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Investigation of a Two-Dimensional Unsteady-State Thermo-Mechanical Model of the Tunnel During a Fire

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Abstract:-The linings of tunnels would suffer severe structural injury or maybe failure e when unprotected from a persistent blaze. Loss of life, property destruction, and prolonged service interruptions are only some of the potential outcomes of a major tunnel fire. Special design factors are required when considering the structural reaction to fire in a tunnel due to the quick increase of gas temperature to more than 1,000°C (1,832°F) and the extended fire duration due to restricted access for rescue workers. The duration of the heating process has a significant impact on the damage. In this paper, a 2D unsteady-state Thermo-Mechanical (TM) model is recognized to examine the time-dependent temperature and stress distributions of tunnel lining below the fire. Ventilation, Smoke Exhaust System, Fire Alarm System (FAS), and Rehabilitation are employed to develop the tunnel during a fire. In the result, according to the temperature criteria and the Residual Stress (RS) condition, the injury development of tunnel lining is analyzed. The findings of the comparison provide theoretical confirmation of the convergence of these two factors.

Keywords: *Tunnel Fire, Ventilation, Themo-mechanical model, Safety evaluation, Tunnel lining*.

1. Introduction

Tunnel fires are a global issue that could lead to infrastructure failures and significant financial and human casualties. Accidents would still happen without the help to explain best efforts to avoid them and monitor for technological issues, and some of them would become disasters if don't have a reliable system for putting out fires. However, the tunnel's structural shape makes firefighting difficult, particularly due to the restricted means of evacuation and the difficulties of involvement by rescue services, while the produced heat is great, and the heat loss is restricted. The large number of tunnel fires that have happened in recent years demonstrates the need to conduct a thorough safety evaluation of tunnels that are at risk of catching fire. This is because tunnel fires could inflict both human casualties and significant financial losses. Due to rapid urbanization and the expansion of fuel and chemical item exports, there is a growing concern for fire safety in road infrastructures, and the scientific community and designers are more interested in developing sophisticated ways capable of addressing this problem [1-2]. It is crucial to evaluate tunnel safety by analyzing linings' responses to fire. The purpose of fire design for tunnel linings should be to maintain the structural stability of the lining at high temperatures and a high enough residual capacity to withstand fire impacts without the lining collapsing [3–5]. This is a challenging problem not just due to the unique characteristics of fire growth in tunnels, but also the complexities of structural element reactivity at extreme temperatures. Several factors affect both the progression of the fire and the physical reaction [6].

When compared to above-ground buildings, tunnels are small and walled off, and the constant heat generated by a fire within a tunnel could inflict severe damage to the tunnel's lining. For instance, the tunnel lining of the Channel Tunnel between France and England was seriously injured in a fire in 1996. The most significant damage was that the spalling complexity of the initial 45cm thick lining section concrete got 40cm [7-8]. Local concrete shedding of the tunnel vault occurred in 1999 because of the Mont Blanc fire near the French-Italian border [9]. In 2011, a substantial quantity of concrete on the tunnel's cross and upper spalled off after a fire at the Xinqidaoliang Tunnel (China) [10-11]. In 2019, a fire seriously damaged the Limaoling Tunnel infrastructure by burning the tunnel vault and separating concrete blocks. The tunnel's bearing capacity is drastically diminished after being exposed to fire. It is crucial, therefore, for the sake of both firefighting and catastrophe resilience to study the load-bearing capability of tunnel structures when under fire attack [12].

1.1. Tunnel Fire

Fires in tunnels are a regular and deadly danger that could result in massive property damage and serious injuries. Tunnel fires are especially dangerous because of the difficulty and length of the evacuation process. Tunnels have been an important part of contemporary transportation networks since the mid-twentieth century, due to their great utility and flexibility in hilly places, as well as their efficacy in addressing the limited land supply in densely populated urban areas. However, tunnel fires are a major infrastructure risk that annually results in substantial financial and social losses[13-17]. Tunnel fire incidents, in comparison to traffic accidents, which are often generated by electrical and/or mechanical flaws in cars, frequently draw greater attention because of the potential for catastrophic results and/or explosions. Smaller flames, on the other hand, could be very dangerous to human life. Tunnel fires generate heat, smoke, and poisonous chemicals, which could result in fatalities for both tunnel users immediately engaged in incidents and other persons during the tunnel's evacuation procedure. The closing of the tunnel once a fire breaks out also creates traffic delays because of the increased travel time. The time it takes to close a tunnel depends on the magnitude of the fire and its implications. The high temperatures that are created by fire have the potential to inflict damage to both equipment and buildings (such as concrete spalling, ceiling collapse, and pavement burning) (e.g., ventilation, lighting, road signs, and monitoring systems). There are a few significant instances mentioned below.

1.1.1. Mont Blanc Tunnel Fire

The Mont Blanc tunnel connects Chamonix to Courmayeur through a single-gallery, two-way, two-lane tunnel (Italy). When it opened in 1965, this 11.6-kilometer tunnel was the largest of its kind anywhere in the world [18-19]. Semi-circular in shape, the tunnel's portion has a roadway width of 7 m and 0.8 m-long sidewalks on both sides. The tunnel's walls (0.5 m thick) were constructed from reinforced concrete, while the road slab and channels below were constructed from concrete without reinforcements [20]. The cross-section of the tunnel is presented in Figure 1.

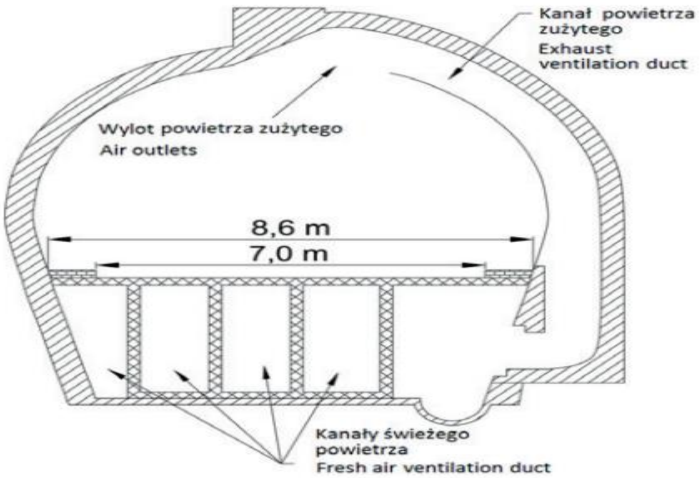

Figure 1: Cross-section of Tunnel

The tunnel was provided with emergency shelters at regular intervals of 600 meters, which protected for two hours in the event of an emergency (18 shelters). Every 300 meters in each direction from the French to the Italian side of the road were marked with a number from 1 to 36 designating emergency stopping areas for vehicles measuring 3.15 meters in width and 30 meters in length. Trucks could reverse directions on the other side of the emergency stop bays [13]. Every 100 meters, there were fire pull box alarm receptacles stocked with two fire extinguishers, and every 150 meters, there was a fire receptacle connected to a water source. There were traffic lights at gateways every 1200 meters of the tunnel, and security cameras were placed every 300 meters before the incident. On March 24, 1999, a terrible accident took place in the tunnel. Seven kilometers outside of France's border, a Volvo refrigerated truck from Belgium was halted due to a fire. A cigarette stub that went into the truck's air filter started the blaze [21]. The fire's location is presented in Figure 2 [22].

