Force Characteristic Analysis of Different Steel Deck Pavement under Temperature Load Coupling Situation

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Abstract. In order to investigate the force characteristic of different steel deck pavement under extreme temperature and load coupling situation, we established the three dimensional extreme high temperature and extreme low temperature field of simple supported beam bridge, the paving structure were double layered SMA, double layered epoxy concrete, SMA+GA, using material elastic modulus changing with temperature. Analysis indicated that the maximum value of high temperature normal stress occurred in the epoxy upper layer pavement, the maximum value of shear stress occurred in the epoxy lower layer pavement, the maximum value of high temperature strain occurred in the upper layer of double layered SMA pavement. The maximum value of low temperature stress occurred in the SMA+GA lower layer pavement, the maximum value of low temperature strain occurred in the SMA+GA upper layer pavement, the maximum value of shear strain occurred in the SMA lower layer pavement. The maximum value of high temperature stress usually occurred in the bottom of pavement layer, maximum strain usually occurred on top of pavement layer. The maximum value of low temperature shear stress and shear strain usually occurred in the bottom of pavement layer, normal strain occurred on top of pavement layer. The stress difference between the upper and lower layers in SMA+GA pavement structure is very large which adversely affected the structural force.

Keywords. Three dimensional temperature field, steel deck pavement, epoxy asphalt concrete, double layered SMA, SMA+GA pavement.

1. Introduction
The steel box girder and orthotropic steel bridge panel are widely used in various types of steel deck pavement (SDP) [1, 2], early damage problem of SDP is always a problem to be solved. The coupling effect of extreme temperature and load is one of the main reasons for the early damage of SDP.

The temperature estimate and research of steel box girder started earlier at home and abroad, 1968.,Capps and Emerson [3, 4] proposed the steel box girder temperature gradient formula suitable for the climatic conditions in Britain after testing and calculated analyzing the traditional structural steel box girder temperature. Lucas etc. [5] expounded the periodic daily changing rule of steel box girder structure temperature by dealing with the data of British Normandy bridge steel box girder temperature. Sang-Hyo Kim etc. [6] set up the temperature field during the construction of cable-stayed bridge.

Compared with the temperature field analysis of steel box girder, analysis of the stress in deck
pavement temperature field is not so much either at home or abroad, Lan, etc. [7] established the temperature field of SMA pavement on steel deck, Chen, etc. [8] analyzed the low temperature differences between deck and road pavement, at extreme low temperature, deck pavement was nearly 7 °C lower than road pavement. Xinjiang area was up to -26 °C. Yu, etc. [9] solved and determined the design temperature of a steel deck pavement structure, achieving that the design value of the maximum temperature of the steel deck pavement structure was 50.90 and the lowest temperature design value was -14.99 °C. Yang, etc. [10] listed part of the large span steel bridge pavement design working temperature in the domestic, the maximum value was -22~80 °C of Junshan bridge.

Wang, etc. [11] analyzed the maximum main stress and maximum shear stress internal the pavement layer at extreme temperature, the extreme high temperature and extreme low temperature were respectively 60°C and -20°C, modulus of extreme high temperature and extreme low temperature both changed from 800MPa to 3000MPa while the modulus changes of the actual pavement materials at actual temperature were not taken into account. Qian, etc. [12] used the sub model to analyze the maximum temperature was 69 °C, the beam section was 12.8 m, the deck pavement modulus was fixed to 1000 MPa, analyzed the internal force response of the bond layer but did not analyze the internal force response of pavement layer. Zhao, etc. [13] calculated according to the temperature-stress formula that the pavement stress of Epoxy Asphalt Concrete was 6.4 MPa, casting asphalt concrete was 5.2 MPa, SMA was 2.29 MPa, with daily temperature range 40°C and quarter temperature range 80°C, but they did not establish the temperature field, and the elastic modulus was fixed.

Deck pavement temperature can be more than 70°C at high temperature and temperature difference in 24 hours can reach more than 40°C, the stress and strain changes caused by temperature difference are also great. The elastic modulus of deck pavement is not a single fixed value but changed with temperature in one day. Therefore, the establishment of 24 hours temperature field under extremely high temperature and low temperature situation and the analysis of deck pavement stress character in extreme temperature and load coupling situation using the elastic modulus changing with temperature are both necessary.

