IMPACT OF CLIMATE RELATED CHANGES IN TEMPERATURE ON CONCRETE PAVEMENT: A FINITE ELEMENT STUDY

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ABSTRACT

Thermal cracking of concrete is a common cause of deterioration and it is due to temperature difference constraining concrete contraction. With the addition of repetitive loading, micro-cracks are expected to propagate through the slab due to both external loadings and erosion in the cracks. This research aims to develop a three-dimensional finite element model of a jointed plain concrete pavement system and evaluate stress characteristics under high severity climate change temperature scenarios for 2007, 2030, 2050 and 2070 in South East Queensland. A series of static analyses are performed to replicate a standard vehicle axle wheel loads approaching and leaving the concrete joint. The tensile stress is measured on the top of the concrete slab at critical locations in both the longitudinal and transverse direction. Results for thermal-expansive stresses show that the likelihood of cracking in concrete increases significantly with changes in temperature gradients due to hotter climate causing downward curling of slab. Further, for temperature loading alone the tensile stress increases by a maximum of 1.37 MPa from 2007 to 2070.

Keywords: concrete pavement, dowel bar, finite element method, thermal cracking, climate change.

INTRODUCTION

South East Queensland (SEQ) is Australia's fastest growing metropolitan region. From 2006 to 2031 its population is expected to grow from 2.8 to 4.4 million (Department of Infrastructure and Planning 2009). At present the state controlled road network in SEQ is approximately 3,138 km (Department of Transport and Main Roads 2009) and local governments are responsible for more than 10,000 km of arterial, sub-arterial and urban roads. SEQ's population is heavily urbanised and is generally concentrated in Brisbane, Gold Coast and Sunshine Coast regions. Based on the Australian trends (CSIRO & BoM 2007), the future climate in SEQ is expected to become hotter and drier. The region will experience an increase in mean annual temperatures and decrease in mean annual rainfall.

The topic of climate change has been recognised globally as an issue of utmost concern as the threat of changes in climate poses problems to all nations of the world (Intergovernmental Panel on Climate Change 2007). Climate change is expected to pose many challenges to the road design, construction and maintenance in the region (Serrao-Neumann 2011). The direct impacts of changes in rainfall patterns can alter moisture balances and influence pavement deterioration. In addition, temperature changes can affect aging of flexible pavements by resulting in cracking of the surface, with a consequent loss of waterproofing. The result is that surface water can enter the flexible pavement causing potholing and fairly rapid loss of surface condition. Rigid or concrete pavements are impacted by temperature changes through alterations in expansion and contraction movements and subsequently cracks form.

Temperature variations cause curling and thermal-expansion stresses within the concrete. Curling stresses result from temperature gradients through the slab depth and thermal-expansion stresses are induced due to uniform changes in temperature that cause the slab to expand. Indirect impacts of changes in rainfall and temperature include increased maintenance costs and intervals to increase resilience and subsequent interruptions to traffic.

The load carrying capacity and low maintenance of concrete road means that it is a usual preference for pavement application subject to high volumes of heavy traffic loads. The concrete pavement system typically consists of a jointed plain, jointed reinforced or continuously reinforced concrete layer. The subbase and road base layers usually consist of rock aggregate which meets certain road specification. This study considers only jointed plain concrete pavement which uses dowel bars and has joints which are transverse to the direction of travel. Note that joints are placed in the concrete slab to control cracking and provide space and freedom for concrete subject to traffic loading and thermal stresses.

Concrete pavements are designed to provide safe and long-lasting road surfaces. However, fatigue and deterioration (i.e. distress) from repeated vehicular loading, temperature and moisture changes over time are the most common observed failure mechanisms and major attributors to pavement maintenance and rehabilitation costs. Thus, a good understanding of pavement distress is crucial to the successful design and operation of road infrastructure. Curling deformation, resulting in thermal-expansion stresses in the concrete slab, is a characteristic phenomenon under environmental and repeated vehicle loads (Huang 2010). Such deformation may lead to void formation due to the accumulated plastic deformation and subsequent disengagement of the base course from the concrete. Distortion of the slab due to both upward and downward curling occurs respectively when the top surface of the slab is cooler than the base course and also when there is a higher temperature on the top surface respectively, as illustrated in Figure 1.

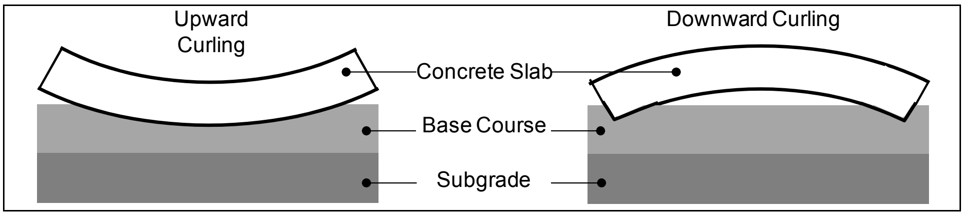


Figure 1: Curling of concrete slab

Distress of the pavement in the form of joint deterioration or cracking also attributes to void formation by allowing moisture infiltration. The combination of distress and layer voids will further reduce the pavement load carrying capacity. Friberg (1938) and von Quintus and Killingsworth (1993) stated that distress is influenced mostly by compressive stress and that the first sign of deterioration is the formation of transverse or longitudinal cracking within the concrete slab. It has also been reported that transverse and longitudinal cracking are more common than D-cracks, corner cracks and meander cracks (Chen et al. 2002; Machemehl 2005). It is frequently understood that the aim of joint design for concrete pavement is to reduce transverse and longitudinal cracking (CCA 2004).

