Estudio experimental y analítico sobre tableros de puente unidos sin juntas a pavimentos continuos de hormigón armado

Experimental and Analytical Study on Jointless Bridge Decks with Continuously Reinforced Concrete Pavements

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RESUMEN

Este artículo presenta resultados de una investigación sobre el comportamiento longitudinal de tableros de puente unidos sin juntas a pavimentos continuos de hormigón armado, sometidos a cambios térmicos. La respuesta del sistema sin juntas depende de la interacción entre el pavimento y su base en las proximidades del puente. Se han realizado ensayos experimentales para caracterizar dicha interacción considerando diferentes tipos de materiales para reducir la fricción entre losa y base, llegando a la conclusión de que los más efectivos son las láminas de polietileno y fieltro asfáltico. Se han desarrollado también modelos analíticos para estudiar la respuesta de un sistema sin juntas con un puente de vigas prefabricadas. En base a los resultados del estudio, se realizan una serie de recomendaciones de diseño.

ABSTRACT

This paper presents results of a recent research on the axial response of jointless (seamless) bridges with continuously reinforced concrete pavements (CRCP) when subjected to thermal changes. This response is governed by the interaction between the pavement and its base near the bridge. Experimental tests were conducted to characterize the concrete slab-base interaction considering different types of interface materials, and polyethylene sheets and felt paper were found to effectively break interface bond and limit the frictional restraint. Analytical models were developed to investigate the axial response of jointless bridge-CRCP systems considering a prototype precast girder bridge. Design recommendations are provided based on the findings of this study.

PALABRAS CLAVE: puente sin juntas, pavimento continuo de hormigón armado, contacto losa-base.
KEYWORDS: jointless bridge, continuously reinforced concrete pavement (CRCP), slab-base interface.

1. Introduction

Expansion joints are commonly used at the ends of bridge superstructures to accommodate thermal movements. If the joints are not properly maintained, they can result in water leakage and corrosion damage in bridge superstructure and substructure components.

Integral and semi-integral abutment solutions have been proposed and employed in many countries to eliminate expansion joints at bridge ends, thus improving the durability of the structure. Nevertheless, this type of solutions still require expansion joints at the end of the approach slab, needing periodic inspection and maintenance. Alternatively, a fully jointless (seamless) system between a bridge and a continuous reinforced concrete pavement (CRCP) was implemented in the WM7 Motorway in Australia [1-2]. The seamless bridge concept completely eliminates expansion joints; thermal movements are then dissipated through the controlled cracking and sliding of the reinforced concrete pavement near the bridge approach. To limit the axial forces in the transition zone of the pavement experiencing sliding, interface materials need to be used to eliminate bond and reduce the frictional restraint between the pavement slab and the base. The axial response of the transition zone of the pavement and bridge deck strongly depends on this slab-base interaction.

To support the design of the Australian seamless bridges, Griffiths et al. [1] evaluated the axial response of the bridge-CRCP systems using simple analytical models of the transition slab. They also conducted push-off tests in the field to evaluate the concrete slab-base interaction using different bonding conditions, and selected two wax coats as bond breaker for the seamless bridge projects. A similar concept of fully jointless bridges with extended approach pavements was studied and implemented in China [3-4]. In addition, Ala and Azizinamini [5-6] investigated how to extend the seamless bridge concept for flexible and jointed plain concrete pavements. Despite these advances, research and field experience on fully jointless bridge-pavement systems is still very limited, which can hinder the practical implementation of this design concept.

This paper presents the main findings of a recent research study completed at the University of Texas at Austin on the axial response and design of fully jointless (seamless) bridges and continuously reinforced concrete pavements (CRCP). Experimental tests were conducted to characterize the concrete slab-base interaction considering different types of interface materials used as bond breakers. They include woven and non-woven geotextiles, polyethylene sheets, and felt paper. Analytical models were also developed to investigate the axial response of jointless bridge-CRCP systems considering a prototypical bridge structure in Texas. The models were used to evaluate the influence of the friction provided at the slab-base interface.

2. Response of jointless bridge-CRCP systems

In a jointless bridge-CRCP system, thermal movements of the bridge are accommodated and dissipated over a transition zone of the pavement. The transition slab is subjected to axial forces and deformations resulting from thermal changes as well as concrete shrinkage. Axial deformations require the pavement to slide over the base, and an interface material (bond breaker) is essential to ensure sliding with limited restraint.

