SIMPLIFIED MODELS FOR ESTIMATING STRESSES AND STRAINS IN PAVEMENTS ON CONCRETE AND STEEL BRIDGES

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ABSTRACT

Simplified models for estimating stresses and strains in pavements both on concrete and steel bridges are presented in this paper. These models represent a very useful tool for a faster prediction of structural behavior of pavements at a preliminary design level.

The simplified model proposed for asphalt pavements on concrete bridges can be identified in the elastic multilayer system, which is represented by the layers of the pavement and waterproofing supported by a rigid half-space (concrete deck). The results obtained show that the validity field of this model is influenced by the thickness and dynamic modulus of the pavement, as well as the stiffness of the waterproofing.

The model developed for the asphalt pavements on steel bridges, instead, can be identified in a small-scale model, compared to the full-scale bridge, which is represented with a supported continuous plate composed by the pavement, waterproofing, and steel deck. In keeping with the international literature, similar models for steel bridges have been validated in laboratory by reduced-scale tests, as a result the author is confident that the model proposed also permits to estimate accurately enough the stresses and strains.

Key words: Simplified models, Stresses and strains, Asphalt Pavements, Road bridges.


1. INTRODUCTION

Methods, which are traditionally used for the design of pavements, make use both of the mechanical properties of materials and the structural response for predicting the pavement performance over time. The mechanistic component lies in determining pavement response in terms of stresses and strains due to the traffic and climate; while the empirical component lies in using this response in distress models (fatigue cracking, rutting, surface deflection, and roughness) that are derived from observed performances. However these methods are based on models of foundation soils. In this respect, the behavior of soils is generally assumed to be
represented in the elastic theory by Winkler’s model or homogeneous, isotropic elastic half-space model. This approach, however, does not appear to be sufficiently appropriate for representing the global behavior of bridges that support pavements. In fact the curvature of deflection of the deck, which is related to the bridge structure type, geometry, and materials strength characteristics, is expected to be under loads significantly different from that of soils; which influences the entity of stresses and strains in asphalt pavements on bridges.

The functions of an asphalt pavement on bridges are to provide: a good surface evenness, appropriate skid resistance, a sufficient protection to the deck from the direct action of traffic and atmospheric agents (rain, freeze-thaw) and de-icing salts. Therefore, in order to limit the dead load on bridges, asphalt pavements on bridges are much thicker than those on foundation soils.

The lack of consideration given both to the structural behavior of the bridge and the stiffness of pavement and waterproofing might bring less accurate estimations of stresses and strains in pavements on bridges. In this respect, three-dimensional finite-element models (3D-FEM) representing the full-scale bridge might be used for the structural analysis of pavements. Then the computed stresses and strains may subsequently be used in distress models to assess the damage accumulated over time. The distress models on bridges are more especially fatigue cracking that begins at the bottom of asphalt pavement, which is caused by the positive bending moments, and fatigue cracking that initiates at the top of asphalt pavement produced by the negative bending moments, as well as rutting and thermal cracking.

Although the full-bridge model represents the best way for making an accurate evaluation of stresses and strains in pavements on bridges, it is time-consuming. Therefore engineers sometimes require simplified models which, even if involving less accurate estimations than the full-model, can be suitable for a faster calculation of stresses and strains. These simplified models represent a very useful tool at a preliminary design level. A preliminary design is made when the designer does not yet know the exact values of the input parameters of the pavement and waterproofing, which will subsequently be measured for that specific bridge project, but uses the average values available or estimated from existing analytical correlations.

The entity of stresses and strains in a pavement on bridges depends on both the deflection of deck and the deflection of pavement that, on the other hand, is strictly correlated also to the vertical stiffness of waterproofing.

With reference to the asphalt pavements on concrete bridges, it is to be said that the contribution of the deck deflection might be in certain cases negligible, as a consequence a simplified model might be based on the elastic multilayer system, which is represented by the layers of the pavement and waterproofing supported by a rigid half-space (concrete deck).

Stresses and strains in pavements on steel bridges are, instead, generally caused prevalently by the local bending of the steel deck; as a result the possibility of using the aforementioned elastic multilayer model does not appear to be appropriate. In this respect, a reduced-scale model, compared to the full-scale bridge, which is represented with a supported continuous plate made by the pavement, waterproofing, and steel deck might be suitable.

