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EFFECT OF ADHESION FAILURE AND TEMPERATURE ON THE MECHANICAL BEHAVIOR OF ORTHOTROPIC STEEL BRIDGE DECK

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Abstract. Orthotropic steel bridge decks (OSBDs) have been widely used in long span bridges with many advantages, however, the long-term performance of the asphalt wearing course is still questionable. There is a lack of understanding the causes of cracking and adhesion failure between the tack coat and the steel plate, etc. Therefore, this paper focuses on the adhesion failure between the asphalt wearing course and the steel plate, and the temperature influence on the mechanical behavior of the orthotropic deck. The five-point bending beam test model using the finite element model is used in this investigation in order to clarify the effect of ratio of adhesion failure and the temperature on the mechanical behavior of the OSBD. The ratio of adhesion failure varies from 0.1 to 0.5, and the temperature changes from 30ºC to 60ºC. The results reveal the influence of temperature and adhesion failure on the mechanical behavior of the OSBD.

Keywords: adhesion failure, orthotropic steel deck bridge, asphalt wearing course, temperature, finite element model.

1. INTRODUCTION

Orthotropic steel bridge decks (OSBD) are widely used for long-span bridges, such as cable-stayed, suspension and truss bridges due to their considerable lightweight and flexibility. OSBDs have been used in Europe since 1960 and then quickly been popular in Asian countries including Vietnam. However, the application of OSBDs in bridges still has many concerns, especially issues related to bridge deck wearing course such as cracking, loss of adhesion between the tack coat and steel plates, etc.

Regarding research on the damage of bridge deck wearing course on OSBDs, a few published works in the world can be listed as studies of Jia et al. [1], Zhang et al. [2], Wolchuk et al. [3], and Liu et al. [4,5]. In Vietnam, in recent years, when vehicles' loads and traffic tend to increase combined with the influence of weather and temperature changes, damages in OSDs have also begun to appear (such as in Thang Long bridge and Thuan Phuoc bridge), which require in-depth studies to resolve those problems. Several studies, which should be mentioned, are the works of Nguyen Quang Tuan et al. [6], Tran Anh Tuan et al [7], and Hoang Viet Hai al [8]. This paper aims to evaluate the influence of levels of adhesion failure between the epoxy asphalt wearing course and the steel plate on the evolution and distribution of strain in an OSBD.

The degree of adhesion failure has been studied in several researches. Recently, Nguyen Dinh Hai et al [9] has been described the adhesion loss under different circles. By changing the ratio of adhesion failure, they examined the influence of the adhesion failure on the behavior of the OSBD under local load. However, the influence of temperature on the OSBD was not clarified in this research.

In this study, a numerical model was created to simulate the mechanical behavior of an OSBD under local loads based upon the configuration of the five-point bending beam test that was first developed at the “École de Ponts et Chaussées” in France. This test configuration has been discussed extensively by Liu et al. [5], Houel et al. [10], Pouget et al. [11] and Olard et al. [12]. The model would be used to examine the influence of the degree of adhesion failure on the mechanical behavior of the OSBD.

2. MODEL DESIGN

2.1. Geometric parameters, materials and loads used in the 5-point bending beam test model

The five-point bending test model used in this study has the shape, dimensions, and material parameters as described in Figure 1, and Tables 1 and 2. These values are the same according to the researches of Nguyen Quang Tuan al [6] and Nguyen Dinh Hai et al [9]. The OSBD composes a layer of epoxy asphalt concrete (EAC) bonded with a steel plate using an epoxy bonding layer. This structure is positioned on 3 supports with one fixed support in the middle as illustrated in Figure 1.

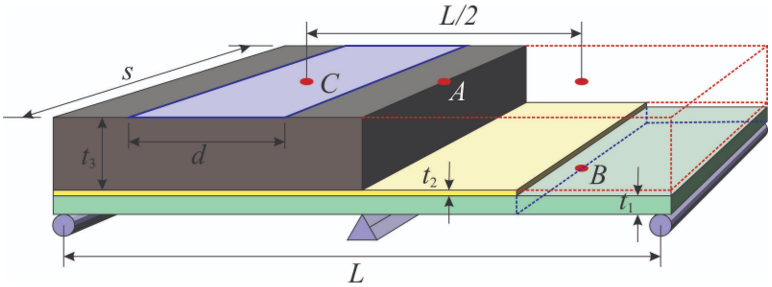


Figure 1. Schematic of the five-point bending test model.

Table 1. Parameters used for modeling.[9]

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

Table 2. Materials properties [6][8].

