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EFFECT OF ULTRA HIGH-PERFORMANCE CONCRETE THICKNESS ON THE MECHANICAL BEHAVIOR OF ORTHOTROPIC STEEL BRIDGE DECK

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Abstract. Orthotropic steel bridge decks structures (OSBDs) have been widely used in long-span bridges to reduce the dead load of the bridge. However, over time, the asphalt wearing course of the bridge deck structure has shown many damages. Recently, ultra-high-performance concrete (UHPC) has been employed to repair and reinforce these structures. Therefore, this paper focuses on the effect of UHPC thickness on the mechanical behavior of the orthotropic deck. The five-point bending beam test model using the finite element method is used in this investigation to clarify the effect of UHPC thickness, the ratio of adhesion failure, and temperature on the mechanical behavior of the OSBDs. The UHPC thickness varies from 30 to 50 mm, the ratio of adhesion failure varies from 0.1 to 0.3, and the temperature changes from 30°C to 60°C. The results show that the presence of the UHPC layer significantly reduces the impact of adhesive layer damage and temperature on the behavior of the OSBDs.

Keywords: orthotropic steel deck bridge, ultra-high-performance concrete, adhesion failure, temperature, finite element model.

1. INTRODUCTION

The use of an asphalt concrete overlay on an orthotropic steel deck is a widely adopted bridge deck structure solution in many countries around the world [1-5]. This can be regarded as a multi-layer material combining steel and asphalt concrete through an adhesive layer under local loads. Asphalt concrete, being a heterogeneous material composed of various components, differs significantly from steel, a homogeneous material, leading to a complex overall behaviour resulting from their combination. This complexity remains a significant topic of interest in global research. Due to the differing mechanical properties of these two materials, their combined performance in practical applications often does not meet the designers' expectations. Thus, research aimed at enhancing the collaborative working capacity between asphalt concrete and steel decks has been a focal point for researchers worldwide for many years. The behavior of bridge decks using asphalt concrete overlay on steel decks has been studied by various authors globally, including research by Hameau et al. 1981 [1], etc. However, the interaction between these two materials frequently results in damage to the bridge deck, a concern that continues to be investigated by many scientists [6,7].

Significant global research on the deterioration of wearing courses on OSBDs includes studies by Jia et al. [2], Zhang et al. [3], Wolchuk et al. [4], and Liu et al. [5,6]. In Vietnam, the increasing vehicle loads and traffic, coupled with weather and temperature variations, have led to emerging damage in OSBDs, as observed in the Thang Long and Thuan Phuoc bridges. This situation necessitates comprehensive studies, such as those by Hoang Viet Hai et al. [8], Tran Anh Tuan et al. [9].

Recently, the study of repair and reinforcement solutions for orthotropic steel decks has become a focus of researchers worldwide. One commonly used solution is the application of Ultra-High-Performance Concrete (UHPC) (Figure 1) combined with the steel deck before applying the asphalt concrete overlay, this method has been used for repairing Thang Long bridges. This type of concrete is not only applied to steel bridge decks but also to reinforced concrete decks [10]. However, further research is needed to analyse the behaviour of these bridge decks with the presence of UHPC.

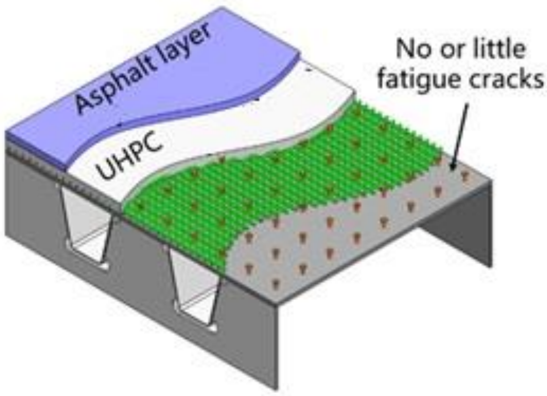


Fig.1. Using UHPC as a solution for repairing orthotropic steel decks [7].

