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Research Paper

Influence of Solar Radiation on the Design Positioning of Bearing Components in Road Bridge Superstructures

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ABSTRACT

Solar radiation represents a dominant climatic action influences the deformation behaviour and serviceability performance of highway bridge superstructures. Due to daily and seasonal variations in ambient temperature and solar position, bridge spans are subjected to non-uniform and time-dependent temperature fields, which may induce spatial thermal deformation and lead to deviations of bearing components from their intended design positioning. This study investigates the influence of solar radiation on the design positioning of bearing components in a road bridge superstructure with an orthotropic steel deck. A refined three-dimensional finite element model is developed using the LIRA-SAPR software, incorporating temperature fields obtained from in-situ measurements, temperature-dependent mechanical properties and shear rigidity of pavement layers, and a staged analysis procedure implemented through the installation subsystem. The numerical results are validated against instrumental field measurements of temperature and bearing displacement. The analysis reveals that non-uniform solar radiation produces asymmetric longitudinal and transverse displacements of movable bearing components, which cannot be adequately captured by simplified thermal assumptions commonly used in design practice. The maximum deviation of bearing positioning reaches values comparable to, and in some cases exceeding, those commonly considered in design practice. The results highlight the spatial nature of thermally induced deformation and demonstrate the necessity of explicitly accounting for solar radiation effects when determining the design positioning and serviceability performance of bearing components in road bridge superstructures.

1 Introduction

Highway bridge superstructures are continuously exposed to environmental actions throughout their service life, among which thermal effects caused by solar radiation play a significant role in structural behaviour. Variations in ambient

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temperature and solar radiation during the day lead to non-uniform and time-dependent temperature fields within bridge spans. Such asymmetric thermal actions may induce spatial deformation, redistribute internal forces, and affect the serviceability of structural components. However, these complex thermal effects are often simplified in conventional bridge design approaches, which typically assume uniform temperature distributions [1–5].

The influence of temperature on structural systems has been extensively studied in bridge engineering. Previous research has shown that solar radiation may generate significant temperature gradients in bridge spans, leading to additional stresses and deformation beyond those predicted by simplified thermal models [4–6]. Field measurements and numerical simulations have confirmed that non-uniform temperature fields can produce complex deformation patterns and significantly influence the structural response of bridge systems [7–9].

With the development of numerical methods, finite element analysis has become an effective tool for investigating thermal behaviour in bridge structures. Recent studies reported that solar radiation induces vertical and transverse temperature gradients in bridge decks, which in turn modify internal force distribution and deformation patterns in steel and composite bridge systems [9–10]. In addition, the behaviour of pavement layers has been shown to significantly influence the overall response of bridge superstructures due to temperature-dependent material properties and shear interaction between pavement and deck layers [6–8].

Particular attention has been given to bridge superstructures with orthotropic steel decks, which are highly sensitive to non-uniform thermal actions due to their thin-walled configuration and high structural redundancy. Numerical and monitoring-based studies demonstrated that uneven solar heating may lead to spatial deformation and additional stresses in such systems, often exceeding those predicted by standard design approaches [9–11]. Field monitoring results further confirm the significant influence of solar radiation on bridge deformation during both construction and service stages [13–14].

Despite the extensive research on temperature fields and thermally induced stresses in bridge structures, most existing studies primarily focus on the stress–strain state of girders, decks, and pavement layers. In contrast, the influence of spatial thermal deformation on the design positioning and displacement behaviour of bridge bearing components has received considerably less attention. Bearing components play a crucial role in controlling the kinematic behaviour of bridge spans, and excessive thermally induced displacements may lead to bearing malfunction, additional constraint forces, and long-term maintenance problems.

This issue is schematically illustrated in Fig. 1. Under conventional longitudinal bending assumptions, bearing behaviour is typically characterised by a single longitudinal displacement component (Fig. 1a). However, non-uniform solar radiation may cause spatial thermal deformation of the bridge superstructure, resulting in a more complex displacement pattern that includes both longitudinal and transverse components (Fig. 1b).

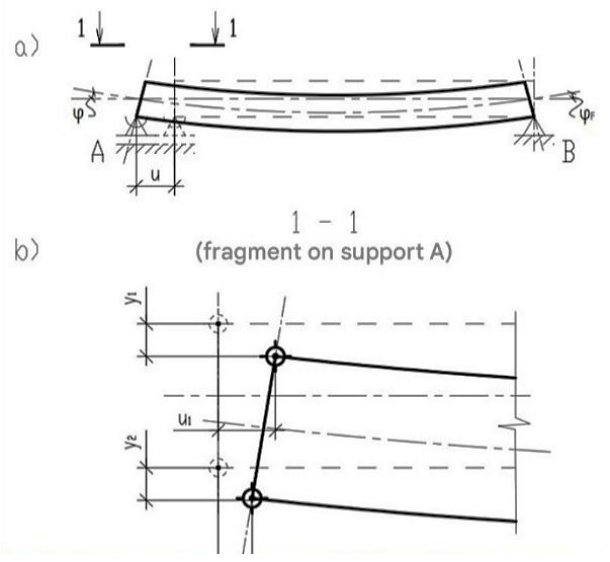


Fig. 1- Displacement diagrams of support components under (a) longitudinal bending and (b) spatial thermal deformation