Studies that deal with the design of pavements on soils and/or bridges can be found more especially in: Medani [1], Wolchuk [2], AASHTO [3], Eurocode [4], Castro [5], Huurman et al. [6], Zhao et al. [7], Xiao et al. [8], AASHTO [9], Song et al. [10], Caliendo and Parisi [11], Caliendo [12], Caliendo [13], Caliendo [14], Caliendo and Guida [15], Poroski et al. [16], Kim et al. [17]. With reference to the software is well to cite the ABAQUS [18] for the resolution in terms of finite element method of the full and/or small-scale bridge, and the
Bisar [19] that uses as computing algorithm the equilibrium differential equations for the resolution of the elastic multilayer system.

Another leading question is that during the process of design of a new pavement, zero maintenance is generally assumed during its service life. Road Management Agencies (RMAs), instead, are increasingly moving towards the practice of maintenance that involves the rehabilitation of pavement based on the resurfacing of the surface layer. The removal and subsequent placement of a new asphalt surface restores the shape and integrity of the travel surface by improving the quality of ride, with a positive impact on road safety. Unfortunately, an evaluation of the effect of this rehabilitation in the design process of pavements, except when one uses the MEPDG [9] for pavements on soils, is not yet possible to make for pavements on bridges. With reference to the tools of management of a pavement on foundation soils during its service life, a help can be found for instance in [15] where the RMAs can predict a resurfacing of wearing course when the performance indicators achieve values lower or higher than fixed values of threshold. In other structures of road engineering, for example, in tunnels, which are not within the scope of this paper, the RMAs can use the risk analysis in order to allow, forbid or limit the circulation of heavy goods vehicles (Caliendo and De Guglielmo [20]) when the risk exceeds the tolerable limit. At the same time, at road intersections, the RMAs can use the micro-simulation technique for the traffic control in order to avoid the congestion (Caliendo [21]) or to improve the safety level [22].

In the light of the above considerations, there are at least three main reasons for justifying this paper. The first is motivated by the need to individualize simplified models which appear to be more appropriate for estimating stresses and strains in pavements on concrete and steel bridges. The second is to have a better understanding about the validity field of the models proposed. Finally, given the lacuna regarding

the performance models of pavements on bridges, the fatigue cracking that initiates at the top of asphalt pavement, which is caused by positive bending moments, and the fatigue cracking, which initiates at the top of asphalt pavement due to negative bending moments, should be investigated more in detail.

The present paper is organized as follows: the next section contains the description of the simplified model of pavements on concrete bridges; while the subsequent sections deal with its validity field. Then the small-scale bridge model of pavements on steel bridges is presented and its validation is commented. Finally the conclusions and addresses for further research are made.

2. ASPHALT PAVEMENT ON CONCRETE BRIDGES

2.1. Simplified Model

In the simplified model proposed, the concrete deck is substituted by a rigid-half space so that stresses and strains due to the bending moment caused by the curvature of the deflection of the deck are neglected. The pavement and waterproofing are considered as an elastic multilayer system, which is represented by the layers of pavement (one or several) and waterproofing, supported by the above mentioned rigid half-space, so that only stresses and strains due to the deflection of the pavement and the stiffness of the waterproofing are computed. Figure 1 shows the simplified model proposed, which is loaded by dual wheels (60 kN) of the rear axle of an Italian standard truck (for more in detail see[12]).
The maximum stresses and strains at the bottom of a typical asphalt pavement (thickness equal to 100 mm) on a concrete bridge, computed by using the proposed simplified model, are reported in Table 1 as a function of the dynamic modulus of pavement ($E_{a,c}^*$).

Table 1 Maximum stresses and strains at the bottom of the pavement on concrete bridge computed by using the simplified model.