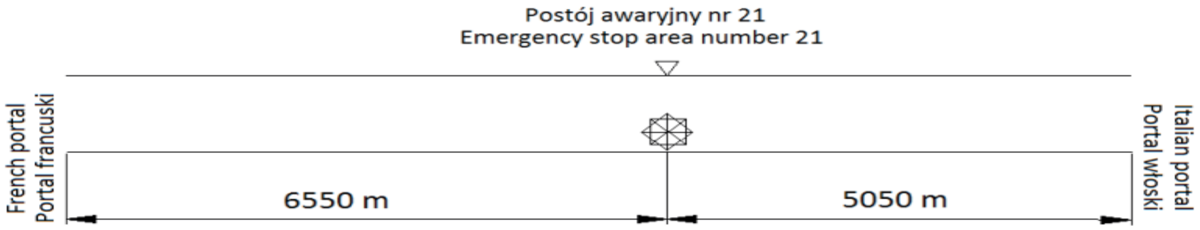

Figure 2: Location of fire in the Mont Blanc tunnel [23].

a. Tauern Tunnel Fire

The Tauern Tunnel connects southern Germany with northern Italy's economic centers, making it one of the more significant north-south travel routes over the Mountains. A vehicle accident on May 29, 1999, caused a massive fire in the Tauern Tunnel. Twenty-four automobiles and sixteen trucks were destroyed. There was a lot of concrete dripping from the roof as well as the sides of the tunnel. The concrete liner broke loose and flowed to a depth of 400 millimeters (16 inches) along a 100-meter (328-foot) stretch of the tunnel in the region where the greatest temperatures were. After the blaze, about 600m3 of spalled concrete with a chip size of around 5mm was eliminated. There was a three-month closure of the tunnel, costing 6.5 million USD in repairs and leaving an additional 19.5 USD in unclaimed toll revenues [24].

b. The 1996 Channel Tunnel fire

On November 18, 1996, a fire broke out in a Heavy-Duty Vehicle (HGD) on shuttle train No. 7539. The shuttle train was traveling from France to England when a fire stopped it 19 kilometers from the tunnel opening on the French side, as seen in Figure 3.

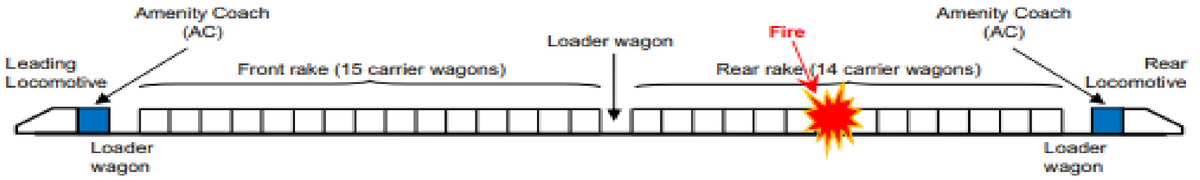

Figure 3: The incident train ''7539'' [25].

It is considered that the following factors contributed to the fire accident:

1.At around 21:42, the HGV shuttle train 7539 departed the French terminal (Figure 3).

2.The disaster train reached the "Running Tunnel South" ('RTS') around 21:48 h, and it is thought that safety officers observed a fire below one of the vehicles and then alerted the "Terminal Control Centre" (TCC) in France.

3.The involved fire exposure system and the tunnel's fire detection system both indicated the presence of fire around 21:53 h. By this point, the train had made its way 10 kilometers inside the RTS.

4.It was at 21:56 h that the French Emergency Centre (FEC) sent a team from the "French First Line of Response" (FRFLR).

5.The incident train ('7539') came to a regulated stop at PK-4131, which is located close to the Service Tunnel (ST) at 21:58.

6.The train driver was unable to evacuate passengers at 22:01 h owing to heavy smoke.

7.The eight-member French firefighting squad arrived at the 'ST' at 22:02 h. It is speculated that the "UK First Line of Response" (UK-FLR) squad also arrived at the "ST" shortly after.

It was verified at 23:39 h that a fire had broken out between doors "4163" and "4201" in the corridor. For almost 5 hours, the combined firefighting units of the United Kingdom and France battled the fire. The fire seriously destroyed the concrete lining and tunnel infrastructure, but there were no casualties [26].

2. Literature Review

The following study expands on the investigation of a 2D unsteady-state TM model of a tunnel during a fire. Several researchers explained their findings as seen below.

Zisis T. et al., (2022) [27] analyze the circumstances that were present in a railway tunnel following an accident involving a train fire as well as the capability of the ventilation system to produce the appropriate situations for the safe removal of passengers. The tunnel's airflow was simulated using a Large Eddy Simulation model (LES). Air critical velocity within the railway tunnel was considered while evaluating the ventilation system's criteria, and the Fractional Effective Dose (FED) value was analyzed to ensure the safety of the evacuating population. It was determined that the most crucial step in a tunnel fire is the activation of the ventilation system.

Qiao R. et al., (2022) [28] developed a mathematical model to forecast the depth of fire damage caused by spalling in concrete. Time-dependent temperature and stress fields of the concrete lining during tunnel fire were generated using the Laplace Transform (LT) and the Series Solution technique for Ordinary Differential Equations (ODE), providing a foundation for damage progression. The suggested mathematical method might be used to forecast the spalling depth of tunnel lining about the temperature increase of tunnel fire. The results of this study could be utilized to recover the damage assessment of tunnels lining under fire.

Yongchao S. et al., (2021) [29] stated that a high-temperature tunnel project is used to inform the development of a three-dimensional TM-coupled numerical model of rock stratum-tunnel, which is then used to compute and assess the stress of tunnel lining in a high-temperature environment. The findings demonstrate that during the onset of lining, primary stress and adjacent rock pressure rise with rising temperature.

Saito S. et al., (2021) [30] used numerical simulation to determine the effect of tunnel wall property on the gas temperature. In addition, the connection between the gas temperature and the thermal parameter of the tunnel walls could be calculated from these data. The findings of the simulation demonstrated that the temperature of the gas under the maximum is about equivalent when the thermal inertia of the tunnel walls are comparable to one another.

Wang Z. et al., (2021) [31] demonstrate how the location of the onset of the one-dimensional flow area in tunnel fires is affected by the tunnel's cross-sectional measurements and Heat Release Rate (HRRs). The Fire Dynamics Simulator (FDS) was used to run a total of 27 simulations, with each one examining the effects of varying parameters such as fire size (5 MW, 15 MW, or 30 MW), tunnel height (4 m, 6 m, or 8 m), and tunnel width (6 m, 9 m, or 12 m). The results of numerical simulations were compared to those of a theoretical model without dimensions, which led to the suggestion of a better correlation for the position of the regional center.

