EFFECT OF PAVEMENT DESIGN PARAMETERS ON THE BEHAVIOUR OF ORTHOTROPIC STEEL BRIDGE DECKS

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ABSTRACT: Using a three-dimensional finite element model, the effects of pavement design parameters on the behaviour of orthotropic steel bridge deck pavements were evaluated. Three types of paving materials of polymer concrete, polymer modified stone mastic asphalt concrete, and mastic asphalt concrete were considered in this analysis. It is observed from this study that the maximum tensile strain occurs at the bottom of the bridge deck pavement on low temperatures and on top of the deck pavement at high temperatures. The maximum tensile strain increases with the decrease or increase of the thickness and temperature of the pavement. As pavement temperature increases from -20°C to 60°C, critical tensile transverse strain increases significantly and corresponding critical locations tends to move from the bottom to the top of the deck pavement.

KEY WORDS: Steel bridge deck pavement, paving materials, three dimensional finite element model, fatigue cracking

1. INTRODUCTION

Construction of long-span bridges has increased rapidly in eastern Asia, especially China and Korea [1, 2]. For the long-span bridges such as cable-stayed bridges, orthotropic steel decks become prevalent compared to concrete decks because of the reduced dead load applied to supporting cables. However, the deflection and vibration developed on steel decks due to traffic and wind loads are relatively greater than those in the concrete decks. The deck pavements of the orthotropic steel deck experience more critical environmental and traffic conditions; hence the service life of the steel bridge deck pavement is shortened. Hence, steel bridge deck pavements need more durable and tougher paving materials. Different types of paving materials have been used for steel bridge deck pavements. Mastic asphalt (MA) or Gussasphalt concrete has been widely used all around world, especially in European countries because of its
superior waterproofing property and fatigue resistance [3]. Polymer modified stone mastic asphalt concrete (PSMA) is another option for the steel deck pavements [4]. The thickness of these bitumen-based materials ranges from 40 to 80 mm [5]. Conversely, a thin layer of polymer concrete (PC) has been applied to the steel deck pavements as a way of reducing the self-weight of the pavements significantly. For example, a thin 10 mm PC was used in the steel deck of the Erasmus Bridge in the Netherlands [6]. Compared to bituminous paving materials, PC is advantageous as it shows faster curing, higher impermeability, and better chloride resistance [7]. Since the typical thickness of the PC is less than 10 mm, the PC bridge deck pavements reduces the dead load significantly, resulting to economical construction cost of cable bridges.

The main objective of this study is to analyze and understand the behaviour of the orthotropic steel deck pavements considering the design characteristics of the deck pavement such as layer thicknesses, material types, interface conditions, vehicle speed and temperature. To accomplish this objective, a three-dimensional FE model was developed for an orthotropic steel deck with a surfacing layer. The FE model was validated through experimental tests. Then stress and strain responses of the steel deck plate and pavements under traffic loading were analyzed under different conditions. Finally it was suggested an appropriate pavement design approach of considering fatigue cracking in the orthotropic steel deck pavement.

2. FINITE ELEMENT MODEL DEVELOPMENT FOR AN ORTHOTROPIC STEEL DECK-PAVEMENT SYSTEM

2.1 Geometry and Boundary Conditions

The three-dimensional FE model developed in this study was based on an orthotropic steel bridge deck with a surfacing layer. The modelled steel deck-pavement structure consists of a deck plate, beam plates, and U-rib stiffeners corresponding to one lane as shown in Figure 1. The steel deck plate is 14 mm thick, 4800 mm wide and 7500 mm long, parallel to the direction of traffic loading. The steel deck plate was supported by eight U-ribs in the longitudinal direction and four cross beams in the transverse direction. The U-rib stiffeners of 6 mm in thickness have a 300 mm-wide and 325 mm-deep shape. The cross beam plate of 8 mm in thickness and 535 mm in depth has an 18 mm-thick and 200 mm-wide flange at the bottom.

![Figure 1. Geometry and boundary condition of the FE model: (a) overall and (b) a part of the steel deck](image-url)
The FE model was constituted using a commercial finite element code, MIDAS Civil 2009. As seen in Figure 1, a total of 83,600 solid elements were used for the pavement layer and deck plate and 10,592 plate elements were used for the U-ribs and cross beams. The girders placed on top of piers to support the cross beam plates were simply modelled as boundary conditions at the two ends of the cross beams. Since the cross section of the cross beams was connected to the girder beams by means of welding and/or bolts, all degree of freedom at the two ends of the crossbeam plates were assumed as fixed condition, i.e., \( u_x = u_y = u_z = 0 \) and \( \phi_x = \phi_y = \phi_z = 0 \).

