Finite element analysis on the stress reduction effects of UHPFRC overlaid steel bridge deck

UHPFRC-鋼剛性床版におけるひずみ低減効果の有限要素解析

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1. INTRODUCTION

Steel bridge decks are widely used due to the advantages, such as light-weight, short construction period and durability, in comparison with reinforced concrete bridge decks. However, the connecting area between transversal rib and deck, namely hotspot, and the bottom surface of deck in midspan area are susceptible to fatigue. Fatigue usually happens in such steel bridge decks caused by repetitive loading from heavy traffic and may extremely decrease the expected service life of steel bridge decks [1]. An even increasing trend of traffic in the last decades undoubtedly made the problem more severe. An idea to improve the work abilities of steel bridge decks is to apply an overlaid reinforcement material.

Ultra-high performance fiber reinforced concrete, namely UHPFRC, is a kind of cementitious material composed of steel fibers and micro silica fume [2]. UHPFRC has outstanding properties such as high strength in tension, compression and extremely low water permeability [3, 4]. Typical compressive and tensile strengths of UHPFRC are 130MPa and 9MPa, respectively [5]. The superior characteristics of UHPFRC make it an appropriate material for reinforcing steel bridge decks.

The study aims to investigate the stress reduction effect of UHPFRC as a reinforcing layer on steel bridge deck using finite element analysis. The model used in finite element analysis is based on a wheel-load running experiment specimen. By applying fine mesh elements in hotspot areas, the model shows good coincidence with experimental results. Maximum strain values of steel bridge deck and hotspots on middle transversal rib are focused. Fatigue life is predicted and discussed based on maximum strain. The investigation result indicates that UHPFRC is suitable as a reinforcing material applied over steel bridge decks because the UHPFRC overlay can effectively decrease the stress and extend the service life of the structure.

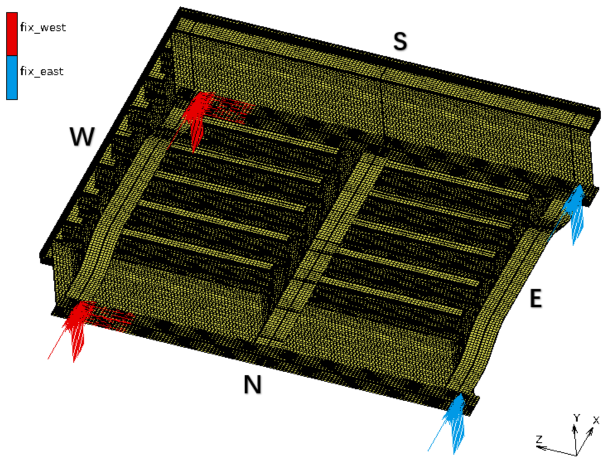

Figure 1 Constraints in displacements of SU1 model

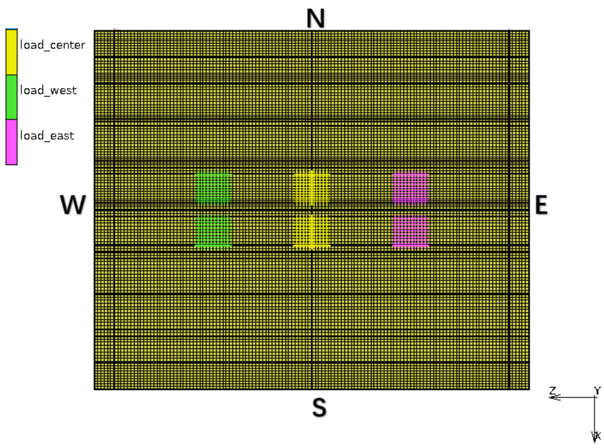

Figure 2 Face loads applied on top surface of SU1 model

2. METHOD

2.1 Profile of finite element analysis model

Finite element analysis is performed by using the software MSC/Marc. The analytical model is based on an orthotropic

Table 1 Material properties in finite element

Material	Elastic modulus (MPa)	Poisson's ratio
UHPFRC	31.3	0.22
Steel	210	0.3

steel bridge deck structure, of which the deck plate is supported by 7 longitudinal and 3 transversal ribs in two perpendicular directions.

For the sake of convenience, besides the XYZ coordinate, four directions of the model are defined in XZ plane as N(north), S(south), E(east) and W(west).