Ilias N. et al., (2021) [32] define the dynamic range of risk variables like carbon monoxide and temperature that contribute to the "chimney effect.". FDS software was used for the modeling, and the finite volume technique was used. The theoretical and modeling findings of back layering length and velocity are evaluated and contrasted. High-risk areas along the tunnel for each potential source of damage are indicated. It is recommended to make use of the findings collected to react to crises caused by a fire in tunnels that are applicable.

Liang K. et al., (2019) [33] emphasize the unique T-shaped layout of the pipe gallery. The FDS program is used to model cable fires, with the spatial temperature change of the corridor and the temperature of the ceiling of the T-shaped corridor being analyzed about the variation in fire source power. The T-junction is the source of the cable fire's potential for further spread. The outcomes of this study establish a reliable benchmark for the performance of firefighting in underground T-shaped cable duct corridors.

Sun Z. et al., (2019) [34] suggest that a Thermo-Hydro-Chemo-Mechanical (THCM) model with all possible couplings be created. Finally, the integrity of the tunnel construction is quantified with the aid of a factor of safety using a unique numerical technique called Discontinuity Layout Optimization (DLO). Numerical experiments are performed using the suggested approach with and without spalling considered. The findings demonstrate that spalling significantly affects the tunnel's structural integrity. As a result, the inner concrete heats up faster and the lining part is thinner.

Zhu et al., (2019) [35] suggested a new approach to reducing drag and heat in hypersonic vehicle design by combining spike and multi-jet methods. Using numerical analysis using a custom algorithm, they factored in the opposing jet's thrust into the drag calculations, considering fluid-thermal interaction. Researchers looked at how changing the jet pressure ratio, jet position, and the length-to-diameter ratio of the spikes affected the flow, drag, and heat characteristics. The results demonstrated that the unique technique, which is impacted by spike length, jet pressure, and lateral jet placement, is superior in its ability to reduce drag and heat. Results help shed light on how to best build hypersonic vehicles for maximum efficiency.

There is a wide range of authors who used the technique and presented their discoveries, as given in Table 1.

Table 1. Summarized the table of reviewed literature.

Authors	**Techniques**	**Outcomes**
Zisis T. et al., (2022) [27]	LES	The findings indicated a good match between the predicted and simulated values; thus, the ventilation system could deliver enough air for smoke extraction.
Qiao R. et al., (2022) [28]	Laplace transform and Series solution	An analytical model is developed to study the temperature and thermal stress distribution of tunnel lining and to determine the susceptibility of spalling depth to warming duration.
Yongchao S. et al., (2021) [29]	TM model	The findings demonstrate that the primary stress and surrounding rock pressures rise with rising temperature during the lining's initiation phase.
Saito S. et al., (2021) [30]	Fourier transform	The numerical findings of heat loss accorded with the theoretic analytical findings not only before but also after thermal infiltration.
Wang Z. et al., (2021) [31]	FDS	A mathematical dimensionless model is compared to numerical simulation findings to offer a better connection for the placement of the demarcation point.
Ilias N. et al., (2021) [32]	Finite element method	The findings should be utilized to deal with fire crises in the tunnels in the issue.
Liang K. et al., (2019) [33]	FDS	The results of this case study establish a reliable benchmark for the fire suppression of underground T-shaped cable duct corridors.
Sun Z. et al., (2019) [34]	DLO	The significance of spalling in the numerical experiments is due to the low thermal diffusivity of concrete, which means that even when the surface temperature of the concrete increases dramatically, the interior concrete is only gradually heated.
Zhu et al.,	custom algorithm	The results demonstrated that the unique technique, which is impacted by spike length, jet pressure, and lateral jet placement, is superior in its

(2019) [35]		ability to reduce drag and heat.

3. Background Study

After a fire, it is necessary to do a TM evaluation to see whether the tunnel lining could be safely re-used. This research presents a mathematical approach to studying the TM characteristics of tunnel lining during the evolution of a fire. This approach considers the RABT curve, which consists of the three phases of heating, holding, and cooling. It is possible to solve for the temperatures and thermal-mechanical stresses as a function of time by utilizing the LT and the Series Solution technique for ODE. It addresses how the tunnel lining's temperature and stress distributions fluctuate over time. The extent of the lining's damage from a fire is calculated using a limit state analysis. Complete and thorough presentation and analysis of all outcomes [36].

4. Problem Formulation

According to a study, the most significant tunnel issues in the nation are lining erosion, water damage, foundation sinking, and mud-pumping, among other things. These issues have a significant impact on both the regular flow of traffic and the safety of transportation through the tunnel. Overheated bearings, brakes, tires, or motors are some of the most prevalent causes of tunnel fires, along with accidents and overheating in conjunction with leaking or electrical failure. The most common reasons for tunnel fire disasters are automobile overheating and traffic accidents. Since many tunnels are being constructed for both road and railway use, fire safety in tunnels is an increasingly pressing concern. The authors studied the 2D unsteady-state TM model of a tunnel during a fire to solve these problems by using some techniques.

5. Research Objectives

•to calculate the minimum rate of smoke removal necessary to ensure fire safety.

•to explore the temporal distributions of tunnel lining's temperature and stresses when under attack.

•to determine the extent of fire damage to reinforced concrete tunnel liners using computational and experimental methods.

6. Research Methodology

A. Technique Used

In this section, the authors used some techniques i.e., the Ventilation process, Smoke Exhaustion, Fire Alarm System, and Rehabilitation Analysis for a 2D unsteady-state TM model of a tunnel during a fire.

a. Ventilation Process

Mechanical and natural ventilation systems are both viable options for tunnels. Natural ventilation systems depend on the piston impact of moving vehicles and climatic variables (outdoor wind, temperature, and pressure difference between the gateways) to push air down the tunnel. Mechanical ventilation systems create airflow with the help of fans and distribute it through a network of ducts and absorbers. These natural effects are found to variable degrees, in every tunnel, irrespective of the presence or absence of artificial ventilation systems. It is common practice to classify mechanical ventilation systems according to the orientation of airflow in the tunnel's highway. Tunnels with longitudinal ventilation systems have airflow that is in the same orientation as the tunnel's axis. On the other hand, the airflow in a complete or semi-transverse system is parallel to the tunnel axis in the cross-sectional plane. Several factors, such as tunnel length, cross-section, and gradient; environmental context; increased traffic; and installation costs, should be considered while deciding on a ventilation system [37].

b. Smoke Exhaustion

Smoke exhaust ductwork is often safeguarded using passive fire protection methods, which are subjected to fire testing, registration, and approved usage and compliance. Smoke extinguishers are installed on buildings, ships, and offshore constructions to aid firefighting and allow for safer evacuation in the event of a fire. Controlling smoke flow in tunnels is crucial to the security of railway passengers and staff. Designers of smoke control systems could choose between two broad methods. The first approach is more passive, whereas the latter is more active. Systems that rely on natural airflow are considered passive, while those that rely on mechanical ventilation are considered active. Mechanical ventilation systems are often used in newly constructed, larger tunnels, whereas natural ventilation systems are used in older, shorter tunnels. Natural ventilation systems have several useful applications [38]. Figure 4 depicts the smoke exhaustion in the tunnel.