On top of the steel bridge deck, one or two surfacing layers were placed as a deck pavement. Three types of paving materials including the PC, PSMA and MA were considered as for the deck pavement. The thickness of the three types of the deck pavement is listed in Table 1. The deck pavement made of the PC is 10 mm thick which is typically used in USA [9]. The other deck pavements made of the PSMA, or a combination of the PSMA and MA, have either a 40 mm-thick single layer [10] or two layers of surface and base courses with the same thickness. The thickness of the double-layered deck pavements is a total of 40 mm, 60 mm and 80 mm. Interface bonding conditions of a multi-layered structure affect overall as well as local behaviours of the structure. A full bonding condition was used for some of PC, PSMA and PSMA/MA cases. For the other PSMA and PSMA/MA cases where a waterproof layer is used, an additional 3.0-mm-thick interlayer was placed at the bottom of the pavement as for the waterproof layer.

### Table 1. Bridge Deck Pavement Configuration

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Waterproof layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
<td>Base</td>
</tr>
<tr>
<td>Polymer concrete (PC)</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Polymer-modified stone mastic asphalt (PSMA)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>PSMA (Surface)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>+ Mastic asphalt (MA) (Base)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>40</td>
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<tr>
<td></td>
<td>20</td>
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<td>30</td>
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<tr>
<td></td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

The materials of the steel deck and pavement used in this FE model were assumed to be isotropic and homogeneous. A simple linear elastic model was implemented to characterize the small strain behaviour of the steel and PC. The elastic modulus and Poisson’s ratio of the steel was assumed as 210 GPa and 0.30, respectively. The elastic modulus of the PC is 140 MPa which was estimated from compressive strength measured at 20°C [11]. The behaviour of the asphaltic materials is dependent on time and temperature, i.e., viscoelastic behaviour, under in-service temperature conditions. Thus, uniaxial dynamic modulus tests were conducted to measure complex modulus of the EA, PSMA and MA at various temperatures and frequencies [12]. Then, the master curves at a reference temperature of 20°C were constructed using a sigmoidal function as shown in Figure 2. Then the moduli at -20°C, 20°C, 40°C and 60°C and at 10 Hz were obtained for the PSMA and MA. The material properties of the PC, PSMA and MA were summarized in Table 2. The Poisson’s ratio of the paving materials was simply assumed as a typical value of 0.30 [13]. On the other hand, the MA has considerably higher elastic moduli of 2.2 GPa and 1.5 GPa at higher temperatures of 40°C and 60°C.
The elastic modulus was calculated to evaluate the effect of loading speed on the behaviour of deck pavements using Equation (1) at the temperature of -20°C and 60°C and at the frequency of 3Hz and 16Hz loading speed respectively [13]. Using the elastic modulus of the bituminous materials at different temperatures and frequencies, the time and temperature behaviour of the bituminous materials could be indirectly considered in the static analysis based FE analysis.

\[ t = \frac{1}{2\pi f} \]  \hspace{1cm} \text{Equation (1)}

### Table 2. Material Properties of the Steel Deck and Pavement

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-20°C</td>
<td>20°C</td>
</tr>
<tr>
<td></td>
<td>3 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Polymer-modified stone mastic asphalt (PSMA)</td>
<td>17.1</td>
<td>17.2</td>
</tr>
<tr>
<td>Mastic asphalt (MA)</td>
<td>16.7</td>
<td>16.7</td>
</tr>
<tr>
<td>Polymer concrete (PC)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3. CRITICAL RESPONSES IN THE DECK PAVEMENT

#### 3.1 Effect of the Location of the Vehicular Loading

The location of vehicular loading with respect to the U-rib stiffeners influences the behaviour of the pavement and steel bridge deck [14, 15, 16]. The dual tires were placed on several locations to identify critical points where maximum stress and/or strain occur in the deck plated and pavement. Comparing pavement responses at each loading location, it was found that the maximum tensile stress and strain were developed where one tire was located between two U-rib stiffeners and the other tire was located at the centre of one U-rib stiffener. When
the vehicular loading is applied to the critical loading location, a transverse stress ($\sigma_{xx}$) contour is plotted in a deformed shape for the 40 mm-thick PSMA pavement without the waterproof layer (see Figure 3).

![Transverse stress distribution in the deck pavement at the critical vehicular location](image)

**Figure 3.** Transverse stress distribution in the deck pavement at the critical vehicular location [8]

### 3.2 Model Validation

**Medium-Scale Deck-Pavement System:** A medium-scale orthotropic steel deck surfaced with the PSMA/MA pavement was built to examine the applicability of the FE model. The pavement has two layers of the 20 mm-thick PSMA wearing surface and 20 mm-thick MA base course and no waterproof layer used. A total of 4.5 tons of the dual-tire loading was applied at a speed of 17 km/h and ambient temperature during the test ranged from 10°C to 15°C. The left-edge of the right-hand side tire was aligned with the top of the right-hand side U-rib stiffener located at the centre of the deck plate.

