped onto the compartment schematic shown in Figure 10. A grey scale is used to signify the criticality of each scenario.

Figure 8. Warehouse with Scenarios

Figure 9. Details of Six Fire Scenarios for the Warehouse

Figure 10. Risk Index Schematic

Table 2. Risk Index Matrix [12]

Table 1—Risk index matrix

		RISK INDEX MATRIX			
		Severity			
		Catastrophic 1	Serious 2	Significant 3	Negligible 4
Probability	Frequent 1	1	1	1	3
	Probable 2	1	1	2	3
	Occasional 3	1	2	2	4
	Remote 4	2	2	3	4
	Improbable 5	3	3	3	4

The actual risk indices values are presented in Figure 11, where the lower index values mean higher potential fire risks. As shown in Figure 11, the most significant fire scenario is fire propagating due to battery train parked inside of the structure and train fire propagating to compartments 11 and 12. Hence, the structural evaluation will be focused on these two compartments.


Figure 11. Critical Fire Scenario Risk Index

Structural Fire Analysis

To understand the impact of fire on the warehouse structure, detailed structural analysis using finite element (FE) analysis was performed: Abaqus Finite Element Software [24] was used to develop a structural analysis model simulating one bay of the warehouse building under fire loading. Figure 12 shows the actual dimensions of the structure (top view). Figure 13 shows the overall geometry of the single-bay model with given dimensions. 2-noded cubic beam elements (B33) were used throughout the model, with tapered cross-sections defined on the columns and fixed support boundary conditions. The frame was subject to self-weight through a gravity dead load and superimposed dead load, which were then held constant as fire loading was directly specified through a temperature field [25]. General static steps with automatic incrementation and nonlinear geometry were used for the gravity load, superimposed dead load, and the application of the temperature field.

Temperature dependent, nonlinear material properties for the steel are shown in Figure 14 based on Eurocode
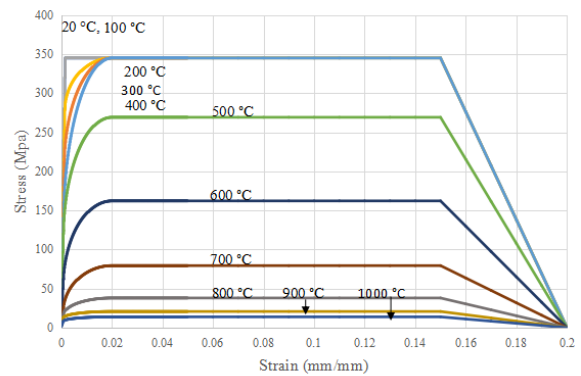
[26] and input in to Abaqus through *Elastic and *Plastic parameters. Temperature dependent coefficient of thermal expansion is shown in Figure 15 based on the thermal strain defined in Eurocode [27]. Density was specified as a constant 7,850 kg/m^3.
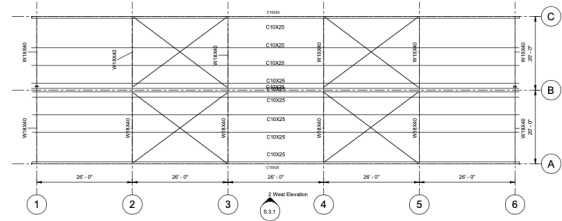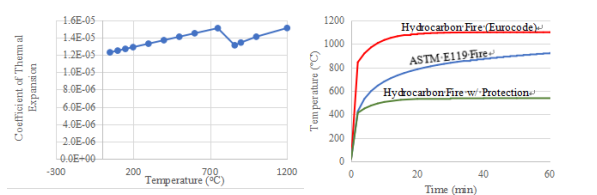

Figure 12. Plan View; Train Warehouse
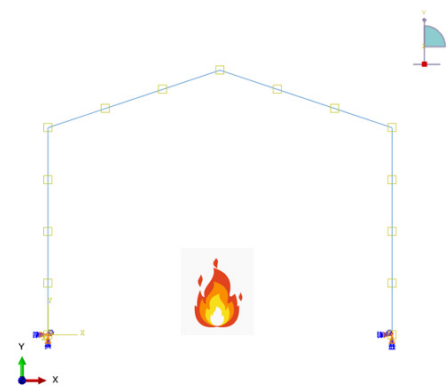
Figure 13. The Overall FE Model Geometry

Figure 14. Temperature Dependent Stress-Strain Curves for Steel

Figure 15. Thermal Characteristics of Fire Used in FE Modeling (a) Temperature Dependent Thermal Expansion and (b) Fire Curves

Fire temperature histories were input as predefined fields, applied directly to the frame members. A heat transfer analysis was not performed as it was assumed that the temperature of the unprotected steel members during an intense fire would closely follow the temperature of the fire. The hydrocarbon fire was chosen as the best approximation of design fire in the absence of specific guidance for a large-scale lithium-ion battery fire. The Eurocode hydrocarbon fire is shown in Figure 15 along with the ASTM E119 [15] standard fire for comparison. Additionally, a modified Eurocode hydrocarbon curve is included for study wherein the hydrocarbon fire curve was scaled to limit the temperature of the steel members to $538^{\circ}C$ – the temperature threshold for steel columns based on ASTM E119. This curve corresponds to a scenario where the steel frame is assumed to be retrofitted with appropriate fire protection.