To do comparison study, two typical models are analyzed. The difference is in the existence or not of overlaid UHPFRC layer. The model only with steel bridge deck is named as S1. The model combined steel bridge deck with overlaid UHPFRC layer is named as SU1. In S1 model, the dimensions of steel bridge deck plate are 3300×2720×12 mm while in SU1 model, the dimensions of UHPFRC reinforced steel bridge deck plate are 3300×2720×37 mm.

All the components use 8-node 3D solid elements. Perfect bond between UHPFRC and steel bridge deck is assumed, with no existence of sliding.

Material properties used in the analysis are the same as those in the wheel-load running experiment as shown in **Table 1**.

Boundary conditions (BCs) are needed to get unique solutions. As shown in **Figure 1**, supports are modeled as two rollers by giving constraints to a single line of nodes. In fix_west, the displacements are fixed in X,Y and Z direction while in fix_east they are fixed in X and Y direction.

Three load cases are defined as static 70kN face loads applied separately on top surface of the deck plate as shown in **Figure 2**. Each load case is composed of two 220×250 mm loading areas simplified from a pair of wheel tire loading areas with irregular shape in the wheel-load running experiment. As the name indicates, load_center is applied in the center while the other two are applied 750 mm away from load_center to the west and east.

2.2 Fine mesh in hotspot area

To improve the accuracy of analytical results in hotspot areas on transversal ribs, mesh is refined in a particular area as shown in **Figure 3**.

The mesh transition area between coarse and fine mesh is located away from the area of interest and is not located in an area with large stress variation to avoid local stress anomalies.

Average dimension of fine mesh elements in hotspot areas is determined by minimum distance of observation points used in 3-point extrapolation which is the method to assume the strain at hotspot. The method will be discussed in section **3.4**.

3. RESULTS AND DISCUSSIONS

3.1 Overview

In the analysis of deck plate, in order to have a comprehensive understanding of deformation and stress distribution, displacement data are obtained from all node points on line WE and SN while the strain data are obtained from all node points on line SN as shown in **Figure 4**. It is to be mentioned that gauges used in wheel-load running experiment are located on bottom surface of steel bridge deck and covered by the lines.

In the analysis of upper and lower areas of interest on transversal rib, similarly, strain data are obtained from all node points on several lines covering strain gauges located on the façade of middle transversal rib as shown in **Figure 5**. Arc lengths of the lines are 264 mm and 230 mm in case of upper and lower area, respectively.

In the analysis of hotspots, strain data are obtained from all node points on the lines which originate from hotspot forwarding opposite of Z direction with arc lengths of 54.15 mm on flanks of middle transversal rib as shown in **Figure 6**.

Experimental data collected from gauges are compared with analytical data to check whether there is a good coincidence. By checking vertical displacement, in-plane strain of deck plate and in-plane strain of middle transversal rib, a good agreement could be found between analytical and experimental data value.

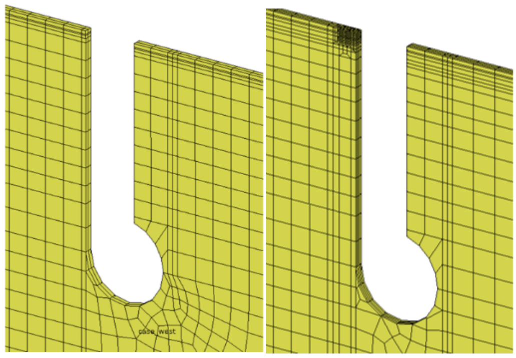

Figure 3 Overview of hotspot area without and with fine mesh on middle transversal rib

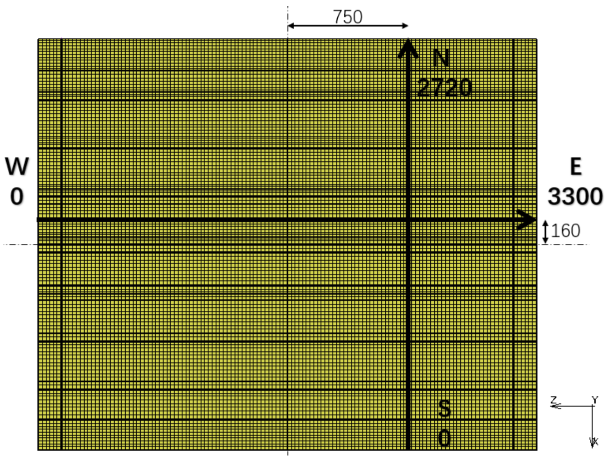

Figure 4 Plan view of SN and WE lines located on bottom surface of steel bridge deck

