Development of a Lamella-Model for the Assessment of Stresses during Hot Asphalt Installation

An Overview and Validation of the Lamella-Model

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Abstract On road bridges, hot asphalt is installed to provide a protective, level and waterproof surface. That wearing surface however must be occasionally renewed after years of traffic loads. On a number of steel highway bridges, it has been observed that fatigue cracks increasingly occurred at the weld seams of orthotropic bridge-decks after such asphalt renewal. The German Federal Highway Research Institute has assigned a research project to RWTH Aachen University to evaluate the response of steel bridges to time- and location-dependent, nonlinear temperature profiles induced by the installed layer of hot asphalt. Since FEM-software even on modern computer systems could not provide solutions for long, large-span bridges due to the required level of detailing, a software-based lamella-model was developed that saves time and computing resources. The lamella-model allows the partition of the bridge into rectangular beam-lamella, which consider precisely the nonlinear temperature profile and provide the determination of the inner forces, stresses, strains and displacements over the cross-section and along the bridge. This paper presents the theoretical background of the lamella-program as well as results calculated exemplarily for a 742-meter-long German highway bridge including the validation with temperature and strain measurements from that bridge during asphalting.

1 Introduction

Over the years, steel bridges have experienced increasing damage due to dynamic loads and higher traffic volume. This damage often manifests in the form of cracks, particularly in weld areas of the bridge deck. The installation of hot asphalt on steel decks has also contributed to the development and growth of cracks as well as to damage at the supports. Given the shorter lifespan of asphalt layers compared to the underlying structural elements, bridges typically require multiple asphalt renewals throughout their service life. The observed correlation between increased damage and asphalt renewal suggests a potential link between the loads associated with these renewals and the resulting damage. Studies have been initiated to investigate this relationship, aiming to quantify the load introduction and stresses in critical areas. These projects are primarily initiated by the German Federal Highway Research Institute (BASt – Bundesanstalt für Straßenwesen) and funded by the Federal Ministry for Digital and Transport (BMDV).

Two primary influences were identified in these projects as relevant for their impact on the load-bearing structure and the initiation of damage. The first significant influence arises from the removal of the asphalt, typically achieved by milling it from the steel deck. This process exerts a dynamic load with high frequency. Subsequently, after the complete removal of asphalt layers, a second influential load occurs during asphalt installation, which often involves using hot material at temperatures between 200 and 230°C, thereby imposing a high temperature load on the load-bearing structure. Furthermore, these loads increased over the past years due to the introduction and advancement of larger machines, leading to higher dynamic and thermal impact on the structure. With a primary focus on thermal loads, previous projects have measured temperature as well as resulting strains and stresses on steel bridges during asphalt installation at various locations such as the steel deck, longitudinal stiffeners and main girders. The results have shown a highly nonlinear temperature profile across the bridge's cross-section, as the steel deck including the stiffeners and the upper parts of the main girders experience very high temperatures followed by a substantial gradient with lower temperatures in the middle and bottom parts of the cross-section. [1,2,3]

Based on these measurements, a recent research project at RWTH Aachen University focused on developing numerical models to evaluate strains and stresses caused by this thermal load. These models are intended to serve as the foundation for parametric studies, investigating the influence of various parameters, such as asphalt installation temperature, laying speed or ambient temperature, on the stresses and deformations that occur at the bridge and the supports. Typically, these results are computed using finite element (FE) analysis software like ANSYS [4] to simulate how the bridge's cross-section and static system responds to thermal loads. A transient thermal analysis was performed using the FE-software to determine the temperature distribution within the system. The time-dependent temperature fields were then utilized as input for subsequent static structural analysis, aiming to calculate the stresses, strains and deformations caused by the thermal expansion. However, this step proved too computationally intensive even for modern computer systems due to the selected long large-span bridge necessitating a high number of elements in the FE-model combined with numerous time steps in both thermal and static structural analyses.

