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Response of Cable-Stayed Bridges Exposed to High-Temperature Fires

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Abstract

Cable-stayed bridges are long-span bridges that are designed to carry comparatively a continuous and large volume of traffic load across water bodies (seas or rivers) or connecting locations (source and destination) that are present across a city terrain, where roads or highways pass below the cable-stayed bridge. The cable-stayed bridges are durable, as they require periodical monitoring and maintenance. Accidents on cable-stayed bridges caused by trucks that carry gasoline/LPG or other inflammable petroleum products lead to a situation of high-temperature fire on the bridge that tends to affect the different components of the bridge such as the bridge deck and its components (deck slab and supporting girders), pylons and the cables. The structural load-bearing capacity of cables and components of the bridge deck decreases with an increase in the temperature of the fire, leading towards degradation of stiffness of the materials due to physio-chemical changes. The present work is a case study, that focuses on the behaviour of the cable-stayed bridge and its structural components (cables, bridge deck and its components) in the situation of a fire taking place on the bridge when an oil tanker catches fire due to a bad accident it undergoes on the bridge. The stability of the bridge in such a fire scenario is assessed by determining the response of the bridge-maximum displacements and internal forces developed in the different components of the bridge, to identify the locations of maximum damage such that, appropriate restoration measures can be adopted to restore the stability of the bridge.

Keywords: *Cable-Stayed Bridge, Fire High Temperature, Structural Stability*

1.0 Introduction

Cable-stayed bridges are an innovative structure which will be preferred in comparison to conventional bridges, for longer spans. The usage of high-strength steel and advanced methods of construction has led to the design of cable-stayed bridges. The safety against fire and explosion, in particular, is mainly considered when it comes to building structures where combustible materials are widely available in the form of wood, paper and different types of chemicals that are stored (in the case of industrial structures). The safety against fire in the case of bridge structures[1] needs to be given more attention.

On December 30, 2017, a fire broke out on an under-construction cable-stayed bridge over the Mondovi in Panaji[2]. Also on Wednesday, May 18, a car caught fire on National Highway 48 on the Signature Bridge in Gurugram, Haryana[3]. In Chennai on March 5, 2016, a car caught fire on the Guruswamy bridge[4]. Another such fire event happened on January 5, 2002, at the intersection in Birmingham, when a tanker carrying nearly 37000 litres of gasoline caught fire on the bridge. Temperatures

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around 1100°C were developed due to the fire[5] on the bridge. Any accident of such fuel tankers on the bridges can lead to a catastrophic fire. These fires on the bridges are characterised by intense fires that reach their peak temperatures within the first few minutes (Garlock *et al.*, 2012)[6]. It is apparent from previous bridge fire events that fire is one of the substantial risks to bridges over their course of existence. Though the probability of bridge fires is comparatively low when compared to fires in buildings, only a small percentage of larger-scale fires have the potential to structurally damage a bridge and its components. The essential bridges that pose a fire hazard may need to be designed from the point of view of fire safety through the application of a fire-based significance factor (V.K.R. Kodur and Naser 2012)[7].

Implementing dependable and suitable design and construction strategies, protection techniques, sensor installations and monitoring methods of bridge fires are important to ensure the safe operation of bridges throughout their whole life cycle. The only way to ensure the protection of people's lives and the structural stability of the bridge is to improve the bridge's fire-resisting capacity. (V.K.R. Kodur and Naser 2021)[8].

With the help of mathematical modelling analysis of cables stayed bridge system are studied under uniformly varying load and point loads with a function of displacements in girder (Straupea and Paeglitis 2013)[9]. This study on Queensboro Bridge helps to understand the analysis of numerical simulation of the entire fire process and structural prediction for the deck subjected to temperature stresses developed due to fire (Gong and Agarwal 2014)[10]. When a high-temperature fire takes place around the central span of the pre-stressed concrete bridge, the vertical displacements tend to increase, thereby leading towards instability and failure (Song *et al.*, 2020)[11]. The shear capacity of the beams decreases as the fire continues to degrade the material properties of reinforced concrete beams (Youssef *et al.*, 2015)[12]. When the temperature in the reinforcing steel embedded in an M20 grade Reinforced Concrete (RC) beam reached a value of 575^{0}C, the beams showed a reduction of 56% in the moment of resistance and in the case of reinforcing steel embedded in M50 grade concrete beams, when the temperature reached around 500^{0}C, a reduction of 34.5% was observed in the bending moment for an exposure time of 1 hour (for M20 and M50 grade RC beams). In the case of RC, beams made up of concrete having higher compressive strength exposed to higher temperatures indicated less reduction in moments compared to concrete having lower compressive strength (Thanaraj *et al.*, 2020)[13].

