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Fatigue Analysis of ECC-Steel Composite Deck under Wheel Trucking Load

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Abstract

This study conducts fatigue analysis of Engineered Cementitious Composite (ECC)-Steel composite deck, and evaluates fatigue durability under wheel trucking load repetitions. In the fatigue analysis, fiber bridging degradation model derived from micromechanics approach is applied to finite element analysis in order to represent the fatigue degradation of ECC. From the analytical result, it is confirmed that deflection is almost constant, and shear force on shear connectors is kept below shear load capacity during 1.2 million cycles of design load. Also, maximum crack width in ECC is controlled below harmful levels against the attack of environmental factors as well as the rupture of waterproof layer. Finally, fatigue at a welded joint between deck plate and U-rib is checked based on JSSC code, and fatigue crack initiation is found to be potentially low.

Keywords: ECC; steel deck; overlay reinforcement; fatigue analysis.

1. INTRODUCTION

In steel decks under traffic load repetitions, fatigue cracks initiate easily at the welded joint of members. To strengthen fatigue durability of steel decks, in recent years, reinforcement with FRCCs (Fiber Reinforced Cementitious Composites) overlay has been applied, and the applicability of ECC (Engineered Cementitious Composite), a kind of SHCC (Strain Hardening Cementitious Composites) has been studied. ECC with high strain capacity is thought to show an advantage in composite effect after the cracking of overlay compared with conventional FRCCs, such as SFRC (Steel Fiber Reinforced Concrete), which is a strain softening type material.

About ECC-steel composites decks, the composite method and fatigue durability were studied by static loading test and wheel trucking test (Mitamura et al. 2006). However, analytical study on fatigue life

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based on the fatigue degradation model of ECC has not been conducted, and it is necessary to estimate fatigue degradation numerically and develop the method of fatigue life prediction. Therefore, this paper conducts the fatigue analysis of ECC-steel composite deck under wheel trucking load repetitions, and discusses fatigue durability.

2. ANALYTICAL MODEL

2.1. Geometric Model

2.1.1. ECC-Steel Composite Deck

The geometric properties of ECC-Steel composite deck are shown in Figure 1. This deck is composed of ECC, steel deck plate, shear connectors, U-ribs and waterproof layer. For the connection between ECC and deck plate, plate type shear connectors made of FRP are introduced. Loading lane is located in the middle of transverse direction and the range is 2,000mm. This lane causes smaller stress and strain on both ECC and steel deck compared with the lane in which double tires stride over the welded joint of U-rib. Fatigue load is set to be 150kN, which corresponds to design load, and maximum number of loading cycles is set to be 1,200,000.

2.1.2. Finite Element Mesh and Boundary Conditions

The finite element mesh of composite deck is shown in Figure 2. By taking advantage of symmetry with respect to the centerline, half of a model is analyzed. Between ECC and deck plate, interface elements are inserted in order to represent interfacial slip. The all sides of composite deck are simply supported. To simulate moving load, seven loading points are prepared on the loading lane, and distributed load acts on each point in numeric order.

2.2. Material Models

2.2.1. ECC

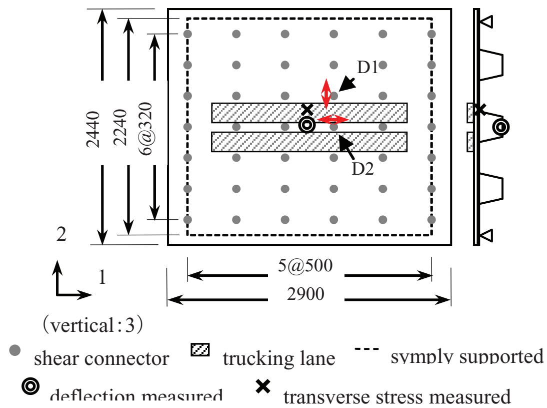
Figure 3 is the stress-strain relation of ECC, and material properties are also shown in the figure. In the fatigue analysis, tensile stress reduction of ECC is applied. Fiber bridging stress degradation is the mechanism of fatigue degradation of ECC, and authors developed fiber bridging stress degradation model based on bridging law, the relation between fiber bridging stress and crack width (Kakuma et al. 2010). Fatigue model adopted in this study is the model derived by introducing criterion of fiber fatigue rupture into bridging law, which assumes ECC reinforced with PVA fibers, and the following equation is applied to finite element analysis.