In this study, a numerical model was developed to simulate the mechanical behavior of an orthotropic steel bridge deck (OSBD) strengthened with UHPC under localized loads based on the five-point bending beam test configuration. By varying the thickness of the UHPC layer on the steel deck, the model is used to examine the influence of UHPC thickness on the mechanical behavior of the OSBD.

2. MODEL DESIGN

2.1.Ultra-high-performance concrete

UHPC used in this study includes the following main constituent materials with the following technical characteristics: Portland cement PC40; Quartz sand; Admixtures and fly ash; The steel fibers incorporated into the concrete have a tensile strength of over 2000 MPa, with a diameter of 0.2 mm and a length of 12 mm.The properties of this UHPC were investigated in our previous research [11], which revealed an average compressive strength of 130 MPa and module elastic equal to 65 GPa.

2.2. Description of the five-point bending test model

Two types of steel bridge deck structures are used in the numerical simulations with thickness and material parameters shown in Figure 2. Structure 1 consists of a 14 mm thick orthotropic steel deck directly bonded to a 70 mm thick asphalt concrete overlay, with a bonding layer thickness of 2 mm. Structure 2 is a lightweight composite deck that includes an orthotropic steel deck combined with ultra-high-performance concrete (UHPC), with an asphalt concrete overlay on top. To assess the role of the UHPC layer, the overlay on this layer is 40 mm thick. Thus, with a 30 mm thick UHPC layer + 40 mm thick overlay, the total thickness will be equivalent to Structure 1. Subsequently, the 40 mm thick overlay is maintained while varying the UHPC layer thickness to 40 mm and 50 mm to evaluate the effect of UHPC thickness on the behavior of the reinforced structure.

The five-point bending test model [12,13] utilized in this study follows the shape, dimensions, and material parameters outlined in Figure 2 and Tables 1 and 2. This structure is supported on three points, with one fixed support at the center, as depicted in Figure 2.

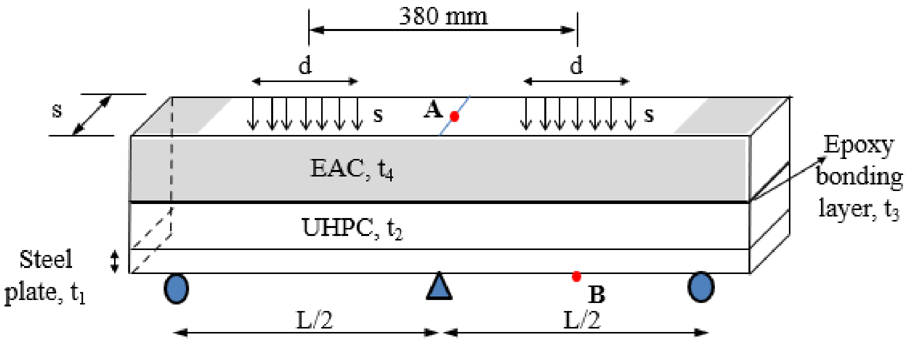


Figure 2. Schematic of the five-point bending test model.

Table 1. Parameters used for modeling.

Items	Symbol	Value	Units
Length of specimen	L	760	mm
Thickness	t_1	14	mm
UHPC layer	t_2	30-50	mm
Epoxy bonding layer	t_3	2	mm
Thickness of epoxy asphalt concrete	t_4	70 or 40	mm
Width of specimen	s	250	mm
Width of distributed load	d	200	mm

Table 2. Materials properties [8].

Material	Modulus elastic (MPa)	Poisson's ratio	Volumetric mass (kg/m^3)	Thermal dilatation (/ºC)
Steel	200.000	0.3	7850	11.7 x 10^{-6}
UHPC	65.000	0.3	2500	11.7 x 10^{-6}
Epoxy bonding	3.500	0.38	1250	-
EAC	5.000	0.35	2695	10 x 10^{-6}

To evaluate the effect of temperature on the behavior of the orthotropic steel deck structure, the elastic modulus of the asphalt concrete is calculated to vary with temperature according to the study by Mohd Raihan Taha [14] using the following formula:

$$E_1(t) = 15000\text{-}7900 * \log(t) \quad (1)$$

where: $E_1(t)$ (MPa) = elastic modulus of the asphalt mixture at temperature t (t≥1ºC)

The model of OSBDs was loaded by two loads that were uniformly distributed on a total area of $2d \times s$, and the total load magnitude was 130 kN.