From the literature study, it is observed that there needs to be more attention given towards research on the study of the stability of bridge structures and their structural components exposed to high-temperature fires, due to accidents of heavy vehicles carrying inflammable materials (Gasoline). The main and cross girders when exposed to temperature influence other integrated members like deck slab, cables and the girder pylon junctions, and their resulting structural behaviour and stability. The large tensile forces in cables need to be analysed from a stability point since the cables are the structural members responsible for transferring axial loads to the pylons. Considering these aspects, a realistic case study has been considered in the present study, to analyse the internal forces developed in the structural elements of a cable-stayed bridge subjected to fires corresponding to higher temperatures to assess the bridge's stability in such a situation. The stability assessment further helps in taking suitable measures to select appropriate retrofit measures.

2.0 Methodology

2.1 Details of Cable Stayed Bridge

The cable-stayed bridge considered in the present study is a 4-lane bridge, that can facilitate traffic in 2 directions. The width of each lane is 3.75m and the entire analysis is carried out in MIDAS CIVIL. The length of the central span is 220m and the length of end spans is 100m each. The bridge consists of 3 spans with 5 main girders which run along the span and cross girders are provided at every 10m interval. The longitudinal cable arrangements are mixed type with 10 cables on each side of the pylons. There are two twin pylons which support the deck for a total span of 420m. The bearings are used to restrain the longitudinal motion of the bridge deck. Table 1 lists the material and section properties of structural elements used in the cable-stayed bridge. Figure 1 shows the 3D view of the bridge considered in the present study. The analysis of the bridge has been carried out by modelling

Table 1. Material and section properties

Structural Elements	Material	Grade	Dimensions in m
Cable	Steel	Fe590	0.2 (dia)
Main Girder	Concrete	M45	0.5x1.8 (cross section)
Cross Girder	Concrete	M45	0.5x1 (cross section)
Slab	Concrete	M45	0.5 (thickness)
Pylon	Concrete	M70	2x2

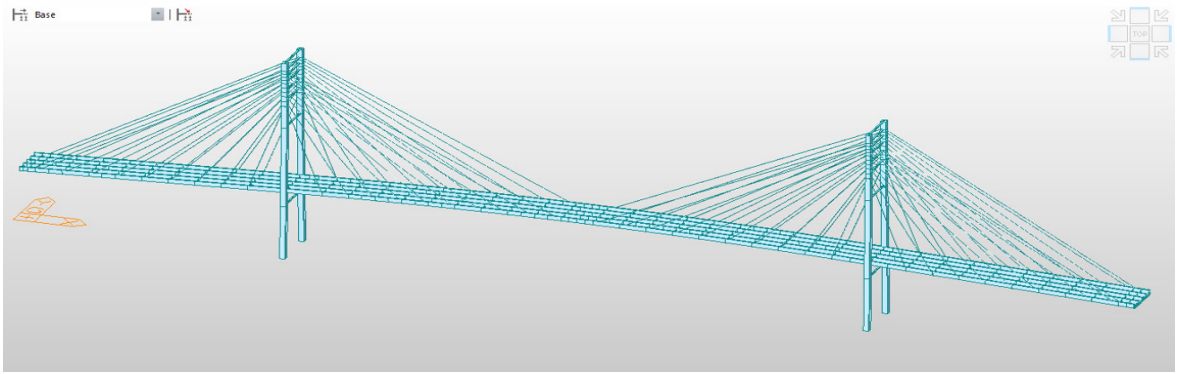


Figure 1. 3D isometric view of cable stayed bridge.

the cable as an equivalent truss element. The decreased axial stiffness in cables due to the effect of sagging is taken into account in the analysis and the component of the non-linear analysis is looked into by considering tangential stiffness as an elastic catenary element to find the initial cable forces. The pylons are modelled with fixed supports at their base. Fe500 grade is considered for the reinforcing steel rebars.

2.2 Behaviour of Structural Elements Exposed to High Temperature

Basic principles in thermal analysis depend on thermal strain. The total strain in the element is the sum of strain due to imposed loading and strain due to thermal effects. The thermal strain will be induced in large magnitude which results in the increase of thermal stresses throughout the length of the beam in the form of axial stresses. These axial stresses developed due to the restrained ends will result in the development of the hogging of the beam. Due to end constraints which prevent the member from expanding longitudinally, which results in larger deflections. The temperature variation also has a substantial impact. When compared to the other surfaces, in the surfaces exposed to higher temperatures, there is a thermal gradient that is developed that leads to differential expansions in the structural members having end restraints. The rapid expansion of the surfaces exposed to higher temperatures causes bending (hogging) of the structural member and this action is referred to as thermal bowing (Usmani *et al.*, 2001)[14].