In this paper, we establish an extreme temperature field ranged from -28°C to 75°C, using the elastic modulus changed with temperature to analyze the stress characteristics of the three kinds of pavement structures in three-dimensional temperature field.

2. Construction of Temperature Field

2.1. Finite Element Mode Establishment
Span of simply supported beam is 48 m, the lower part of the structure is double column pier. The width of steel box girder is 22 m, the height is 2.1 m, one single box with four chambers, five webs, 4m distance, web with longitudinal rib, U-rib on top plate only, the 150 mm high longitudinal ribs are arranged on the bottom plate with distance of 400 mm, the diaphragm distance is 2 m with a manhole in middle.

Deck pavement using SOLID45 element simulation, the orthotropic steel deck plate using SHELL63 element simulation, bearing using steel plate to support simulation, beneath the web, the material parameters are shown in table 1, parameters of steel box girder are shown in table 2.

| Material       | Density Kg/m³ | Elastic modulus Pa | Poisson ratio |
|----------------|---------------|--------------------|---------------|
| Steel          | 7850          | 2.1e¹¹             | 0.3           |
| Deck pavement  | 2400          | Change with temp   | 0.3           |
Table 2. The parameters of steel box girder (mm).

| Parameter                          | Value  |
|-----------------------------------|--------|
| Steel deck cover plate thickness  | 22/36  |
| Commonly/Fulcrum                  |        |
| Longitudinal rib-inclined web space| 300    |
| Horizontal separator thickness    | 12/30  |
| Commonly/Fulcrum                  |        |
| Straight web thickness            | 20     |
| Horizontal separator distance     | 2000   |
| Commonly/Cross/Fulcrum            |        |
| Inclined web thickness            | 20     |
| Bottom plate thickness            | 22/24/36|
| Commonly/Cross/Fulcrum            |        |
| Roof U rib thickness              | 10     |
| Longitudinal rib height           | 150    |
| U rib center distance             | 600    |
| Longitudinal rib thickness        | 20     |
| U rib height                      | 280    |
| Longitudinal rib-floor space      | 400    |
| U rib open width                  | 300    |
| Longitudinal rib-roof space       | 300    |
| U rib closed width                | 170    |

Vertical load action is Lane load, according to the load action position of the maximum stress of mid span generated by moving load, the action position is 22.6 m in the near mid span of the beam. Horizontal force is half the vertical force only acting in the 140 kN position of rear axle.

2.2. Deck Pavement Structure and Elastic Modulus

2.2.1. Deck Pavement Structure. Deck pave double layered epoxy asphalt concrete 0.025 m+0.025 m; double layered SMA (top 0.033mSMA-13+, bottom 0.037mSMA-10); SMA+ casting type asphalt concrete double layered composite structure (0.035mSMA-13+0.04m casting type asphalt concrete).

2.2.2. Elastic Modulus of Pavement Materials. (1) Elastic modulus of epoxy asphalt concrete

The Elastic modulus of similar asphalt concrete according to references [14-17] are chosen to be fitted, and the fitting curve equation is obtained:

\[ y = -4300.95787 \cdot e^{-\frac{T}{41.58688}} + 22369.12759 \]  \hspace{1cm} (1)

The fitting value of epoxy asphalt mixture at 70°C according to equation (1) is less than 0, therefore, we use data from the reference of Xue et al. [16] to fit the equation 2 to obtain the modulus of 60°C and 70°C, the elastic modulus of epoxy asphalt mixture changing with temperature are shown in table 3.

\[ y = -497.19758 \cdot e^{-\frac{T}{20.23058}} + 27060.64337 \]  \hspace{1cm} (2)

(2) SMA mixture

According to the stiffness modulus value of SMA-13 mixture in literature [18-21], we fitted the equation of SMA-13’s elastic modulus changing with temperature. The fitting equation is divided into two sections, section -40°C~40°C is fitted into a three power exponent equation, see equation 3, section 40°C~80°C is fitted into a primary power exponent equation, see equation 4.

\[ y = 3661.60879 \cdot e^{-\frac{T}{54.48046}} + 3661.49941 \cdot e^{-\frac{T}{54.48072}} + 3659.31301 \cdot e^{-\frac{T}{54.47424}} - 4705.66519 \]  \hspace{1cm} (3)

\[ y = 1790.666 \cdot e^{-\frac{T}{24.72729}} + 61.99432 \]  \hspace{1cm} (4)