The response of the jointless system to a temperature decrease is characterized by a movement of the transition pavement toward the bridge, activating restraint at the slab-base interface in the opposite direction (Figure 1). This interaction generates tensile forces, especially in pavement regions closest to the bridge (Figure 1). The tensile force are absorbed by the reinforced concrete slab of the transition zone and the deformations are distributed across multiple cracks in the slab. Axial forces and displacements peak near the bridge abutment, and displacements are completely dissipated at the end opposite end of the transition zone. As a result of the seamless connection with the pavement, the bridge superstructure is also subjected to axial tension forces. The response of the system to a temperature increase results in a movement of the transition pavement away from the bridge, activating the base restraint in the opposite direction. Hence, in this case axial compression forces are applied on the pavement. From a design standpoint, the temperature decrease provides a more unfavorable situation and should be considered for serviceability checks of crack control.

In the axial response of the seamless system, a bond breaker provides controlled friction for the slab to slide within the transition zone. An overly high coefficient of friction could lead to high axial forces and severe cracking, while an excessively low coefficient of friction may require a very long transition zone to dissipate movements. The Australian seamless bridge systems employed wax coatings with a coefficient of friction of 0.8. The performance of additional bond breakers were investigated in the present research, as described in the next section.

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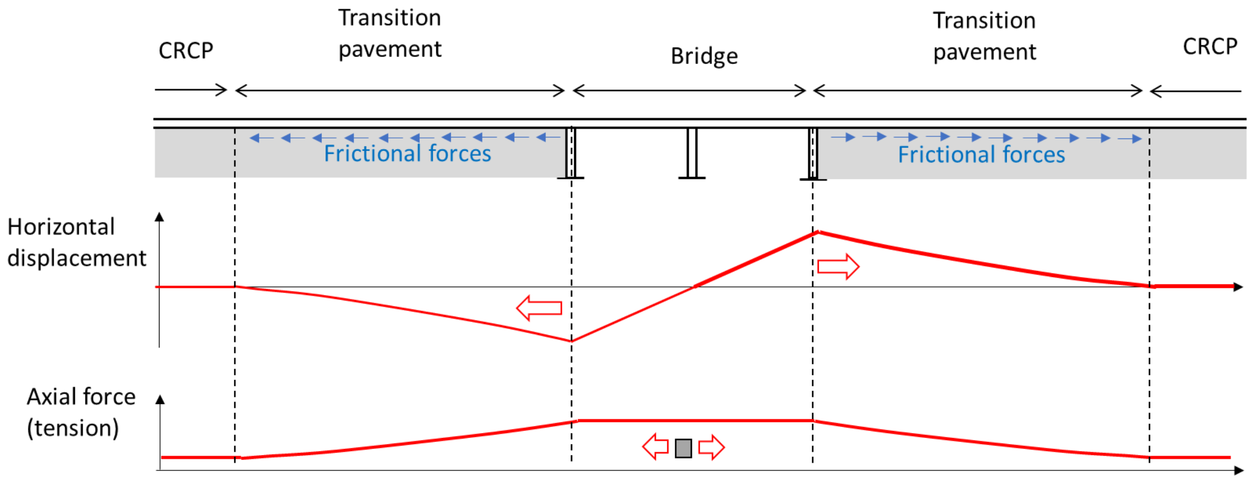


Figure 1. Response of jointless bridge-CRCP system under temperature decrease (bridge expansion)

3. Experimental characterization of slab-base interaction

The experimental study on the slab-base interaction was aimed to characterize the effectiveness of different interface materials to be used as bond breakers in transition zones of fully jointless bridge-pavement systems. In a preliminary testing phase, unit-cell shear tests were conducted in a soil shear box of 0.5 m x 0.5 m to identify potential bond breakers from a variety of interface materials typically used in infrastructure projects. They included polyethylene (PE) sheets, woven and non-woven geotextiles, and thin layers of hot-mixed asphalt (HMA). From these preliminary tests, it was concluded that slab-base interfaces with a thin HMA layer, woven geotextile and non-woven geotextile retained a strong adhesion and very high shear strength. Hence, these interface materials were deemed not appropriate to be used as bond breakers. More details about this preliminary phase can be found in Chen et al. [7-8]. A large-scale testing program was then conducted focused on different types of polyethylene sheets incorporating as well asphalt-saturated organic felt paper, which is impermeable and has previously been used in bridge applications. This testing program is described in this section.