When the temperature rises, there is a physio-chemical change in the material properties of concrete. When concrete is exposed to high temperatures, the compressive and tensile strength of concrete decreases steeply and this phenomenon is visibly observed through the development of an increased number of microcracks, at around 600^{0}C (Venkatesh Kodur, 2014, Tolentino *et al.*, 2002)[15,16]. Similarly, reinforcing steel which is embedded in concrete to take

tension loses part of its tensile strength (Kumar *et al.*, 2021)[17].

2.3 Analysis of Cable-Stayed Bridge

The cable-stayed bridge is analysed for dead, live and temperature loads along with their combinations. The live load considered is a Class 70R-tracked vehicle with a total axle load of 700 kN as per IRC 6-2017. The location of the vehicle carrying gasoline that had caught fire due to an accident on the bridge is considered near the pylon to study the bridge deck, girders and pylon interaction for temperature exposures: 300^{0}C, 450^0 C and 600^0 C. Above said temperatures are individually applied on the beam elements and plate elements (bridge deck slab) considering the temperature gradient variation across the bridge deck slab and girders sections. Figure 2 shows the location of the vehicle that has caught fire on the bridge deck near the pylon.

3.0 Results and Discussions

The following figures illustrate the analytical findings and show how internal forces and stresses change in the elements as the temperature starts to rise. Figures 3 to 11 show the internal forces and vertical displacements of beam elements B1, B2, B3, B4, B5, B6 and B7 for the load cases: 1.5(Dead load(DL)+ Live load(LL)) (for limit state of collapse), for serviceable limit state:

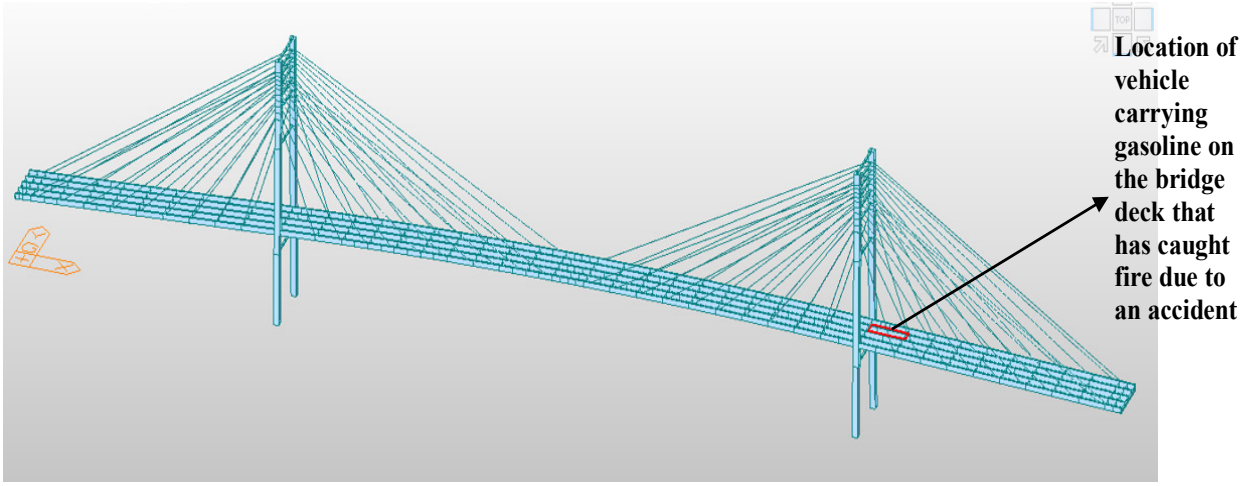


Figure 2. Location of fire accident near the pylon.