2.3. Adhesion failure modelling

The failure of the bonding layer between the steel plate, UHPC, and asphalt concrete can result from various complex factors such as loading conditions, temperature fluctuations, environmental humidity, and construction techniques. Once construction is complete, this bonding layer is situated within the bridge deck's asphalt wearing course, making it challenging to assess the extent and location of damage without destructive testing. Therefore, this study aims to simulate random locations and distributions of adhesion failure zones before establishing a relationship between the degree of damage and the strain, stress, and displacement at several specific points in the structure. Simulation of bonding layer failure has been conducted in previous studies by Tran and al [9] through evaluating the impact of adhesion failure on the steel deck. In this paper, we apply a similar approach to the bonding between the asphalt concrete and UHPC layers.

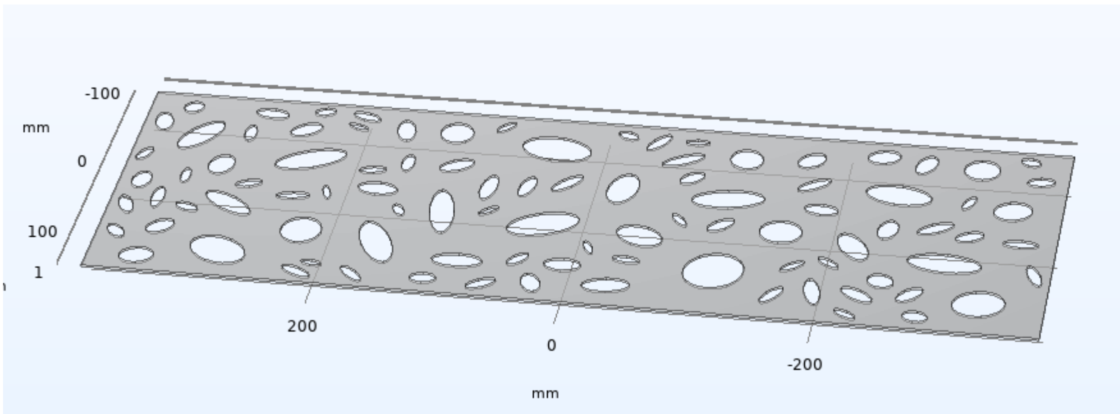


Figure 3. Illustration of random failure in the bonding layer with a ratio of 0.2.

2.4. Structural simulation using finite element

The size and coordinates of the failure ellipses are randomly generated before being incorporated into the finite element software- Comsol Multiphysics. Adhesion failure is simulated using empty domains, represented as ellipses with a thickness equal to that of the epoxy bonding layer, as illustrated in Figure 4.