<table>
<thead>
<tr>
<th>$E_{a,c}^*$ (N/mm$^2$)</th>
<th>$\sigma_x$ (N/mm$^2$)</th>
<th>$\sigma_y$ (N/mm$^2$)</th>
<th>$\varepsilon_x$</th>
<th>$\varepsilon_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>0.405</td>
<td>0.580</td>
<td>$1.80 \times 10^{-4}$</td>
<td>$3.80 \times 10^{-4}$</td>
</tr>
<tr>
<td>4,500</td>
<td>0.400</td>
<td>0.570</td>
<td>$7.10 \times 10^{-5}$</td>
<td>$1.70 \times 10^{-4}$</td>
</tr>
<tr>
<td>6,000</td>
<td>0.392</td>
<td>0.568</td>
<td>$5.75 \times 10^{-5}$</td>
<td>$1.25 \times 10^{-4}$</td>
</tr>
<tr>
<td>10,000</td>
<td>0.393</td>
<td>0.571</td>
<td>$3.40 \times 10^{-5}$</td>
<td>$7.41 \times 10^{-5}$</td>
</tr>
<tr>
<td>20,000</td>
<td>0.335</td>
<td>0.591</td>
<td>$1.61 \times 10^{-5}$</td>
<td>$3.56 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 2 shows the maximum stresses and strains at the top of the pavement on concrete bridge computed by means of the aforementioned simplified model of elastic multilayer system.

Table 2 Maximum stresses and strains at the top of the pavement on concrete bridges computed by using the simplified model.

<table>
<thead>
<tr>
<th>$E_{a,c}^*$ (N/mm$^2$)</th>
<th>$\sigma_x$ (N/mm$^2$)</th>
<th>$\sigma_y$ (N/mm$^2$)</th>
<th>$\varepsilon_x$</th>
<th>$\varepsilon_y$</th>
</tr>
</thead>
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<tr>
<td>2,000</td>
<td>0.128</td>
<td>0.20</td>
<td>$5.23 \times 10^{-5}$</td>
<td>$6.33 \times 10^{-5}$</td>
</tr>
<tr>
<td>4,500</td>
<td>0.125</td>
<td>0.198</td>
<td>$2.46 \times 10^{-5}$</td>
<td>$2.91 \times 10^{-5}$</td>
</tr>
<tr>
<td>6,000</td>
<td>0.13</td>
<td>0.197</td>
<td>$1.95 \times 10^{-5}$</td>
<td>$2.23 \times 10^{-5}$</td>
</tr>
<tr>
<td>10,000</td>
<td>0.153</td>
<td>0.20</td>
<td>$1.54 \times 10^{-5}$</td>
<td>$1.53 \times 10^{-5}$</td>
</tr>
<tr>
<td>20,000</td>
<td>0.213</td>
<td>0.21</td>
<td>$1.16 \times 10^{-5}$</td>
<td>$9.58 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

The results show that the maximum tensile stresses and strains in pavements on concrete bridges are found to be greater at the bottom rather than at the top of the pavement. This is attributable to the cumulative effect of the positive bending moments caused by the curvature of the concrete deck and the deflection of the pavement, respectively.

As a consequence the distress model type of pavements on concrete bridge is more especially identifiable in the fatigue cracking caused by the positive bending moment (resulting in cracks at the bottom of the pavement that will propagate to the pavement top).
2.2. Simplified Model Validation
The results obtained with the simplified model were validated by the full-scale concrete bridge model.

In particular the validity field was investigated for three different pavement thicknesses (70, 100, and 150 mm) and two waterproofing types (being characterized by high and low vertical stiffness, respectively) on thirty five different concrete bridges. For each concrete bridge a 3D-FE full-scale model was generated, and maximum stresses and strains at the bottom and top of the pavement for each of the pre-selected thickness of the pavement and vertical stiffness of the waterproofing were computed by ABAQUS software.

The results showed that the validity field of this simplified model is as follows: (i) with a high vertical stiffness of the waterproofing the simplified model can be used for values of the dynamic modulus of the pavement $E_{a,c}^{*} \leq 10,000$ N/mm$^2$ and thicknesses of the pavement contained in the range 70÷100 mm; (ii) with a much lower vertical stiffness of the waterproofing the simplified model can be used for $E_{a,c}^{*} \leq 10,000$ N/mm$^2$ and thickness of the pavement contained in the range 70÷150 mm.

Thereby, when the vertical stiffness of the waterproofing decreases the simplified model is applicable for a wider range of thicknesses of the asphalt pavement on concrete bridges.