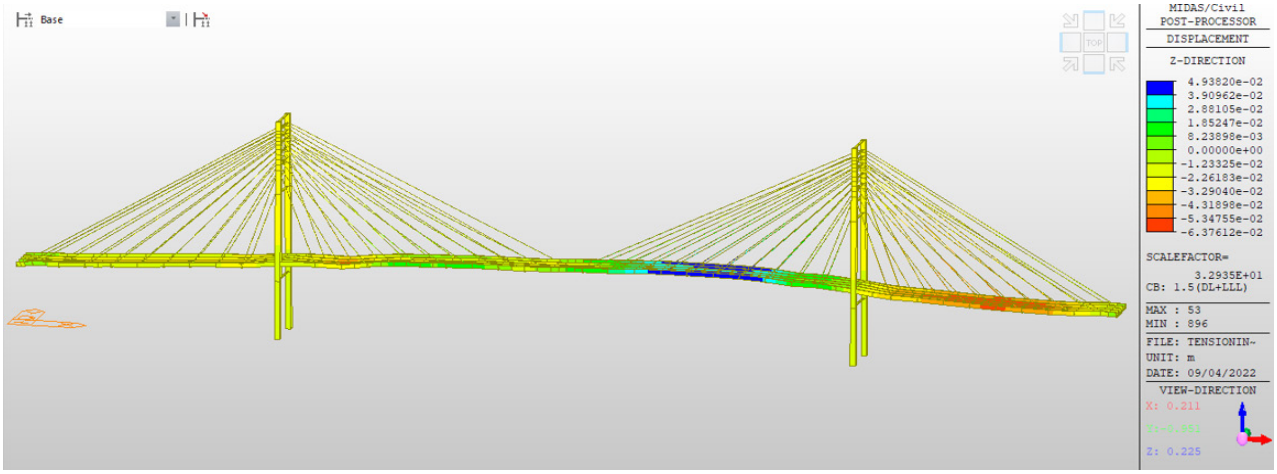


Figure 3. Vertical displacements of the bridge due to ambient temperature.

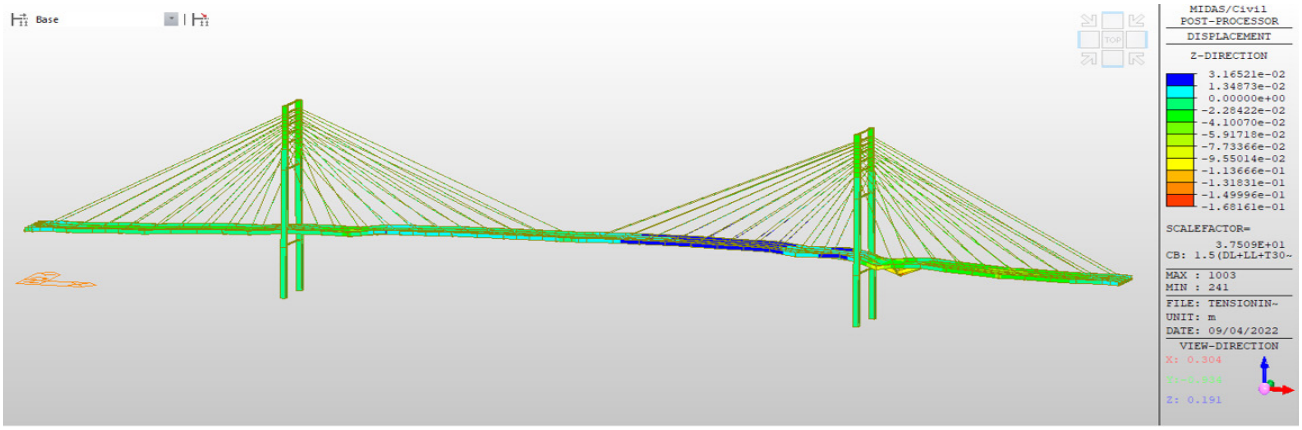


Figure 4. Vertical displacements in the bridge for 300^{0}C temperature exposure.