3.1 Test specimens and setup

Large-scale testing consisted of push-off tests on concrete slabs subjected to cyclic displacement demands. The test specimens comprised a compacted base constructed inside a box (2.4 m x 1.8 m x 0.18 m), a cast-in-place concrete slab (1.5 m x 0.6 m x 0.15 m) constructed on top of the base, and an interface material between the base and slab (Figure 2a). All tests series included a cement stabilized base (CSB), and in two cases the CSB was topped with a 25-mm-thick HMA layer following common practice in some US states. The interface materials considered in the test program were the following:

- Smooth polyethylene (PE) sheets (ASTM E1745, 2017) with 0.15 mm of thickness.
- High-density polyethylene (HDPE) sheets with 1 mm of thickness and single-sided asperities.
- Double-sided textured linear low-density polyethylene (LLDPE) sheet with 1.5 mm of thickness.
- Asphalt-saturated organic felt paper (Type II, ASTM D4869).

The test setup and instrumentation are shown in Figure 2. The load was applied using two hydraulic jacks on each side of the slab, which alternatively pushed the slab in each direction. The average interface shear force was calculated based on the applied force measured using load cells attached to the jacks. Four displacement transducers measured the relative displacement between the slab and the base.

During a test, the slab was subjected to cyclic lateral loading to simulate the effects of bridge expansion-contraction on the transition zone. The loading protocol comprised eight cycles of +/- 25 mm. The tests were repeated under three normal stresses (3.5 kPa, 8 kPa, and 13.8 kPa), by using slabs of varying thicknesses, in order to determine the coefficient of friction of the interface.

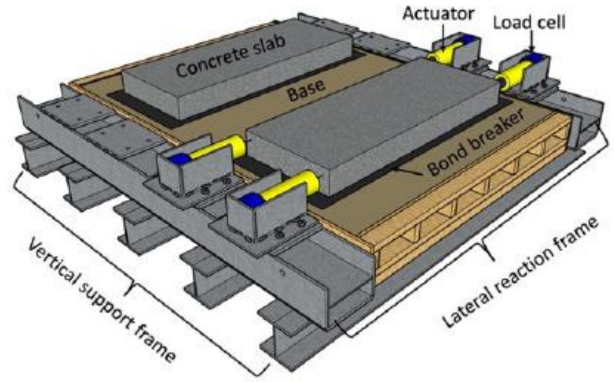
3.2 Push-off test results

The results of the tests were analyzed in terms of the average shear stress vs. slip of the interface. Figure 3a provides sample shear-stress displacement relations for CSB with textured LLDPE sheet as interface material. While in the first cycle of loading a small peak was observed in some tests, subsequent cycles showed a relatively steady shear resistance. As shown in Figure 3a, this shear resistance increases with the level of normal stress. The results of the tests showed that this increase was approximately linear with the normal stress, consistent with Coulomb's linear friction model.

Figure 3b presents the linearized steady shear strength envelope obtained for the different interfaces, following the Coulomb's model. The linear regression fit confirms no adhesion at the slab-base interface, and the coefficient of friction is determined by the slope. Smooth PE sheets showed the lowest friction coefficient μ of around 0.25, while the spike HDPE sheet increased it slightly to 0.3. The double-sided textured LLDPE sheet raised μ to around 0.4, and felt paper provided the highest μ value of approximately 0.7. Topping the CSB surface with a thin HMA layer slightly increased the friction coefficient for textured LLDPE and felt paper, as shown in Figure 3b. This is likely due to the rougher HMA surface in contact with the bond breaker.

The results of the tests have indicated that the various types of PE sheets and the felt paper were effective in eliminating the adhesion at the interface. Smooth PE sheets provide very low friction resistance, which may require a very long transition slab to dissipate bridge movements. In addition, tearing of smooth PE sheets was observed at several locations after the tests, which questions its durability in field conditions. Double-sided textured LLDPE sheets and felt paper were more robust and provide a range of friction coefficients (0.4-0.8) which are closer to that of the interface solution adopted in the

Australian bridges. This range of friction coefficients limits the frictional restraint while being able to dissipate bridge movements in ashorter distance. This effect is studied more in depth in the analytical studies presented in the next section.