$$\frac{\sigma_N}{\sigma_1}(\delta_{\max}, N) = \mathrm{Exp}[\{0.0001 - (0.022\delta_{\max})^{1.2}\}(\mathrm{Log}N)^{4.6}] \tag{1}$$

where σ_N/σ_1=stress ratio, δ_{max}=maximum crack width, and N=number of cycles after cracking

In this study, smeared crack model is used to represent crack behavior of ECC, and crack width is obtained from maximum tensile strain by the procedure shown in Figure 4.

Then, the reduction of shear stiffness and compressive stiffness after cracking is considered. In addition, the reduction of cracking strength under fatigue is defined from cumulative fatigue damage based on Miner's rule.



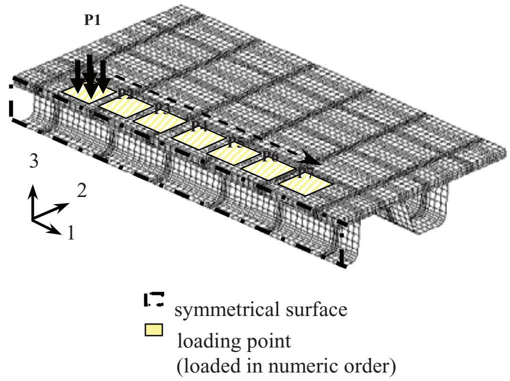


Figure 1: Dimensions of ECC-Steel deck; Figure 2: Finite element mesh

2.2.2. Other Materials

Steel is modeled as an elastic-perfect plastic body. For yield criterion, von Mises's law is adopted. Shear connectors are modeled as an elastic body, material properties of which are determined by volume of both FRP and stuffed ECC. For interface between ECC and deck plate, large stiffness in normal direction and small stiffness in tangent direction are defined, which reflects that waterproof layer does not resist against interfacial slip. Interfaces between ECC and shear connectors and between shear connectors and deck plate are assumed to be perfectly bonded.

2.3. List of measurement

From analysis, the changes of deflection and shear force on shear connectors are obtained. The measurement points are shown in Figure 1, and arrows in the figure mean the direction of measured shear force. Crack distribution in overlay ECC is also observed. The thickness of ECC is divided into three layers in finite element model, and each is called "1st", "2nd", and "3rd" from bottom to top. In addition, transverse stress at the welded joint between deck plate and U-rib is measured in order to check the possibility of fatigue crack initiation. Fatigue assessment is carried out based on JSSC code (1993), and E-class welding is assumed (Figure 5).

3. ANALYTICAL RESULT

3.1. Deflection

Figure 6(a) is the relation between deflection and number of cycles. After the comparative large slope of deflection increase in initial loading cycles, the slope becomes almost constant. The increase ratio of deflection after 1,200,000 cycles is about 1.0%.

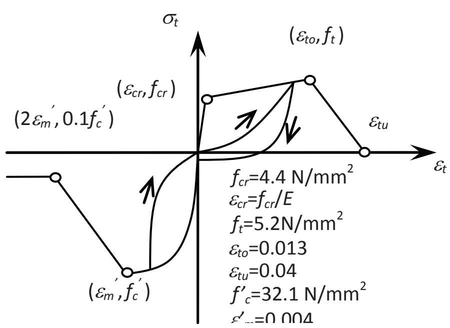
3.2. Shear Force on Shear Connectors

Figure 6(b)(c) is the change of shear force on shear connectors, D1 and D2. Table 1 is maximum shear force obtained from shear test (Mitamura et al. 2006). The transmission mechanism of shear force in the analytical model, which has no shear resistance of waterproof layer, seems to be similar to ECC-PL type.

As same as the change of deflection, the slope of shear force increase is large in initial stage, and it tends to be uniform with the increase of number of cycles. Shear force in 1,200,000the cycels (48.9kN) is below maximum shear force except for ECC-PL-WP(1) type, in which strength development of ECC is low due to the age. Therefore, when considering shear force tends to be overestimated due to the model without shear resistance of waterproof layer, it is thought that composite effect through shear connectors is sufficiently maintained under the load condition in this study.