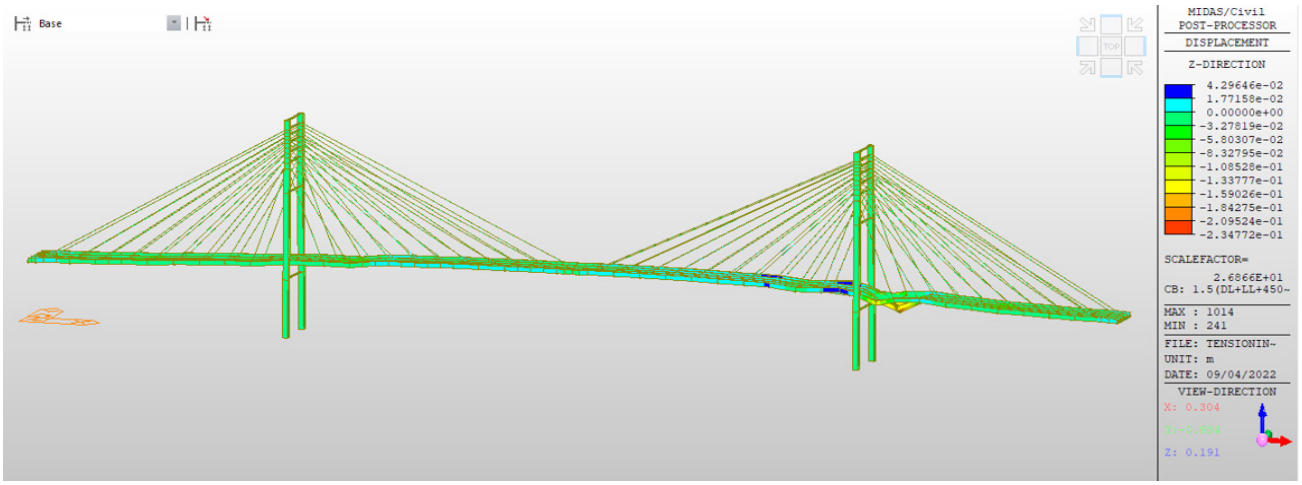


Figure 5. Vertical displacements in bridge for 450^{0}C exposure temperature .

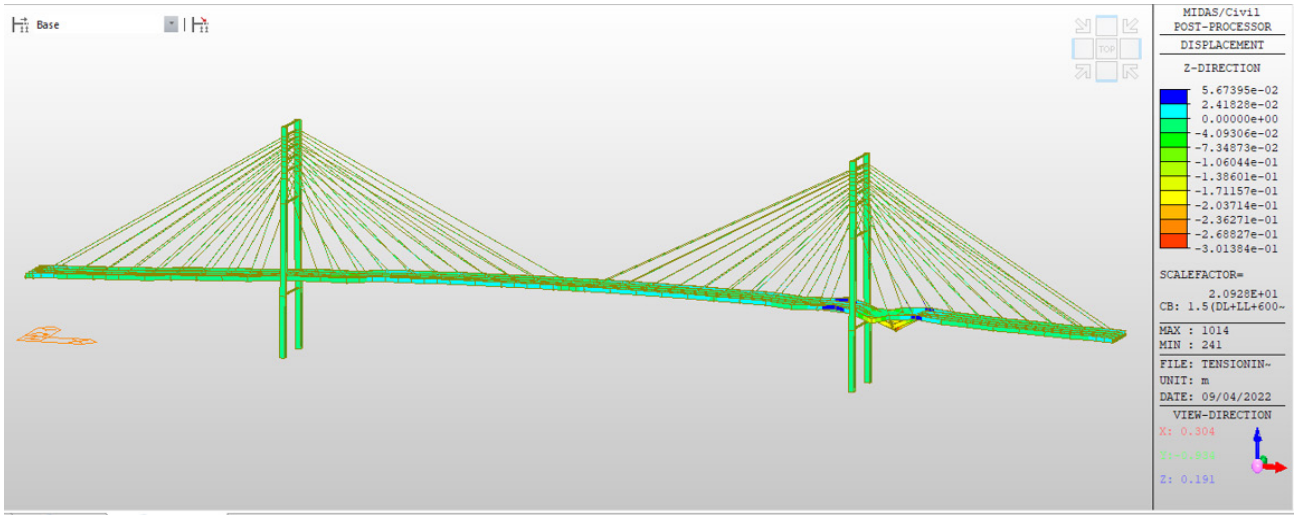


Figure 6. Vertical displacements of the bridge when exposed to a temperature of 600^{0}C

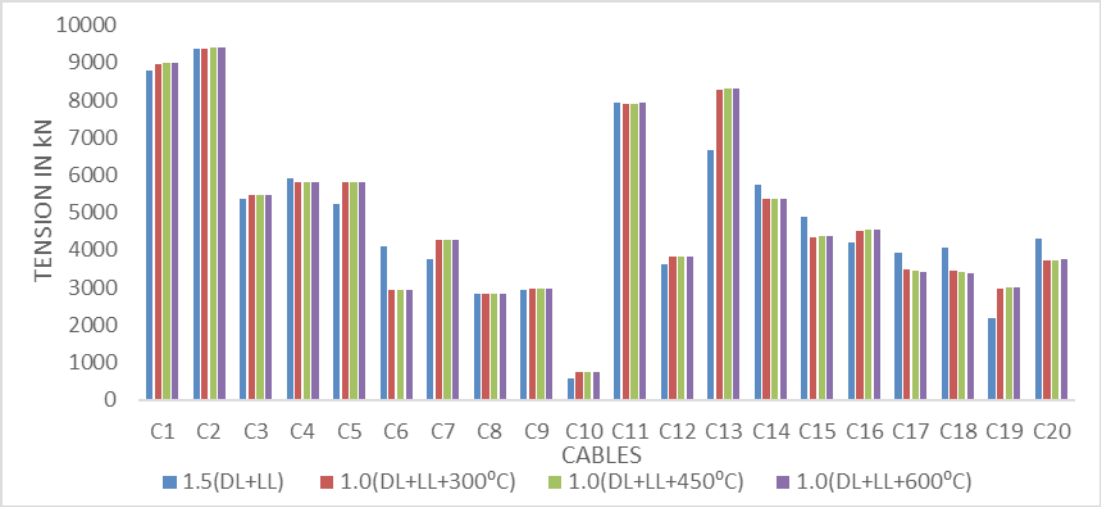


Figure 7. Tension forces in cables.