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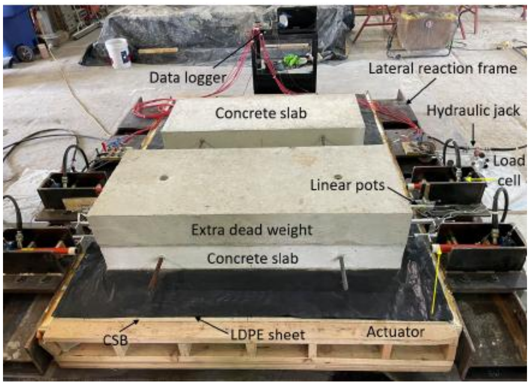
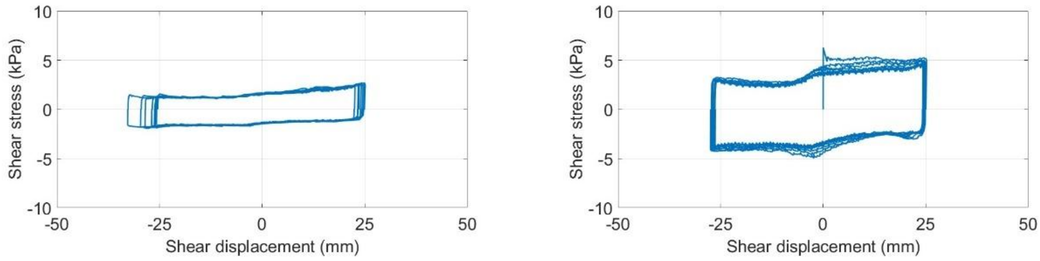


(b)

Figure 2. Large-scale push-off tests: (a) setup, (b) instrumentation (figures from [7])



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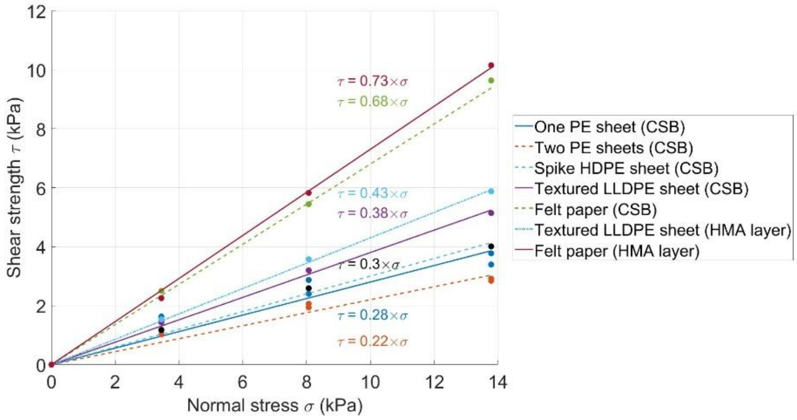


(b)

Figure 3. Experimental results: (a) shear stress-displacement relations for CSB and textured LLDPE sheet, (b) summary of shear strength vs. normal stress results (adapted from [7])

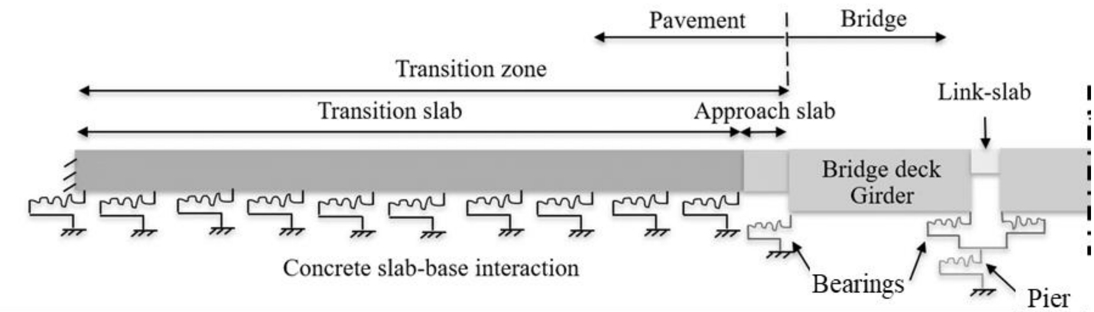
4. Numerical modeling of bridge-CRCP systems

The axial response of fully jointless bridge-CRCP systems under thermal changes was studied using one-dimensional finite element (FE) models. The models were developed using Abaqus [9] considering nonlinear behavior of concrete, steel reinforcement, and the concrete slab-base interface. The analytical study focused on a prototype prestressed concrete girder bridge and CRCP designed according to US standards. A numerical parametric study was also conducted to investigate the effects of the slab-base friction coefficient on the response of the jointless system.