In order to obtain a solution for the structural behaviour under the thermal load, another solution was presented by writing a program in the software MATLAB [5]. In this program, the investigated bridge cross-section is considered with all necessary degrees of freedom to precisely calculate the requested results such as stresses and deformations along the bridge due to the asphalt installation process. This paper briefly presents the development process including the motivation and theory behind the lamella-program, the validation of the results compared to an FE-model of an exemplary short bridge and the results compared to the real-time measurements of the long, large-span reference bridge.

2 Development and Validation of a Lamella-Program

2.1 Motivation for the Lamella-Program

In the framework of the project, a reference bridge with an open cross-section was selected to calculate and validate the stresses and strains for the thermal load induced by the asphalt renewal and on which temperature and strain measurements were taken during the asphalt laying process. The German highway bridge is called *Mühlenfließbrücke* and spans 742 meters across 13 fields with varying lengths ranging from 47 to 61 meters, featuring a separate superstructure for each traffic direction. The bridge is supported in the longitudinal direction at the column-axis between fields 6 and 7. Longitudinal deformations resulting from temperature changes of the cross-section propagate outward from the middle of the bridge's length towards both ends, causing the greatest horizontal deformation at the end supports.

The investigated bridge cross-section, depicted in the form of the FE-model in Figure 1, comprises an 18.25-meter-wide orthotropic steel deck (2). This deck consists of two cantilevers (6.50 and 2.45 meters) and a central section between the main girders with a width of 9.30 meters, including a 1.5 mm insulation layer and a 35 mm asphalt layer (1) on top. The steel deck is 12 mm thick and reinforced with trapezoidal stiffeners (3) at intervals of approximately 600 mm, along with transverse girders (4) every 4 meters. To facilitate drainage, the steel deck has a surface inclination of 2.5%, resulting in main girders of varying heights. The first girder (5) along the longer cantilever has a height of 2.87 meters, while the other main girder (6) along the shorter cantilever measures 2.97 meters in height.

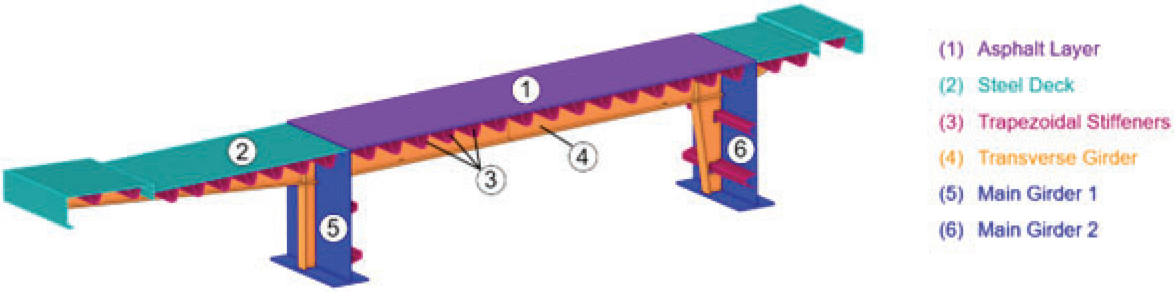

Figure 1: Visualisation of the primary structural elements of the bridge *Mühlenfließbrücke*

Through multiple inspections, damage was mainly noted at the welds between the steel deck and the trapezoidal stiffeners as well as the welds connecting the main girders to the steel deck. These damages were particularly found following the renewal of the asphalt layer, subsequent to milling off the old layers and installing the new layers using hot asphalt material. This study, conducted at RWTH Aachen University, focused on analysing the influence coming from the hot asphalt installation including the possible contribution to these damages.

To accurately predict stresses, strains and deformations coming from the thermal load, a comprehensive numerical model is essential. Due to the varying temperature distribution along the bridge's length and over time, a detailed model representing the entire 742-meter long structure is required. This allows for the evaluation of various temperature combinations and their corresponding structural responses.

Figure 2 illustrates the temperature evolution during asphalt installation at specific time intervals along the bridge and for a given nonlinear temperature profile along the height and width of the bridge's cross-section. The highest temperature is initially found at the top surface of the steel deck directly after the section is asphalted, but it gradually cools down as the paving machine progresses along the bridge.