(3) Casting (GA) asphalt concrete

The elastic modulus of casting (GA) asphalt concrete in the range of -40°C~80°C are obtained by fitting the comprehensive data from literatures [22, 23] into a curve equation. According to the comprehensive data, the data below 25°C is fitted as a linear function, see equation 5, the data above 25°C is fitted as an exponential function, see equation 6.
\[ y = 23033.62108 - 795.80135 \cdot T \]  
\[ y = 12252.03045 \cdot e^{(-T/17.05274)} + 382.0536 \]

(4) SMA-10 Elastic modulus of mixture

Zhang et al. [23] compared the initial stiffness modulus and decay stiffness modulus of casting asphalt concrete and SMA-10 asphalt mixture in previous literature, they found that the initial stiffness modulus and decay stiffness modulus of SMA-10 asphalt mixture were both about half the value of casting asphalt concrete. As a result, we could define the half value of the elastic modulus of casting asphalt concrete as the elastic modulus of SMA-10 asphalt mixture.

The elastic modulus of all kinds of asphalt mixture changing with temperature are shown in table 3.

Table 3. The elastic modulus of deck pavement material changing with temperature (MPa).

| Temp/°C | Epoxy asphalt concrete | SMA-13 | GA | SMA-10 |
|--------|------------------------|--------|----|--------|
| -40    | 54228.11               | 18180.46 | 54865.66 | 27432.83 |
| -30    | 41718.45               | 14342.53 | 46907.65 | 23453.83 |
| -20    | 31882.52               | 11148.2  | 38949.64 | 19474.82 |
| -10    | 24148.87               | 8489.555 | 30991.63 | 15495.82 |
| 0      | 18068.17               | 6276.756 | 23033.62 | 11516.81 |
| 10     | 13287.12               | 4435.037 | 15075.61 | 7537.805 |
| 20     | 9527.946               | 2902.168 | 7117.6  | 3558.8 |
| 30     | 6572.235               | 2491.538 | 1245.769 | 517.4581 |
| 40     | 4248.261               | 1626.357 | 745.2526 | 372.6263 |
| 50     | 2421                   | 717.116  | 584.1076 | 247.2299 |

2.3. Temperature Field Analysis

According to the transient analysis by ANSYS, experiments proves that the internal temperature of the steel girder body is very close to the ambient during 5:00 AM–6:00 AM, TUNIF command is used to set the initial uniform temperature in this model. The value of the integrated heat transfer coefficient [24, 25] and the comprehensive temperature Tsa are assigned to the boundary surface, analysis time from 0:00–23:00, it is divided into 24 load steps to impose the temperature load, and the Table array is used to define the temperature load. The steel box girder and deck pavement thermal parameters are listed in table 4.

Table 4. The steel box girder and deck pavement thermal parameters.

| Parameter              | Absorption coefficient /α | Thermal expansion coefficient | Radiation rate/ε | Thermal conductivity k/W.(m.°C)^{-1} | Specific heat capacity c/J · (kg · °C)^{-1} | Density ρ/kg · m^3 |
|------------------------|----------------------------|-------------------------------|------------------|---------------------------------------|---------------------------------------------|-------------------|
| Steel box girder       | 0.82                       | 1.2E-5                        | 0.60             | 60.5                                  | 434                                         | 7850              |
| SMA-10                 | 0.9                        | 2.8E-5                        | 0.6              | 2.46                                  | 920                                         | 2100              |
| SMA-13                 | 0.9                        | 2.8E-5                        | 0.6              | 2.05                                  | 1168                                        | 2100              |
| EA(Upper strata)       | 0.9                        | 1.7E-5                        | 0.6              | 1.1                                   | 993                                         | 2100              |
| EA(Lower stratum)      | 0.9                        | 1.7E-5                        | 0.6              | 1.3                                   | 969                                         | 2050              |
| GA                     | 0.9                        | 2.14E-5                       | 0.6              | 2.46                                  | 920                                         | 2100              |
Through the temperature field analysis of various pavement structures, we found that the maximum temperature is located on the top surface of deck pavement corresponding to the center of the rectangular deck separated by the web plate and the transverse plate. Due to the heat transfer effect of the steel, the internal temperature of deck pavement in the corresponding position of the web plate and the transverse plate is slightly lower, the temperature of the web plate located to the cross section for 4m and -4m is lower than that of other web plates, and the temperature of the two ends of the beam is the lowest. Figure 1 (a) shows the 16:00 temperature field of double layered SMA deck pavement at high temperature, figure (b) shows the 16:00 temperature field of double layered SMA deck pavement at low temperature. The temperature fields of Double layered epoxy pavement, SMA+GA pavement are similar to SMA pavement. The temperature fields at low temperature and high temperature have similar law, and differently the temperature of the two ends are the highest at low temperature.