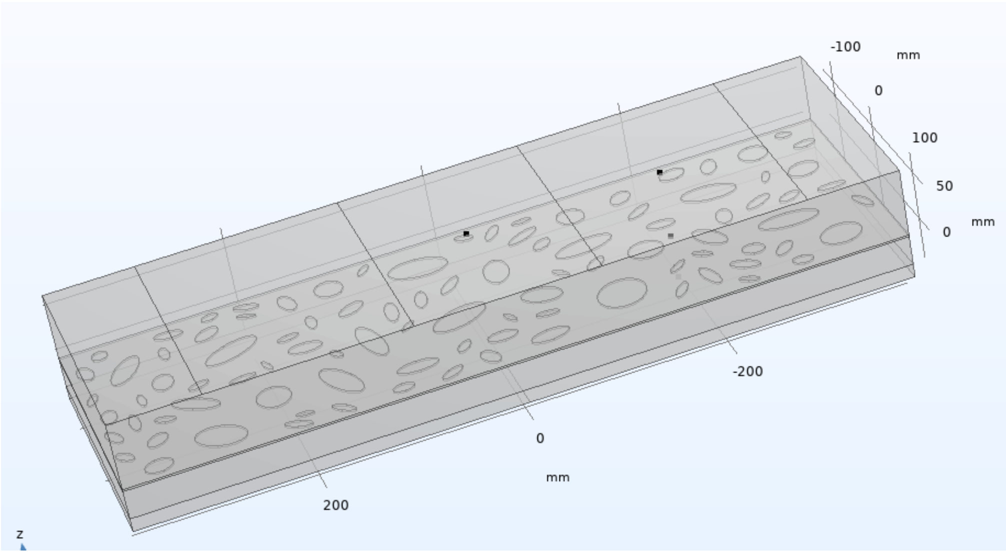


Figure 4. Simulation of the area of adhesion failure in the bonding layer.

The non-failure portion of the bonding layer is modeled to be perfectly bonded to the asphalt wearing course with either the steel plate or UHPC. All three types of materials—steel or UHPC, asphalt concrete, and the bonding layer—are modeled to be linearly elastic, with material parameters listed in Table 2. The entire structure is meshed with approximately 200,000 tetrahedral elements, as shown in Figure 5.

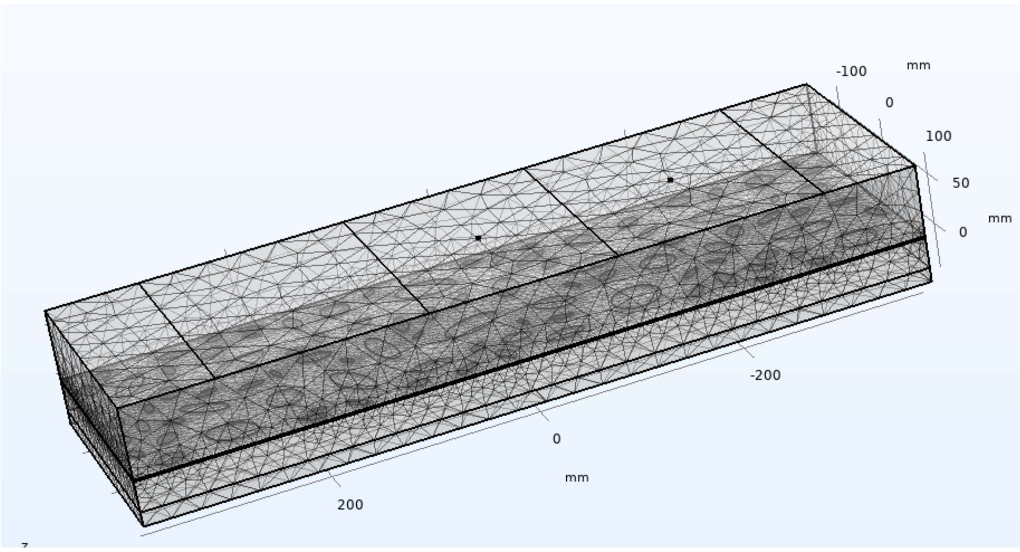


Figure 5. Simulation of the area of adhesion failure in the bonding layer.

3. RESULTS AND DISCUSSION

3.1. Influence of UHPC thickness

In this section, the effect of UHPC thickness on the mechanical behavior of orthotropic steel bridge decks is analyzed by comparing the behavior of this structure with or without a UHPC layer with thicknesses varying from 30 to 50 mm. Figure 6 and Figure 7 illustrate the deformation and deflection at point A (Figure 6) and the deflection at point B (Figure 7) when the UHPC layer thickness changes and at the temperature of 30°C, 40°C, 50°C and 60°C.