For accurate numerical investigations, it is crucial to use small time intervals and sections where the nonlinear temperature profiles are assumed to be constant along the longitudinal direction of the bridge. The section length can be controlled using a discretisation length dx, which corresponds to the element length in a finite element mesh.

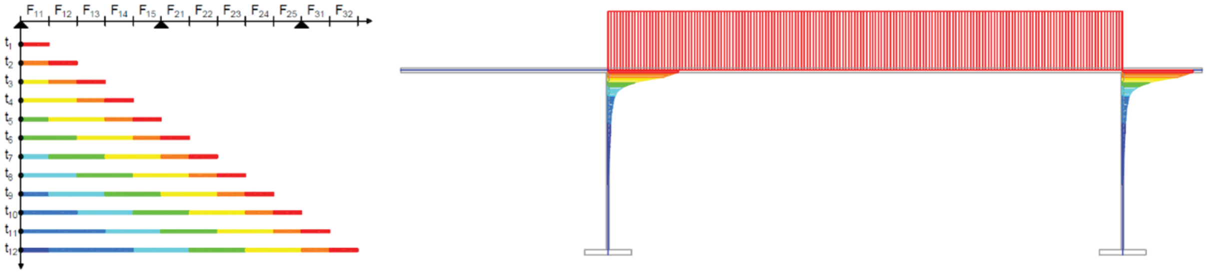

Figure 2: Transient temperature evolution during asphalt installation along the bridge and through the cross-section

Within the project framework, the finite element software ANSYS [4] was employed to model the bridge's cross-section in detail and to use scripting capabilities to incorporate complex, time-varying temperature loads for transient thermal analysis. The reference bridge's considerable length of 742 meters resulted in an FE-model with millions of degrees of freedom and combined with the transient analysis it resulted in even more equations, which needed to be solved. This posed a significant challenge even for modern computational systems and exceeds the capabilities when calculating this large-scale model in thermal as well as structural transient analyses. Creating a shorter sub-model or using analytical approaches were not viable either, as the stress results as well as the deformation could not be represented because of the high dependency on the temperature profiles over several fields of the bridge as well as the height of the cross-section.

To address these challenges, an already developed MATLAB-code for a lamella-model, used to calculate stresses, strains and deformations of composite-beams [6], was adapted to match specific geometrical and material properties of the investigated bridge. Additionally, it was adjusted to account for the thermal loads resulting from the asphalt installation. The following chapter provides an overview of the essential components of the program, including the geometry and load input, the solution of equilibrium equations and the output of results.

2.2 Theoretical Framework of the Lamella-Program

Similar to modern finite element simulations, the numerical solution used in the lamella-program requires input data for geometry, boundary conditions (such as loads and supports) and material properties. This information is used to construct a system of equations, which is then solved. The program subsequently generates tabular or graphical results for the desired parameters. The flow-chart in Figure 3 illustrates this process.

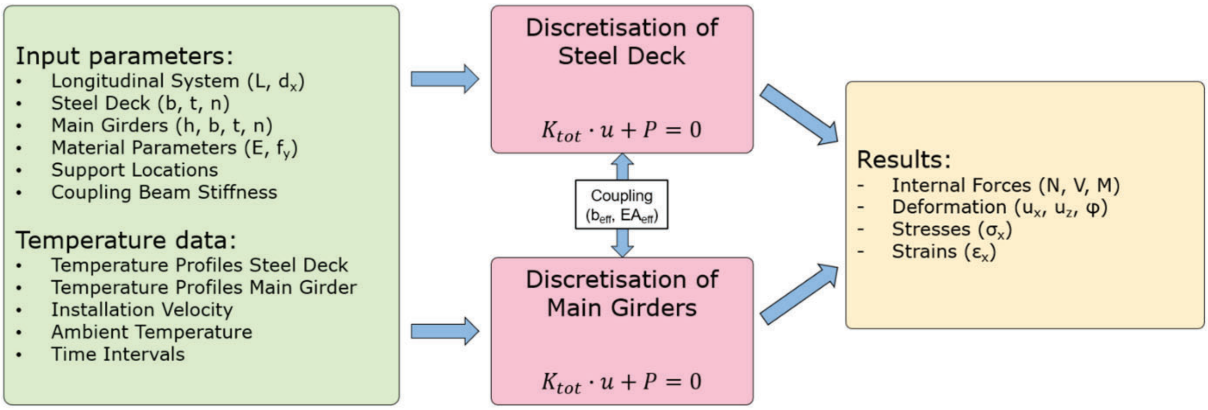

Figure 3: Flow-chart of the lamella-program including input parameters, discretisation of the steel deck and main girders as well as the coupling between them and output results