Therefore, a detailed investigation of the influence of solar radiation on the spatial displacement and design positioning of bridge bearings is required. In this study, the spatial thermal deformation behaviour of a highway bridge superstructure with an orthotropic steel deck subjected to non-uniform solar radiation is investigated. A refined three-dimensional finite element model is developed using LIRA-SAPR, incorporating measured temperature fields, temperature-dependent pavement properties, and staged structural analysis. The numerical results are validated using field measurements, and the findings aim to improve the design and installation of bearing components in bridge structures subjected to significant climatic temperature variations.

2 Finite element model of the superstructure

2.1 Structural configuration and finite element discretisation

The analysed highway bridge superstructure is a steel system with an orthotropic deck, representative of medium-span road bridge structures widely adopted in modern highway infrastructure. The superstructure consists of a single span with a total length of 43.1 m and is supported by two main longitudinal I-section girders with a height of 2400 mm. These primary girders carry an orthotropic steel deck with a 12 mm thick top plate, forming a total deck width of 11,340 mm. Owing to its thin-walled components and internally highly redundant structural system, such a configuration is particularly sensitive to non-uniform thermal actions induced by solar radiation. To investigate the influence of solar radiation on the design positioning of bearing components, a three-dimensional spatial finite element (FE) model of the superstructure was developed using the LIRA-SAPR software package. The model explicitly includes the main load-bearing steel elements as well as the pavement layers, enabling simulation of non-uniform temperature distribution over the depth of the bridge cross-section and assessment of spatial thermal deformation effects.

The discretisation strategy of the finite element model was selected to provide an adequate balance between computational efficiency and accuracy in predicting deformation behaviour and stress–strain response. Volumetric finite elements were employed to model the orthotropic deck and pavement layers, allowing detailed representation of temperature gradients through the thickness of these components. Shell elements were adopted for the main longitudinal girders and stiffening elements, while beam (rod) elements were used to represent transverse beams and bracing members. This combination of element types ensures a realistic representation of the structural behaviour under combined mechanical and thermal actions. The overall three-dimensional finite element model of the bridge superstructure, including the global geometry, element discretisation, and representation of the main structural components, is illustrated in Figs. 2–5.

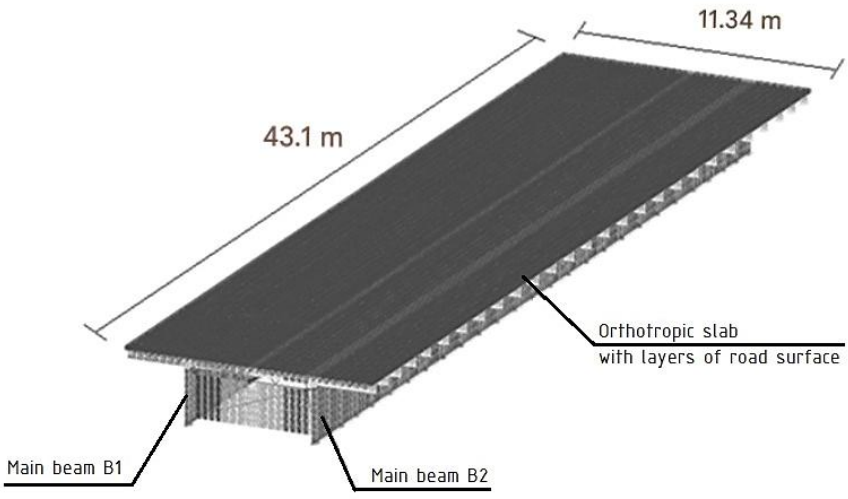
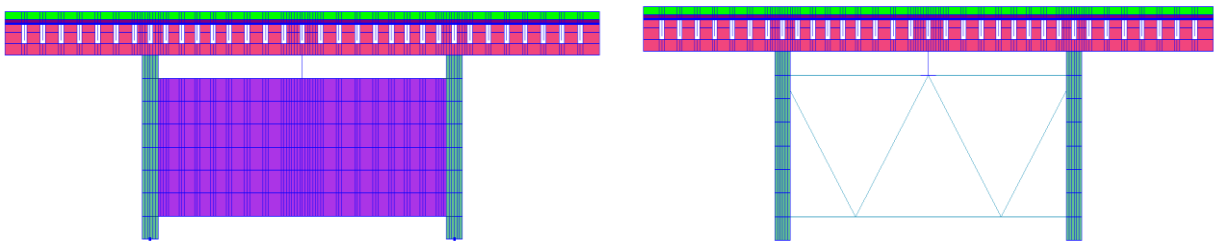