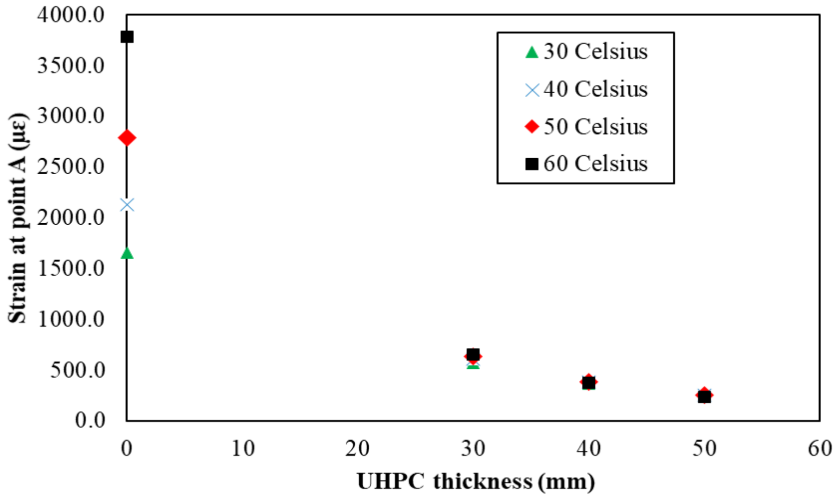


Figure 6. Relationship between strain and UHPC thickness at point A.

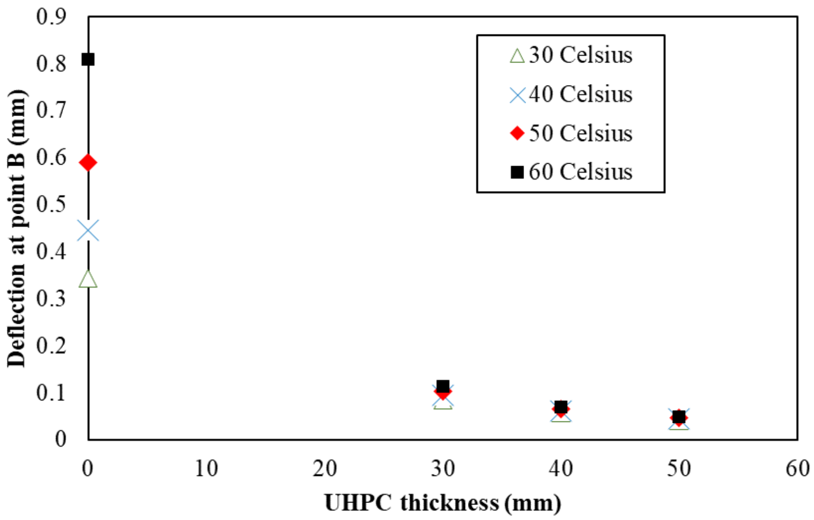


Figure 7. Relationship between deflection and UHPC thickness at point B.

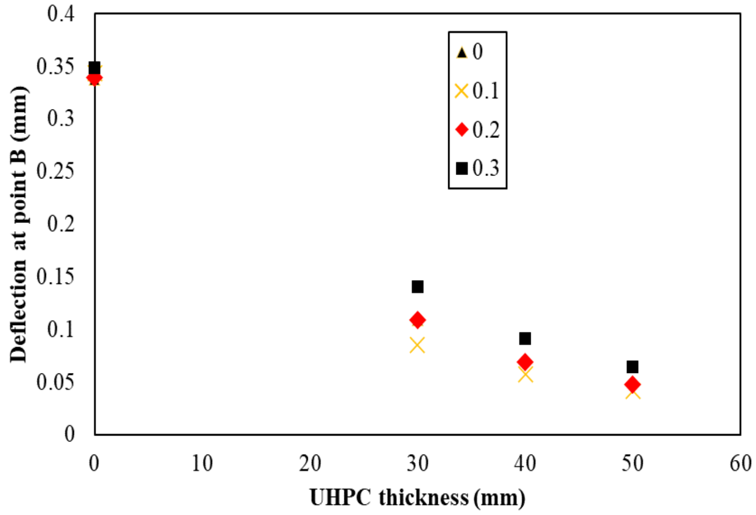
Figure 6 shows a significant deformation at point A, from 1600 με to 3800 με, when the temperature of the asphalt concrete changes from 30°C to 60°C, decreasing to 570-650 με with the presence of a 30 mm thick UHPC layer reinforcing the steel deck. This strain continues to decrease when the UHPC layer thickness increases to 40 mm and 50 mm.