3.3. Crack Distribution

Figure 7 is crack distribution in ECC at 1st, 600,000th and 1,200,000th cycle respectively. At 1st cycle, the range just under loading lane in 1st layer has many cracks along a symmetric line due to flexural action by loading. In this layer, cracks also distribute between a symmetric line and shear connectors. In this range, tensile stress becomes large because fixed beam is locally formed due to perfect bonding between shear connectors and deck plate. At 600,000th cycles, cracks develop in 2nd layer, especially in interval of shear connectors lining to transverse direction. These are grown cracks initiated in 1st layer due to fixed beam condition. Also, in this cycle, cracks are discovered on the top of ECC overlay. Upper part of ECC on the welded joint of U-ribs is put under tensile stress repetitions, and fatigue crack is easily initiated. At 1,200,000th cycles, the remarkable increase of cracks is not seen, and cracks are almost saturated.



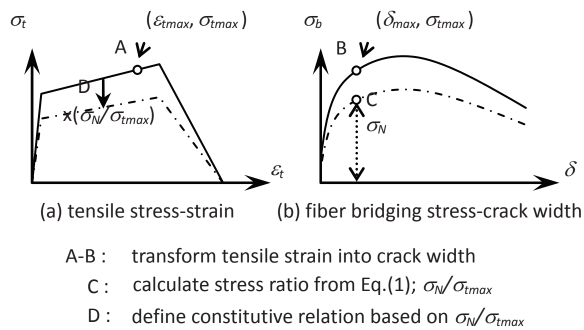


Figure 3: Stress-strain relation of ECC; Figure 4: Procedure of fatigue analysis

4. DISCUSSION

4.1. Crack Width

Maximum crack width in ECC is an important index to evaluate the rupture of waterproof layer and structural durability against environmental actions. For the former, crack width has to be below 0.25mm to prevent the rupture (JRA 2007). For the latter, 0.1mm is the critical value to need repair from the point of durability against environmental deterioration (JCI 2003). The obtained maximum crack width is 0.04mm, which is almost constant through 1,200,000 cycles, and this satisfies above criterions. Therefore, it shows that overlay reinforcement with ECC with the ability to control crack width is benefit to improve long-term durability of steel decks.

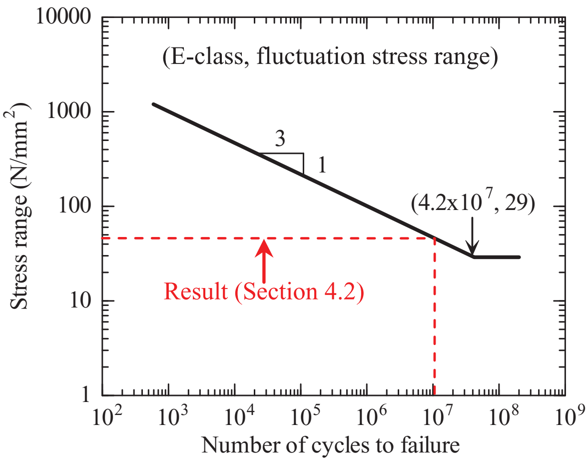


Figure 5: Fatigue design curve (JSSC 1993)

Table 1: Result of shear test (Mitamura et al. 2006)

Structural type*	Max. force (kN)
ECC-PL	67, 77
ECC-PL-WP(1)	36, 38, 33
ECC-PL-WP(2)	50.2***