To build the system of equations, input parameters for defining the geometry, material, supports and loading conditions are needed. In longitudinal direction of the bridge, the whole length needs to be specified and divided into equally long beam elements through the discretisation length d_x. For the cross-sectional values, the steel deck and main girders are defined by the overall height, width and thickness as well as the number of parallel beam-lamellas. Each lamella consists of beam elements with two nodes and geometrical parameters such as the length d_x, height and width from the defined values assigned to it. Arranged perpendicular to the beam-lamellas and connected to the nodes are the coupling-beams, which need proportionally high stiffness values in comparison to the main beam-lamellas in order to transfer the forces and displacements without leading to too much shear deformation. The resulting mesh of lamella- and coupling-beams is positioned in a plane, resulting in a planar stress state and three degrees of freedom at each node: u_x, u_y and φ_z. All nodes multiplied by the three degrees of freedom builds the total size of the vector u for the entire bridge, which needs to be solved in order to get the desired results of stresses and deformations. To meet the equilibrium condition, the stiffness matrix K_{tot} needs to be derived from the geometry of each corresponding lamella and provides the link between the vector u and the load vector P, which contains the temperature load at each node and degree of freedom.

The nonlinear temperature profiles for the steel deck and the main girders represent the load for these nodes and are taken from calibrated FE-models (geometry in Figure 1) at the exact positions corresponding with the outer edges of the lamellas. The average value of the lamella temperature corresponds to the normal force entry in the load vector P (ux-position), whereas the difference between the upper and the lower edge temperature values is assigned to the bending moment entry of the vector P (φ_z-position). The nonlinear temperature can be captured more accurately and ensure better results in the end, if the discretisation length d_x in the longitudinal bridge direction is relatively small and the cross-section is sliced into a higher number of lamellas.

Because of the planar system with three degrees of freedom at each node, it is unfeasible to represent the steel deck and the main girders, which are oriented perpendicular to one another, within a single continuous lamella-model. The solution to this is the coupling of two separate equation sets, one containing the steel deck with two lamellas representing the respective main girder lamella and one containing the main girders, where the upper flange is the coupling lamella with the geometry of the steel deck including an effective width. Both models for the steel deck and the main girders are exemplarily visualized in Figure 4 including the nodes, beam-lamella and coupling beams as well as the notation for the present degrees of freedom.

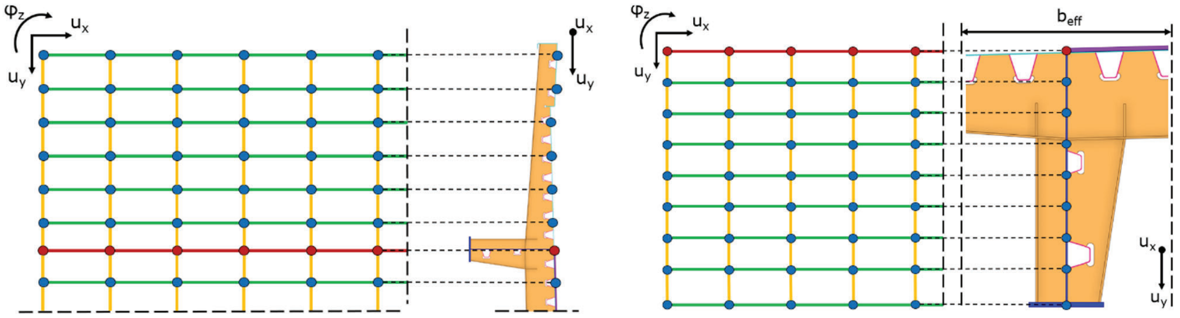

Figure 4: Exemplary discretisation of the steel deck (left) and the main girders (right) for the lamella-model including: beam-lamella (green), equivalent lamella for main girder / steel deck (red) and coupling-beam lamella (yellow)