This means that the stresses and strains caused by the deflection of the concrete deck may be neglected in the aforementioned cases.

The simplified model represents a useful tool for a faster estimation of stresses and strains in asphalt pavements on concrete bridges at a preliminary design level, which is when the designer does not yet know the exact values of the input parameters of the pavement and waterproofing but uses the average values available or estimated from existing analytical correlations. The simplified model, however, will not take place of the real-scale concrete bridge model. The latter, in contrast, should be used when better information on the exact values of input parameters is obtained from direct measurements (e.g. from laboratory tests) for the design of that specific bridge.

3. ASPHALT PAVEMENT ON STEEL BRIDGES
3.1. Small-Scale Model
Unlike concrete decks, steel decks are subject to considerable local effects. These local effects, which are generally considered to be prevalent when compared to those attributable to the global deformation of the steel bridge, are caused by: (i) local deflection of the steel deck under the wheel loads; (ii) differential deflections of the directly loaded and unloaded stiffeners (stiffeners are used for the reinforcement of steel deck). This means that in the evaluation of stresses and strains in pavements on steel bridges, since the local effects of the steel deck cannot be neglected, a simplified model based on the elastic multilayer system in which the deck is assume to be a rigid half-space does not appear to be appropriate. In this respect, reduced-scale models might be suitable.

The small-scale model proposed in this paper, as a part of the full-scale steel bridge, can be represented by a simply supported continuous plate that is made by the pavement, waterproofing and orthotropic deck (deck plate and stiffeners). The pavement and waterproofing are considered to be as an integral part of the structural deck system. More especially the reduced model consists in a plate on five longitudinal spans supported by six crossbeams. The distance between the crossbeams is equal to 3.25 m so that the model is 16.25 m long. This longitudinal length was preselected in order to take into account the current length of Italian trucks (the maximum length is 18.0 m). The width of the cross
section of the proposed model is 1.8 m. This contains three closed trapezoidal-shaped stiffeners. The distance between the stiffeners is 600 mm and each stiffener is 300 mm high with a thickness of 7 mm. The spans of the steel deck plate are equal to 300 mm and its thickness is 12 mm. The deck plate is waterproofed for a 2 mm thick and the asphalt pavement has a thickness of 100 mm. Figure 2 shows a view of the model proposed between two consecutive crossbeams only.

Figure 2 Small-scale model proposed (view of a part between two consecutive crossbeams).

For the resolution of the aforementioned small-scale model a 3D-FM method with associate software ABAQUS was used.

Two different lateral load positions of a standard truck were considered in order to investigate the effects on pavement due to the maximum differential deflections of the directly loaded and unloaded stiffeners. This is when the vehicle is with its rear axle in the middle of the longitudinal length of the proposed model (or equivalently in the middle of the distance between the two central crossbeams), and the dual wheels of rear axle are placed between the welds of a stiffener (Position A) or over a weld of a stiffener (Position B). The former and latter load position were preselected for evaluating the effects of the positive and negative bending moment, respectively. Figures 3 and 4 show the two load positions investigated (for more in detail see [13]).

Figure 3 Dual wheels of the rear axle are placed between the welds of a stiffener (Position A) for capturing the effects of positive bending moment.
Figure 4 Dual wheels of the rear axle are placed over a weld of a stiffener (Position B) for capturing the effects of negative bending moment.

Tables 3 and 4 contain the values of the maximum stresses and strains in the asphalt pavement according to the ABAQUS finite-element software as a function of the dynamic modulus ($E_{a,c}$) of the pavement for the two aforementioned load positions (A and B, respectively). These are expressed as $\sigma_x$ and $\varepsilon_x$ in the transversal direction, $\sigma_y$ and $\varepsilon_y$ in the longitudinal direction, and finally $\sigma_z$ and $\varepsilon_z$ in the vertical direction. Note that positive and negative signs are for the tensile and compressive stresses, respectively.

By comparing Table 3 with Table 4, the results show that for the aforementioned cumulative effects attributable to the positive bending moment of steel deck and the deflection of pavement, the maximum tensile stresses and strains are at the bottom of pavement. With reference to the top of pavement, compressive stresses and strains are found also when the negative bending moment is considered. This means that the tensile stresses and strains caused by the negative bending moment of the steel deck are lower than compressive stresses and strains due to the deflection of pavement.