* PL: shear connector, WP: waterproof

** ECC-PL-WP(2) was conducted after wheel trucking test

*** average of 13 specimens

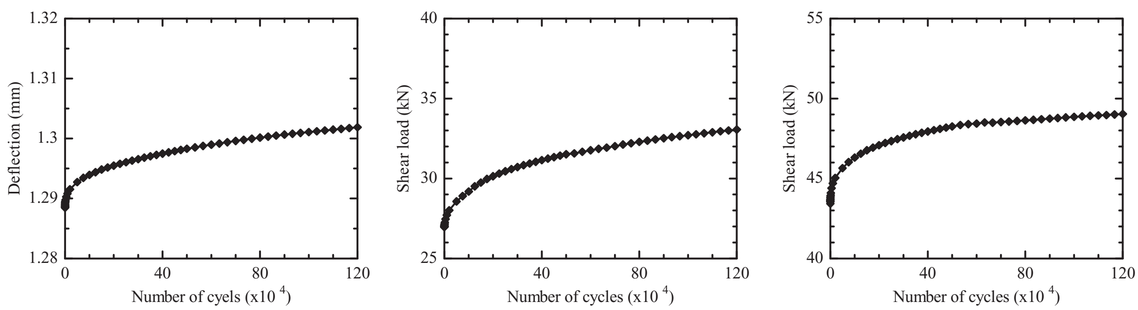


Figure 6: Analytical result; (a): Deflection; (b): Shear force (D1); (c): Shear force (D2)

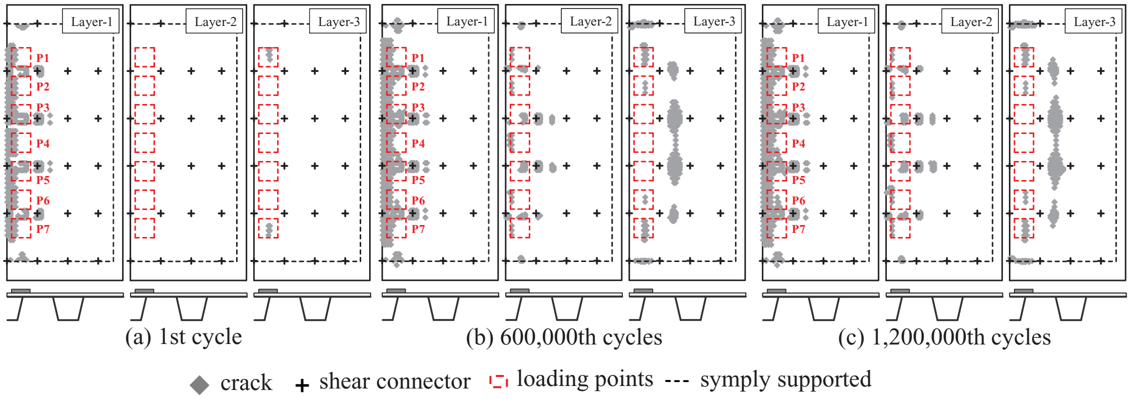


Figure 7: Crack distribution

4.2. Fatigue Assessment

Fatigue assessment about fatigue crack initiation at welded joint is carried out based on JSSC code. Checked position is shown in Figure 1. Equivalent stress range calculated from the following equation (JRA 2002) is 45.9N/mm^2, and number of cycles to cause fatigue crack is estimated to be 10,600,000 cycles when assuming E-class welding (Figure 5).

$$\Delta\sigma_{eq} = \sqrt[3]{\frac{\sum \Delta\sigma_i{}^3 n_i}{\sum n_i}} \quad (2)$$

where $\Delta\sigma_{eq}$=equivalent stress range (N/mm^2), $\Delta\sigma_i$=stress range measured in one cycle (N/mm^2), and n_i=number of cycles with $\Delta\sigma_i$

When heavy traffic volume of 2,400vehicles/day/lane is assumed, 10,600,000 cycles corresponds to service period of 403 years in JRA equation (2002).

$$n_{Ti} = ADTT_{SLi} \times \gamma_n \times 365 \times Y \quad (3)$$

where n_{Ti}=number of repetitions, $ADTT_{SLi}$=heavy traffic volume (vehicle/day/lane), γ_n=coefficient (0.03), and Y=service period (year)

Hence, from fatigue assessment after 1,200,000 cycles, more than 100 years service life is expected under repetitions of design load on the loading lane in this study.

5. CONCLUSIONS

This study conducted fatigue analysis of ECC-Steel composite deck under wheel trucking load repetitions. As a result, it was found that sufficient structural durability was given from the point of both composite structure through shear connectors and crack width. Also, the result of fatigue assessment showed the low potentiality of fatigue crack initiation at welded joint under the prepared loading condition.

For further studies, it is essential to evaluate fatigue durability under severer loading condition, i.e. fatigue life prediction under other trucking lane should be carried out.

Acknowledgment

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