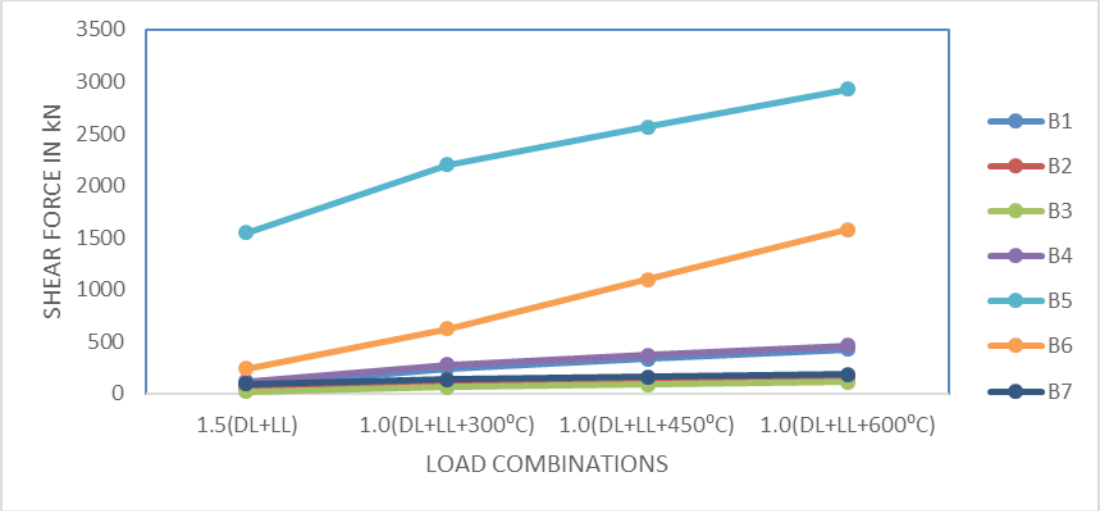


Figure 8. Variation of shear forces in beams.