Cracking of the concrete is an important performance-related factor that needs to be considered in the concrete pavement design process. Transverse cracks are one of the primary failure modes and it is due to downward curling and thermal stresses during the day-time. This study therefore aims to evaluate flexural tensile stress characteristics within the concrete slab to give further insight into cracking. A finite element model of the symmetrical half of the three-dimensional (3D) pavement model is developed with realistic vehicular loadings and restraint conditions. The most critical load conditions will be considered in the finite element modelling by applying a series of heavy single axle loading and also high severity climate change related temperature increases for 2030, 2050 and 2070. Ultimately, the findings from this research will provide information on the detailed behaviour of stresses for different temperature loadings. This will then help in identifying techniques for reducing cracking by, for example, shorter joint spacing, thicker slab, stronger flexural strength of concrete, tied shoulders or wider lanes will aid performance.

The cost of construction and maintenance for concrete pavement is high and therefore it is essential that this road asset is properly monitored during the life of the pavement. From the early days of concrete pavement analysis, attention has always been concentrated on stresses induced by wheel loads. However, the impact of changes in climatic conditions in the future, such as the increase in global temperatures, on the pavement deterioration has not been fully evaluated. The main objective of this research is to study the performance of the concrete joint with dowel bars subject to an increase in temperature under the climate change conditions in South East Queensland. The scope of this study includes:

- developing a 3D finite element model of the symmetrical half of the pavement system featuring a series of static standard vehicle axle wheel loads approaching and leaving the concrete joint; and,
- evaluating the thermal-expansion stresses of the concrete slab due to changes in the temperature gradient based on climate change data in SEQ.

METHODOLOGY

The modelling and simulation herein are performed using Strand7 Finite Element Analysis (FEA) System (Strand7 2004). The pavement section selected for this study resembles the typical concrete pavement structure constructed in SEQ. The 3D representation of the three types of pavement layers, i.e. concrete slab, base course and subgrade, are defined and full friction is applied at the boundaries. Illustrated in Figure 2 is the finite element model including vehicular loading, nodal temperatures and restraint conditions applied to the pavement. These loading and restraint conditions are commonly assumed in previous literature (Al-Hadidy 2009); Ju 2009).