Fig. 2- Finite element model of the bridge superstructure

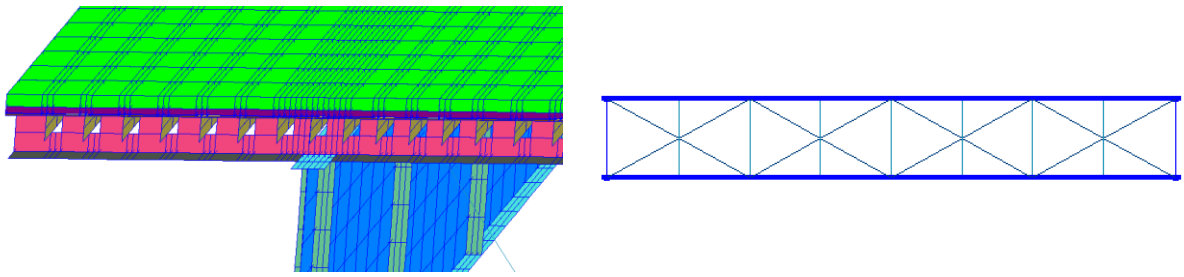
The cross-section of the span structure is shown in Fig. 3.

Fig. 4 shows the connection of the main beam with the cross beam of the orthotropic slab and the general view of the longitudinal connections.



(a) (b)

Fig. 3- Cross-section of the span structure: a) on the support; b) in the span



(a) connection between the main beam and the cross beam of the orthotropic slab

(b) general view of the longitudinal connections

Fig. 4- FE model of a superstructure with an orthotropic slab

The finite element model of the pavement structure is shown in Fig. 5.

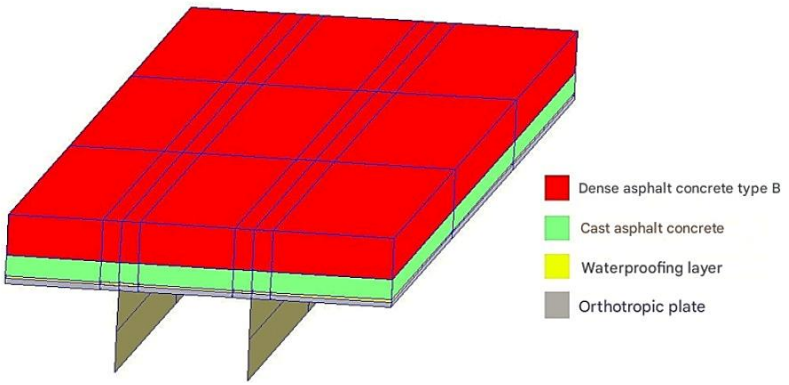


Fig. 5- FE model of the road pavement layers in a superstructure with an orthotropic slab

To improve the accuracy of the thermo-mechanical analysis, the finite element mesh was locally refined in regions corresponding to temperature measurement points. Such refinement enables more precise modelling of spatial temperature gradients and associated thermal strains, which is essential for reliable evaluation of spatial deformation patterns and the resulting deviations in the design positioning of bearing components. The overall finite element discretisation adopted in this study provides sufficient resolution to capture the key features of the superstructure response under non-uniform solar radiation.

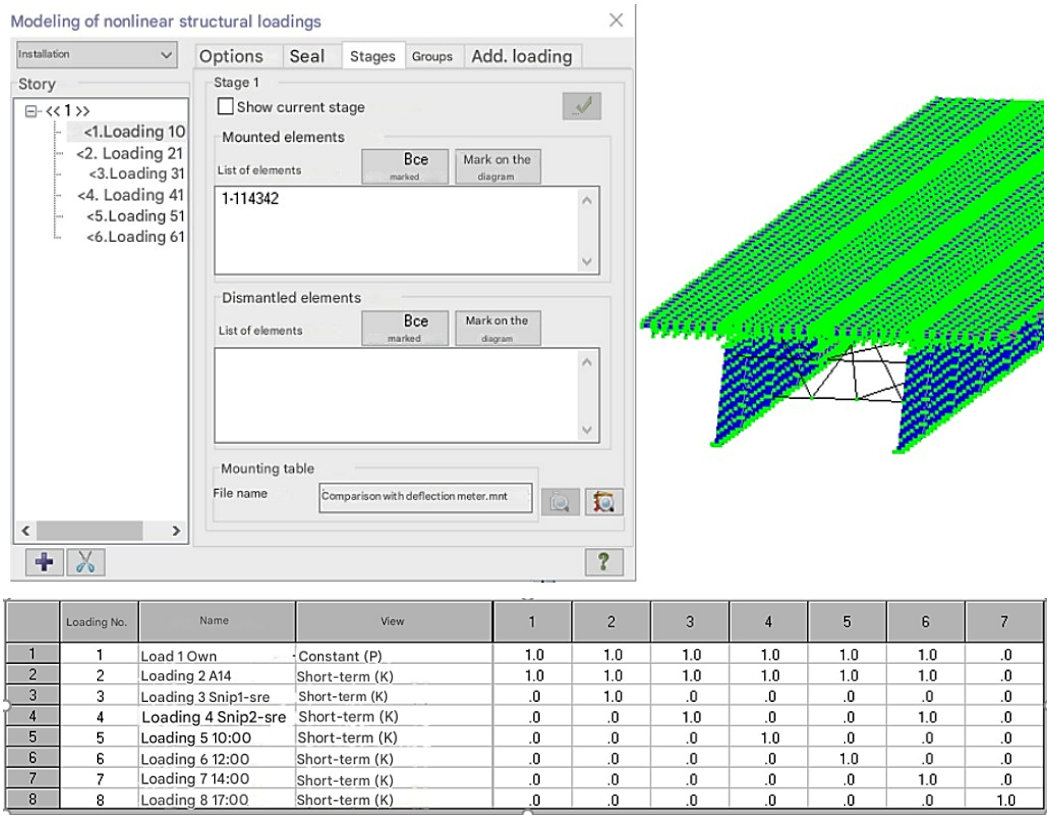
2.2 Modelling of pavement layers and connecting elements