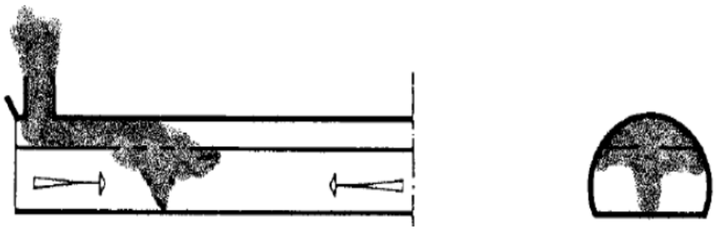

Figure 4: Structure of Smoke exhaustion in tunnel [39].

c. Fire Alarm System

A Firewall Alarm System (FAS) is a set of sensors and alerting systems meant to sound off in the occurrence of a fire, carbon monoxide leak, or another emergency. Alarms might be set off automatically by smoke and heat detectors, or manually by using devices like call points or pulsations. Electric bells, sounders, and horns could all be mounted on the wall as alarms. Alternatively, the building could be equipped with speaker strobes that trigger an alarm and broadcast a voice evacuated message warning the inhabitants to keep away from the elevators. There are a variety of fire alarm sounders on the market, and depending on the location and who made the system, one could be able to choose between a low, medium, or high frequency and tone. In Europe, FAS often produces a sound like a siren's pulsing tone. In the United States and Canada, horns are the common name for electronic FAS that can be left on continuously or be programmed to sound a variety of various alarms. The loudness of fire alarm warning devices is also adjustable. Devices that need human activation include fire alarm boxes, pulling stations, break glass channels, and (in Europe) call points. Manual fire alarm activation devices are placed in common areas (near the exits) and are easy to recognize and use. Common methods of activation include pushing a lever or shattering glass. There is a wide variety of automatically activated devices designed to react to various noticeable physical changes caused by fire, including indicted thermal energy, heat detectors, products of burning, smoke detectors, radiant power, flame sensors, combustion gases, fire gas detectors, and the statement of extinguishers, water-flow detectors [40].

d. Rehabilitation

Rehabilitation is a topic that is highly studied across the world. A disability affects over a billion individuals worldwide, or over 15% of the population, thus this is not shocking. In addition, a current report found that 2.41 billion people worldwide live with situations that affect their regular features and would benefit from rehabilitation services, with approximately one-third of these people involving rehabilitation services at some point during their illness or damage [41]. Over the next 30 years, the percentage of worldwide people over 60 would double, and a vast number of them would have to deal with chronic illnesses, especially non-communicable ones. Globally, the number of persons suffering a reduction in functioning due to this shifting health and demographic patterns is rapidly increasing, creating massive unfulfilled rehabilitation requirements. The lowest and most vulnerable members of society have the greatest number of unfulfilled requirements, and nations with low and intermediate incomes, as well as those in war zones, are typically unable to meet this growing demand for rehabilitation services [42-43]. The World Health Organization (WHO) lists the promotion of great health, protection of illnesses, treatment, and palliative care as important basics of Universal Health Coverage (UHC). Thus, the purpose of rehabilitation is to help people become as self-sufficient as possible in Activities of Daily Living (ADL), in the areas of job, leisure, and education, so that they can have a fulfilled life.

Rehabilitation plays a crucial role in obtaining not only personal health compensation but also a universal health purpose that permits the expansion of a beneficial and functioning worldwide population [44].

7. Proposed Methodology

In this section, the authors discuss the proposed work of this paper and Figure 5 depicts the flowchart of the proposed methodology

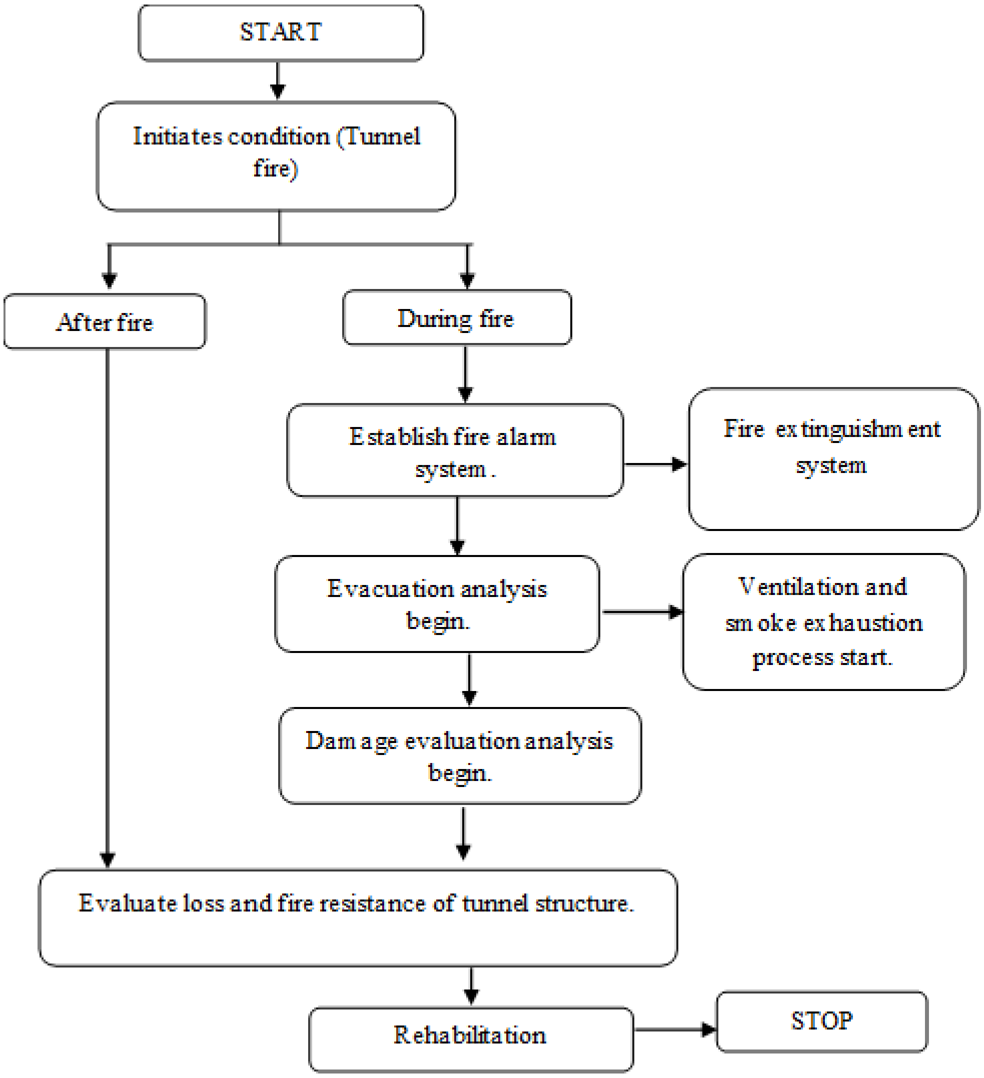

Figure 5: Proposed Methodology

The following steps of the proposed methodology are explained in given below:

Step 1: In the first step, start the two-initiate condition of the tunnel fire i.e., after the fire and during the fire.