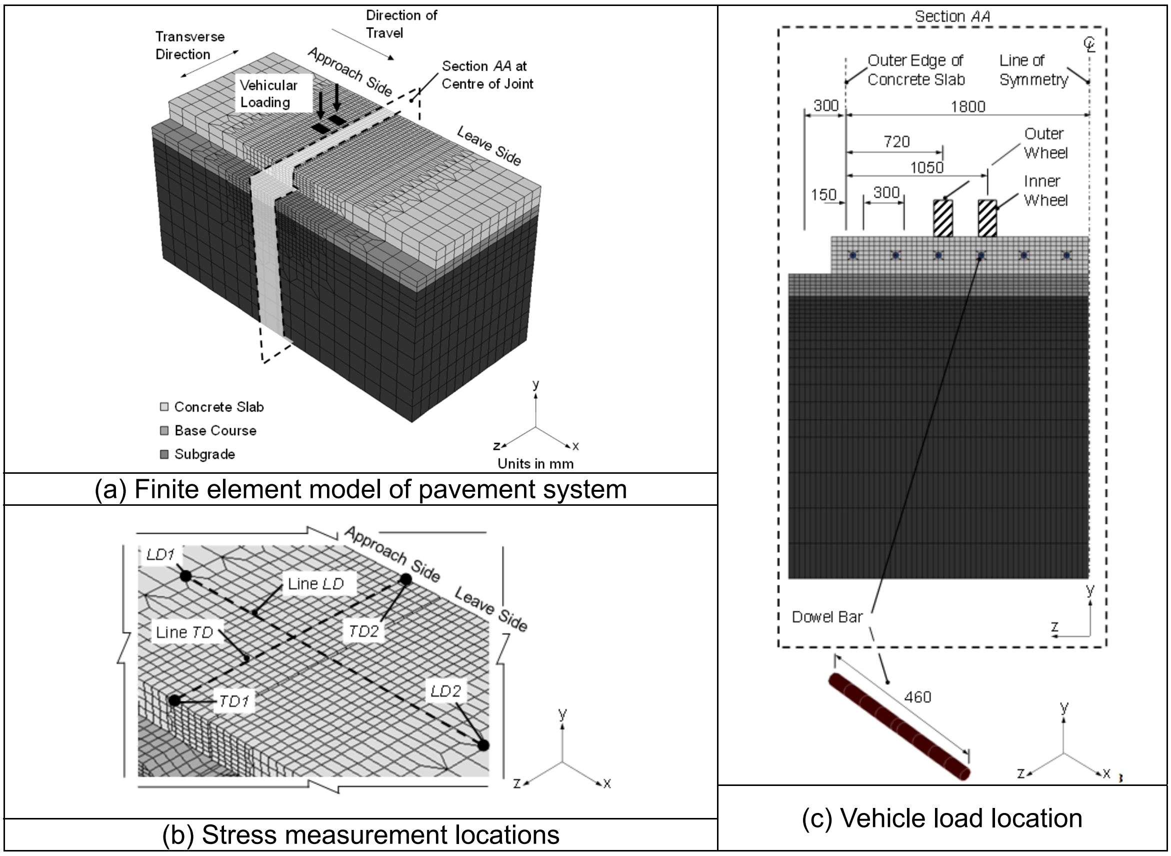


Figure 2: Details of symmetrical half of the pavement system model, vehicular loading, dowel bar and joint

Dowel bars are modelled using beam elements with a defined diameter of 32 mm (see Figure 2 (c)). The mesh size is reduced in the vicinity of the concrete slab-dowel bar interface to aid the accuracy of results. The total numbers of 8 node hexahedral brick elements are 8976 for the concrete slab, 8624 for the base course and 24640 for the subgrade. The total number of nodal points for the entire pavement model is 46102. The bottom surface of the pavement is restraint from deforming in all directions and roller restraints are applied to the sides of the pavement. The material properties are provided in Table 1 and are assumed to be linear, homogeneous and elastic in behaviour. The thermal expansion, conductivity and specific heat of the concrete slab is assumed to be $1\times10^{-5}/^{o}C$, $1.37\times10^{-3}J/s/mm/^{o}C$ and $880J/kg/^{o}C$, respectively.

Table 1: Material properties and layer thicknesses

Description	Concrete slab	Base course	Subgrade	Dowel bar	Plastic sleeve of dowel bar
Young's modulus (MPa)	28,000	350	50	200,000	16.7
Layer thickness (mm)	250	150	1,900	*N/A*	*N/A*
Poisson's ratio	0.18	0.4	0.4	0.3	0.3
Density (kg/m^3)	2,400	2,000	1,800	7,830	1,890

Loading conditions

In the single axle dual wheel system shown in Figure 1, each wheel carries a 20 kN load. For the symmetrical half of the pavement system model, only two 20 kN wheel loads are considered. The equivalent contact pressure of each of the two tyres is assumed to be distributed uniformly over a rectangular area of $2.63\times10^{-2}m^2$ (i.e. 759.73 kPa). A total of five loading cases are considered to replicate a vehicle approaching and leaving the joint as shown in Figure 3. In the first (LC1), second (LC2), third (LC3), and forth (LC4) load cases, the respective resultant force is 292.5, 195, 97.5 and 48.75 mm away from the centre of the joint, and the resultant force of the fifth load case (LC5) lies on the centre of the joint. Note that only LC1 and LC5 are discussed herein.