Figure 1. 16:00 Temperature field of Double layered SMA pavement.

Figure 2 shows the panel point of the maximum temperature of double layered epoxy pavement changing situation during 24 hours, the 24 hours temperature changing curves of double layered SMA pavement and SMA+GA pavement are similar to double layered epoxy pavement. The paving material is divided into four layers, and the temperatures of the top surface of each pavement layer and the top surface of the steel deck are plotted in the figure.

Figure 2. Double layered epoxy pavement 24 hours temperature changing curve.

The highest temperature of the top surface of pavement layer of double layered epoxy pavement under low temperature situation appears at 12:00 which is 0.02 °C higher than 13:00, the highest temperature of the top surface of pavement layer of other pavement structures all appear at 13:00, the highest temperature of deck all appear at 14:00. The maximum temperature difference between the surface of paving layer and steel deck is close to 7 °C. Table 5 lists the maximum temperatures of the
It is can be seen from the figure of temperature changing curve and table 5, pavement materials have influence on the pavement layer, the heat conduction rate of epoxy asphalt is relatively low, so the pavement surface temperature of the double layered epoxy structure is the highest, the temperature difference between the pavement surface and the steel deck is also the highest. The surface temperature difference between the upper and lower layers of the epoxy double layered structure is 4.18 °C which is also the highest followed by the SMA+GA pavement, the upper and lower layers surface temperature difference is 3.78 °C.

3. Load-Temperature Coupling Analysis

3.1. The Stress and Strain Response of Two Kinds of Temperature Fields
Both high and low temperature stress field of three kinds of deck pavement structure are calculated, and extract the anisotropic stress and strain of high and low temperature field at 6:00 and 14:00 under the situation of temperature gradient and load coupling, compare the stress and strain changes of different kinds of pavement structure at the maximum temperature with the minimum temperature.

Figure 3 shows the anisotropic stress and strain values of different kinds of pavement structure in
hand low temperature fields at 6:00 and 14:00, the horizontal axis “Conditions” of different panels represents different kinds of pavement situation, the representation of specific numerical value is shown in Table 6. The response values corresponding to the two adjacent digital are connected, such as 1-2, 3-4, 5-6, 7-8, 9-10, 11-12, so it is easy to observe the response changing situation of same pavement structure at 6:00 and 14:00.

Figure 3. The maximum anisotropic stress and strain of different kinds of pavement structures in high and low temperature fields at two time periods.
Figure 3(a) shows the numerical value of normal stress of different pavement structures in high temperature field at 14:00 and 6:00, as we can see from this figure, most of the short connection line tilt outward which means that most of the normal stress of different pavement structures at 14:00 is less than 6:00. The difference of the anisotropic normal stress of different pavement structures at 14:00 is not obvious, but at 6:00, in addition to the vertical and longitudinal tensile stress of the double layer epoxy asphalt concrete, other stresses are greater. The normal stress difference of SMA+GA and double SMA pavement structure at 14:00 and 6:00 is not significant. Z direction tensile stress of each pavement structure is compressive stress at 14:00 and tensile stress at 6:00. The maximum normal stress occurs in the upper layer of the double layered epoxy pavement.

Figure 3(b) shows shear stresses of different pavement structures considering the load and temperature coupling condition, as we can see from this figure, most of the anisotropic shear stresses at 14:00 are less than 6:00, the value and the change value of XY direction shear stress are both larger, the YZ direction shear stress of the upper layer of different pavement structures is larger and not affected by the temperature change, the YZ direction shear stress of the lower layer of different pavement structures at 14:00 is less than 6:00. Generally speaking, the value and change value of the shear stresses of both upper and lower layer of double layered epoxy pavement structure are larger than other pavement structures.