Figure 7 shows that the deflection at point B decreases with the presence of UHPC concrete. The deformation decreases from 0.33-0.81 mm to 0.1-0.13 mm with the presence of 30 mm UHPC concrete. The deflection continues to decrease as the UHPC layer thickness increases to 40 mm and 50 mm.

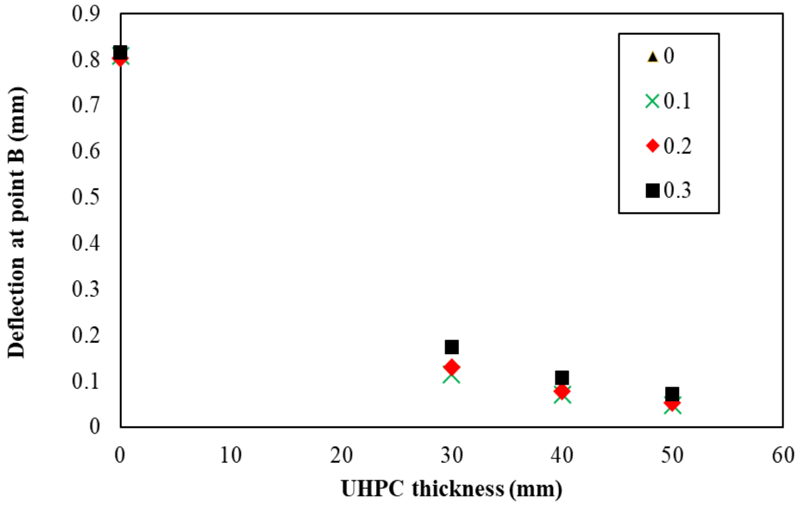
In all cases shown in Figure 6 and Figure 7, with the presence of the UHPC layer on the steel deck, the deformation at point A and the deflection at point B both tend to decrease significantly as the UHPC layer thickness increases from 30 mm to 50 mm. The presence of the UHPC layer mitigates the impact of temperature on the behavior of the orthotropic steel deck structure.

3.2. Effect of the ratio of adhesion failure

By varying the damage of the bonding layer with a ratio from 0 to 0.3, we compared the deflection at point B when the UHPC layer thickness changes from 0 to 50 mm in two cases at 30°C and 60°C. The results are summarized in Figure 8 and Figure 9.

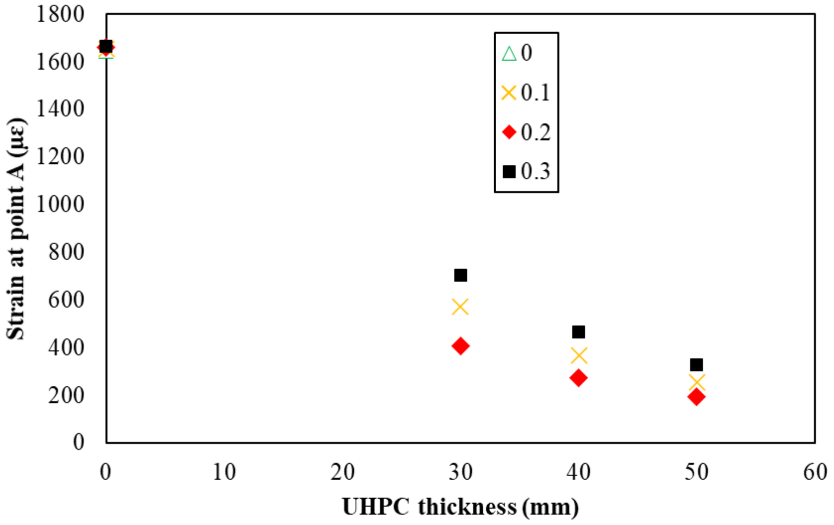


(a)