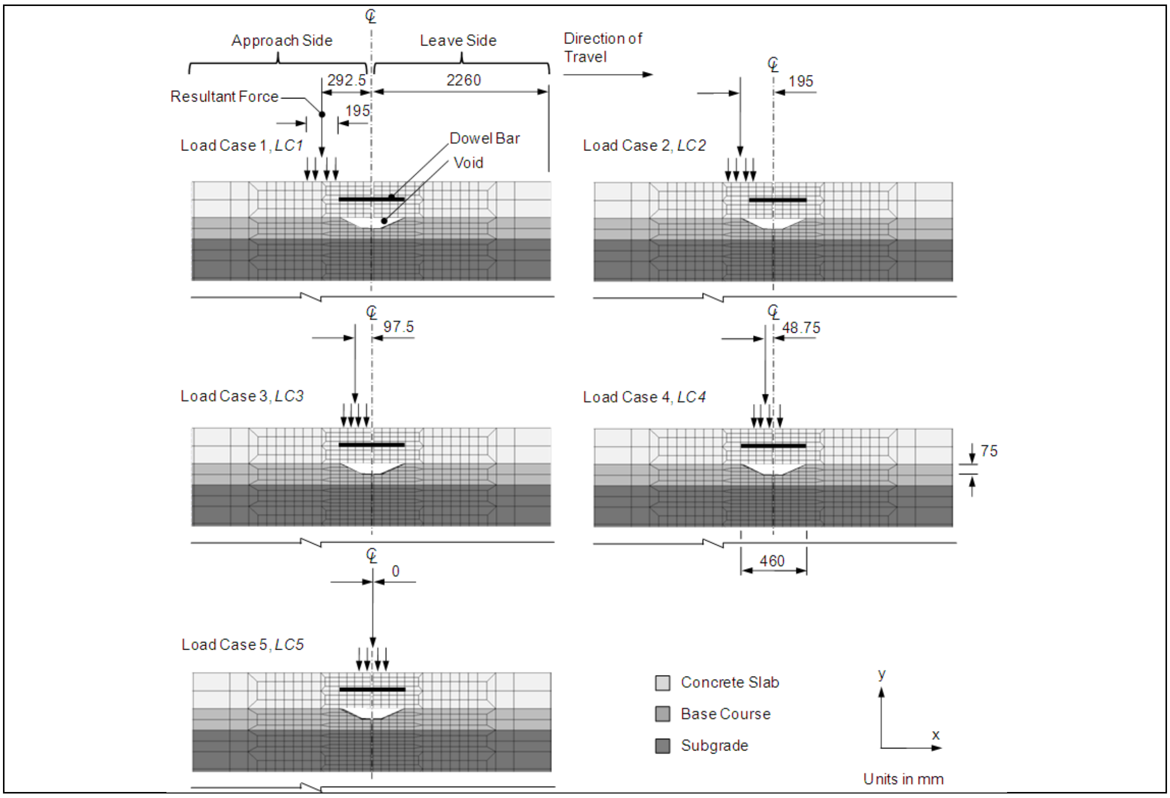


Figure 3: Loading scenarios

Temperature

The minimum and maximum mean daily temperatures for Burleigh Heads weather station (station identification 040034) was collected for every month of the years from 1960 to 2099 using the Climate Tool and database provided by Austroads (Austroads 2008). The database features a wide range of historical climate data from 1960 to 2007 obtained from the Bureau of Meteorology. The tool provides future climate data from 2008 to 2099 based on the simulations by CSIRO in 2004.

Since this study is concerned about the possibility of thermal cracking historical temperature information for February is used because it indicates on average the highest temperatures when compared to other months. Climate change is expected to bring warmer nights and days to Queensland (Intergovernmental Panel on Climate Change 2007). This raises the question as to what thermal-expansion stresses the pavement will be subject to in the future (i.e. 2008 to 2099) since the stress condition depends on the magnitude of temperature increase and if this increase occurs during night and/or day. As the first step, this research only considers a scenario of '*hotter days*' where future increases in temperature only occur during the daytime and the night time temperatures would remain relatively unchange. To model the '*hotter days*' scenario, the entire pavement system is assumed to be at an absolute minimum temperature (i.e. 20.5 °C for night time) before the maximum (or daytime) temperature is applied to the top surface of the concrete slab. This will result in downward curling of the pavement. Figure 4 provides the historical and projected temperatures for high, average and lower severity levels of both maximum and minimum daily temperature in February.

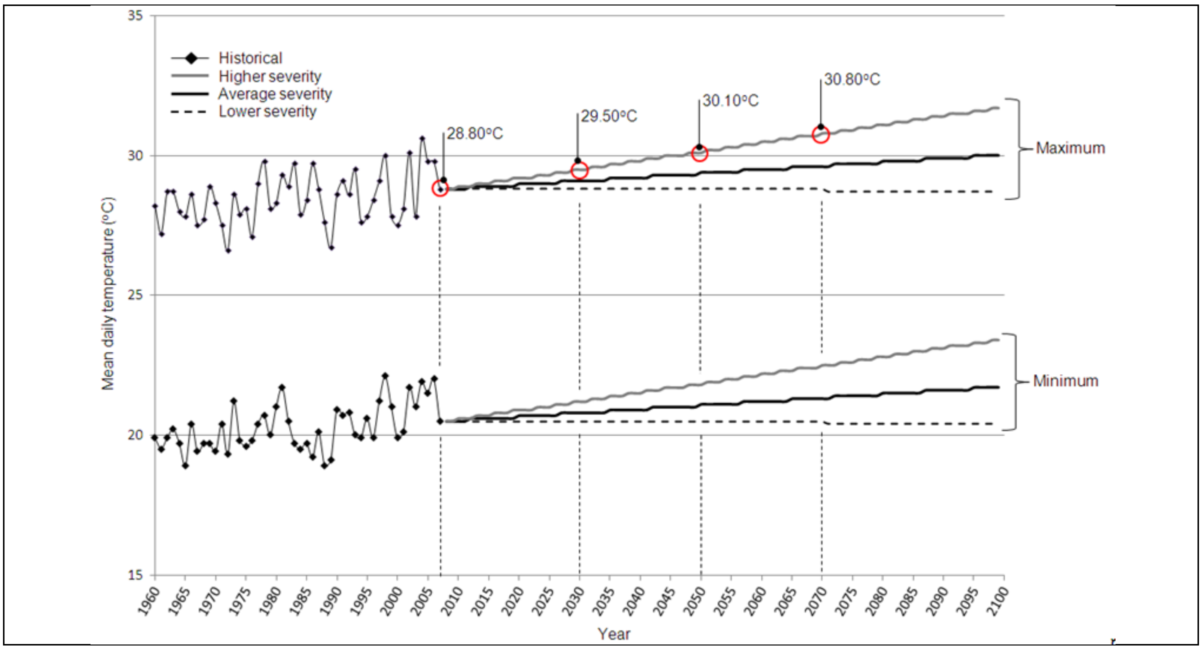


Figure 4: Mean minimum and maximum daily temperatures for Burleigh Heads in February

Figure 4 and Table 2 provides details of the nodal temperatures applied to the top surface of the concrete slab and the projected increase in maximum temperature under high severity climate change projections. These temperatures result in thermal-expansion stresses which are proportional to the difference between the element's temperature at the top surface and the night time temperature. For example, in 2030 the thermal-expansion stresses are relative to the temperature difference between 29.5 and 20.5 °C.