Figure 3(c) shows the positive strain of different pavement structures under load temperature coupling situation. The equivalent strain and vertical compressive strain in figure 6 are larger, followed by vertical and lateral compressive strain and vertical tensile strain. The lower layer positive strain of different pavement structures is smaller than the upper layer; there is a law of anisotropic strain that almost all the strain at 14:00 is greater than 6:00. The value and change value of the positive strain of SMA+GA pavement upper layer are greater. The positive strain of double layered pavement structure lower layer is mostly less than the upper layer.

Figure 3(d) shows the shear strains of different pavement structures under load temperature coupling situation. As shown in figure 7, the shear strain at 14:00 is larger than 6:00, and the 14:00 shear strain is affected by the horizontal load, shear strain of YZ direction increased significantly; the upper layer shear strain of different pavement structures is larger than the lower layer. The upper layer shear strain of double layered SMA pavement structure is the largest, followed by the SMA+GA structure upper layer and SMA structure lower layer shear strain, the lower layer shear strain of double layered epoxy pavement is smaller, the SMA+GA lower layer pavement is the minimum.

Figure 3(e) shows the positive stress of different pavement structures under low temperature and load temperature coupling situation, as shown in this figure, the equivalent stress and the transverse and longitudinal compressive stress is high and change substantially, mostly the positive stress at 14:00 is larger than 6:00, the transverse and longitudinal compressive stress of some pavement structures is negative at 14:00 and positive at 6:00, the vertical tensile and compressive stress is small. The lower layer normal stress of double layered SMA pavement and SMA+GA pavement is less than the upper layer. The maximum positive stress occurs in the lower layer of SMA+GA pavement, secondly occurred in the upper layer of double layered epoxy concrete pavement.

Figure 3(f) shows the shear stress of different pavement structures under low temperature and load temperature coupling situation, we can conclude that the YZ direction positive and negative shear stress is larger and followed by the XY direction positive and negative shear stress. In addition the XZ direction shear stress of most pavement layers at 14:00 is less than 6:00, the shear stress of the rest directions at 14:00 is greater than 6:00. The lower layer shear stress of different pavement layers is greater than the upper layer, the lower layer shear stress of SMA+GA pavement and epoxy asphalt concrete pavement is larger.

Figure 3(g) shows the positive strain of different pavement structures under load temperature coupling situation, we can conclude that the transverse tensile strain at 14:00 is less than 6:00, the strain of rest directions at 14:00 is larger than 6:00. The upper layer positive strain of different pavement structures is larger than the lower layer. The equivalent stress and the transverse and longitudinal compressive stress of all pavement structures are higher followed by the longitudinal...
tensile stress.

From Figure 3 (h) shows that the effect of load on shear strain at low temperature is relatively small. The shear strain of all directions at 14:00 is larger than 6:00. The change of lower layer in different double layered pavement structures is larger than the upper layer.

3.2. The Maximum Stress and Strain Response of Two Kinds of Temperature Fields

Tables 7 and 8 listed the maximum tensile and compressive stress and strain as well as shear stress and strain obtained by analyzing the high temperature and low temperature fields of different pavements.

| Pavement type                  | Maximum compressive stress | Type | Maximum tensile stress | Type | Maximum shear stress | Type |
|--------------------------------|-----------------------------|------|------------------------|------|----------------------|------|
| Epoxy lower layer             | -2.00E+06                   | Z    | 7.14E+05               | X    | 4.55E+05             | XY   |
| Epoxy upper layer             | -2.62E+06                   | Z    | 9.08E+05               | X    | 3.23E+05             | XY   |
| SMA+GA lower layer            | -1.02E+06                   | Z    | 2.67E+05               | X    | 2.49E+05             | XY   |
| SMA+GA upper layer            | -1.02E+06                   | Z    | 1.68E+05               | X    | 2.80E+05             | YZ   |
| SMA lower layer               | -7.98E+05                   | Y    | 1.11E+05               | X    | 2.02E+05             | YZ   |
| SMA upper layer               | -1.03E+06                   | Z    | 1.75E+05               | X    | 2.81E+05             | YZ   |
| Pavement type                 | Maximum compressive strain  | Type | Maximum tensile strain | Type | Maximum shear strain | Type |
| Epoxy lower layer             | -1.03E-03                   | Y    | 5.35E-04               | Y    | 1.17E-03             | YZ   |
| Epoxy upper layer             | -1.22E-03                   | Y    | 6.50E-04               | Y    | 2.02E-03             | YZ   |
| SMA+GA lower layer            | -9.40E-04                   | X    | 6.38E-04               | Y    | 7.96E-04             | YZ   |
| SMA+GA upper layer            | -2.76E-03                   | Y    | 1.26E-03               | Y    | 2.61E-03             | YZ   |
| SMA lower layer               | -1.43E-03                   | Z    | 1.01E-03               | Y    | 1.56E-03             | YZ   |
| SMA upper layer               | -2.80E-03                   | Y    | 1.29E-03               | Y    | 2.65E-03             | YZ   |