The steel deck lamella discretisation on the left-hand side of Figure 4 is illustrated in the top view, in which each longitudinal lamella-beam has the geometrical properties of the width between each neighboured lamella incorporated, as it is provided from the user in the input data. At the connection points of the steel deck to the respective main girder web, an additional lamella is introduced to represent the cross-sectional properties of the underlying main girders. Due to the relatively large values of these cross-sectional properties, such as the area and the moment of inertia, the equivalent lamella-beam exhibits high stiffness at these locations and effectively redirects internal forces towards it. This phenomenon, known as 'shear lag', necessitates precise consideration of the deformation capabilities of the main girder. This encompasses not only the longitudinal stiffness EA, but also the behaviour of rotational stiffness. The influence can be represented by a rotational spring positioned at the centre of gravity of the entire bridge cross-section. Integrating this rotational spring stiffness with the longitudinal stiffness EA, which is the sole property that the bridge deck's lamella-beam can capture from the main girders below, involves transforming the rotational spring into a linear spring located in the steel deck position. Consequently, the longitudinal stiffness EA and the equivalent spring stiffness can be combined or subtracted from each other, depending on whether the bending moment at that location is positive or negative.

Similarly, for the lamella-model shown on the right-hand side of Figure 4, the main girders are discretized with the same longitudinal length of d_x as the steel deck, incorporating one lamella for the upper and lower flanges, as well as several lamellas for the web plate to accurately account for the nonlinear temperature field in the main girder. The upper flange in the main girder is equal to the steel deck. However, including the entire width of the steel deck in the properties of the upper flange lamella would make the cross-section disproportionally stiff. As a consequence, this would lead to excessively low stress and deformation results. To address this issue, an effective width is introduced in accordance with EN 1993-1-5 [7]. This geometric parameter represents the equivalent width of the upper flange, ensuring a constant stress value across the width for a given load, which is equally large as the realistic stress distribution. As a result, this value is influenced by the bending moment and consequently varies over time due to the change of temperature and depending on the location (e.g. support or field area). In areas where the paving machine has not yet traversed the section, the effective width is equal to the entire steel deck width.

Once all essential elements, including geometry, nonlinear temperature load and the coupling of the steel deck with the main girders, have been implemented, results can be achieved by solving the equation system for the degree of freedom vector u. The internal forces, deformations as well as resulting stresses and strains are presented as output data in tabular format for subsequent post-processing. Additionally, an initial visual summary of the main results is depicted in the programs interface. To verify the accuracy of the results, the validation of the lamella-program will be demonstrated in the following chapters using an FE-model of a short exemplary bridge and the measured data from the reference bridge *Mühlenfließbrücke*.

2.3 Comparison and Validation of the Lamella-Model with FEM

While programming the described lamella-model, which includes various aspects such as the effective width for the main girder calculation and the rotational stiffness for the steel deck calculation, it was necessary to validate it against other conventional methods. As it is not feasible to calculate an FE-model of the reference bridge for its entire length, which lead to the lamella-program in the first place, an exemplary bridge with the same cross-section but only two fields, each spanning over 22.5 meter, was modelled and simulated for the thermal load. Concurrently, it was calculated using the lamella-program.

In order to compare the results from both methods, the stresses across the width of the steel deck and along the height of the main girders are assessed at the midspans and middle support. Additionally, considering the time-dependency, stress states are compared at various points in relation to the asphalting process.

Figure 5 provides an illustrative display of the stress outcomes in the steel deck at the midpoint of the first field, one thousand seconds after the beginning of asphalt installation. At this location, temperatures reach their peak, resulting in high compression stresses of up to 140 MPa. Since the asphalt layer is only laid between the two main girders, the cantilevered sections of the steel deck remain relatively cool and consequently exhibit tensile stresses. Both models yield almost identical results across the steel deck, a pattern observed at other locations along the bridge and at various time points with different temperature values.