Table 2: Historic and climate change projected temperatures

Year	Climate change projected increase in maximum temperature (°C)	Day temperature of concrete slab surface (°C)		Night temperature (°C)	Difference between day and night temperatures (°C)
		Mean	Extreme		
2007	0.00	26.30	28.80	20.50	5.80 (for mean)
2030	0.70	-	29.50		9.00
2050	1.30	-	30.10		9.60
2070	2.00	-	30.80		10.30

- Information not provided.

Results

The tensile stresses measured along longitudinal (*LD*) and transverse (*TD*) lines are detailed herein for the historical and future temperature data of February under higher severity climate change projections and vehicular loading (see Figure 2 (b)). The start and finish points of *LD* (i.e. *LD1* and *LD2*) and *TD* (i.e. *TD1* and *TD2*) are also identified in Figures 2 (b) and 8 for ease of discussion. Illustrated in Figure 5 are the temperature contours under downward curling as obtained by steady state heat analyses using Strand7 (2004). Note that the temperature is assumed to be linearly distributed throughout the concrete slab.

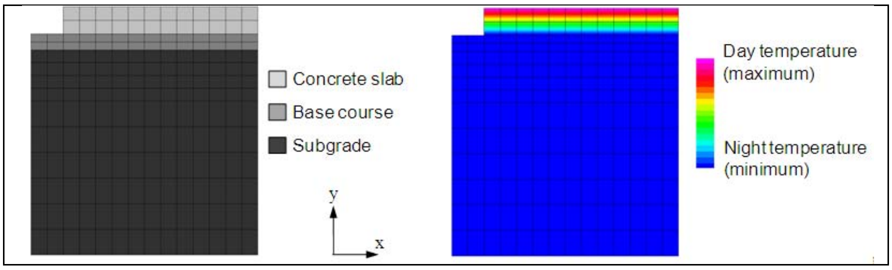


Figure 5: Temperature contour for downward curling

Figures 6 and 7 respectively show the tensile stress distributions along the lines *LD* and *TD*. Associated stress contours are presented in Figures 8 and 9. From Figures 6 and 8 it can be seen that the stress along line *LD* increases as the vehicular load approaches the joint from LC1 to LC5. This increase is less obvious on the leave side (i.e. or after a longitudinal distance of 1200 mm along *LD*). The stress is reduced for LC1 on the approach side because the vehicle load induces compression on the top concrete surface. Note that the linear homogenous material properties of the pavement layers means that the stress increases in linear increments for all the years from 2007 to 2070. The impact of only changing the temperature and without vehicle loading is shown in Figures 6 and 9. On an average the tensile stress is 1.14 MPa along *LD* higher in 2070 than compared to 2007. Importantly, the stress shows an increase just after 900 and 1500 mm along the line *LD*. This peak could be due to the influence of the dowel bars and joint.