![Orthotropic steel bridge deck with PSMA/MA pavement section used for FE model validation](image)

**Figure 4.** Orthotropic steel bridge deck with PSMA/MA pavement section used for FE model validation [8]

For the model validation, the responses of the deck and pavement were measured in two locations of the deck plate and pavement. Tensile strain was measured on top of the pavement between the tires using a strain gauge. Vertical displacement was measured at the bottom of the deck plate under the left tire and between the U-rib stiffeners using a linear variable differential transducer (LVDT). The vertical displacement and tensile strain measured at the two locations were 0.79 mm and 361 $\mu$ε in average, respectively. The responses calculated in the FE model were 0.71 mm and 365 $\mu$ε and corresponding errors are 10.1% and -1.1%, respectively. Thus the medium-scale FE model could predict the structural behaviour of the orthotropic steel deck pavement in a reasonable confidence. Hence, it can be applicable to use the full-scale FE model expanded from the medium-scale FE model. More details on the experimental results and FE model validation can be found elsewhere [8].
**Effect of the Vehicular Speed**: The effect of the vehicular speed on the behaviour of bridge deck pavement was evaluated. Polymer-modified stone mastic asphalt (PSMA) and mastic asphalt (MA) pavement with 40mm thickness was selected for the evaluation. Figure 5 shows that the maximum transverse tensile strain occurred independent of vehicular speed at the different conditions. As shown in table 1, the dynamic modulus of pavement is largely dependent on temperature than the vehicular speed. Thus the vehicular speed was fixed at 10 Hz for further analysis.

![Figure 5. Maximum transverse strain variations of the PSMA/MA Pavement](image)

**3.3 Effect of the Modulus of the Waterproof Layer**

The behaviour of the deck plate and pavement can be influenced by the use of the waterproof layer which results in additional shear displacement at the deck plate and pavement interface due to relatively lower stiffness than surrounding layers. The waterproof layer made of various materials could have a wide range of modulus. In this study, the elastic modulus of the 3.0-mm-thick waterproof layer (Ewp) was assumed as 5 MPa, representing low level of the stiffness as suggested in a previous study [14]. Then, the effect of the stiffness of the waterproof layer on the critical location of the bridge deck pavements was examined.

Figure 6 shows the in-depth transverse strains (εxx) distribution at the sections 2 and 3 for the 60 mm thick PSMA/MA pavement. At the section 2, compressive strain developed in the pavement and maximum tensile strain occurred at the bottom of the deck plate where is fully bonded to the pavement; but moved to the bottom of the pavement when the waterproof layer is used. At the section 3, tensile strain developed in the pavement thoroughly when the deck plated is fully bonded to the pavement; maximum tensile strain occurred on top of the pavement for both the cases with and without the waterproof layer. It means that the usage of the waterproof layer resulted to the occurrence of tensile strain at the bottom of the pavement under the tire and the increase of tensile strain on top of the pavement between the tires. Also, the magnitude of tensile strain in the pavement increases as the stiffness of the water proofing layer decreases. Similar results were also observed from other pavement cases and a previous study [17]. Thus the behaviour of the pavement will be examined in the three locations of the bottom of the pavement of section 2 and both top and bottom of the pavement of section 3.
Figure 6. In-depth transverse strain distribution for the 60 mm-thick PSMA/MA pavement with and without the waterproof layer at the (a) section 2 and (b) section 3.

4. SENSITIVITY ANALYSIS FOR PAVEMENT DESIGN

4.1 Behaviour of the Polymer Concrete (PC) Deck Pavement

The PC deck pavement is 10 mm thick only and attached to the deck plate directly with no waterproof layer. Hence no pavement design variable was considered in its sensitivity analysis. Transverse strain distributions in depth at the sections 2 and 3 are shown in Figure 7. Due to the full bonding between the deck plate and pavement, a neutral axis of the deck-pavement structure exists in the middle of the deck plate, resulting in only compressive strain at the section 2 and tensile strain at the section 3 through the pavement. The maximum tensile strain was $689 \mu \varepsilon$ on the PC deck pavement surface between the tires (the section 3). Thus fatigue cracks could be initiated at the surface of the pavement on top of the stiffener and develop downward.

Figure 7. In-depth transverse strain distribution of the PC pavement.