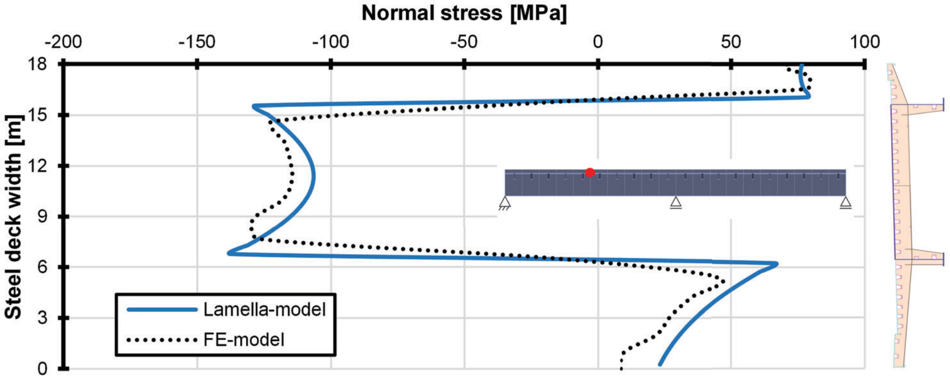

Figure 5: Stress results of the steel deck from the lamella-model and an FE-model of an exemplary 2-field bridge 1,000 seconds after asphalting (Location: midspan of the first field)

Similar to the steel deck, the stresses in the main girder are also compared between the lamella- and FE-model to validate the results, as shown in Figure 6. The highly nonlinear temperature profile along the height of the main girders (see Figure 2) introduces nonlinearity in the stresses as well. Particularly near the steel deck (height 0 to 0.5 m), high tensile stresses are evident due to the significant temperature gradient. The results from both methods exhibit strong similarities, with minor deviations likely attributed to the coarse discretisation in the FE-model.

The previous two comparisons only depict stress results in relation to the width of the steel deck or the height of the main girder, with a constant time point after the start of asphalt installation. In order to compare stress results between the lamella-model and the FE-model based on the time elapsed since asphalt installation, a specific location is selected at the steel deck directly above the first main girder (width equal to 6 m) and the results are visualised in Figure 7. Once more, the two curves exhibit a very good agreement.

In conclusion, the stress results from the validation of the lamella-model are comparable to those obtained from a detailed but more resource-intensive FE-simulation. To highlight the advantage of the self-programmed lamella-model, the computational time required to solve the FE-model

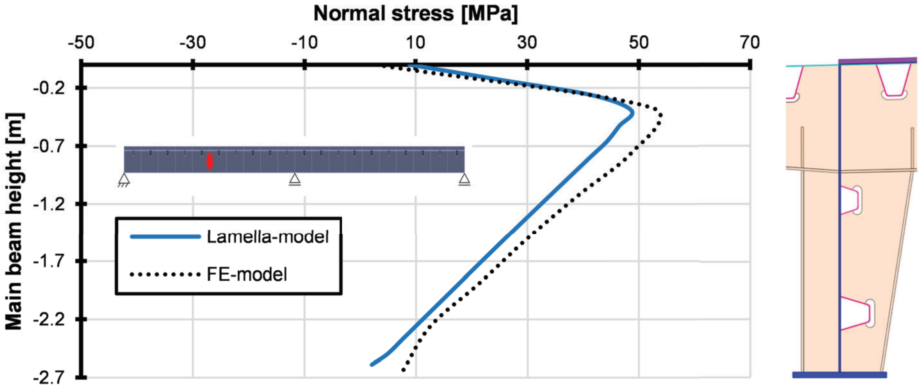

Figure 6: Stress results of the first main girder from the lamella-model and an FE-model of an exemplary 2-field bridge 1,000 seconds after asphalting (Location: midspan of the first field)