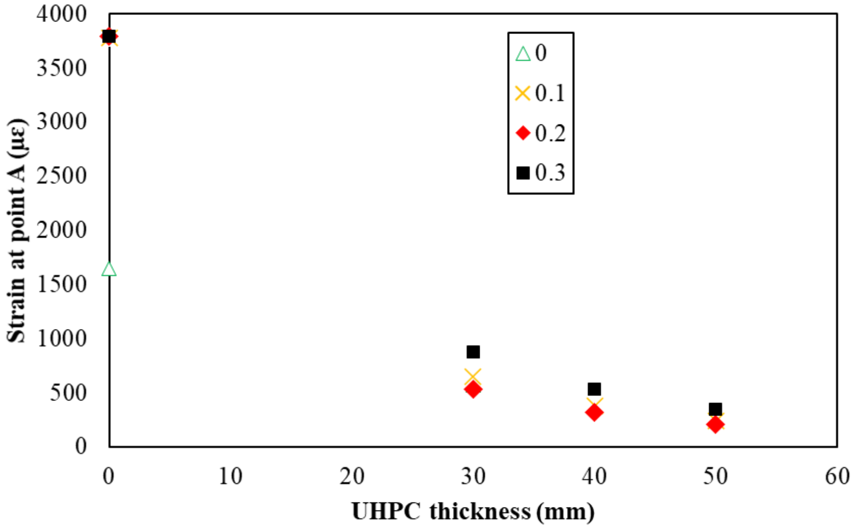


(b)

Figure 8. Relationship between deflection and UHPC thickness at point B with different adhesion failure ratios. a) 30 °C; b) 60 °C



(a)



(b)

Figure 9. Relationship between strain and UHPC thickness at point A with different adhesion failure ratios. a) 30 ^{0}C; b) 60 ^{0}C

Figures 8 and 9 show that damage to the adhesive layer changes the deflection at point B and the deformation at point A. Logically, as the level of adhesive damage increases, the stress and deformation also increase correspondingly. This change is smaller with the presence of a UHPC layer reinforcing the steel deck. When the steel deck is reinforced with a 30 mm thick UHPC layer, at 30°C, the deformation at point A reaches 570 με and increases to 650 με when the temperature rises to 60°C with a damage rate of 0.1. For the case of a 50 mm thick UHPC layer, at 30°C, the deformation at point A reaches 320 με and increases to 350 με when the temperature rises to 60°C with an adhesive damage rate of 0.3.

Similarly, the deflection at point B, when reinforced with a 30 mm thick UHPC layer, at 30°C, the deflection at point B reaches 0.08 mm and increases to 0.11 mm when the temperature rises to 60°C with an adhesive damage rate of 0.1. For the case of the steel deck reinforced with a 50 mm thick UHPC layer, at 30°C, the deflection at point B reaches 0.064 mm and increases to 0.07 mm when the temperature rises to 60°C with an adhesive damage rate of 0.3.

Thus, in all cases, increasing the UHPC layer thickness from 30 mm to 50 mm reduces the impact of temperature and adhesive layer damage on the behavior of the orthotropic steel deck structure under load.

4. CONCLUSIONS

In this study, numerical simulations of the combination of UHPC thickness and adhesion failure in the five-point bending test model were performed, taking the effect of temperature into account to analyze the local behavior of an OSBDs with an asphalt wearing course. In the simulations, the ratio of bonding damage was controlled up to a value of 0.3, the UHPC layer thickness varied from 30 mm to 50 mm, and the temperature ranged from 30°C to 60°C. Important findings from this study are summarized as follows:

(1) The UHPC thickness has an influence on the mechanical behavior of the OSBDs. With the presence of the UHPC layer reinforcing the steel deck, the deformation and deflection of the structure are reduced by three times compared to the case with only the asphalt concrete layer.

(2) When the UHPC layer thickness increases from 30 mm to 50 mm, the stress and deformation of the structure continue to decrease. In the case of the same UHPC thickness, the stress and deformation of the structure increase as the temperature rises from 30°C to 60°C. In the case of a 50 mm thick UHPC layer, the temperature and adhesive layer damage do not significantly affect the behavior of the structure

The study analyzed the effects of UHPC thickness, degree of adhesion failure, and temperature on the structural behavior of the OSBDs. Future research should investigate the impact of temperature-dependent bonding layer properties and the viscoelasticity of the asphalt wearing course on the mechanical behavior of such structures.