4.1 Description of the FE models

Figure 4 presents the modeling scheme of a three-span jointless bridge with link slabs in the deck (only half of the system is modeled considering symmetry conditions). A fixed end is considered at the CRCP, sufficiently away from the bridge where the thermal movements are completely dissipated. The model includes bridge superstructure elements (deck and girders), bearings and piers. Truss elements are used for the pavement and deck, considering nonlinear response of concrete and steel reinforcement. Linear springs model the lateral stiffness of bearings and piers, while nonlinear link elements represent the frictional interaction at the concrete slab-base interface in the transition zone. The frictional links are distributed uniformly along the transition slab elements at each node. The abutments and foundations are assumed rigid for simplicity given their high longitudinal stiffness as compared to the rest of elements.

The stress-strain response of concrete is represented using the damage-plasticity model in Abaqus, which considers nonlinear response in compression and cracking in tension (Figure 4). An elastic-perfectly plastic model is assumed for steel reinforcement, although steel is expected to behave in the linear range for the thermal loads. The shear stress-displacement response of the nonlinear slab-base links is idealized as an elastic-perfectly plastic law, calibrated to the results of the push-off tests presented in the previous section. Additional details about the modeling scheme and material constitutive models are provided in Chen et al. [8].



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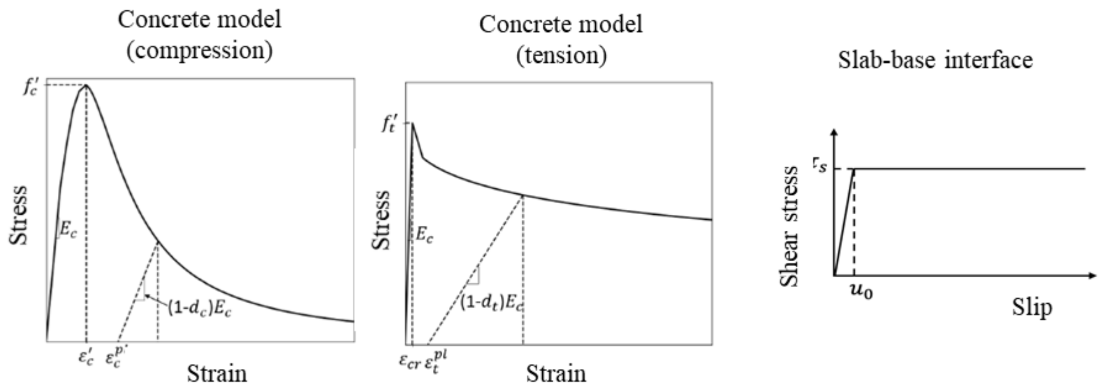

(b)

Figure 4. FE model of the jointless bridge-CRCP system: (a) general scheme, (b) constitutive models for concrete and slab-base interface (adapted from [8])

4.2 Analysis of prototype jointless bridge-CRCP system

The analytical study focuses on a bridge structure representing typical mid-span precast concrete girder bridges in Texas, except that a seamless connection with CRCP is considered. The prototype bridge has three 30-m spans and a width of 12 m. The superstructure has five precast Tx54 I-girders, and a 21.5 cm-thick deck comprising partial-depth precast concrete panels (PCP) and a cast-in-place (CIP) concrete layer. The supestructure has CIP link slabs to achieve continuity in the deck. The reinforcement ratio in the CIP portion of the deck is 0.7% and that of the link slabs is 2.5% (these values have been increased with respect to conventional practice, given the higher axial tension demands introduced by the jointless connection). The CRCP pavement away from the bridge has 28 cm of thickness and a reinforcement ratio of 0.75%, considering conventional pavement designs. While the pavement thickness is considered constant along the transition slab, the reinforcement ratios are gradually increased towards the bridge as follows: 1.1% (at 30-60 m from the abutment), 1.45% (at 9-30 m from the abutment) and 2% (at 0-9 m from the abutment). Felt paper is considered for the slab-base interface, which provides μ =0.7 based on the experimental results described previously.

The axial response of the jointless system was analyzed using the FE scheme described in Section 4.1, for a maximum temperature decrease of 31ºC [10-11]. In this situation, the pavement and deck would be placed in tension and would tend to crack. According to the US bridge and pavement standards, crack width control is satisfied if the maximum tensile stress in steel reinforcement does not exceed 60% of the yield strength of steel in bridge components [10] and 2/3 of the yield strength of steel in the pavement [12].