In order to realistically capture the thermo-mechanical response of the bridge superstructure under solar radiation, the pavement system was explicitly included in the finite element model. The pavement layers were represented as a multilayer system placed on top of the orthotropic steel deck, allowing the influence of temperature-dependent mechanical properties

and shear interaction between layers to be taken into account. Such modelling is essential for evaluating spatial thermal deformation, as pavement layers significantly affect both temperature distribution and overall stiffness characteristics of the superstructure.

The mechanical interaction between the pavement layers and the steel deck was modelled using elastic connecting elements of type FE55 available in the LIRA-SAPR software. These connector elements enable simulation of shear interaction between adjacent layers while allowing relative slip, thereby providing a more realistic representation of pavement–deck interaction compared with rigid connection assumptions. The stiffness parameters of the FE55 elements were selected in accordance with experimentally established values reported in previous studies, ensuring consistency with observed behaviour of pavement systems subjected to thermal actions.

The adopted modelling approach for the pavement layers and the assumed interaction schemes between the pavement system and the orthotropic steel deck are illustrated in Figs. 6–8.

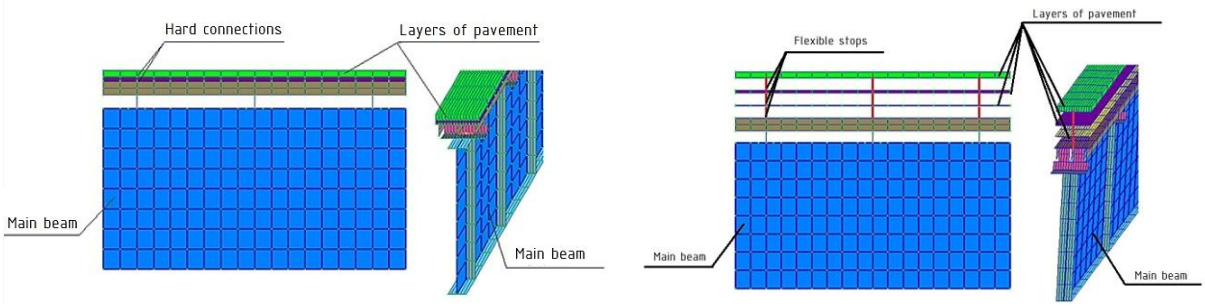


	Loading No.	Name	View	1	2	3	4	5	6	7
1	1	Load 1 Own	Constant (P)	1.0	1.0	1.0	1.0	1.0	1.0	.0
2	2	Loading 2 A14	Short-term (K)	1.0	1.0	1.0	1.0	1.0	1.0	.0
3	3	Loading 3 Snip1-sre	Short-term (K)	.0	1.0	.0	.0	.0	.0	.0
4	4	Loading 4 Snip2-sre	Short-term (K)	.0	.0	1.0	.0	.0	1.0	.0
5	5	Loading 5 10:00	Short-term (K)	.0	.0	.0	1.0	.0	.0	.0
6	6	Loading 6 12:00	Short-term (K)	.0	.0	.0	.0	1.0	.0	.0
7	7	Loading 7 14:00	Short-term (K)	.0	.0	.0	.0	.0	1.0	.0
8	8	Loading 8 17:00	Short-term (K)	.0	.0	.0	.0	.0	.0	1.0

Fig. 6- Simulation of stage-by-stage loading using the installation subsystem in the LIRA-SAPR complex

To evaluate the influence of modelling assumptions on the design positioning of bearing components, two alternative interaction schemes between the pavement layers and the orthotropic deck were considered. In the first scheme, a rigid connection was assumed, enforcing full compatibility of displacements between layers. In the second scheme, a flexible connection was adopted using FE55 elements, allowing relative shear deformation. Comparison of these two modelling approaches makes it possible to assess the role of pavement layer interaction in the development of spatial thermal deformation and its contribution to bearing positioning deviations. The shear rigidity of the pavement layers is taken into account. Two finite element models were developed: one with flexible restraints and another with rigid restraints as shown in Fig. 7.