Step 2: Now in this step, the fire alarm system would be set up during the actual firefighting procedure.

Step 3: In this phase, the authors will extinguish the fire using the extinguisher system.

Step 4: After the third step, the procedure of removing persons from particularly hazardous areas in the case of an emergency inside the tunnel.

Step 5: At this stage, the process of smoke removal and ventilation would begin appropriately.

Step 6: After the exhaustion, the damage evaluation analysis process begins when a tunnel has been damaged by fire, it is important to have a system to assess the extent of the damage. (1) useful information for methodical decision-making as opposed to haphazard fixes, and (2) objective measures of performance for use in creating solutions that are both reliable and affordable.

Step 7: Now in this step evaluate the loss and a building's ability to withstand fire is measured by how long it takes for the building to stop performing its intended function, either owing to the spread of the fire or the building's undesirable deformation or collapse.

Step 8: Finally, in this step start the process of rehabilitation which is rehabilitation precedes rebuilding because subsurface structures are costly and time-consuming.

8. Results and Implementation

This section of the research details the implementation carried out using the suggested technique, and the implementation tools are provided below.

A. Tool Used

In this research, the authors used the Matrix Laboratory (MATLAB) tool to obtain the results. MATLAB was created by MathWorks and is a commercial programming language and numerical computing environment that supports many examples. Matrix operations, charting of functions and data, procedure development, user interface design, and connecting with other programming languages are all probable with MATLAB. The findings provided to support the suggested effort stated below are as follows.

(i) Figure 6 illustrates the RWS curve, the RABT/ZTV curve, and the temperature curve used in tunnel fires. All curves show a steady increase in temperature beginning about 200 degrees Celsius. The RWS curve shows the quickest increase, reaching 1000°C in about 40 minutes, followed by the RABT/ZTV curve with a more gradual increase, reaching 1000°C in about 60 minutes, and finally the temperature curve used, showing the sluggishest increase, reaching 1000°C in about 80 minutes. Each curve then reaches a maximum of 1000 °C and stays there for a while before beginning to fall. The RWS curve cools to 200°C again in around 120 minutes, the fastest of the three. On the other hand, the RABT/ZTV curve decreases more slowly, returning to 200°C in about 140 minutes, while the temperature curve used follows the slowest fall, returning to 200°C in around 160 minutes.

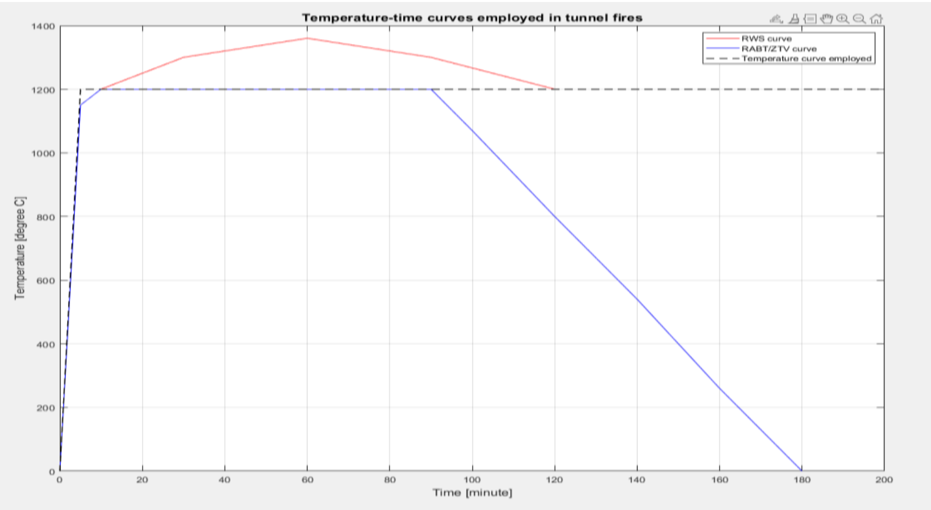

Figure 6: The use of temperature-time curves in the context of tunnel fires

(ii) The starting temperature of the tunnel lining might be represented as:

$$\Theta(R, 0) = 0 \quad (1)$$

Figure 7 shows the simplified temperature loading, where the maximum temperature is represented by Θa; temperature increase from zero to 1200 degrees Celsius in seconds signified as τ_0. As a result, authors could write the temperature boundary conditions as:

$$R = R_a: \Theta(R_a, \tau) = \begin{cases} \Theta_a, \frac{\tau}{\tau_0} 0 \le \tau \le \tau_0 \\ \Theta_a \, \tau > \tau_0, \end{cases} \tag{2}$$

$$R = R_b; \frac{\partial \Theta(R_b, \tau)}{\partial R} + H_2 \Theta(R_b, \tau) = H_2 \Theta_b \tag{3}$$

where Ra and Rb are the non-dimensional inner and outside radii, respectively. The greatest temperature during the fire is denoted by the non-dimensional symbol Θa. Θb represents the arbitrary ambient temperature. The external heat transfer coefficient H2 is a non-dimensional quantity. τ_0 is the non-dimensional time required for the temperatures to increase from 0 to 1200°C. Figure 7 depicts the two phases that comprise a fire's progression: the rising stage (0 ≤ τ ≤ τ0) and the holding stage (τ ≥ τ0).

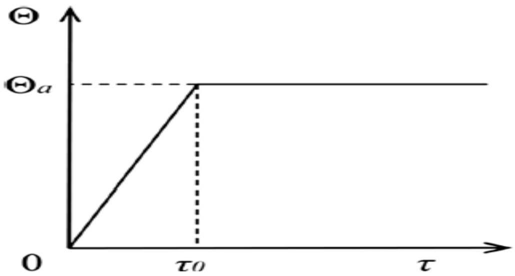

Figure 7: The inner surface's reduced temperatures loading

(iii) It can be seen from Figure 8 that, for any point τn within the range of τ ＞ τ0, the inner surface temperature can be expressed as Θ1(τ)-Θ1(τ-τ0), where Θ1(τ-τ0) is parallel to the line Θ1(τ). Hence, the inner surface temperature for τ ＞ τ0 can be expressed as:

$$\Theta_2(\tau) = \Theta_1(\tau) - \Theta_m(\tau) = \frac{\Theta_a}{\tau_0}\tau - \frac{\Theta_a}{\tau_0}(\tau - \tau_0); \quad \tau > \tau_0 \tag{4}$$

Based on the solution of the temperature field for 0≤τ < τ0, the solution of time-dependent temperature of tunnel lining for τ＞τ0 could be expressed as

$$\Theta_2(R, \tau) = \Theta_1(R, \tau) - \Theta_1(R, \tau - \tau_0); \ \tau > \tau_0 \tag{5}$$

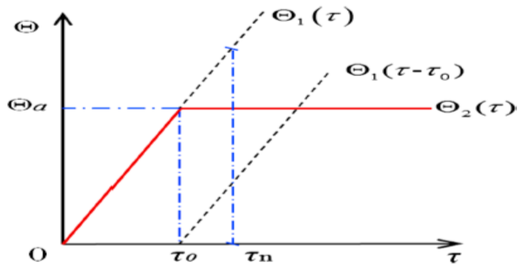

Figure 8: An example of a temperature-time plot when τ ＞ τ0.