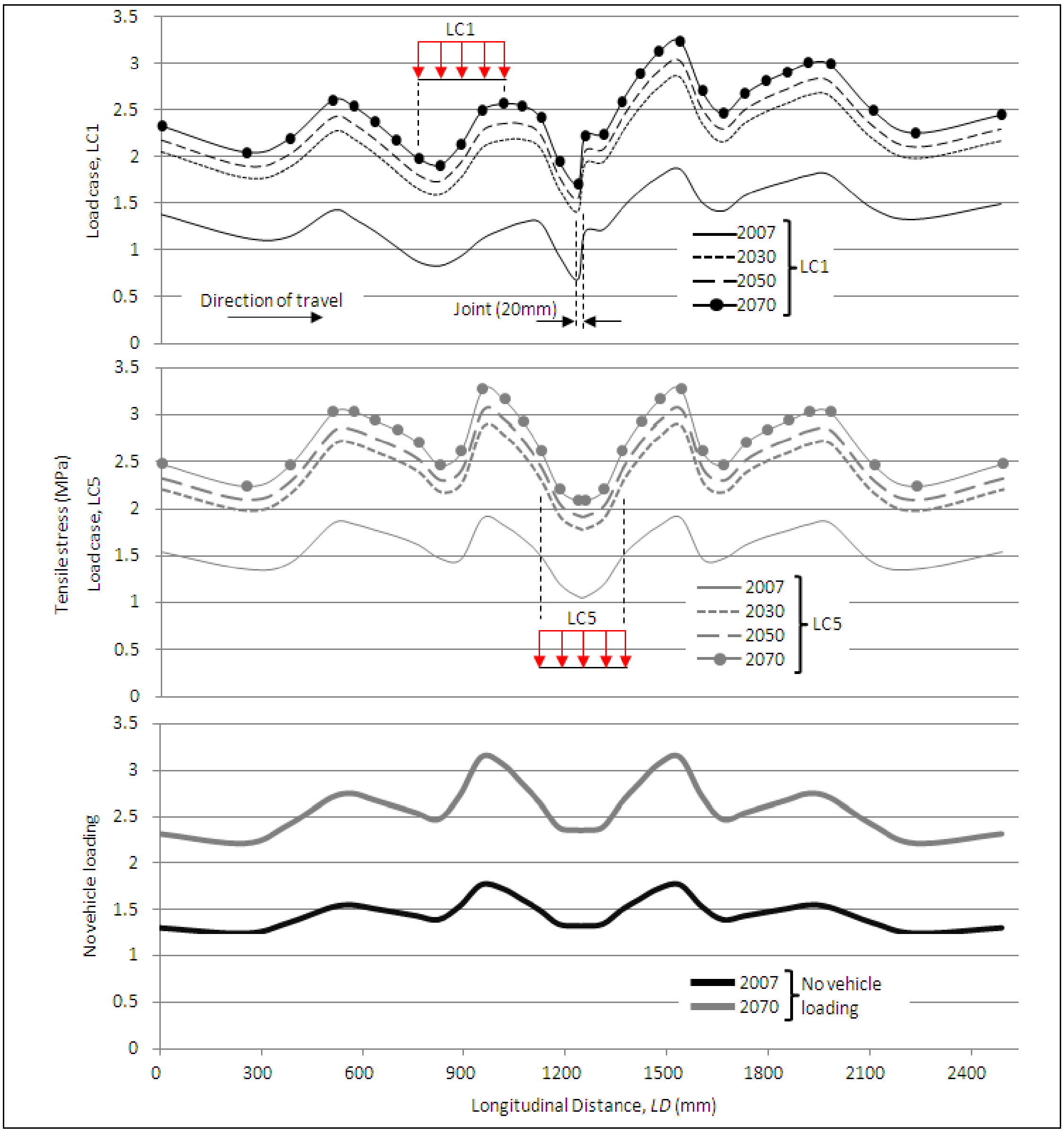


Figure 6: Tensile stress distribution along longitudinal direction

The distribution and contours of tensile stress along the line *TD* is illustrated in Figures 7 and 8. As in Figure 6, it can again be seen that the stress increases as the vehicular load approaches the joint from LC1 to LC5. The distribution of stress is significantly different for LC1 compared to LC5 mainly due to the vehicle load being positioned on the line *TD* for LC1. The sudden decrease at around 750 and 1050 mm is caused by the compressive vehicle loading. The impact of only changing the temperature and without vehicle loading again shows an average tensile stress increase of 1.37 MPa along *TD* from 2007 to 2070.