According to table 8, the maximum anisotropic tensile and compressive stresses as well as the maximum positive and negative shear stresses appear at 6:00. While the maximum compressive stress of double layered SMA lower layer is Y direction compressive stress, the others are Z direction compressive stress. About the shear stress, except for the maximum positive shear stresses of SMA+GA pavement upper layer and double layered SMA are YZ direction positive shear stresses; the others are XY direction shear stress. The maximum positive stress at high temperature is the positive stress of epoxy upper layer pavement; the maximum compressive stress is -2.62 Mpa, the maximum tensile stress is 0.908 Mpa, the maximum shear stress is the shear stress of epoxy lower layer pavement which is 0.455 Mpa.
Table 8. Maximum stress and strain at low temperature.

| Pavement type     | Maximum compressive stress | Type | Maximum tensile stress | Type | Maximum shear stress | Type |
|-------------------|-----------------------------|------|------------------------|------|----------------------|------|
| Epoxy lower layer | -9.47E+06                   | Z    | 3.89E+06               | X    | 2.59E+06             | YZ   |
| Epoxy upper layer | -1.16E+07                   | Z    | 3.36E+06               | X    | 1.01E+06             | YZ   |
| SMA+GA lower layer| -1.37E+07                   | Z    | 4.71E+06               | X    | 3.44E+06             | YZ   |
| SMA+GA upper layer| -5.94E+06                   | Z    | 1.46E+06               | X    | 8.13E+05             | YZ   |
| SMA lower layer   | -9.16E+06                   | Z    | 2.72E+06               | X    | 2.50E+06             | YZ   |
| SMA upper layer   | -6.23E+06                   | Z    | 1.52E+06               | X    | 7.71E+05             | YZ   |
| Pavement type     | Maximum compressive strain  | Type | Maximum tensile strain | Type | Maximum shear strain | Type |
| Epoxy lower layer | -3.04E-04                   | Z    | 1.44E-04               | Y    | 2.28E-04             | YZ   |
| Epoxy upper layer | -3.62E-04                   | Z    | 2.06E-04               | Y    | 1.60E-04             | XZ   |
| SMA+GA lower layer| -3.44E-04                   | Z    | 1.72E-04               | Y    | 2.44E-04             | YZ   |
| SMA+GA upper layer| -5.13E-04                   | X    | 3.01E-04               | Y    | 1.63E-04             | XZ   |
| SMA lower layer   | -4.41E-04                   | Z    | 2.43E-04               | Y    | 3.57E-04             | YZ   |
| SMA upper layer   | -5.27E-04                   | X    | 3.19E-04               | Y    | 1.83E-04             | XZ   |

The maximum compressive strain and maximum shear strain of different pavements are listed in the "type" column in table 8. The maximum anisotropic positive strain and shear strain are both the strain at 14:00. The maximum compressive strain of SMA+GA lower layer is X direction compressive strain, the maximum compressive strain of double layered SMA lower layer is Z direction compressive strain, the others are Y direction compressive strain. The maximum shear strain is YZ direction shear strain. The maximum strain at high temperature is the upper layer strain of double layered SMA pavement; the maximum compressive strain is 2830 με which is the upper layer Y direction compressive stress of double layered SMA pavement, the maximum tensile strain is the upper layer internal tensile strain of double layered SMA pavement which is 1290 με.