(iv) Figure 9 depicts the temperature distribution of a humidifying agent as a curve showing the temperature fluctuation with respect to distance from the heated surface. Beginning at a relatively high temperature close to the surface, the curve gradually lowers as the humidifying agent recedes into the depths. Two types of analysis, theoretical and numerical, have been used to get the figure. An intriguing concordance is seen between the theoretical analysis (derived from a simpler model of the humidifying process) and the numerical analysis (based on a more complicated model), indicating the practical correctness of the simplified model. The figure also highlights the impact of humidifying agent type on temperature distribution; while water is utilized in this example, steam or ethylene glycol may also be used.

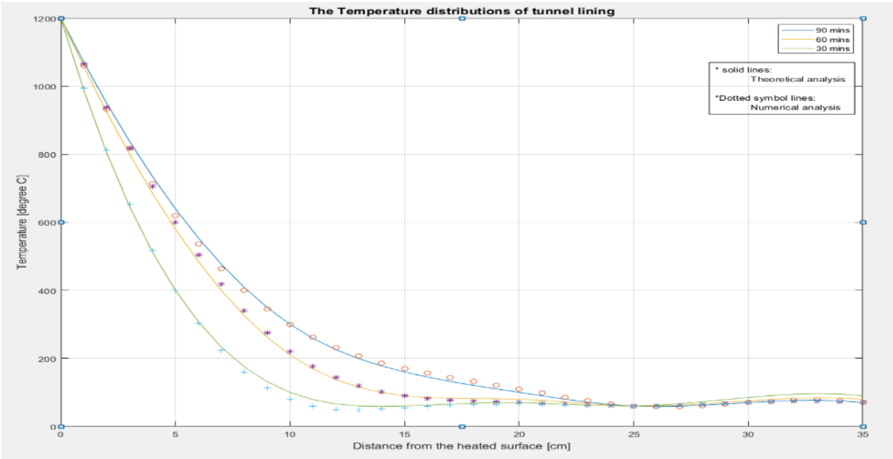

Figure 9: Temperature patterns in tunnel lining

(v) The figure 10 demonstrates that the distribution of circumferential stress throughout the circumference of the tunnel lining is not consistent over the whole circumference. The sides of the lining are subject to the least amount of tension compared to the top and bottom of the lining. This is because the top and bottom of the lining are the only parts of the lining that are required to hold the weight of the soil that is placed on top of it, while the sides of the lining are not.

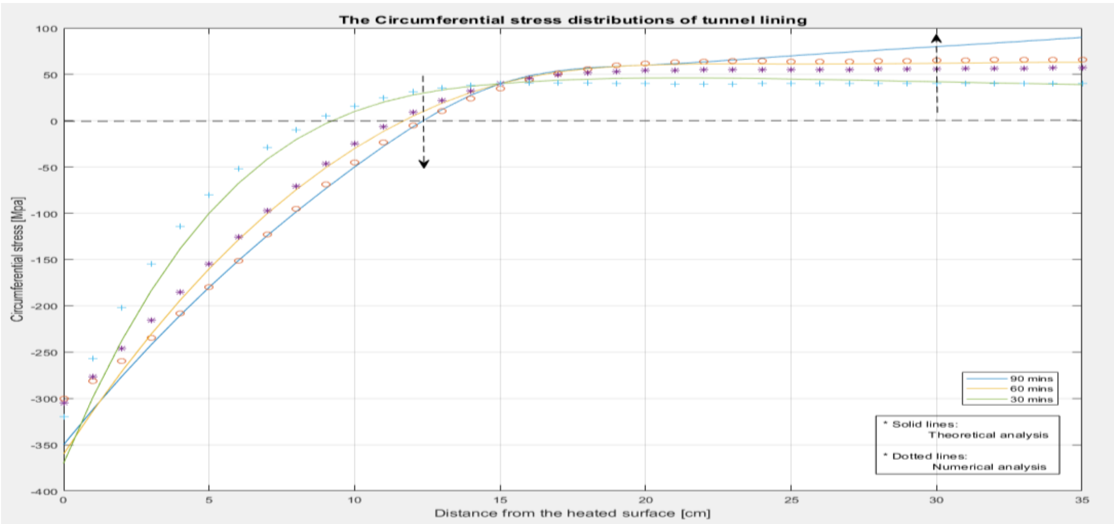

Figure 10: The radial and tangential stress distributions in tunnel linings

(vi) The figure 11 shows the relationship between water's specific heat capacity and pressure. The amount of heat required to increase the temperature of one gram of a material by one degree Celsius is known as its specific heat capacity. It shows that the specific heat capacity of water decreases with increasing temperature. This is because the increased mobility of water molecules at higher temperatures results in less energy being required to heat the same amount of water. Since water molecules require more energy to separate when they are closer together due to increased pressure, the graph also shows an increase in the specific heat capacity of water with increasing pressure. This connection between temperature, pressure, and specific heat capacity gives useful insights into the thermodynamic behavior of water under diverse situations.

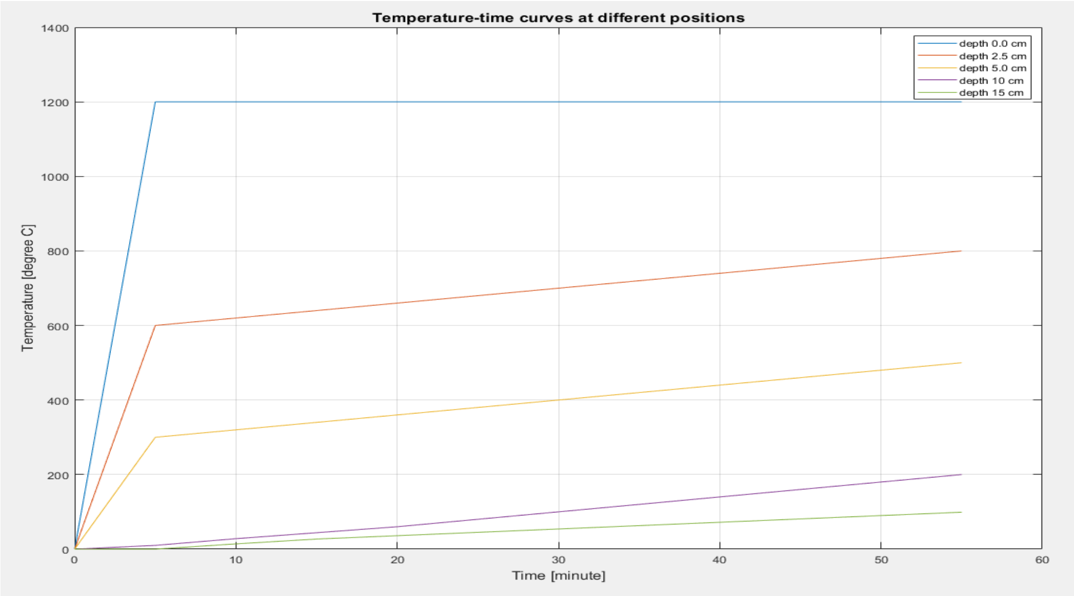

Figure 11: Location-specific time-temperature plots.