Material	**Modulus elastic** (Mpa)	**Poisson's ratio**	**Volumetric mass** (kg/m^3)	**Thermal dilatation** (/^{o}C)
Steel	200.000	0,3	7850	11.7 x 10^{-6}
Epoxy bonding	3.500	0,38	1250	-
EAC	5.000	0,35	2695	10 x 10^{-6}

The model of OSBD 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.

2.2. Adhesion failure modelling

The failure of the bonding layer between the steel plate and asphalt concrete might come from many complex reasons such as loading conditions, temperature changes, environmental humidity, construction technology, etc. After the construction stage, the bonding layer is located inside the bridge deck asphalt wearing course. It is difficult to determine the level and location of the damage in this layer without destructing the structure. Therefore, this study aims to simulate the random locations and distributions of the adhesion failure zones before building a relationship between the damage degree and the strain, stress, and displacement at several special points in this structure.

The shape of the bonding layer failure could be very diverse. However, in this approach, the adhesion failure in the form of non-intersecting ellipses is randomly distributed. The number of ellipses is selected to be N=100, the centers of the ellipses are distributed according to the law of continuously uniform distribution as shown in Figure 2.

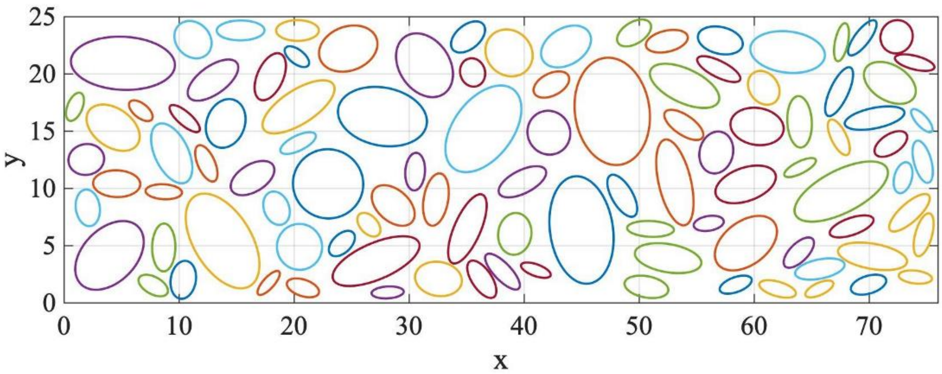


Figure 2. Random distribution of failure zones in the bonding layer

2.3. Effect of temperature on elastic modulus of asphalt wearing course

The stiffness of the asphalt wearing course is determined by the quality of the materials used and is usually measured as a modulus (E). The stiffness of this material is also affected by changes in the weather or season in the region. Temperature changes will affect the elastic modulus of the asphalt concrete layer. An empirical equation to describe the relationship between temperature and the elastic modulus of asphalt concrete was developed by AASHTO (1993). The study of Mohd Raihan Taha [13] shows that a relationship between temperature and the elastic modulus of asphalt mixtures can be calculated using Eq. (1).

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

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

This relation was used to setup the calculation of the five-point bending test model. In this study, the elastic modulus of the epoxy is considered not changing with temperature.

2.4. Structural simulation using finite element

The size and coordinates of the failure ellipses are randomly generated before being inserted into the finite element-based software - Comsol Multiphysic. The adhesion failure was simulated by the empty domains, i.e. ellipses with a thickness equal to the thickness of the epoxy bonding layer, as shown in Figure 3.

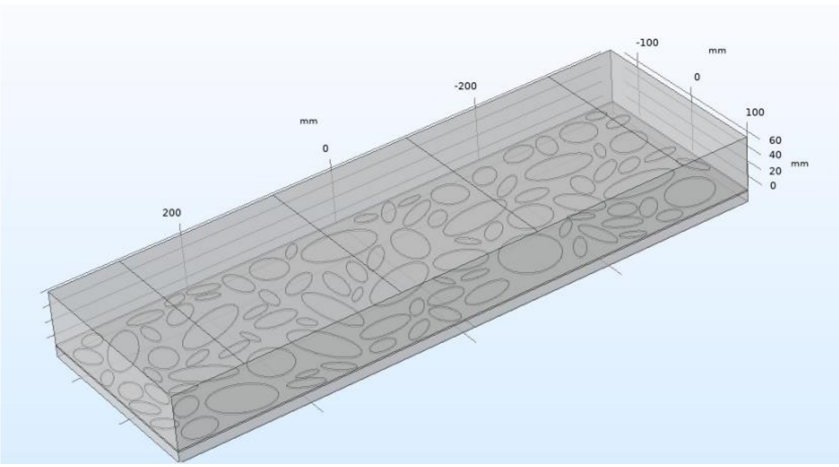


Figure 3. Simulation of the area of adhesion failure in the bonding layer.