As the positive and negative shear strains are numerically approximate only with different symbols, here we just list the positive strain. According to table 8, the maximum tensile stresses at low temperature all occur at 6:00, the maximum compressive stresses all occur at 14:00, and the maximum shear stress occurs at 14:00. All the maximum tensile stresses are X direction tensile stress, all the maximum compressive stresses are Z direction compressive stress. The maximum positive stress and shear stress all occur in the SMA+GA pavement structure lower layer, the maximum tensile stress is 4.71 Mpa, the maximum compressive stress is -13.7 Mpa, the maximum shear stress is 3.44 Mpa. The maximum positive and negative shear stress occurs in YZ direction at 14:00.

The maximum tensile strain at low temperature occurs at 6:00, the maximum compressive strain
occurs at 14:00, the maximum shear strain at low temperature occurs at 14:00. The maximum is Y
direction tensile strain; while the maximum compressive strain is X direction in the SMA+GA
pavement upper layer and SMA pavement upper layer, the others are Z direction compressive strain.
All the maximum shear strains are YZ direction shear strain. The strain types of the maximum shear
strains are listed in Table 8. The maximum tensile strain is the Y direction tensile strain in SMA
pavement upper layer which is 319 με, the maximum compressive strain is the X direction compressive
strain in SMA pavement upper layer which is 527 με, the maximum shear strain is the YZ direction
shear strain in SMA pavement lower layer which is 357 με.

3.3. The Positions of the Maximum Stress and Strain Response of Twokinds of Temperature Fields

Figure 4 (a) shows the high temperature equivalent strain nephogram in the upper layer of the double
layered SMA pavement, (b) shows the low temperature equivalent stress in the lower layer of
SMA+GA pavement. Due to the length of this article other pictures are not listed here.

![Figure 4](image1.png)

Figure 4. Strain nephogram of pavement,(a) Equivalent strain in the upper layer of double layer SMA
pavement at high temperature; (b) Equivalent stress of SMA+GA pavement at low temperature.

Figures 5 (a) and (b) are respectively the lateral variation nephogram of the equivalent strain in
high temperature double layered SMA pavement and the lateral variation nephogram of the equivalent
stress in low temperature SMA+GA pavement, we can conclude that the strain of load position at high
temperature is larger, but the stress of load position at low temperature is slightly higher than other
positions. As a result, the load effect on stress and strain is little at low temperature, but the influence
of temperature is much larger.

![Figure 5](image2.png)

Figure 5. Stress nephogram of pavement;(a) Lateral variation of equivalent strain in double layered
SMA at high temperature; (b) Lateral variation of equivalent stress in SMA+GA at low temperature.
According to the analysis of the anisotropic stress and strain nephogram, the most maximum shear stress and strain of double layered epoxy pavement, double layered SMA pavement, SMA+GA pavement are located in the bottom of pavement layer, the maximum positive stress and strain is located on the surface of pavement. The stress and strain of the load position, the lateral edge, the longitudinal end and the top of the web pavements of different pavements are larger; especially the top of the ±4 m web pavements is the maximum stress and strain concentration position. At high temperatures, the stress and strain at the load position of the pavement layer are larger; the longitudinal stress in the horizontal and longitudinal section of different pavements is particularly large when the temperature is low.

3.4 Stress and Strain Response Time History of Two Kinds of Temperature Field

In order to display the change of maximum stress and strain with time at the high and low temperature fields, figures 6-7 show the 24 hour time history curve of the stress and strain in high temperature maximum strain position and low temperature maximum stress position.

Figure 6 shows the 24 hour time history curve of strain at the node of the maximum YZ direction positive shear strain and equivalent strain position in high temperature double layered SMA pavement upper layer. The "bottom, 1layer, 2layer" and "top" refer to the 24 hour strain time history curves of the four nodes in the four layers of the pavement in the maximum response position from bottom to top. Thus, the maximum normal strain and shear strain are both on top of the pavement layer, the strain decline from large to small vertically.

![Figure 6](image)

Figure 6. Strain time history curve of double layered SMA at high temperature; (a) YZ time history curve of double layered SMA upper layer at high temperature (b) EEQV time history curve of double layered SMA upper layer at high temperature.