(vii) Figure 12 depicts the development of damage to the tunnel's lining in response to several fire situations. There is a non-linear progression in the damage level of tunnel lining over time. If a fire burns for a long enough time, it will cause significant destruction. Damage is proportional to the maximum temperature reached by a fire. Additionally, a fire's peak temperature, duration, and heat flow are all linked to its destructive depth.

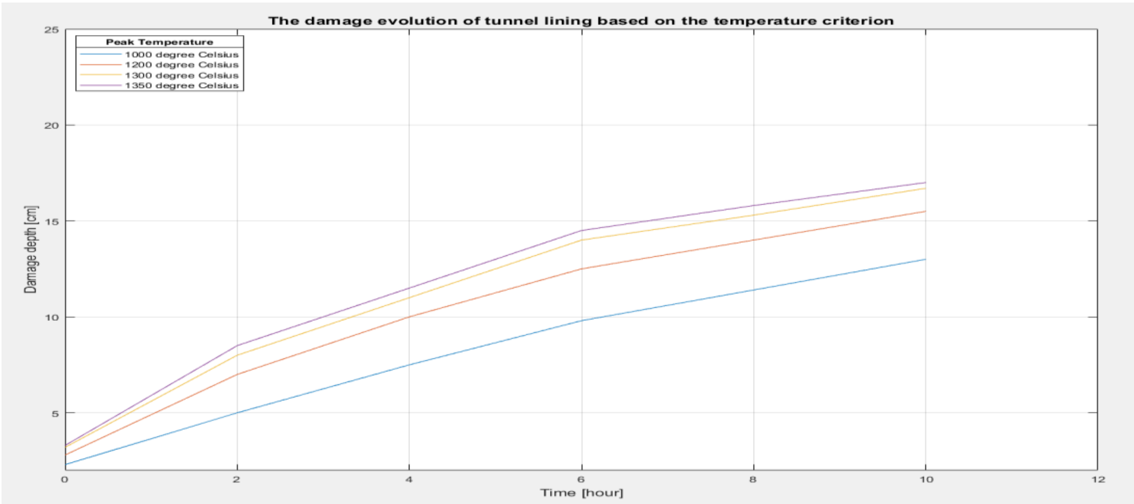

Figure 12: The temperature-based deterioration of tunnel lining over time.

(viii) Figure 13 shows that the residual stress ratio increases with temperature, implying that the material becomes more vulnerable to residual stresses at higher temperatures. The enhanced ductility of the material at these temperatures is responsible for this phenomenon. High-strength materials also have a greater residual stress ratio, as seen by the graph. The fact that high-strength materials can endure and support more residual stress because they have a higher yield stress exemplifies this. Insightful knowledge of how materials respond to changes in temperature and mechanical stress may be gained by observing the interactions between these three variables.

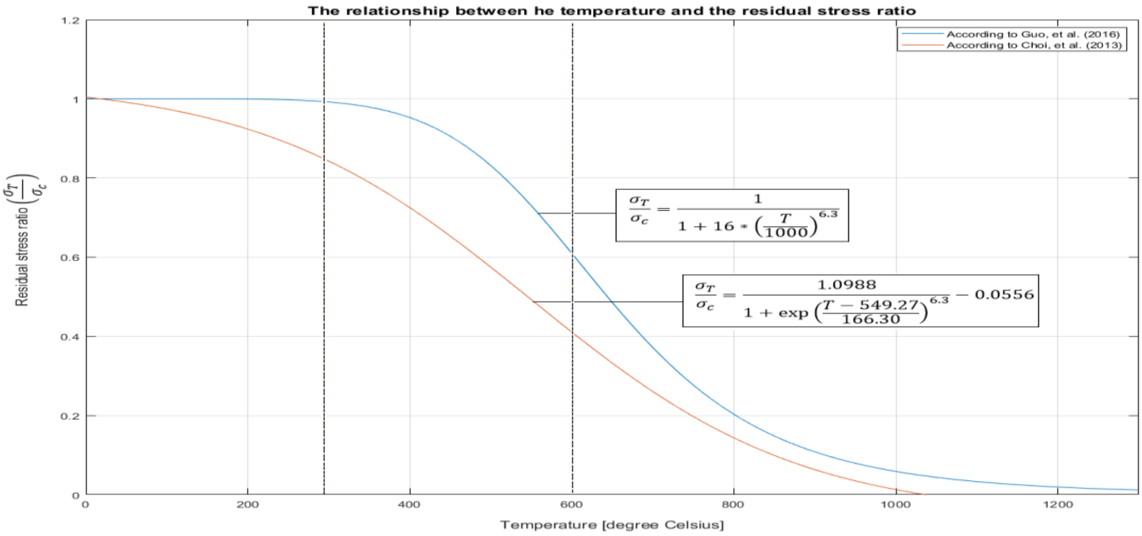

Figure 13: The correlation that exists between temperatures and RS ratio

(ix) Figure 14 illustrates that silicon is a semiconductor that may be altered in its electrical conductivity by varying its doping concentration, as seen in the graph. To modify a material's electrical characteristics, doping entails incorporating impurities into the structure. Silicon's electrical conductivity increases with both temperature and doping levels, as seen in the graph. More free charge carriers in the silicon are responsible for the temperature-dependent conductivity boost. The higher the temperature, the more probable it is that the silicon's electrons will move violently enough to escape their atomic bonds and become free charge carriers. Similarly, the improved electrical conductivity associated with higher doping levels is a result of the impurities producing new energy levels in the silicon band gap. With more potential energy levels available, more electrons can be liberated from their atomic connections, increasing the number of free charge carriers in the universe. This complex interplay between material features and external influences in semiconductor behavior is highlighted by the fact that temperature and doping level both affect electrical conductivity.