Non-failure part of the bonding layer is modeled to be perfectly bonded to the asphalt wearing course and the steel plate. All the three types of materials including the steel, asphalt concrete and bonding layer are modeled to be linearly elastic with material parameters listed in Table 2. The whole structure is meshed with a total number of approximately 200,000 tetrahedral elements as shown in Figure 4.

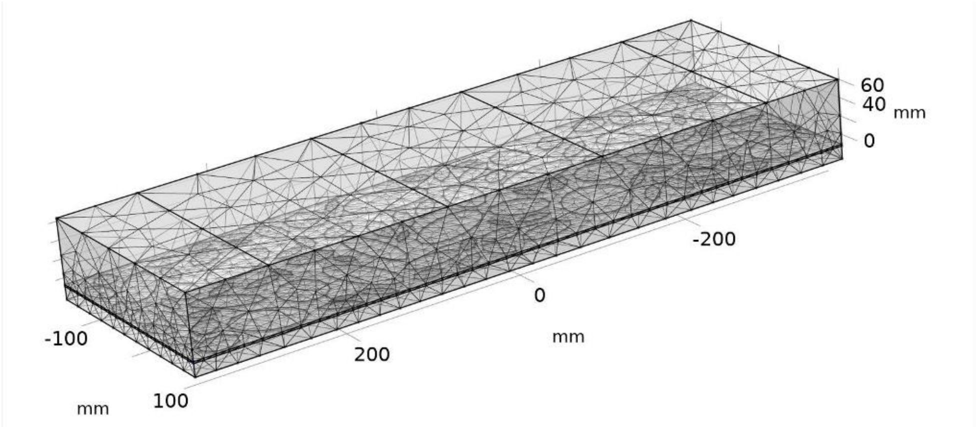
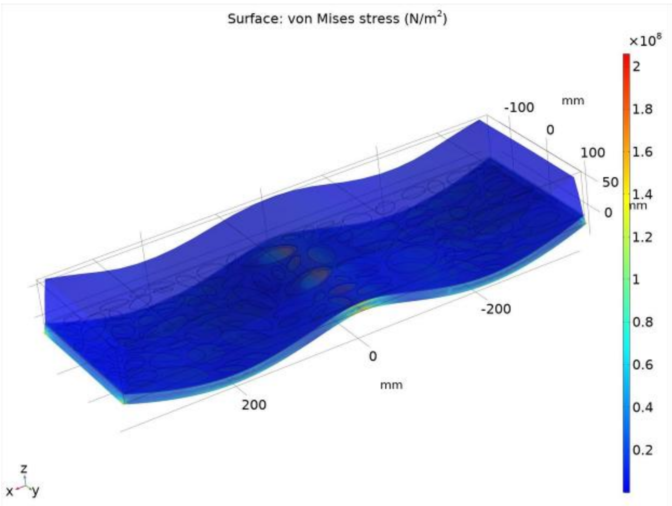


Figure 4. Discrete image of the OSBD using tetrahedral mesh.

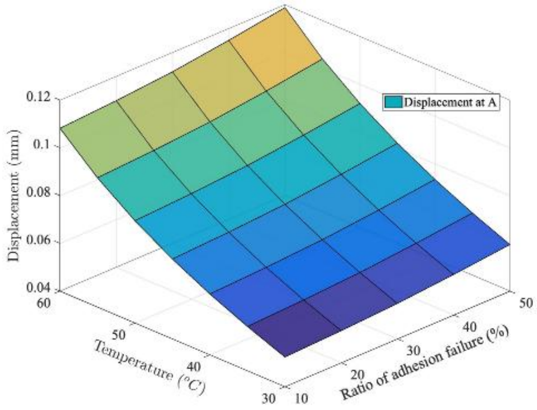
3. RESULTS AND DISCUSSION

In this section, random adhesion failure ellipses are performed corresponding to the adhesion failure ratio from 0.1 to 0.5. The influence of the degree of adhesion failure on the mechanical behavior of the model is analyzed. Figure 5 illustrates the model strain in the case of 0.5 adhesion failure.