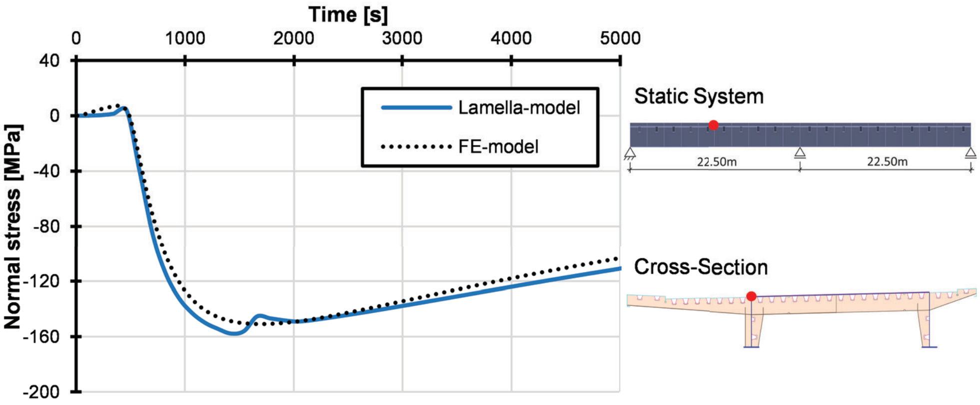

Figure 7: Transient stress results from the lamella-model and an FE-model of an exemplary 2-field bridge (Location: midspan of the first field at the transition point of the steel deck and the first main girder)

for the exemplary two-field bridge was 30 hours, whereas the lamella-model produced equivalent transient stress results in just about 10 minutes.

2.4 Results for Long Large-Span Reference Bridge Mühlenfließbrücke

After validating the lamella-model with the hypothetical two-field bridge system, the analysis of the entire reference bridge can be conducted. This involves inputting the entire length of the bridge, establishing supports at the appropriate nodes and implementing a suitable discretisation of the longitudinal system and cross-section to ensure accurate results.

With a total bridge length of 742 meter and an asphalt laying speed of 1.3 m/min, the paving machine requires approximately 34,000 seconds to asphalt the entire length of the bridge. In order to assess the stresses during the heating and the cooling phase of the structure, a total simulation time of 80,000 seconds is selected. By this time, even the steel cross-section in the last field nearly returns to its initial temperature prior to asphalt installation.

The diagram on the left-hand side in Figure 8 presents the measured stress data during asphalt installation in one of the middle fields of the bridge. Strain gauges were strategically positioned at the top of the web of the first main girder near its weld to the steel deck. Initially, asphalting of the first bridge fields causes a nearly zero stress response. However, as the paving machine progresses towards the measurement position, thermal expansion induces a bending moment in the upcoming fields. The closer the machine approaches, the higher the bending moment and subsequent stress response become. Notably, due to thermal expansion occurring exclusively on the top side, the sign of the bending moment changes for each asphalted field. Only after asphalting in direct proximity to where the strain gauges are located do both bending moment and resulting stresses notably increase and peak at their highest value. Subsequently, as cooling of the cross-section commences, stresses gradually diminish towards their initial values.

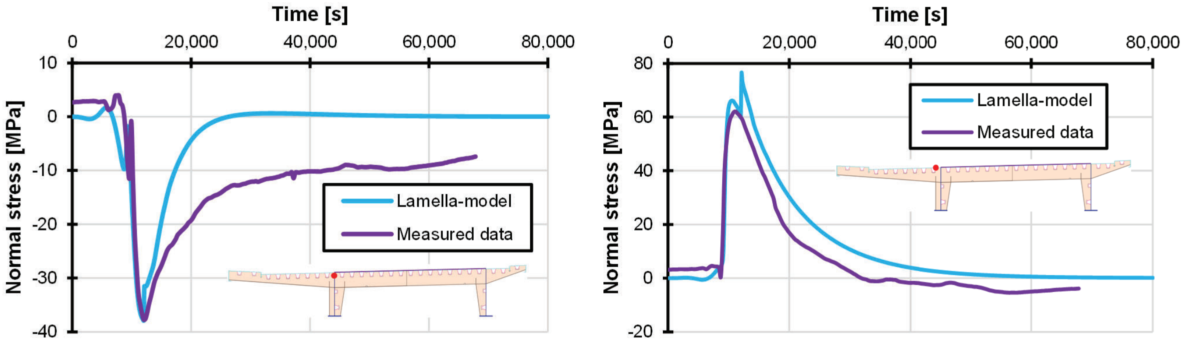

Figure 8: Comparison of lamella-model stress results with measured data during asphalting at the upper end of main girder web 1 (left) and at the long cantilever of the steel deck (right)