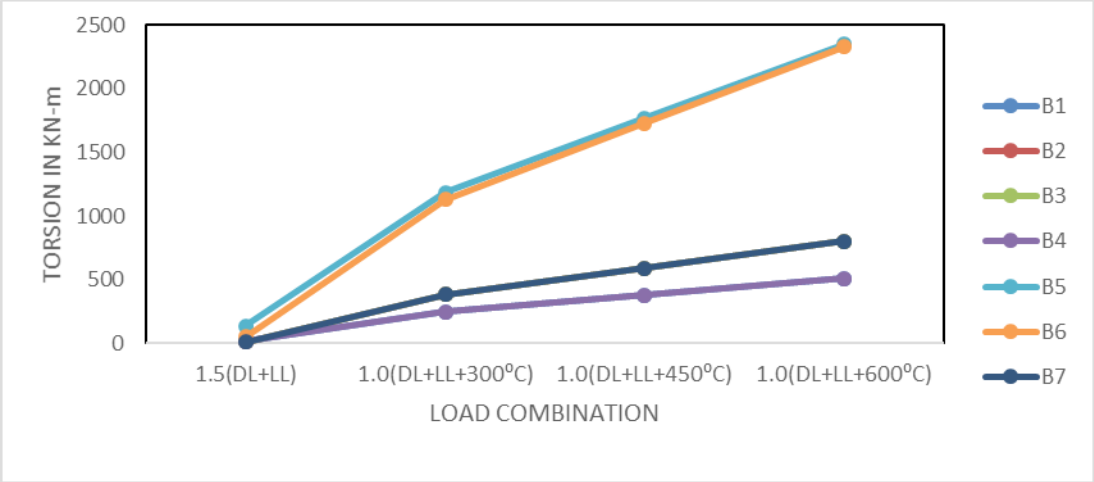


Figure 9. Variation of torsions in beams

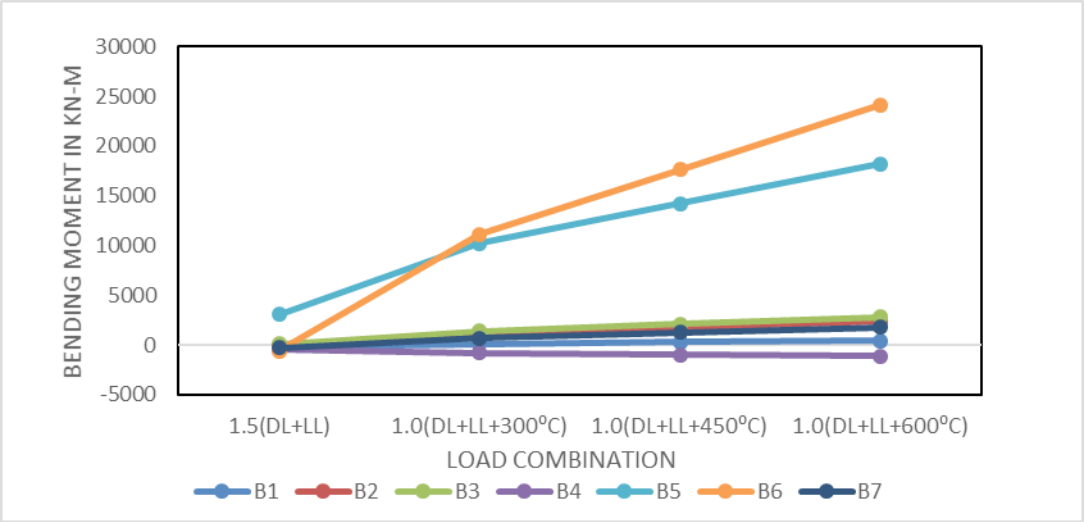


Figure 10. Variation of bending moments in beams.

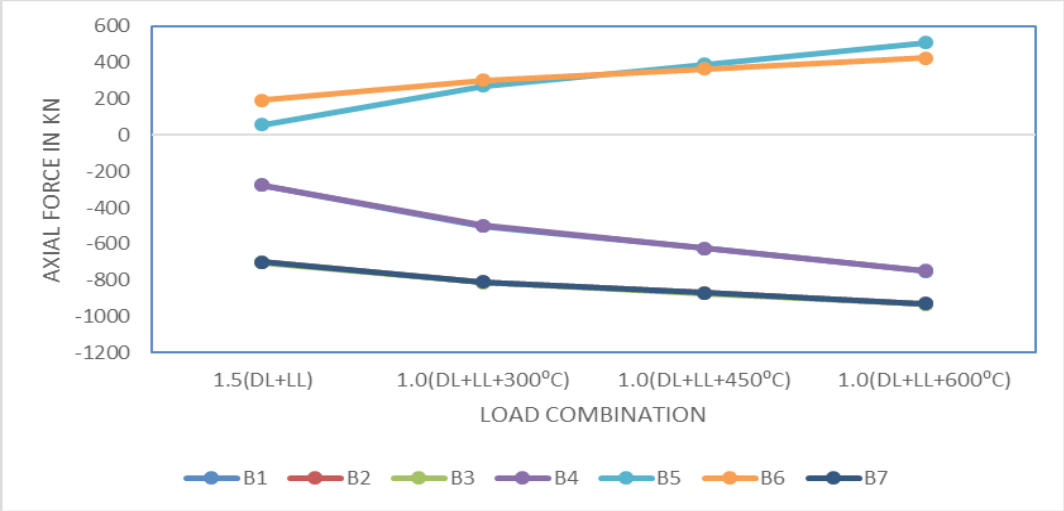


Figure 11. Variation of axial forces in beams.