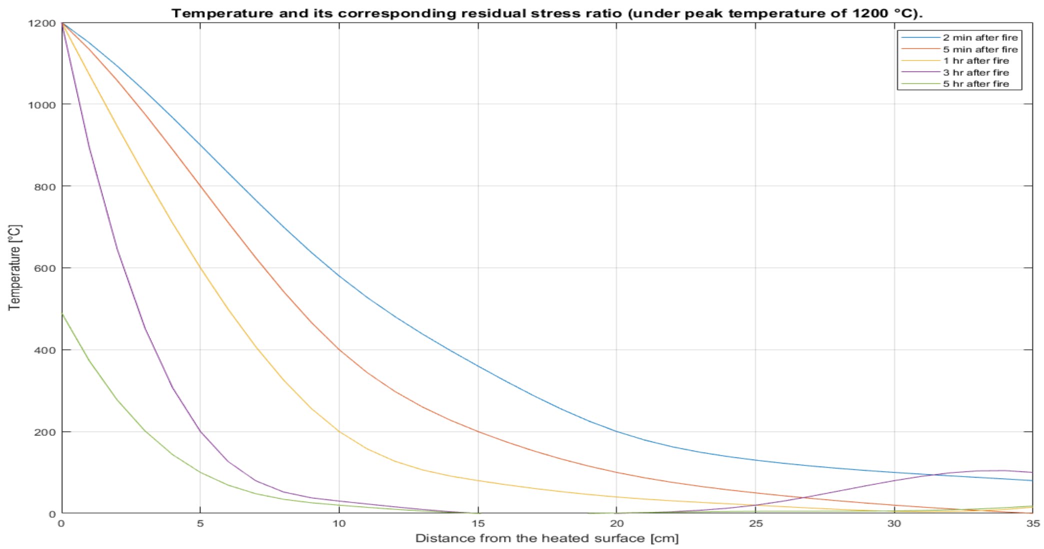

Figure 14: The correlation between temperatures and the RS value

(x) Since the thermal expansion of the heated concrete is constrained by the cool section of the tunnel lining, the Working Stress Ratio (WSR) is larger at the heated surface. The RS ratio is low, however, since the material quality drops down rapidly around the hot spot. When the WSR is more than the RS ratio, as measured by the RS criterion, the lining section is inevitably compromised. Fire damage depth was calculable as shown in Figure 15; the intersection of the two lines indicates the worst affected area.

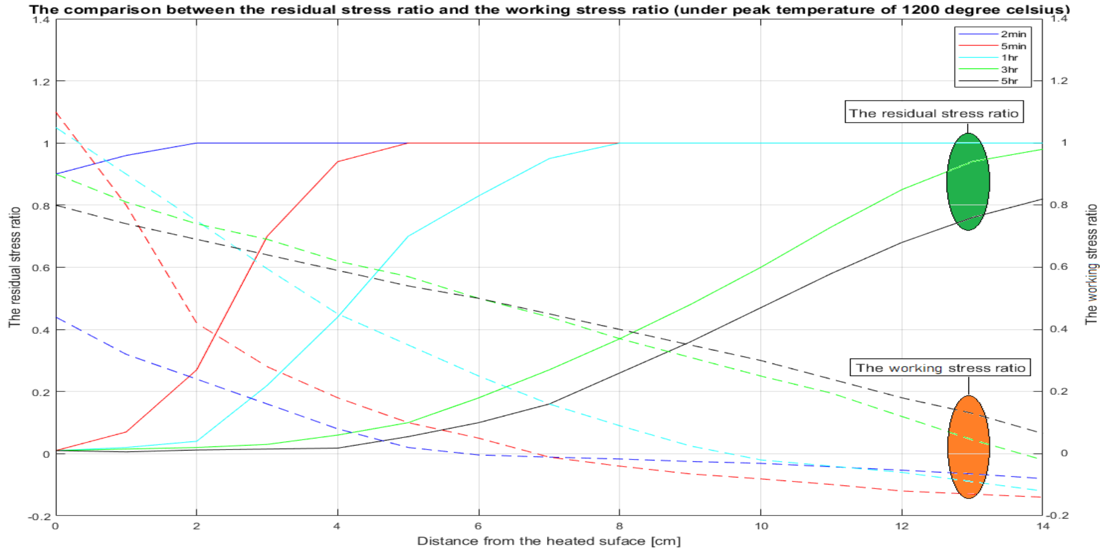

Figure 15: The correlation between RS and WSR

(xi) The ratio of the depth of the fire to the thickness of the line lining a tunnel may be expressed numerically as D/t. Damage depth of the liner is displayed in terms of temperature criteria and RS criteria in Figure 16. The RS criterion and the temperature criterion arrive to approximately identical damage depths within 1h. As more time passes, the damage depth established by the temperature criterion supersedes the damage depth established by the RS condition. And the bigger the gap, the longer it takes.

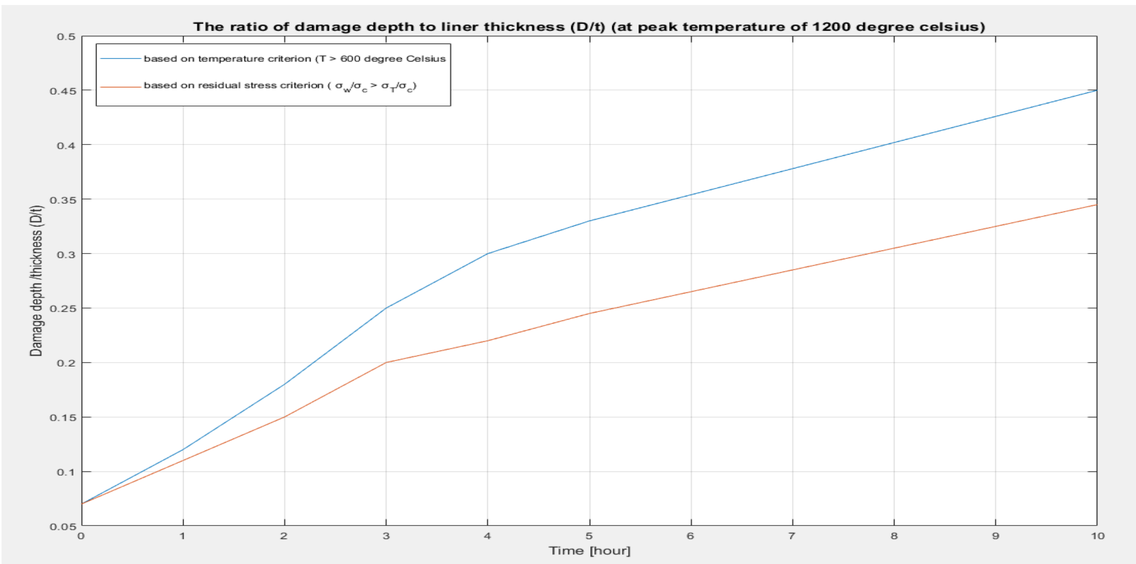

Figure 16: D/t is the ratio of destruction to liner thickness

9. Conclusion and Future Work

Tunnel fires are one of the most dangerous threats posed by flames throughout the world every year. As a result, they cause a significant amount of economic damage and lives. Throughout the past half-century, several full-scale and reduced-scale tunnel fire experiments, in addition to simulation studies, have been carried out to identify critical fire occurrences and important indications that might guide the design of tunnel fire safety systems. Because of the significant number of tunnels that are now under construction for both highways and trains, the issue of fire safety has become extremely important. The 2D unsteady-state TM model of a tunnel, when a fire is occurring, was shown by this research. The growth of a fire within the tunnel is mimicked by employing a few different strategies, including Ventilation, the Smoke Exhaust System, Rehabilitation, and the Fire Alarm System. The length of time that the tunnel spent in its holding condition is the most important criterion that plays a role in deciding whether or not the tunnel is safe to use following a fire on RS in the tunnel lining. Aside from that, the step of chilling only has a marginal effect on RS, which means that it may be ignored. There is a time-dependent increase in damage depth, the magnitude of which is mostly determined by the length of time that the holding stage remains in effect. The hope is that in the not-too-distant future, it will be beneficial in lowering the danger of accidents and fires occurring in road tunnels.

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