The adopted modelling strategy enables explicit consideration of the combined effects of temperature-dependent pavement stiffness, shear interaction between layers, and non-uniform thermal loading. This approach provides a more accurate description of the superstructure response under solar radiation and allows reliable evaluation of the resulting deviations in the design positioning of bearing components. In the computational model, the connecting elements are represented using special two-node FE 55 elastic connectors, which operate linearly in tension and compression. These elements are characterized by linear stiffness in all six degrees of freedom (see Fig. 8).



(a) with rigid connections *(b) with flexible restraints*

Fig. 7- Two variants of the finite element model of a span structure with an orthotropic slab

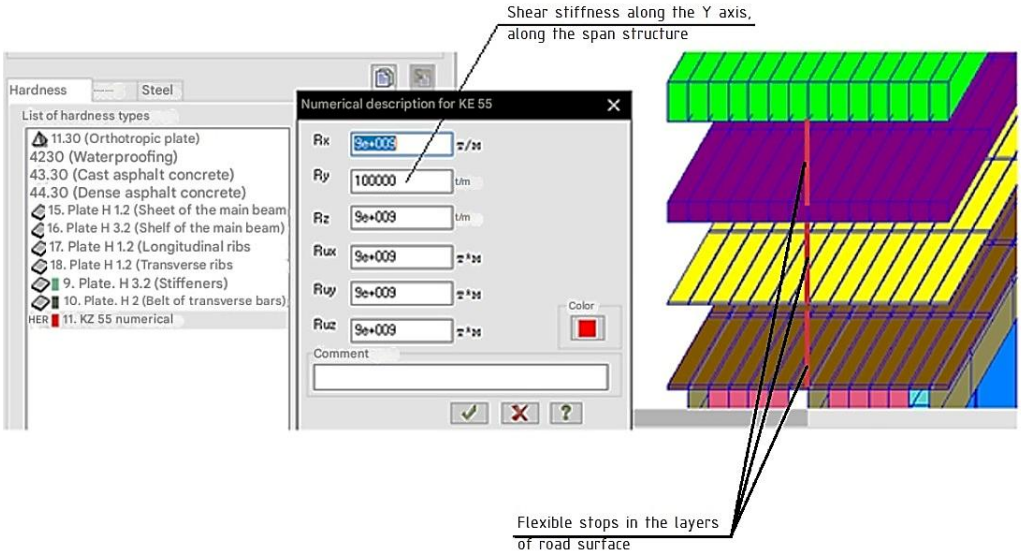


Fig. 8- Modeling of connecting elements in the pavement layers

2.3 Thermal loading and staged analysis procedure

To realistically reproduce the development of thermally induced deformation during the service life of the bridge superstructure, a staged analysis procedure was adopted using the INSTALLATION subsystem of the LIRA-SAPR software. This approach enables sequential application of loads and actions, thereby accounting for the cumulative nature of deformation and stress development and providing a consistent framework for evaluating the influence of solar radiation on the design positioning of bearing components.

At the initial stage, the self-weight of the steel superstructure was applied. This was followed by the installation of pavement layers in accordance with the adopted construction sequence. Subsequently, thermal actions induced by solar radiation were introduced as a separate loading stage. Such a staged calculation procedure allows mechanical deformation arising from dead loads to be clearly distinguished from thermally induced deformation and makes it possible to trace the accumulation of displacement effects throughout the analysis process.

Thermal loading was defined on the basis of non-uniform temperature fields obtained from in-situ measurements. The measured temperature data were processed to construct spatially varying temperature distributions, which were then applied to the finite element model as thermal loads. The adopted thermal representation accounts for temperature gradients over the depth of the bridge cross-section as well as asymmetric heating across the width of the superstructure, reflecting actual exposure conditions under solar radiation at different times of the day.

The temperature measurement campaign was conducted during the summer period using thermocouples installed at several locations across the bridge cross-section, including the pavement surface, orthotropic deck plate, and lower flange of the main girders. The sensors had an accuracy of ±0.5 °C and were connected to an automatic data acquisition system with a

sampling interval of 10 minutes. Measurements were carried out over several consecutive days under typical clear-sky conditions to capture representative solar radiation effects.

The thermal and mechanical properties of the structural components were defined according to standard values reported in the literature. Temperature-dependent material properties were considered for the pavement layers, including elastic modulus and shear rigidity. The stiffness parameters of the FE55 connector elements representing pavement–deck interaction were adopted from experimentally calibrated values reported in previous studies.