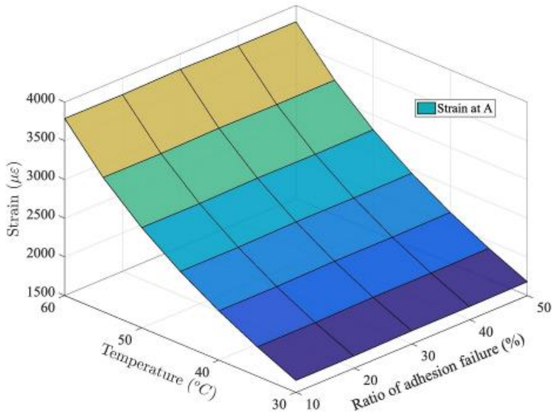


Hình 5. Behavior of OSBD in the case of 0.5 adhesion failure.

The outputs are strain, stress and displacement at the 3 positions on the five-point bending beam test model (Figure 1) as follows: point A (the middle top of the asphalt layer at the support, point B (bottom of the steel plate at mid-span), and point C (top of the asphalt layer at mid-span). The averages of strain, stress and displacement of 10 random ellipses are calculated using the Monte Carlo formula, which was also mentioned in the work of Lachihab and Sab's [14,15].



(a)



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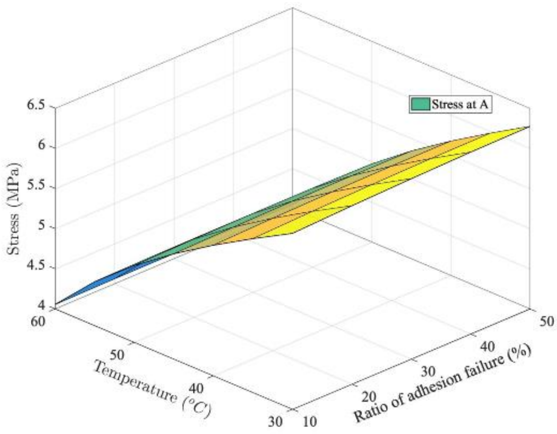
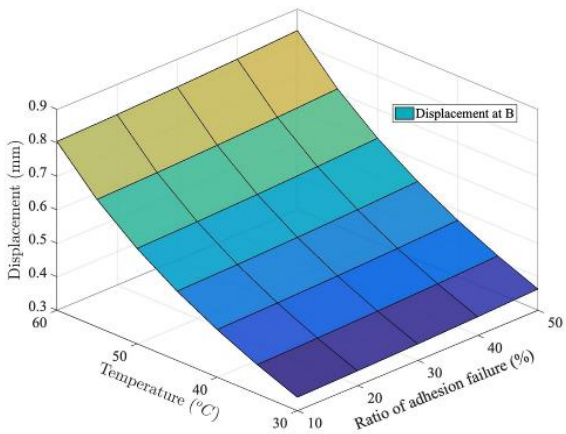
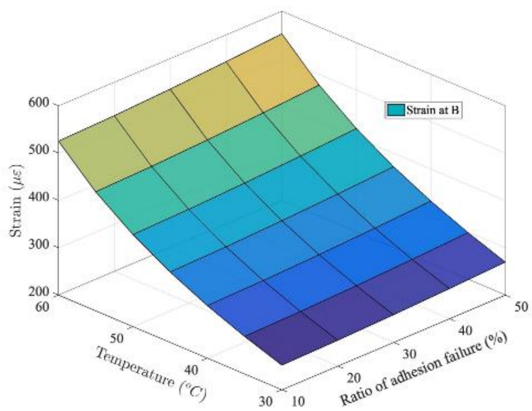


(c)

Figure 6. Relationship between strain, displacement, stress and ratio of adhesion failure, temperature at point A.



(a)



