Bridging stress degradation model of UHPFRC from numerically fitting fatigue flexural test results using FEA

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1. INTRODUCTION

UHPFRC (Ultra-High Performance Fiber Reinforced Concrete) is a cement-based composite material strengthened with fibers. Due to its excellent mechanical properties including a more than 130 MPa of compressive strength and a more than 9 MPa of tensile strength [1], it is able to withstand heavy loads with a relatively smaller dimension. Besides, the high density of this composite provides it extremely low water and gas permeability coefficients, which make UHPFRC durable and strong in resisting environment attacks. As a result, UHPFRC is widely used for bridge repairing and maintenance.

Even though it is believed that UHPFRCs can effectively improve the performance and durability of existing structures, the investigations of the fatigue characteristics of UHPFRC are very limited, especially in the material level. More specifically, the bridging stress degradation model which represents the reduction of transferred stress of a under fatigue loads is still not available for the UHPFRC so far. However, this model is a necessary preparation for modelling the fatigue performance of UHPFRC structures.

Therefore, the purpose of this paper is to obtain the bridging stress degradation model of UHPFRC under cyclic loads through fitting experimental results and finite element analysis (FEA) results of a UHPFRC beam subjected to a four-point fatigue bending load.

2. METHOD

In this study, a nonlinear FEM software, MSC/MARC, is used to simulate the behavior of UHPFRC under both static test and fatigue test. The tensile properties of UHPFRC under both static as well as fatigue, i.e. the bridging stress model, are determined by fitting the experimental results and FEM results of UHPFRC beams under static and fatigue flexural loads, respectively. Dimensions of the beam specimen used for static and fatigue tests are shown in **Fig. 1**. Analytical model is shown in **Fig. 2**. A half model is used considering the symmetry property. The Poisson's ratio and Young's module of the loading plate which is made from steel are assumed as 0.3 and 200 GPa, respectively. Stress-strain relations of UHPFRC in both compression and tension are shown in **Fig.3**. The bridging stress degradation is expressed as a function of two parameters which are the maximum tensile strain $\varepsilon_{t\,max}$ and number of cycle N [2]. The employed bridging stress degradation model of UHPFRC is expressed as

$$\frac{\sigma_N}{\sigma_1} = f(\varepsilon_{t\,max}, N) \le 1 \tag{1}$$

$$\frac{\sigma_N}{\sigma_1} = 1 - (a_0 + a_1\varepsilon_{t\,max})log_{10}(N) \tag{2}$$

where σ_N/σ_1 is bridging stress degradation ratio between the *Nth* and the first cycles. a_0 and a_1 are the degradation coefficients depending on the material.

2.1 4-point static test

Based on the Japanese Industrial Standard, the experiments of this study are conducted with a load speed of 0.1mm/min. Material properties are determined by trials of $\varepsilon_{cr}, \varepsilon_u, \sigma_{cr}, \sigma_u$ (see. **Fig. 3**) in the analysis until the FEM results fit with the experimental results.

2.2 4-point bending fatigue test

In the 4-point bending fatigue tests, the load levels are calculated based on the load capacity of static test. In this study, three load level ratios, 0.2~0.95, 0.2~0.9, 0.2~0.85, with respect to the static load capacity are employed for the fatigue test. Load frequency is 3Hz. Material properties obtained in static test are used for determining the bridging stress degradation model. The degradation model is determined by trials of the degradation coefficients a_0 and a_1 in the analysis until the FEM results fit with those from experiment. In analysis, 0.95, 0.9, 0.85, 0.75 are used for the stress level.

3. RESULT AND DISCUSSION

3.1 4-point static test

Comparison of the load to deflection relation from analysis and experiments are shown in **Fig. 4**. Material properties is determined by fitting the experimental results of the static test are shown in **Table1**. Principal value of strain is shown in **Fig.5**. Average load capacity of experiment and load capacity of analysis are 7.4688kN and 7.65kN respectively. In static

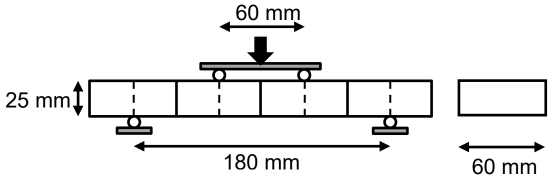

Fig. 1 Dimension of specimen

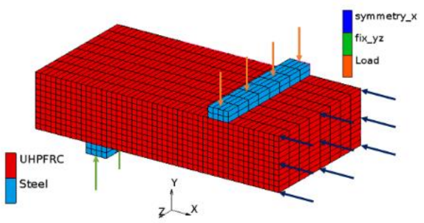

Fig. 2 Analytical model

Table 1 Material properties of UHPFRC from fitting

Point	Param.	Value	Point	Param.	Value
①	σ_{cu}	26.6MPa	③	σ_{t0}	16MPa)
	ε_{cu}	0.01275		ε_{t0}	0.012
②	σ_{cr}	10.65MPa	④	ε_{tu}	0.03
	ε_{cr}	0.000308			

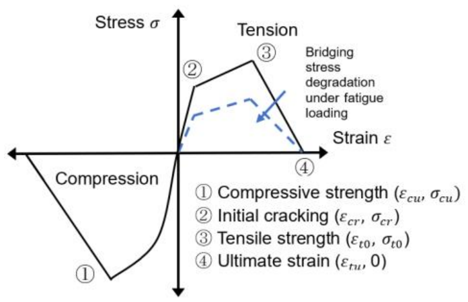

Fig. 3 Stress-strain relations of UHPFRC

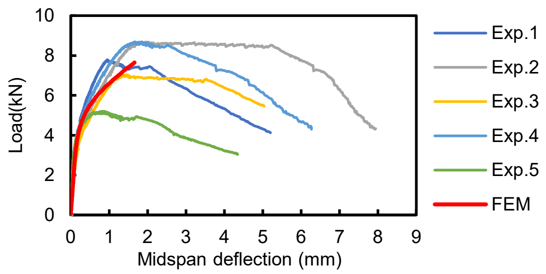

Fig. 4 Evolution of midspan deflection from analysis and experiment.