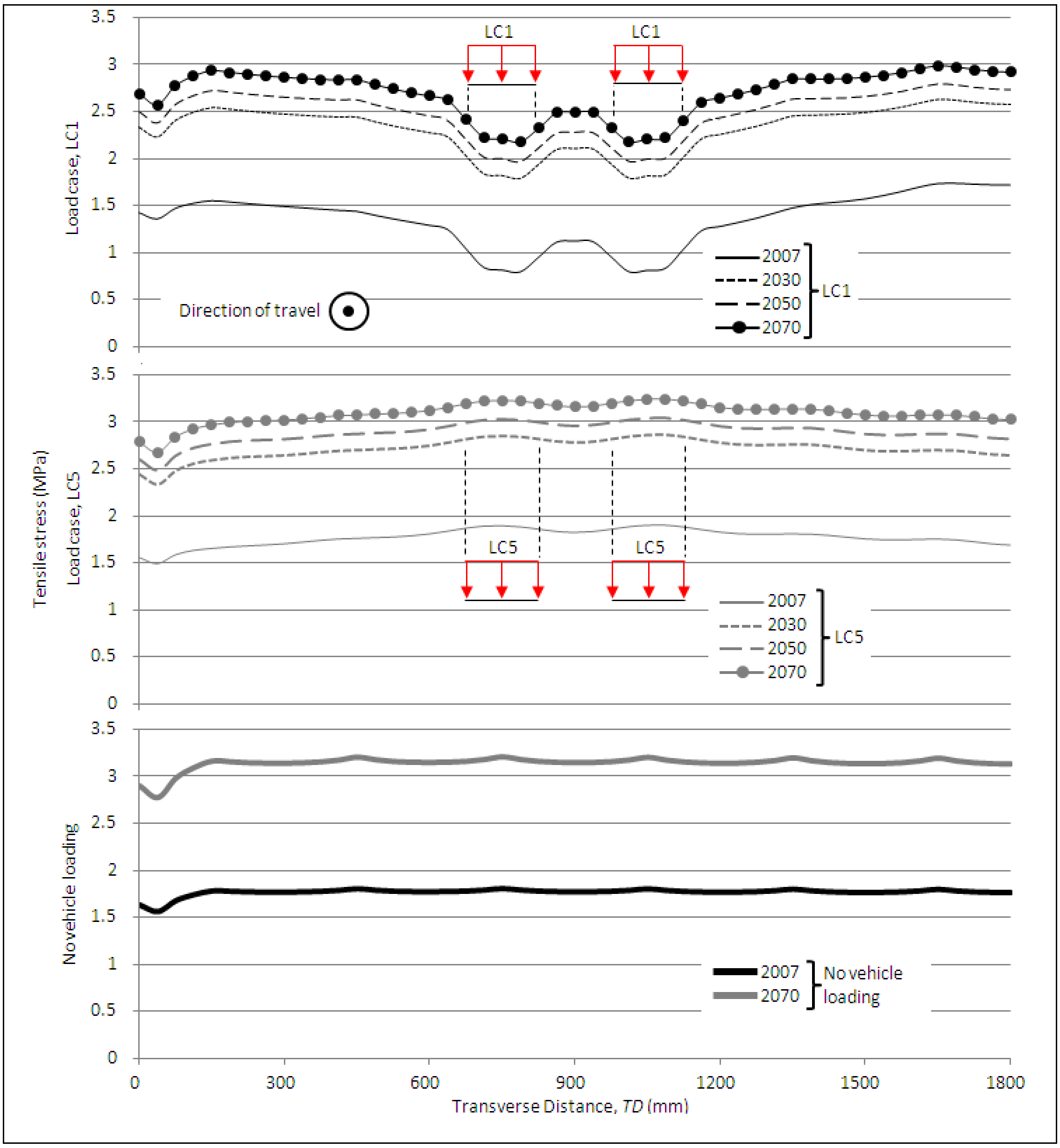
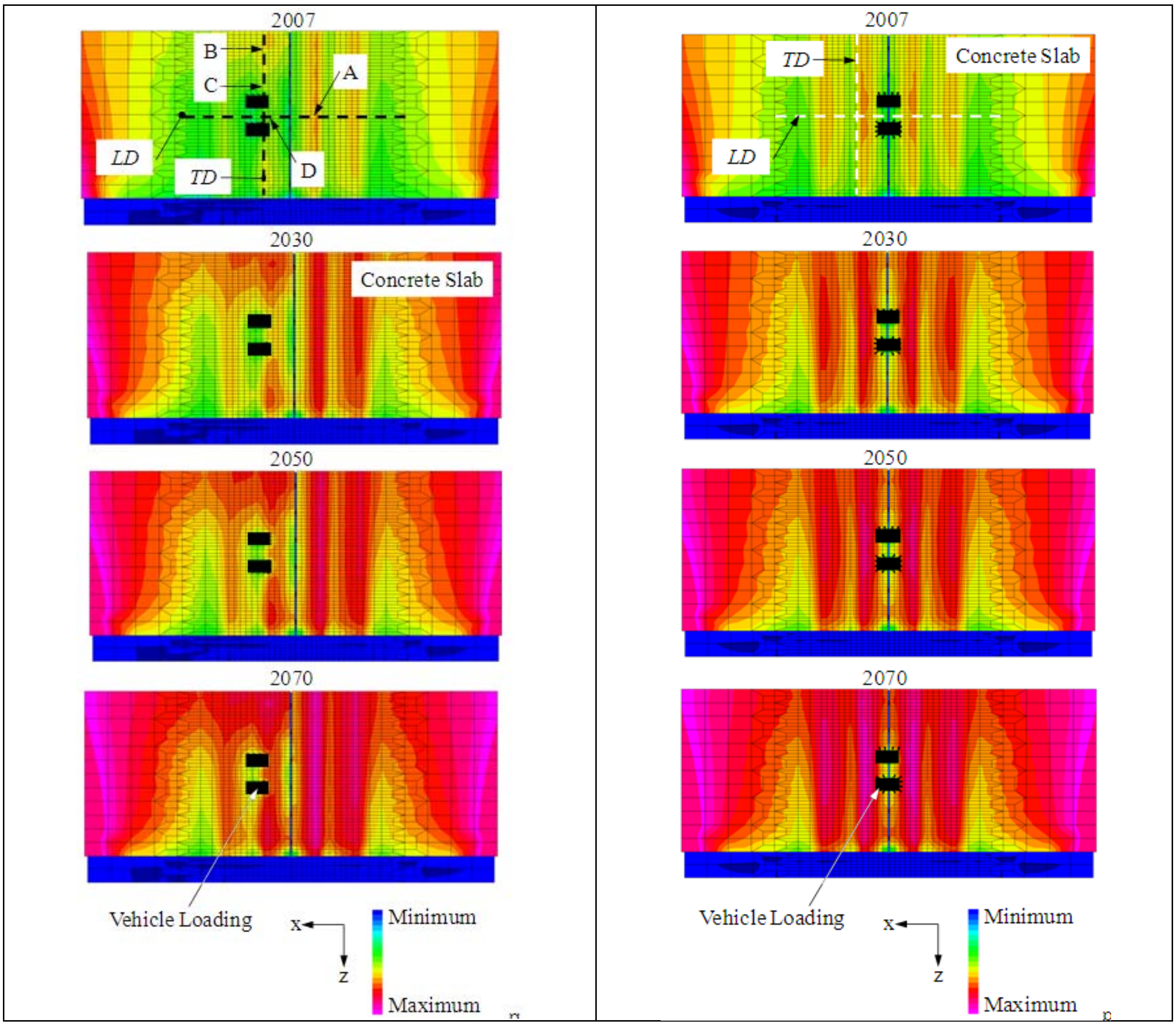