Figure 5 presents the distributions along the transition pavement and bridge deck of the horizontal displacement, axial force, and maximum steel stress (steel stress at crack locations) obtained for the temperature decreased, according to the results of the FE model. In the graphs, only half of the bridge-pavement system is represented considering symmetry conditions with respect to the center of the bridge. Positive displacement is movement towards the bridge center, and positive forces and stresses are in tension. As shown in Figure 5, the temperature decrease causes the bridge and transition pavement to move toward the bridge center, with the movements dissipating in the pavement at a distance of around 90 m from the abutment. This transition zone of 90 m is subjected to higher tensile forces than the conventional CRCP portion, being this the reason for the additional amount of reinforcement of the transition slab. The bridge deck also experiences axial tensile forces as result of the seamless connection, for which extra reinforcement was also provided. The maximum tensile stress demands in the pavement and deck reinforcement depend on the level of axial load and amount of reinforcement of the different sections. For the most part, the steel stress remains below the design stress limits for crack control, which are 276 MPa for the pavement and 249 MPa for the deck (for a Grade 60 steel, f_y=415 MPa). Only specific sections exceed these values, which means that additional reinforcement would need to be provided in these regions to meet the cracking limit state for the given scenario.

4.3 Influence of friction at slab-base interface

The influence of the concrete slab-base interaction on the response of the prototype jointless system was studied with the FE model by varying the coefficient of friction of the interface. Specifically, the response under temperature decrease was evaluated for μ = 0.25, 0.4, 0.7, and 1.0. The baseline model uses the felt paper (μ=0.7), while the lower μ values represent interfaces with smooth PE sheets (μ=0.2) and textured LLDPE sheets (μ=0.4). The upper bound value of μ=1.0 reflects a case in which additional resistance is provided from unintended adhesion.

The results of the analyses with different coefficients of friction are presented in Figure 6 in terms of the distributions of horizontal displacement and steel stress at cracks. As shown, higher friction coefficients reduce the transition length but increase the steel stress at cracks. The case with μ = 0.25 (smooth PE sheets) increases significantly the transition length to 135 m, while interfaces with high friction (μ ≥ 1.0) will result in increased steel stress demands in the pavement. The range of μ=0.4-0.7 provides a reasonable balance between steel stress demands and length of the transition zone, which determine the extra amount of steel required for the transition pavement.