**Table 3** Maximum stresses and strains in the pavement computed by the proposed small-scale FE model (Load Position A for capturing the effects of positive bending moment).

<table>
<thead>
<tr>
<th>$E_{a,c}$ (N/mm$^2$)</th>
<th>$\sigma_x$ (N/mm$^2$)</th>
<th>$\sigma_y$ (N/mm$^2$)</th>
<th>$\sigma_z$ (N/mm$^2$)</th>
<th>$\varepsilon_x$ $10^4$</th>
<th>$\varepsilon_y$ $10^4$</th>
<th>$\varepsilon_z$ $10^4$</th>
<th>$\sigma_x$ (N/mm$^2$)</th>
<th>$\sigma_y$ (N/mm$^2$)</th>
<th>$\sigma_z$ (N/mm$^2$)</th>
<th>$\varepsilon_x$ $10^4$</th>
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<th>$\varepsilon_z$ $10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>3.2</td>
<td>3.2</td>
<td>-0.12</td>
<td>8.44</td>
<td>8.5</td>
<td>-16</td>
<td>-3.4</td>
<td>-3.4</td>
<td>-0.7</td>
<td>7.3</td>
<td>6.6</td>
<td>13.1</td>
</tr>
<tr>
<td>4,500</td>
<td>3.36</td>
<td>3.16</td>
<td>-0.12</td>
<td>4.22</td>
<td>3.56</td>
<td>-7.2</td>
<td>-3.7</td>
<td>-3.4</td>
<td>-0.7</td>
<td>3.8</td>
<td>2.9</td>
<td>6.0</td>
</tr>
<tr>
<td>6,000</td>
<td>3.37</td>
<td>3.06</td>
<td>-0.1</td>
<td>3.3</td>
<td>2.53</td>
<td>-5.2</td>
<td>-3.8</td>
<td>-3.5</td>
<td>-0.7</td>
<td>3.0</td>
<td>2.3</td>
<td>4.5</td>
</tr>
<tr>
<td>10,000</td>
<td>3.35</td>
<td>2.86</td>
<td>-0.05</td>
<td>2.2</td>
<td>1.5</td>
<td>-2.6</td>
<td>-3.8</td>
<td>-3.39</td>
<td>-0.7</td>
<td>2.2</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>20,000</td>
<td>2.84</td>
<td>2.01</td>
<td>0</td>
<td>1.16</td>
<td>0.6</td>
<td>-0.6</td>
<td>-3.66</td>
<td>-3.05</td>
<td>-0.7</td>
<td>1.34</td>
<td>0.96</td>
<td>0.52</td>
</tr>
</tbody>
</table>

**Table 4** Maximum stresses and strains in the pavement computed by the proposed small-scale FE model (Load Position B for capturing the effects of negative bending moment).

<table>
<thead>
<tr>
<th>$E_{a,c}$ (N/mm$^2$)</th>
<th>$\sigma_x$ (N/mm$^2$)</th>
<th>$\sigma_y$ (N/mm$^2$)</th>
<th>$\sigma_z$ (N/mm$^2$)</th>
<th>$\varepsilon_x$ $10^4$</th>
<th>$\varepsilon_y$ $10^4$</th>
<th>$\varepsilon_z$ $10^4$</th>
<th>$\sigma_x$ (N/mm$^2$)</th>
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<th>$\sigma_z$ (N/mm$^2$)</th>
<th>$\varepsilon_x$ $10^4$</th>
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</tr>
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<tbody>
<tr>
<td>2,000</td>
<td>2.9</td>
<td>3.2</td>
<td>-0.2</td>
<td>7.35</td>
<td>9.3</td>
<td>-16</td>
<td>-3.3</td>
<td>-3.3</td>
<td>-0.7</td>
<td>6.5</td>
<td>6.8</td>
<td>13</td>
</tr>
<tr>
<td>4,500</td>
<td>3.0</td>
<td>3.0</td>
<td>-0.27</td>
<td>3.75</td>
<td>3.75</td>
<td>-7.0</td>
<td>-3.38</td>
<td>-3.27</td>
<td>-0.7</td>
<td>3.3</td>
<td>2.9</td>
<td>5.56</td>
</tr>
<tr>
<td>6,000</td>
<td>2.93</td>
<td>2.81</td>
<td>-0.31</td>
<td>2.92</td>
<td>2.63</td>
<td>-5.0</td>
<td>-3.38</td>
<td>-3.26</td>
<td>-0.7</td>
<td>2.5</td>
<td>2.2</td>
<td>4</td>
</tr>
<tr>
<td>10,000</td>
<td>2.7</td>
<td>2.44</td>
<td>-0.42</td>
<td>1.9</td>
<td>1.5</td>
<td>-2.5</td>
<td>-3.23</td>
<td>-3.08</td>
<td>-0.7</td>
<td>1.7</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>20,000</td>
<td>1.95</td>
<td>1.52</td>
<td>-0.67</td>
<td>0.87</td>
<td>0.6</td>
<td>-0.8</td>
<td>-2.7</td>
<td>-2.7</td>
<td>-0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.36</td>
</tr>
</tbody>
</table>
As a consequence also the distress model of pavements on steel bridges is more especially identifiable in the fatigue cracking caused by the positive bending moment.