3. Discussion

The final critical fire scenario resulted in the following risk index schematic shown in Figure 11. The critical fire scenario of the warehouse sourced from scenario two, which is the inside fire ignition scenario. This was the most significant scenario, as it had the lowest risk index values per compartment of the warehouse being analyzed. Because of the potential severity, this scenario was chosen to be analyzed in the Abaqus model. Scenario one (external adjacent fire) is also presented for comparison.

The following cases were modelled in Abaqus. Case 1 models a full hydrocarbon fire on the entire frame based on a Scenario two interior fire. Case 2 models a hydrocarbon fire with protection on the entire frame, again exposed to interior fire. Case 3 models a full hydrocarbon fire on only half of the frame, representative of a Scenario three exterior fire.

The results of the modeled frame with the different fire cases are shown in Figures 17, 18, and 19, with correspondence to Figure 16. Case 1 resulted in a maximum vertical displacement at the middle of the frame of 0.11 m at 5 minutes. There was a maximum horizontal displacement at the left upper node of 0.151 m at 13 minutes. There was a maximum stress of 27 MPa at 2 minutes and then decreases to 9.6 MPa for 3 more minutes. By approximately 5 minutes into the fire, the stresses in the steel reached the reduced yield strength of the material at that given time and corresponding temperature of the steel, indicating the onset of plastic behavior.
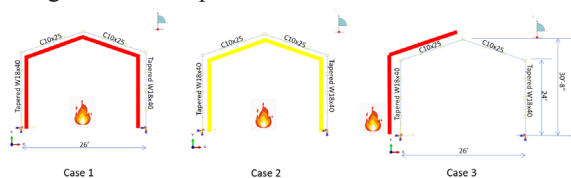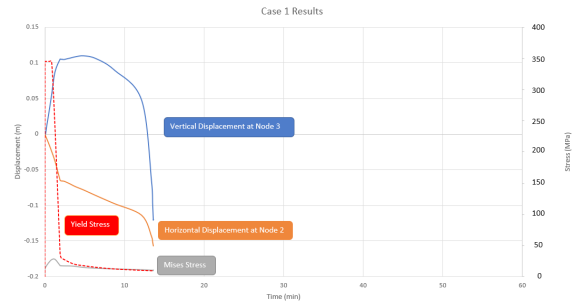

Figure 16. Cases Modeled in Abaqus

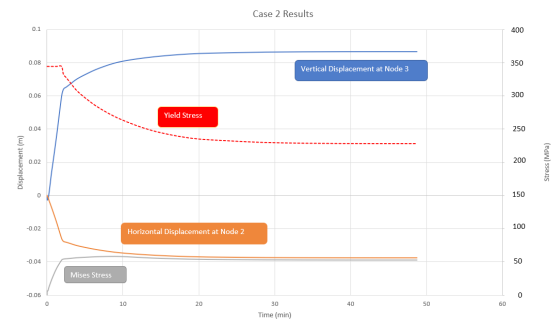

Figure 17. Case 1 Results
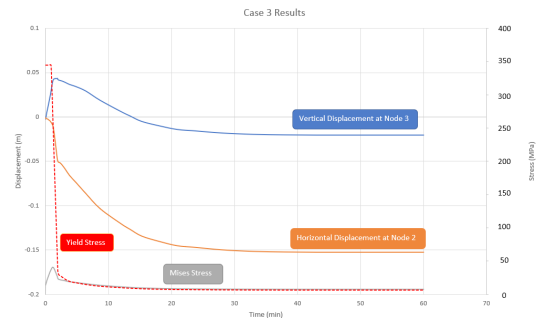

Figure 18. Case 2 Results

Figure 19. Case 3 Results

Case 2 resulted in a maximum vertical displacement of 0.085 m at 20 minutes. There was a maximum horizontal displacement 0.037 m at 34 minutes. There was a maximum stress of 58 MPa at 10 minutes and reduces to 43 MPa at 48 minutes. The stresses in the steel members were significantly below the yield stress during the duration of the fire.