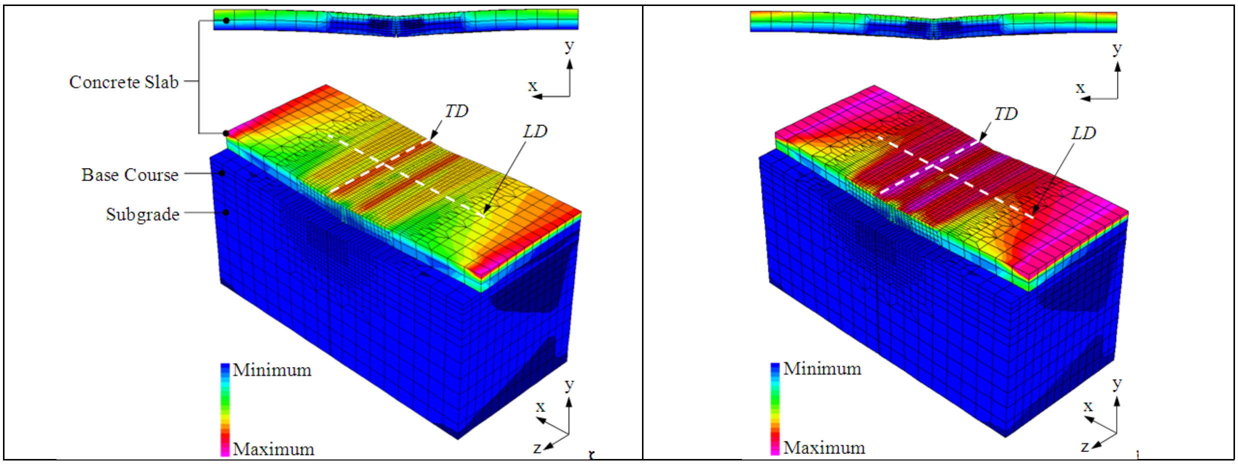
Figure 7: Tensile stress distribution along transverse direction



(a) LC1 ***(b) LC5***

Figure 8: Tensile stress contours in concrete slab

In an attempt to show the impact of the change in temperature of 4.5 °C (i.e. 30.8 – 26.3 °C) from 2007 to 2070, Figure 9 shows the tensile stress and displacement characteristics for LC1.



(a) Countour for 2007 ***(b) Countour for 2070***

Figure 9: Tensile stress contours under no vehicular loading

Tables 3 (a) and (b) presents the maximum stresses and associated locations (points A to D in Figure 9 (a)) along the lines *LD* and *TD*. The location of the maximum stress is indicated in both Table 3 and Figure 8. The failure load is taken as $0.4\times\sqrt{f_{cu}}$, where f_{cu} = 40.00 MPa and therefore the maximum tensile stress is 2.53 MPa. The allowable tensile stress is exceeded by all maximum stresses under climate change condition in year 2030, 2050 and 2070.

Table 3: Maximum tensile stress at top of concrete slab

Year	Increase in maximum temperature (°C)	Line	Location along line (mm)	Maximum tensile stress (MPa)
(a) Load case, LC1				
2007	0.00	*LD*	A	1.87
		TD	B	1.74
2030	0.70	*LD*	A	2.85
		TD	B	2.62
2050	1.30	*LD*	A	3.03
		TD	B	2.79
2070	2.00	*LD*	A	3.25
		TD	B	2.99
(b) Load case, LC5				
2007	0.00	*LD*	A	1.90
		TD	C	1.90
2030	0.70	*LD*	A	2.88
		TD	C	2.86
2050	1.30	*LD*	A	3.06
		TD	C	3.04

CONCLUSION

A plain jointed concrete pavement with concrete, base course and subgrade layers was modelled as a 3D finite element model. The impact of changes in temperature for high severity climate change projections was evaluated under vehicle loading and with the escalation of daily maximum temperature. Tensile stress was measured along longitudinal and transverse lines on the top surface of the concrete for all loadings. Compared to the maximum stress magnitude measured in 2030 an average increase of 0.20 and 0.18 MPa is found for 2050 and 2070 respectively, along the lines *LD* and *TD*. Further, only changing the temperature and without vehicle loading gives an average tensile stress increase of 1.14 MPa along *LD* and 1.37 MPa along *TD* from 2007 to 2070. All maximum stresses for 2030 to 2070 measured along *LD* and *TD* exceeds the failure load defined by $0.4\times\sqrt{f_{cu}}$. Overall, the impacts of thermal-expansive stresses are severe under climate change projections and future research should aim to validate the findings from this theoretical research. Further research may also evaluate the upward curling and non-linear temperature gradients through the concrete slab.

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