Upon reviewing the results obtained from the lamella-model, it becomes evident that the same aspects observed in the measurement data are reflected in the calculations. With minor time-shifts aside, the curves of the measured data and the lamella-model exhibit complete overlap, including maximum stress results of approximately -38 MPa. The primary discrepancy between the two curves arises after asphalting of the corresponding field, when the cross-section begins to cool down.

One potential explanation for this disparity could stem from the calibrated FE-section-model, which provides input temperature data for the lamella-model. If the cooling rate is not accurately represented, causing the model to cool down faster than in reality, then stresses would diminish more rapidly. Another possible explanation could be attributed to the additional weight from the asphalt layer installed atop the steel deck during asphalting. This extra permanent load influences strain gauge measurements, whereas the lamella-model solely captures stress changes due to the thermal load. This distinction is also apparent at the initial offset of measured data, while the lamella-model commences and converges to a value of 0 MPa.

The tensile stresses in the cantilever parts of the steel deck, as depicted in the diagram on the right-hand side of Figure 8, are more critical than the compressive stresses shown before, particularly concerning potential damages to the welds of the bridge deck. These measured data are obtained at the longitudinal stiffener closest to the main girder, representing the location of the highest tensile force in the cantilever. As one moves towards the end of the cantilever, the stresses diminish (compare Figure 5).

Like the comparison at the previous location, the stress comparison between the strain gauges and the lamella-model results demonstrates good agreement at this location of the cross-section too. Even during the cooling of the cross-section, the stresses are nearly overlapping. This observation could further support the impact of the weight of the newly installed asphalt layer, given that it is only applied on the steel deck between the main girders and not on the cantilevers.

Following the validation of the lamella-program using an FE-model and measured data from the reference bridge, it became feasible to investigate the impact of various asphalt installation parameters such as laying temperature, laying speed and ambient temperature within the scope of the project. Additionally, the global stresses at the edges of the beam-lamella can be combined with locally derived stress concentrations from the FE-model to assess the maximum stresses in the welds that possibly contribute to the observed damages. A comprehensive analysis and interpretation of these results is presented in the project report [8].

3 Conclusion

To investigate the impact of asphalt installation on the performance of an orthotropic steel bridge, a lamella-program was created to compute the stresses and deformations resulting from thermal expansion. Specifically, a numerical lamella-beam-model representing the precise geometry of the German highway bridge *Mühlenfließbrücke* was developed to accurately capture the complex nonlinear temperature load. A comparable model constructed using FE-software was too large to be processed by modern computer systems.

The lamella-program resolves the equations for each degree of freedom within the lamella-model and encompasses various factors such as equivalent stiffness values and the establishment of an effective width in accordance with Eurocode standards to accurately capture the stress distribution resulting from asphalt installation. The outcomes are validated against an exemplary FE-model and measured data from the reference bridge during asphalt installation, showing strong agreement. The computational time required by the lamella-program is approximately 200 times less than that of the solid FE-model.

The program includes key elements for efficiently obtaining the required stress and deformation results through a brief simulation. For future research, there is potential to incorporate additional degrees of freedom (three-dimensional modelling) to represent the entire cross-section without the need for segmentation into distinct components. This could also facilitate the acquisition of out-of-plane results for the steel deck and main girders, potentially accounting for constraint stresses not currently accounted for in the results. Furthermore, the thermal load could be integrated with other loads stemming from self-weight and traffic, enabling comprehensive capture of total stress amplitudes leading to structural damage in the steel bridge deck.

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