The last case resulted in a maximum vertical displacement at the middle node of 0.041 m at 1.2 minutes. There was a maximum horizontal displacement at the upper left node of 0.15 m at 60 minutes. The stress was at its maximum at 0.5 minutes resulting in 29 MPa. At approximately 3 minutes into the fire, the stresses in the steel reached the reduced yield strength of the material at that given time and corresponding temperature of the steel, indicating the onset of plastic behavior. This onset of plastic

behavior occurs earlier in Case 3 than in Case 1. Only half the frame is exposed to fire, while the unexposed portion of the frame maintains its full yield strength and stiffness. The cooler, stronger, adjacent members provide restraint against thermal expansion of the heated portion of the frame. Additional thermally induced forces then develop in the heated members, ultimately increasing the stress in the heated members.

Fire Protection Strategies

Common active fire protection strategies include automatic sprinklers and fire/smoke alarms. Common passive fire protection strategies include smoke barriers, fire doors and windows, fire stops, fire dampers, finishes, furnishings, and materials that prevent or delay the rise of temperature caused by the fire. The increase in temperature results primarily from radiation from a nearby fire. Additional heat transfer may occur from direct flame contact of the fire to the structure. Fire protection materials will insulate the member and slow the conduction of heat from the surface throughout the member, thus reducing the total temperature load on the structure. The thickness and nature of the insulated protection material, size of the steel member, and weight of the structure must be taken into consideration when choosing a fire-resistant material.

Specific fire protection strategies that can be implemented for the steel warehouse that have been identified are:

(1) Gypsum board is suggested to be installed at the fire-critical locations within the warehouse – Gypsum board is a fire protection material that is commonly used in buildings due to its ease of insulation and appearance. It acts as a physical barrier to prevent the spread of the fire for a period of time.

(2) Sprayed fire resistive material (SFRM) that insulates steel from the heat of a fire is recommended for the steel members - SFRMs are generally suitable for interior use, however more robust SFRM has been developed primarily for use in petrochemical plants. Cementitious SFRM has low density (15 lb/ft^3, 240 kg/m^3), medium density (20-27 lb/ft^3, 320-433 kg/m^3), and high density (40-80 lb/ft^3, 641-1,281 kg/m^3) variations.

(3) Blanket insulation may be installed into the concealed spaces between the roof structure, potentially reducing the hourly rating of the fire.

Other than the proposed three strategies, concrete encasing is also recommended – even though it is the least economical material to be used for fire protection purposes. Concrete encasing can be used externally and internally.

Based on the FE analysis outcomes, a proper fire protection strategy can be designed and implemented for the structure in order to meet required fire resistance ratings. Fire resistance ratings are calculated based on the length of time a structural member or assembly can meet certain criteria during fire exposure. ASTM E119 specifies stability, insulation, and integration criteria for a structure exposed to a standard fire.

Application to Energy Storage in Micro-Grid

Current study has also extensive application to the mass use of lithium-ion batteries for energy storage applications. Mega watt (Mw) power supply using lithium-ion battery based energy storage solutions have been suggested to deter power outage problems during severe storms for suburban housings – a technology often described as micro-gridding.

4. Conclusions

Lithium-ion battery stacks have been suggested as a possible implementation for electrified propulsion of all modes of transportation. However, studies on lithium ion battery fire are limited and design guidelines to prevent fire damages due to lithium ion battery fire are almost non-existent. The 2017, battery packed train fire in Houston, TX, served as a cautionary tale for such incident.

This paper reviewed existing fire studies on train fires, identified several guidelines that have the potential to address the battery fire issue and demonstrated the process of fire risk evaluation using a rail repair warehouse as a case study. The analyses included a fire risk potential analysis using dynamic modeling, a fire risk quantification evaluation and a structural fire analysis. Using the fire risk analysis, the worst-case scenario is identified as fire reaching the warehouse back entrance (scenario 2) with a critical fire risk index of 1.5. The results of a 2D finite element analysis of potential fire for the steel warehouse indicated that the worst fire scenario can result in significant damages within minutes (Case 3 with maximum displacement of 0.041 m at middle node of roof at 1.2 minutes).

Based on the fire risk analysis, specific fire protection strategies have been identified for the steel warehouse. It should be noted that the fire scenarios can be made worse as putting out fire from Li-ion batteries are made difficult due to sustained fire propagation over extended time period that may last days.

This paper lays out the critical steps that are needed in order to establish the information necessary for the establishment of a fire protection strategy for infrastructures subjected to potential lithium-ion battery fire. The analyses performed are consistent with the fire analysis process as recommended by APTA.

Acknowledgements

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Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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