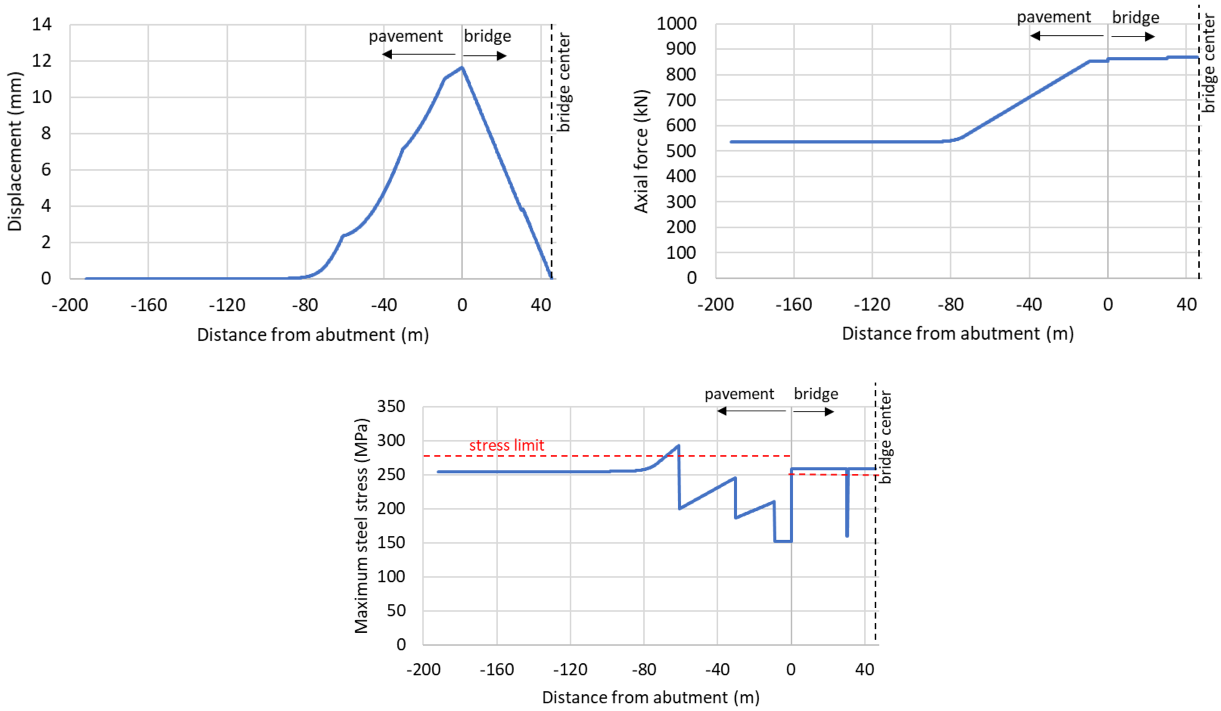

Figure 5. Axial response of jointless bridge-CRCP system under temperature decrease

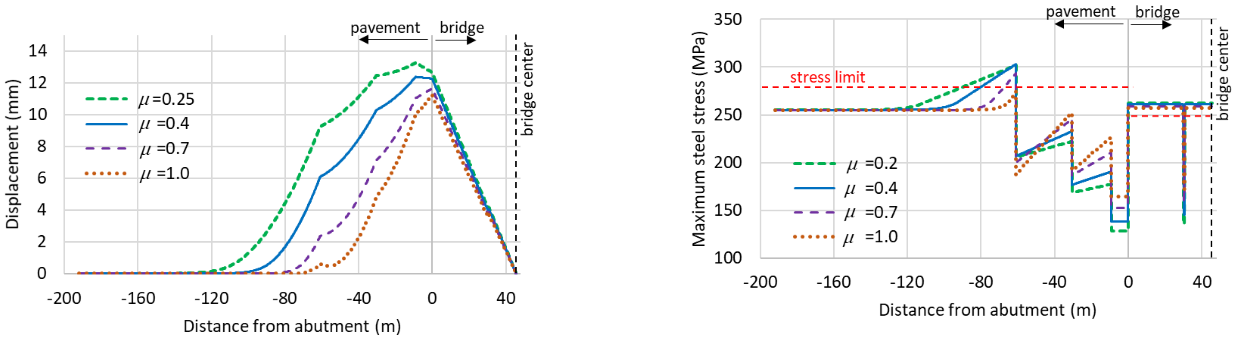

Figure 6. Axial response of jointless bridge-CRCP system for different coefficients of friction

5. Conclusions

Fully jointless (seamless) bridges-CRCP systems completely eliminate the need for expansion joints, allowing for improved durability of bridge components and reduced maintenance costs. In this type of system, thermal bridge movements need to be dissipated within the transition zone of the pavement, in which axial tensile forces are expected in service. Interface materials play a key role in the behavior and design of the jointless system, as they control the level of restraint to slab movement and the resulting tensile demands. The following conclusions and design recommendations are provided based on the results of the experimental and analytical studies presented in this paper:

- Experimental tests on interface materials indicate that polyethylene (PE) sheets and felt paper are effective in breaking the bond between the concrete slab and the base, and provide controlled friction. The lowest coefficient of friction was obtained for smooth PE sheets (μ=0.25) but this interface material is vulnerable to tearing damage. Double-sided LLDPE sheets (μ = 0.4) and asphalt-saturated organic felt paper (μ = 0.7) were found to provide adequate friction and durability, and thus are recommended as interface materials. Geotextiles, which are commonly used as interface materials in roadway projects, are not appropriate for this specific type of application because they are not effective in breaking the bond.
- The numerical analysis of a mid-span jointless bridge indicated that to effectively control cracks the reinforcement ratios need to increase to 1–2% in the pavement within 60 m of the bridge abutments, and to 2.5% in the link slabs of the bridge deck. Crack control was ensured by limiting the tensile stress of steel reinforcement at cracks to 60% and 66% of the yield strength of steel in the deck and pavement, respectively, based on US standards.
- The numerical results confirmed that the restraint of the concrete slab-base interface has a strong effect on the axial demands of the transition pavement. Friction coefficients between 0.4 and 0.8 were found to provide a good balance between transition length and tensile stress demands in the reinforcement of the pavement.

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