Boundary conditions were defined to represent the actual bearing configuration of the bridge span. One support was modelled as a fixed bearing restraining longitudinal and transverse translations, while the opposite support was modelled as a movable bearing allowing longitudinal displacement. Rotational degrees of freedom were released to simulate realistic bearing behaviour. The numerical analysis was performed under linear elastic assumptions. Thermal loads were applied through sequential load steps within the staged analysis framework implemented in the INSTALLATION subsystem of LIRA-SAPR.

The staged analysis framework enables explicit evaluation of spatial thermal deformation and the resulting deviations of bearing components from their intended design positioning. In particular, the procedure allows assessment of both longitudinal and transverse displacement components of movable bearing components arising from non-uniform solar radiation, which are not captured by conventional simplified uniform temperature assumptions commonly adopted in bridge design practice.

Overall, the adopted thermal loading representation and staged analysis procedure provide a physically consistent methodological basis for investigating the influence of solar radiation on the spatial deformation behaviour of bridge superstructures. The detailed temperature fields and the corresponding structural responses obtained from this procedure are presented and discussed in the following section.

3 Results and discussion

3.1 Non-uniform temperature fields induced by solar radiation

The non-uniform temperature fields measured on the bridge superstructure under solar radiation constitute the primary input for evaluating spatial thermal deformation and the resulting deviations in the design positioning of bearing components. Field measurements indicate pronounced temperature gradients over the depth of the cross-section and asymmetric temperature distribution across the width of the superstructure, particularly during periods of intense solar exposure.

The representative temperature fields recorded at different times of the day and subsequently applied in the numerical model are presented in Fig. 9.

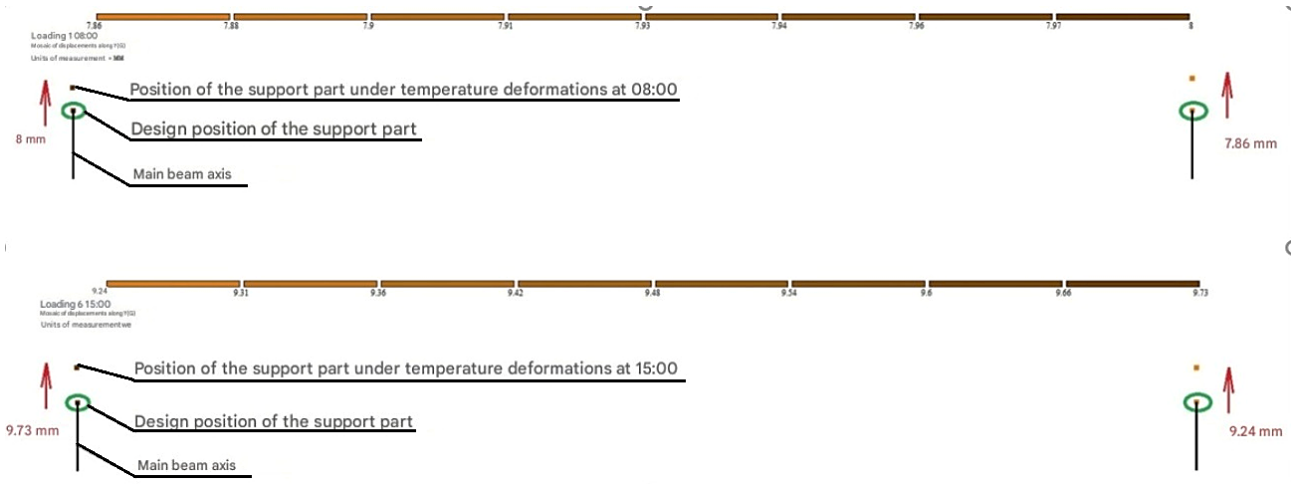


Fig. 9- Longitudinal displacements of the support components beneath the main beams at 08:00 and 15:00 on a typical hot day

The results show that the temperature of the deck surface and pavement layers increases rapidly under direct solar radiation, while the lower parts of the steel girders remain comparatively cooler. This non-uniform heating pattern leads to significant vertical and transverse temperature gradients, which cannot be adequately represented by uniform temperature assumptions typically adopted in design practice.

It is observed that the magnitude and spatial distribution of temperature gradients vary with solar position and exposure duration. In particular, the maximum gradients occur during afternoon hours, when solar radiation intensity and exposure angle produce highly asymmetric heating of the orthotropic deck and pavement system. These findings are consistent with previous monitoring-based studies reported in the literature and confirm the necessity of explicitly accounting for non-uniform thermal fields when assessing the deformation behaviour of bridge superstructures subjected to solar radiation.

3.2 Spatial thermal deformation and bearing positioning deviations

The application of the measured non-uniform temperature fields leads to pronounced spatial thermal deformation of the bridge superstructure. The resulting deformation pattern is characterised by a combination of longitudinal bending, transverse warping, and torsional effects, which collectively govern the displacement behaviour of movable bearing components.