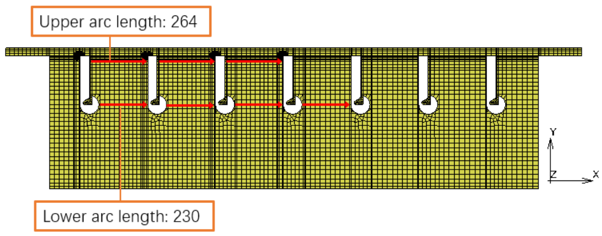

Figure 5 Side view of lines covering strain gauges on middle transversal rib

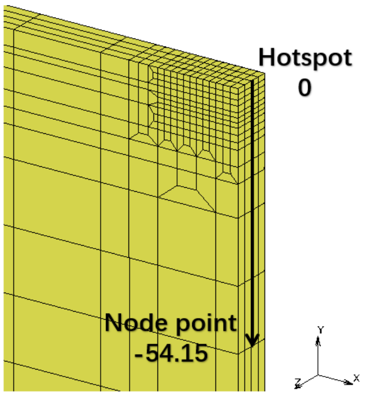

Figure 6 Line covering hotspot on flanks of middle transversal rib

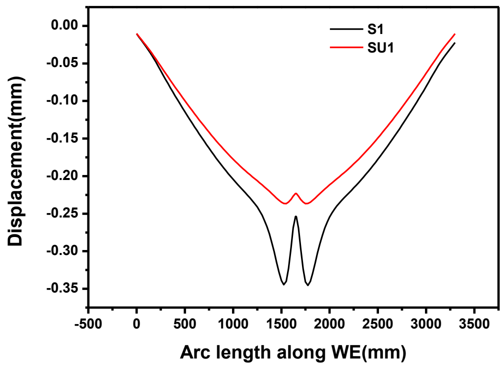

Figure 7 Displacement in Y direction along WE under load_center

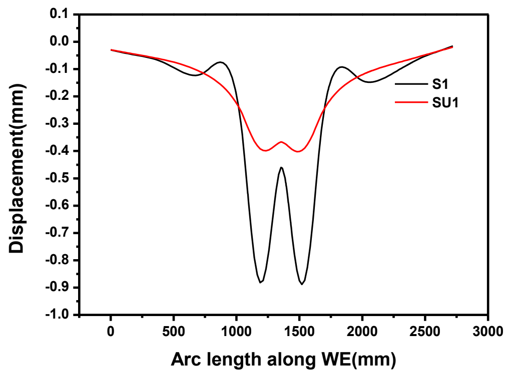

Figure 8 Displacement in Y direction along SN under load_east

3.2 Displacement results

Typical displacements in Y direction of S1 and SU1 model along lines WE and SN are shown in **Figure 7** and **Figure 8**.

In either case, a small and steady displacement result could be observed in SU1 model which is reinforced with UHPFRC layer. It indicates that the application of UHPFRC layer could decrease the deformation of steel bridge deck under static load.

3.3 Strain results

Strain distribution of specific areas are investigated as listed:

(1)Strain in X and Z direction on bottom surface of steel bridge deck

(2)Strain in X and Z direction on top surface of UHPFRC layer

(3)Strain in X and Y direction of upper interested areas on façade of middle transversal rib

(4)Strain in X and Y direction of lower interested areas on façade of middle transversal rib

(5)Strain in Y direction of upper interested areas on flanks of middle transversal rib(hotspot)

(6)Strain in Y direction of lower interested areas on flanks of middle transversal rib

Through the investigation, it could be observed that strain results in (1) and (5) are especially large. Distributions of two relatively large strain cases on steel bridge deck and middle transversal rib are shown in **Figure 9** and **Figure 10**, respectively.

As is shown in **Figure 9**, several large strain values happening both in tension and compression are depressed by UHPFRC layer. By comparing two curves shown in **Figure 10**, strains near hotspot are also reduced due to the existence of UHPFRC layer. Moreover, it is known that there will be a sharp drop of strain value between hotspot and one node point below it. The drop may result from the limitation of finite element analysis in which the hotspot is just located at the intersection of two perpendicular components.

3.4 Fatigue life prediction

After the discussion in section **3.3**, maximum strain values on steel bridge deck and middle transversal rib are confirmed to be located on SN line under load_east and third hotspot from North under load_center.

In other words, each of the two node points where maximum strain exists is the most dangerous location under fatigue.

Maximum strain of steel bridge deck is -488μ located on SN line 1335 mm away from node point S in model S1. Accordingly, at the same location of SU1 model the strain is -70μ.