3.2. Small-Scale Model Validation and Addresses of Research

The proposed small-scale model for estimating stresses and strains in pavements on steel bridges, is similar to other models available in the international literature. In this respect, should be cited more especially the work of Kim et al. [17]. These authors validated their small-scale FE model, which presents characteristics comparable to that proposed in the present paper, in laboratory by means of reduced-scale tests. Therefore the author is confident that also the model here developed permits to estimate accurately enough the stresses and strains in pavement on steel bridges. However, for a more consolidated verification of the results obtained, research needs to be addressed towards building in laboratory a reduced-scale model and compared the results obtained.

Other points of interest that are worth to be investigated, regard specific distress models of pavements on steel bridges, as well as on concrete bridges. More especially fatigue laws, concerning both cracking that begins at the bottom of asphalt pavement and cracking that initiates at the top of pavement, should be developed. Rutting and thermal cracking laws should be also proposed.

4. SUMMARY AND CONCLUSIONS

This study investigated on simplified models for estimating stresses and strains in pavements both on concrete and steel bridges. Some of the findings obtained are summarized as follows.

The simplified model developed for asphalt pavements on concrete bridges can be identified in the elastic multilayer system, which is represented by the layers of the pavement and waterproofing supported by a rigid half-space (concrete deck). The results obtained show that the validity field of this model is influenced by the thickness and dynamic modulus of the pavement, as well as the stiffness of the waterproofing. In particular, with a high vertical stiffness of the waterproofing the simplified model can be used for values of the dynamic modulus of the pavement $E_{a,c}^* \leq 10,000 \text{ N/mm}^2$ and thicknesses of the pavement contained in the range 70-100 mm. When the vertical stiffness of the waterproofing is much lower, the simplified model can be used for $E_{a,c}^* \leq 10,000 \text{ N/mm}^2$ and a wider range of the thickness of the pavement 70-150 mm. This means that the contribution due to the deflection of the concrete deck may be neglected in these cases.

The simplified model developed for pavements on steel bridges can be identified in a small-scale model, compared to the full-scale bridge, which is presented with a supported continuous plate composed by the pavement, waterproofing, and steel deck. The proposed model appears to be validated by the results contained in the international literature. For a more consolidated verification of results, tests in laboratory should be made on a reduced-scale model that represents the long-span steel bridge.

The results show, both for the concrete and steel bridges, that the maximum tensile stresses and strains in pavement are found to be greater at the bottom rather than at the top of the pavement. This is attributable to the cumulative effect of the positive bending moments caused by the curvature of the deck and the deflection of the pavement, respectively. As a consequence the distress model of pavements on bridges is more especially identifiable in the fatigue cracking caused by the positive bending moment (resulting in cracks at the bottom of the pavement that will propagate to the pavement top).

However, there are still some points of interest that are worth to be investigated. More especially specific fatigue laws, as well as rutting and thermal cracking laws, should be
Simplified Models for Estimating Stresses and Strains in Pavements on Concrete and Steel Bridges

investigated for making a further incremental step possible in the field of the structural behaviour of pavements on bridges.

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