The calculated deviations in the design positioning of bearing components resulting from spatial thermal deformation are illustrated in Fig. 10. Unlike conventional longitudinal thermal expansion, which produces a single dominant displacement component, the spatial deformation induced by solar radiation results in asymmetric longitudinal displacements of the bearing components at opposite sides of the superstructure, accompanied by non-negligible transverse displacement components. This behaviour is schematically consistent with the displacement patterns illustrated earlier in Fig. 1. Fig. 10 presents the variation in longitudinal displacements of the support components beneath the main beams relative to their design positions throughout the day during the hot season.

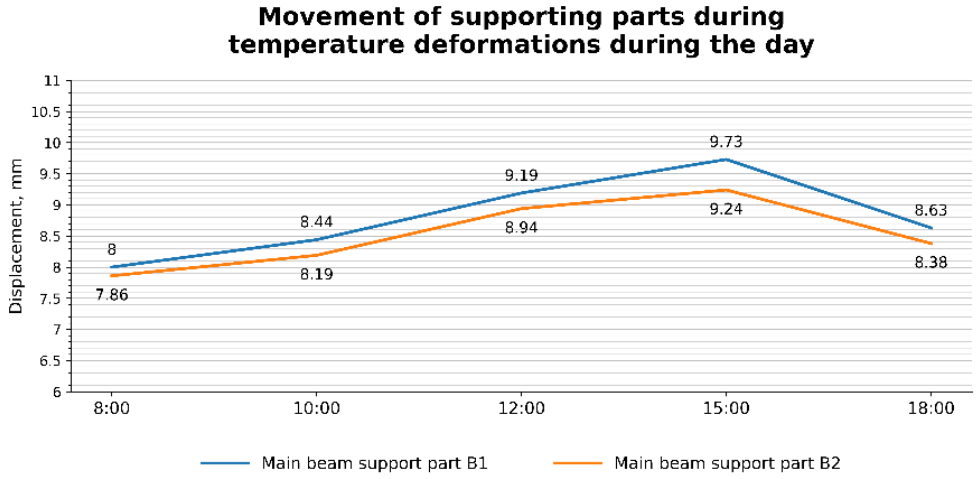


Fig. 10- Graphs of longitudinal displacement variations of support components beneath the main beams throughout the day in hot weather

Quantitative analysis indicates that the maximum deviation of bearing positioning reaches values on the order of several millimetres, with peak values occurring during periods corresponding to the most unfavourable temperature gradients identified in Fig. 9. The magnitude of these deviations is comparable to, and in certain cases exceeds, the displacement allowances commonly considered in design and installation practice. This observation highlights that neglecting spatial thermal deformation may lead to an underestimation of bearing positioning demands and associated serviceability implications.

3.3 Influence of modelling assumptions and engineering implications

The comparison between rigid and flexible pavement–deck interaction models demonstrates that the shear rigidity and temperature-dependent mechanical properties of pavement layers significantly influence the spatial deformation response of the superstructure. Models incorporating flexible interaction through FE55 connecting elements generally predict reduced

internal stresses but increased spatial deformation, leading to larger deviations in bearing positioning compared with rigid interaction assumptions. This finding underscores the importance of accurately representing pavement behaviour when evaluating thermally induced deformation effects. From an engineering perspective, the obtained results indicate that solar radiation induced spatial thermal deformation represents a critical factor governing the design positioning and long-term serviceability of bearing components in road bridge superstructures with orthotropic steel decks. The asymmetric nature of bearing deviations revealed in Fig. 10 cannot be captured by simplified one-dimensional thermal expansion models and may result in unintended restraint forces, increased wear, and potential malfunction of bearing systems if not properly accounted for. Overall, the results demonstrate that explicit consideration of non-uniform temperature fields and spatial thermal deformation is essential for reliable assessment of bearing positioning during both the design and installation stages. The findings provide quantitative evidence supporting the need for refined analytical approaches when evaluating the thermo-mechanical behaviour of bridge superstructures exposed to significant solar radiation.

To validate the numerical model, calculated bearing displacements were compared with field measurements obtained from the monitoring system installed on the bridge. Fig. 11 presents a comparison between measured and simulated displacement values throughout a representative hot day. The results show good agreement between numerical predictions and field measurements. Table 1 summarises the comparison between measured and calculated bearing displacements at selected time instants. The deviation between the two data sets generally remains within 5–10%, confirming that the adopted modelling approach adequately reproduces the observed thermo-mechanical behaviour of the bridge superstructure.