Figures 7(a)–(c) show the 24 hour time history curve of the node in the maximum YZ direction positive shear stress and equivalent stress and Z direction compressive stress positions in low temperature SMA+GA pavement lower layer. Therefore, the largest shear stress was showed in the bottom of the pavement layer, and the value of stress decreased from large to small in the vertical direction. However, there were two curves in the division point of both layers for double deck pavement in figures 7(b) and (c), which were marked as “2layer” and “2layer-top” respectively. “2layer” performed the stress of the top of the base course, and “2layer-top” was to showed the stress of the bottom of the top surface course. The stress value in the bottom of the top surface course showed mutations, yet the stress in the whole double deck pavement decreased from large to small. One thing should be demonstrated that four layer units were used to divide the double deck pavement in vertical direction, therefore, it could be exactly described the variation of stress in the vertical direction.
Figure 7. Stress time history curve of SMA+GA at low temperature; (a) YZ time history curve of SMA+GAlower layer at low temperature; (b) SEQV time history curve of SMA+GAlower layer at low temperature; (c) Z direction time history curve of SMA+GAlower layer at low temperature.

Figure 8 provided the continuous varied cloud picture of stress in vertical direction at the position with maximum equivalent stress and maximum compressive stress. The results from figure 8 showed that the stress in the middle of the top surface course for SMA+GA was smallest, the stress in the middle of the base course was largest, and the difference between the two stresses was significant. Figure 9 summarized the cloud picture variation of compressive stress in vertical direction of SMA pavement at high temperature. The results form figure 9 performed that the smallest stress showed in the middle of the top surface course, the largest stress showed the bottom of pavement, and the difference between the two stresses was not significant. Therefore, the stress in SMA+GA pavement was not coordinate, and it had a strong negative effect on structure stress.

Figure 8. Stress vertical variate cloud picture of low temperature SMA+GA; (a) The vertical variation of equivalent stress of low temperature SMA+GA (b) The vertical variation of vertical stress of low temperature SMA+GA.

Figure 9. Vertical stress vertical variation of High temperature double layered SMA.
4. Conclusions
Based on the stress and strain analysis of the three kinds of pavement structure including epoxy asphalt concrete, double layer SMA and SMA+GA in extreme high temperature and extreme low temperature field, the conclusion is drawn as follows:

High temperature anisotropic tensile and compressive stress and the maximum positive and negative shear stress all occur at 6:00. The maximum high temperature normal stress occurs in the upper layer of epoxy pavement, the maximum compressive stress is -2.62 MPa, the maximum tensile stress is 0.908 MPa. The maximum shear stress occurs in the lower layer of epoxy pavement, the maximum shear stress is 0.455 MPa. The maximum anisotropic normal strain and shear strain at high temperature are both the strain at 14:00. The maximum high temperature strain is the upper layer strain of double layer SMA pavement. The maximum shear strain is 2730 με, the maximum compressive strain is the Y direction compressive strain of double layered SMA pavement which is 2830 με. The maximum tensile strain is the internal upper layer tensile strain of double layered SMA pavement which is 1290 με.

The maximum tensile stress at low temperature occurs at 6:00, the maximum compressive stress occurs at 14:00, and the maximum shear stress occurs at 14:00. The maximum normal stress, shear stress and equivalent stress all occur in the lower layer of SMA+GA pavement structure, the maximum tensile stress is 4.71 MPa, the maximum compressive stress is -13.7 MPa, the maximum shear stress is 3.44 MPa. Both the maximum positive and negative shear stress and the maximum change of them occur in the YZ direction at 14:00.

The maximum tensile stress at low temperature occurs at 6:00, the maximum compressive stress occurs at 14:00, the maximum equivalent strain at low temperature occurs at 14:00, the maximum shear strain at low temperature occurs at 14:00. The maximum tensile strain is the upper layer Y direction tensile strain of SMA pavement which is 319 με, the maximum compressive strain is the upper layer X direction compressive strain of SMA pavement which is 527 με, the maximum shear strain is the lower layer YZ direction shear strain of SMA pavement which is 357 με.

The high temperature maximum stress generally occurs at the bottom of the pavement layer, the maximum strain generally occurs at the top of the pavement layer. The maximum shear stress and shear strain at low temperature usually occur at the bottom of the pavement layer, and the positive strain occurs at the top of the pavement layer. However, the normal stress and the equivalent stress may occur in the middle of the lower layer for the double layered pavement. Especially for the SMA+GA pavement structure, because the performance difference of the two kinds of materials is large, the stress difference between upper layer and lower layer is very big which is negative to the structure stress. The maximum stress and strain usually occur in the middle web of both sides, horizontal separator and transverse edge, longitudinal end, corner and the top, bottom and middle of lower layer of the load position pavement.

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