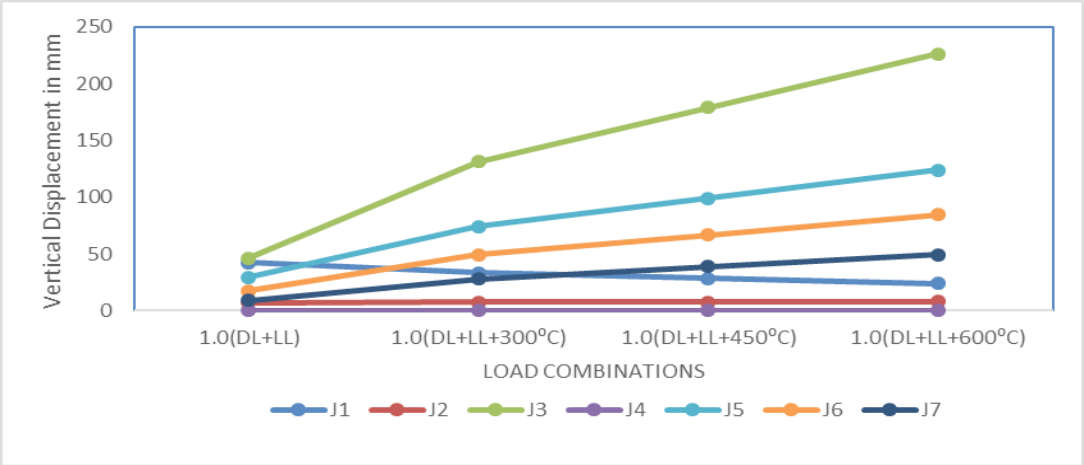


Figure 12. Variation of vertical displacements at the nodes of beams.

1.0(DL+LL+T300^{0}C), 1.0(DL+LL+T450^{0}C), 1.0(DL+LL+T600^{0}C).

- The variation of tension in cables with an increase in exposure temperatures individually is shown in Figure 7. It is observed, that the case of the cables that are located in a zone close to the fire accident zone, show an increase in the axial forces in tension. Whereas, in the case of the cables that are not located near the zone of fire accident on the bridge, there is less variation in the axial forces in the cables.
- Figure 8 shows the variation of Shear forces in beams for different temperatures of exposure. It is known that, when there is an increase in the exposure of temperature, the compressive strength of concrete is found to decrease15[9], which leads towards a reduction in the load carrying capacity (shear capacity) of the RC bridge girders due to degradation in material stiffness. In the case study considered here the bridge girders have exhibited a trend of linear increase in shear forces along with exposure to higher temperatures due to the reduced shear capacity in members, at the location of the fire accident on the bridge deck.
- Figures 9 and 10 show the response of the torsion and bending moment in beam elements exposed to higher temperatures. As discussed earlier due to the reason of existence of end restraints, the deformation in the beams takes place due to thermal stresses developed leading towards the bowing mode of deformation in the beams. This is attributed to the fact that during ambient temperature exposure, the beams B1, B2, B3, B4 and B7 deform in sagging mode and tend to hog (bowing action) when exposed to high temperature. In Figure 10 it may be observed, the direction of moments changed from negative to positive (that is, sagging to hogging) and their magnitudes were found to have increased.
- The axial forces developed in the bridge girders are shown in Figure 11. As a result of an increase in temperature exposure, the axial forces thus developed in girders have larger values. The increase in the axial forces in the girders is attributed to the thermal expansion of the member that has been restrained.
- Figure 12 shows the increase in vertical displacements in the girders due to temperature exposure. The displacements in the girders which are less than 50mm subjected to ambient temperature reached up to 250mm when the exposure temperature was at 600^{0}C.
- From this study, it can be comprehended that the behaviour of cable-stayed bridges due to fire accidents causing high-temperature conditions has applications in the mining industry and mining areas that help in managing the risk of fires in mining operations where overhead walkways(bridges) exist, where the safety of such structures in the mining areas need to be restored due to accidental fires.

4.0 Conclusions

- The structural response of the elements of a cable-stayed bridge response in the current work, when exposed to 3 different temperatures of exposures, has been studied individually towards the assessment of bridge stability in case of fire-induced loading.
- The bowing action in girders exposed to high temperatures tends to cause permanent deformation in the girders and deck slab.
- For a fire exposure temperature of 300^{0}C, the deflection in most of the beam elements is in the range of 30mm to 70mm. In case the cases of temperature exposures for 450^{0}C & 600^{0}C, the deflections of the girders and deck slab are larger (100mm for 300^{0}C and 120 mm for 600^{0}C) and the forces developed across the cross sections of the girders and deck slab due to thermal exposure are higher in magnitude. For higher temperatures of exposures (450^{0}C and 600^{0}C), the structural members cannot be restored and the entire member needs to be replaced.
- The torsional moment in the beam elements increased at a larger rate.
- The tension forces developed in the cables present at the zone of fire incident are observed to have increased in turn results in further possible failure of cables in tension or failure of the anchorage

zones of the cable due to large magnitudes of pull-out forces leading towards instability of the bridge.

- Based on the distresses in the structural members that have been identified in the different structural members of the bridge, that are located at the zone of the fire accident, appropriate retrofit solutions can be applied to restore the stability of the bridge when the damage takes place in the girders, deck slab is within repairable limits that is exposed to a particular temperature of exposure.
- Understanding the behaviour and response of cable-stayed bridges exposed to high-temperature fires helps in suitably designing elevated walkways, support structures and transportation systems, within the mining industry, such that, the safety and resilience of such structures in the mining areas are enhanced due to fire accidents.

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