4.2 Behaviour of the PSMA and PSMA/MA Deck Pavement

4.2.1 Effect of Pavement Thickness and Interface Bonding Conditions

The effect of the pavement thickness and interface bonding conditions on the behaviour of the deck pavement was examined when the PSMA and PSMA/MA are used in the deck pavement. The thickness of the PSMA and PSMA/MA deck pavement ranges from 40 mm to 80 mm. The moduli of the waterproof layer were assumed in
three level of 5 MPa; in addition, the full bonding condition where the waterproof layer is not used was considered. Figure 8 shows maximum tensile strain variations with respect to the pavement thickness at the sections 2 and 3 and at a temperature of 20°C under the various interface bonding conditions for the PSMA and PSMA/MA pavements. The maximum transverse strain was developed in tension for all the cases regardless of the modulus of the waterproof layer and thickness of the pavement except one case for the full bonding condition at the section 2. In most cases, the maximum tensile strain decreased with the increase of the thickness of the deck pavement and the modulus of the waterproof layer. As the modulus of the waterproof layer increased from 5 to 50 MPa, for example, the maximum tensile strain was reduced by 50% (from 442 to 220 με) at the section 2 and by 28% (from 423 to 306 με) at the section 3 in the 40 mm thick PSMA deck pavement. For the 80 mm-thick PSMA deck pavement, the maximum tensile strain was reduced by 38% (from 240 to 150 με) at the section 2 but increased by 62% (50 to 81 με) at the section 3. The same pattern was also found in the behaviour of the PSMA/MA deck pavement.

Figure 8. Maximum transverse strain variations with respect to the thickness of the PSMA and PSMA/MA deck pavement at 20°C

4.3 Effect of Pavement Temperature

Since the behaviour of asphaltic materials is sensitive to temperature, the effect of the pavement temperature on the critical pavement responses was investigated for the PSMA/MA deck pavements. For the 80 mm-thick PSMA deck pavements, in-depth strain distributions at -20°C and 60°C were compared as shown in Figure 9. However, when the waterproof layer with Ewp of 10 MPa is used, critical maximum tensile strain of 78 με was developed at the bottom of the pavement of the section 2 and 768με on top of the pavement of the section 3. For the EA and PSMA/MA deck pavements, critical maximum tensile strain and corresponding critical locations under various temperatures from -20°C to 60°C and two interface conditions are listed in Table 3. Of the all
critical tensile strain, 89% (33% in the section 2 and 56% in the section 3) was developed at the bottom of the pavement at the lower temperatures of -20°C and 100% on top of the pavement in the section 3 at the higher temperatures of 40°C and 60°C as shown in Figure 10. It indicates that bottom-up fatigue damage can be accumulated at lower temperatures while top-down fatigue damage at higher temperatures.

Figure 9 In-depth transverse strain distributions for the 80 mm-thick PSMA/MA pavements at -20°C and 60°C: (a) section 2 and (b) section 3

Figure 10. Percentage of critical locations for the deck pavements at various temperatures

5. CONCLUSIONS

This study evaluated the effect of pavement design parameters on the behaviour of orthotropic steel bridge deck pavements under traffic loading. A three-dimensional finite element model was developed to obtain critical responses in the deck pavement under different conditions. Three different paving materials were used in the wearing and base courses of the deck pavement: Polymer concrete (PC), polymer-modified stone mastic asphalt concrete (PSMA) and mastic asphalt concrete (MA). Sensitivity analysis was done for the pavement type, thickness, interface conditions, vehicle speed and temperature. Some of the important findings obtained from this study were summarized as follows:

[1] Under dual-wheel tires loading, maximum tensile strain occurred either at the bottom of the pavement under the centre of a tire because of positive bending or on top of the pavement between the tires above a U-rib stiffener because of negative bending.

[2] The critical tensile transverse strain increases with the decrease of pavement thickness and modulus of the waterproof layer, and with the increase of pavement temperature.
[3] Better interface bonding condition enables to enhance not only the bottom-up fatigue cracking resistance significantly, especially for thin (40 mm thick) deck pavements, but also increase top-down fatigue cracking resistance potentials slightly.


[5] Bottom-up fatigue damage is more dominant at a lower temperature of -20°C while top-down fatigue damage at higher temperatures of 40°C and 60°C.

From this study, greater stress or strain occurred in relatively thinner deck pavements, meaning that thin deck pavements may have shorter fatigue life than thick deck pavements. However, fatigue life of materials is dependent not only resultant stress and stress but also fatigue resistance of the materials. Thin deck pavements can be resistant against fatigue cracking better than thick deck pavement if the thin pavement materials have higher fatigue resistance at higher stress and/or strain levels. Thus, the fatigue resistance of the paving materials at a high level needs to be evaluated in experimental tests for the design of thin deck pavements.

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