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REFERENCES

[1]. R. Wolchuk, Steel orthotropic decks developments in the 1990s, Transportation Research Record, 1688 (1990) 30-37. https://doi.org/10.3141/1688-04

[2]. X. Jia, B. Huang, B. F. Bowers, T. E. Rutherford, Investigation of Tack Coat Failure in Orthotropic Steel Bridge Deck Overlay, Transportation Research Record: Journal of the Transportation Research Board, 2444 (2014) 28-37. https://doi.org/10.3141/2444-04

[3]. H. Zhang, Q. Mao, Z. Zhu, Y. Pan, J. Wan, C. Zhou, J. Qian, Experimental study on service performance of epoxy asphalt steel deck pavement of cable stayed bridge, Case Studies in Construction Materials (2020). https://doi.org/10.1016/j.cscm.2020.e00392.

[4]. R. Wolchuk, Structural behaviour of surfacings on steel orthotropic decks and considerations for practical design, Struct. Eng. Int., 12 (2002) 124-129. https://doi.org/10.2749/101686602777965586

[5]. X. Liu, T. O. Medani, A. Scarpas, M. Huurman, Experimental and numerical characterization of a membrane material for orthotropic steel deck bridges: Part 2: Development and implementation of a nonlinear constitutive model, Finite Elem. Anal. Des., 44 (2008) 580-584. https://doi.org/10.1016/j.finel.2008.01.012

[6]. X. Liu, J. Li, G. Tzimiris, T. Scarpas, Modelling of five-point bending beam test for asphalt surfacing system on orthotropic steel deck bridges, Int. J. Pavement Eng., 9 (2019) 1697440. https://doi.org/10.1080/10298436.2019.1697440

[7]. W.Yang, UHPC-based strengthening technique for orthotropic steel decks with significant fatigue cracking issues, Journal of Constructional Steel Research, 176 (2021) 106393 https://doi.org/10.1016/j.jcsr.2020.106393

[8]. V. H. Hoang, Q. T. Nguyen, A. T. Tran, T. C. H. Tran, T. A. Do, Mechanical behavior of the asphalt wearing surface on an orthotropic steel bridge deck under cyclic loading, Case Studies in Construction Materials, (2021). https://doi.org/10.1016/j.cscm.2021.e00836

[9]. A. T. Tran, V. H. Hoang, T. A. Do, D. N. Tran, Effect of adhesion failure and temperature on the mechanical behavior of orthotropic steel bridge deck, Transport and Communications Science Journal, 73 (2022) 52-60. https://doi.org/10.47869/tcsj.73.1.5

[10]. V.H. Hoang, T.A. Do, A.T. Tran, X.H. Nguyen, Flexural capacity of reinforced concrete slabs retrofitted with ultra-high-performance concrete and fiber-reinforced polymer, Innovative Infrastructure Solution, 9 (2024) 113. https://doi.org/10.1007/s41062-024-01410-y

[11]. V. H. Hoang, Experimental and numerical study on tensile behavior of ultra high-performance concrete, Transport and Communications Science Journal, 74 (2023) 709-717. https://doi.org/10.47869/tcsj.74.6.2

[12]. A. Houel, T. L. N'Guyen, L. Arnaud, Monitoring and designing of wearing courses for orthotropic steel decks throughout the five-point bending test, Advanced Testing and Characterisation of Bituminous Materials, 1 and 2 (2009) 433–442. https://doi.org/10.1201/9780203092989-48

[13]. S. Pouget, C. Sauzeat, H. Di Benedetto, F. Orlard, Numerical simulation of the five-point bending test designed to study bituminous wearing courses on orthotropic steel bridge, Materials and Structrures, 43 (2010) 319-330. https://doi.org/10.1617/s11527-009-9491-1

[14]. M. R. Taha, S. Hardwiyono, N. I. M. Yusoff, M. R. Hainin, J. Wu, K. A. M. Nayan, Study of the effect of temperature changes on the elastic modulus of flexible pavement layers, Research Journal of Applied Sciences, Engineering and Technology, 5 (2013) 1661-1667. http://dx.doi.org/10.19026/rjaset.5.4920