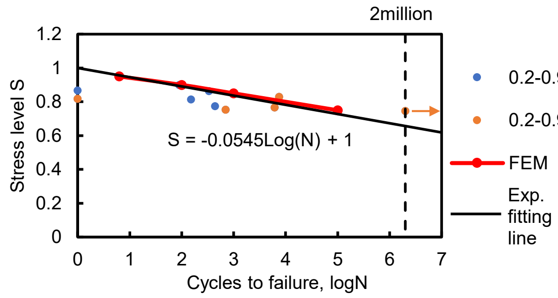

Fig. 7 S-N relation

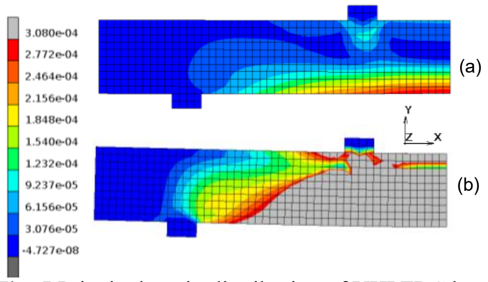

Fig. 5 Principal strain distribution of UHPFRC beam under static at a) initial cracking b) just before failure

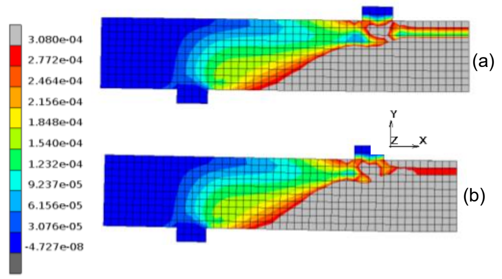

Fig. 8 Principal strain distribution of UHPFRC beam under fatigue (S=0.85) at a) N=1 b) just before failure

analysis, the calculation stops at the load capacity due to convergence difficulties. This may be induced by the widely distributed cracked elements (see. **Fig. 5(b)**). In terms of the softening behavior, it will be tried to obtain from now on.

3.2 4-point fatigue test

The flexural fatigue characteristics such as S-N relations and the evolution of midspan deflection can be obtained from the 4-point fatigue test analysis. Evolutions of midspan deflection from analysis are shown in **Fig.6** for 4 different fatigue load levels. It is found that the evolution of midspan deflection depends on number of loading cycles and the fatigue stress level. When the stress level decreases, the number of cycles to failure increased and the midspan deflection at the final failure reduced. The fatigue stress level to fatigue life relation (S-N relation) is shown in **Fig.7**. S is defined as the ratio of the maximum flexural stress to the static flexural strength. Both analytical and experimental results are shown in **Fig. 7**. Strain distribution is shown in **Fig. 8**. The gray area represents the cracked elements. Even though there is almost no propagation of the cracked range, the maximum strain increased by 1.73 times from 7.192×10^{-3} at the 1st cycle to 1.245×10^{-2} just before failure. It shows that repeated load fatigue the material and make strain bigger but UHPFRC can still sustain. It is because the cracking strength and strain are much smaller than the tensile strength and the corresponding strain, respectively, due to the existence of the strain-hardening domain. This proves that UHPFRC has high durability even after the crack initiation. Moreover, the bridging stress degradation model is obtained by changing the degradation coefficients, a_0 , a_1 , to make the analytical S-N relation approach to the experimental S-N relation. It is found that when the coefficient a_0 and/or a_1 is increased the slope of

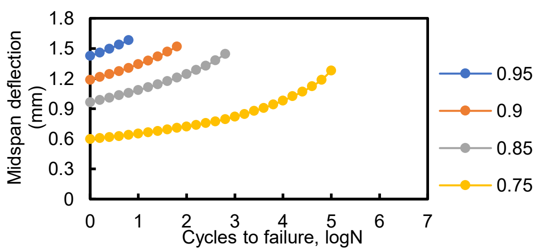

Fig. 6 Evolution of mid span deflection from analysis

S-N relation becomes sharp. After several trials, once the analytical and experimental S-N relations can fit well with each other, the degradation relation of UHPFRC is obtained and shown in below.

$$\frac{\sigma_N}{\sigma_1} = 1 - (0.015 + 5\varepsilon_{t\,max})log_{10}(N) \qquad (3)$$

In the logarithmic graph, it is found that the cycles to failure increases with respect to the decrease of the fatigue stress level. In terms of the values of a_0 and a_1, it is reported that they are 0.025, 15 and 0.030, 6 for Engineered Cementitious Composites (ECCs), PVA-ECC and PE-ECC, respectively, and 0.08, 4 for concrete [3)]. Thus, this may lead to the conclusion that UHPFRC has higher durability than them.

4. CONCLUSION

In this study, the bridging stress degradation model of UHPFRC is obtained from numerically fitting fatigue flexural test results using FEA. It is found from the obtained two degradation coefficients that the UHPFRC exhibit a high fatigue endurance limit (about 0.7) and a slow degradation rate compared to other cementitious materials, e.g. concrete and ECCs, which means the durability of UHPFRC is more superior.

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