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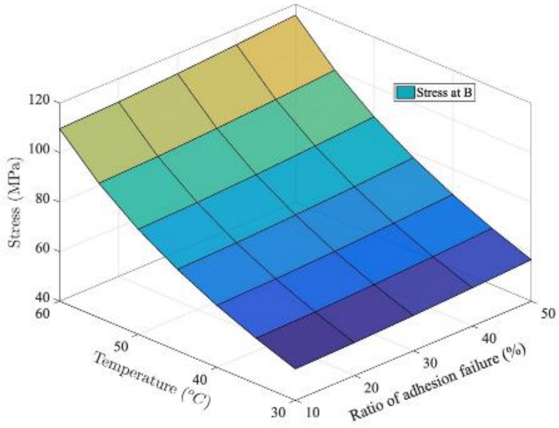
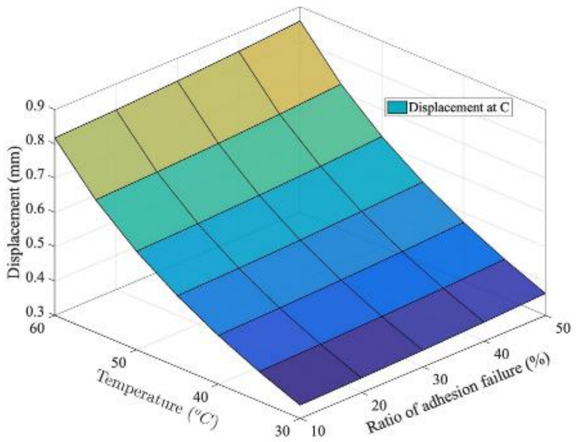
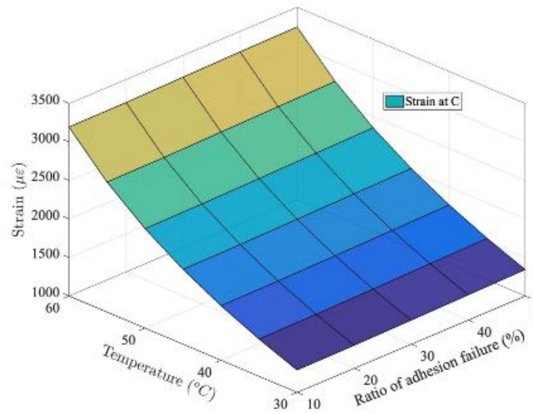


(c)

Figure 7. Relationship between strain, displacement, stress and ratio of adhesion failure, temperature at point B.



(a)



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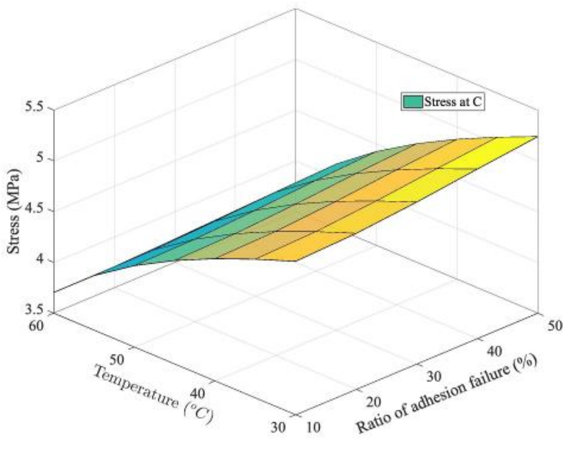

(c)

Figure 8. Relationship between strain, displacement, stress and ratio of adhesion failure, temperature at point C.

Figures 6 through 8 indicate the structural response at points A, B, and C with the varying ratio of adhesion failure and the temperature ranging from 30^{o}C to 60^{o}C. These figures show that: (*i*) the strain and displacement increase when the ratio of the bonding layer failure and temperature increase; (*ii*) when the ratio of the adhesion failure increase, the strain and displacement at points A, B, and C increase, but the temperature has larger effect on the strain evolution at these points; (*ii*) the strain is very large at point A, as this value reaches 1200 με at 30°C and a ratio of adhesion failure of 0.1, 1500 με at 30°C and a ratio of adhesion failure of 0.5, and 3700 με at 60°C and ratio of adhesion failure of 0.1.

The influence of the degree of adhesion failure and temperature on the structural behavior of the five-point bending beam test model are analyzed. The temperature has more important effect on strain, stress, and displacement evolutions at points A, B, C.

4. CONCLUSIONS

In this study, numerical simulations of adhesion failure in the five-point bending test model have been performed and the effect of temperature has been taken into account to analyze the local behavior of an OSBD with an asphalt wearing course. In the simulations, the ratio of bonding damage is controlled at a value up to 0.5, while the temperature varies from 30°C to 60°C. Important findings from this study are summarized as follows:

(1) The degree of adhesion failure has an influence on the mechanical behavior of the OSBD. When the degree of adhesion failure increases, the strain, stress and displacement at points A, B, and C also increase. This trend appears more clearly when the temperature rises from 30°C to 60°C.

(2) The strain at point A increases approximately 300% when the temperature increases from 30°C to 60°C.

The study analyzed the basic effects of the degree of adhesion failure and temperature on structural behavior of the OSDs. Further work should investigate the effect of the temperature dependent bonding layer properties, and the viscoelasticity of the asphalt wearing course on the mechanical behavior of such structures.

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