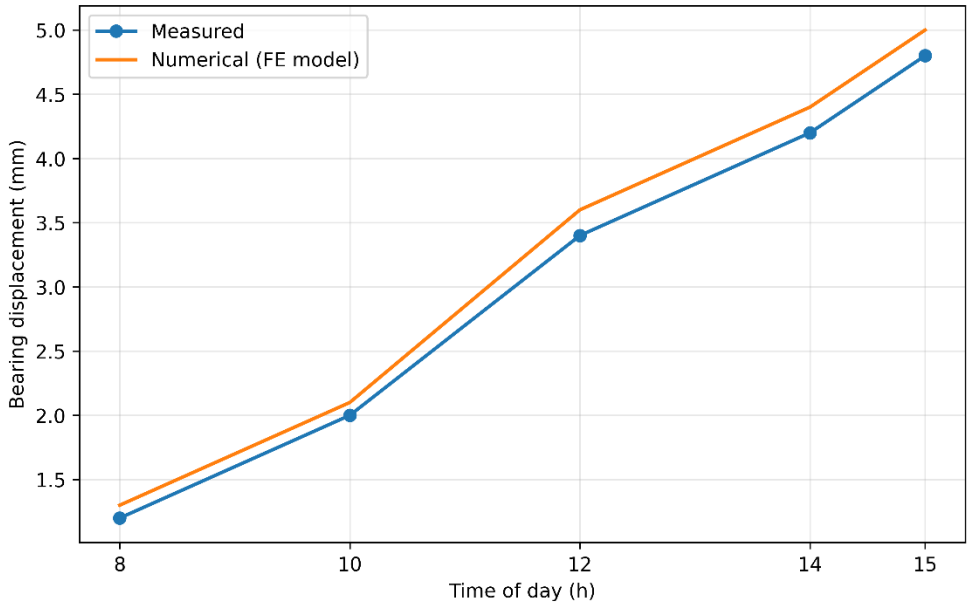


Fig. 11- Comparison between measured and simulated longitudinal displacements of bearing components during a typical hot day

To evaluate the accuracy of the numerical model, the calculated bearing displacements were compared with field measurements. The comparison indicates good agreement between measured and simulated results, with deviations generally below 10%. The root mean square error (RMSE) between measured and simulated displacement values was below 0.2 mm.

Table 1. Comparison between measured and simulated bearing displacements

Time	Measured displacement (mm)	Numerical displacement (mm)	Error (%)
08:00	1.2	1.3	8.3
10:00	2.0	2.1	5.0
12:00	3.4	3.6	5.9
14:00	4.2	4.4	4.8
15:00	4.8	5.0	4.2

3.4 Sensitivity analysis

A limited sensitivity analysis was performed to assess the influence of key modelling parameters on the predicted bearing displacements. The investigated parameters included pavement layer stiffness, shear stiffness of the FE55 connector elements, and mesh density of the finite element model. The results indicate that variations in pavement stiffness and connector shear stiffness have the most significant influence on spatial deformation behaviour, whereas mesh refinement produced only minor variations in predicted displacements. Overall, the sensitivity analysis confirms the robustness of the obtained numerical results.

4 Conclusions

This study investigated the influence of solar radiation on the design positioning of bearing components in road bridge superstructures with orthotropic steel decks, with particular emphasis on the role of non-uniform temperature fields and spatial thermal deformation. Based on a refined three-dimensional finite element model incorporating measured temperature data, pavement layer interaction, and staged analysis, the following conclusions can be drawn. Non-uniform solar radiation induces pronounced spatial thermal deformation of the bridge superstructure, characterised by asymmetric longitudinal and transverse displacement components. Unlike conventional uniform temperature effects, this spatial deformation leads to different displacement responses at individual bearing locations, resulting in deviations of bearing components from their intended design positions. The magnitude of thermally induced bearing positioning deviations is shown to be comparable to, and in certain cases exceed, displacement allowances commonly considered in bridge design and installation practice. These deviations occur primarily during periods of unfavourable temperature gradients associated with intense solar exposure and cannot be adequately captured by simplified one-dimensional thermal expansion models.

The modelling results further demonstrate that pavement layer behaviour and shear interaction with the orthotropic steel deck significantly influence the spatial deformation response. Flexible interaction models incorporating temperature-dependent pavement properties predict increased spatial deformation and larger bearing positioning deviations compared with rigid interaction assumptions. This finding highlights the importance of accurately representing pavement deck interaction when evaluating thermo-mechanical effects in bridge superstructures. From an engineering standpoint, the results indicate that solar radiation–induced spatial thermal deformation constitutes a critical factor governing the design positioning and serviceability performance of bearing components in road bridge superstructures. Neglecting these effects may lead to unintended restraint forces, increased bearing wear, and potential operational issues during the service life of the structure.

Overall, the findings underline the necessity of explicitly accounting for non-uniform solar radiation effects when determining the design positioning of bearing components, particularly for bridge superstructures with orthotropic steel decks that are highly sensitive to asymmetric thermal actions. The presented methodology and results provide a quantitative basis for improving design and installation procedures and may contribute to the refinement of analytical approaches for assessing thermal effects in bridge engineering practice.

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Declaration of Competing Interests

No competing interests are at stake and there is no conflict of interest with other people or organizations that could inappropriately influence or bias the content of the paper.

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