Maximum strain at hotspot is determined by 3-point linear extrapolation as shown in **Figure 11**. When arc length equals 0, maximum hotspot strain of S1 is -383μ while the strain of SU1 is -313μ.

Maximum strain values are used in fatigue life prediction. The functions are listed as follows [6]:

$$\sigma = E \cdot \varepsilon \tag{1}$$

$$\sigma_k^m \cdot N = C \tag{2}$$

$$C = (FAT)^m \cdot (2 \times 10^6) \tag{3}$$

where ε is maximum strain, E is elastic modulus of steel, σ_k^m is equivalent stress range, N is total cycles and FAT is basic fatigue strength of 200 million cycles. In this case, m=3 and FAT=80MPa. Years of fatigue life is determined as

$$\frac{N \times 100}{3200000} \tag{4}$$

Both fatigue life prediction results for steel bridge deck and hotspot are shown in **Table 2** and **Table 3**. In both cases, the structure without reinforcement of UHPFRC layer couldn't

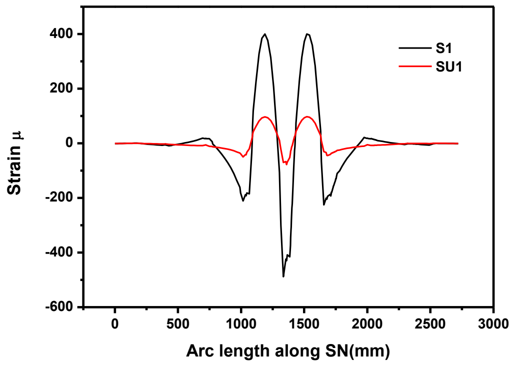

Figure 9 Strain in Z direction along SN under load_east

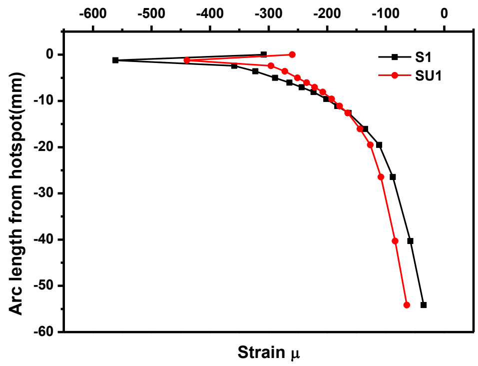

Figure 10 Strain in Y direction originating from hotspot under load_center

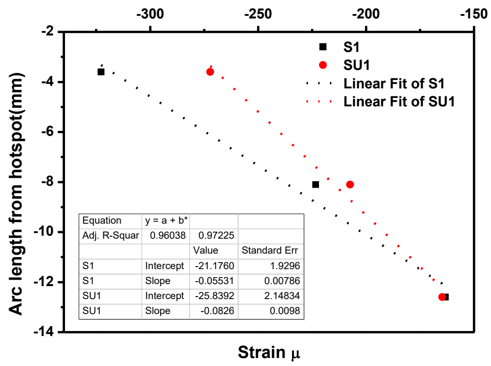

Figure 11 3-point linear extrapolation of hotspot strain

Table 2 Steel bridge deck fatigue life prediction

	Strain ε (μ)	Equivalent stress range σ_k (MPa)	Fatigue life (year)	Safety
S1	-488	102.48	29.7<100	NG
SU1	-70	14.7 (14.3%)	10075>100	OK

Table 3 Hotspot fatigue life prediction

	Strain ε (μ)	Equivalent stress range σ_k (MPa)	Fatigue life (year)	Safety
S1	-383	80.43	61.5<100	NG
SU1	-313	65.73 (81.7%)	112.7>100	OK

overcome a 100-year service life. On the contrary, the structure can work more than 100 years with the existence of UHPFRC overlay.

4. CONCLUSIONS

In this study, stress distribution of UHPFRC reinforced steel bridge deck are investigated by using finite element analysis. The finite element model shows good coincidence with the specimen used in the wheel-load running experiment. Fatigue life is also predicted and discussed based on the analysis.

The study shows that the maximum stress of whole structure is found on the bottom surface of steel bridge deck. After applying the UHPFRC reinforcement layer, the maximum stress is decreased by 85.7%. Service life of the structure is remarkably elongated with the existence of UHPFRC overlay.

The study shows the suitableness of UHPFRC as a kind of reinforcement material applied over steel bridge decks as it can effectively reduce the stress on bottom surface of steel bridge deck and at hotspot.

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