Experimental Prediction of Potential Fatigue Crack Path on Concrete Surface

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ABSTRACT. *Before the 21th century, it was difficult to predict the potential fatigue crack path of heterogeneous materials by experimental approaches. The crack path was usually analyzed by numerical simulation programs in the world during that period. However, numerical programs were not always consistent with the experimental results because of the variety of materials used in structures. Along with the development of Digital Speckle Correlation Method (DSCM) in recent years, this new non-destructive testing technique has presented its advantages in on-line prediction and inspection of the potential crack paths on specimen surfaces. To testify the feasibility and accuracy of DSCM system, two different concrete specimens under flexural fatigue loading and a matched software UU© were employed in this paper. By use of global and local strain fields on target surfaces, the start of potential fatigue crack path predicted by DSCM system is coincident with the real one observed from experiments. It is testified that DSCM system is accurate and effective in on-line prediction of potential fatigue crack path of heterogeneous specimen under flexural cyclic loading. Especially, the experimental results show that it is beneficial to the safety evaluation and structural design of critical components or structures in practice. In addition, fatigue testing circumstances should be still and clean to assure more precise analysis results of DSCM system.*

Keywords: *flexural fatigue, concrete, crack path, strain field, DSCM*

INTRODUCTION

Prediction of potential fatigue crack path is vital for safety evaluation and structural design of critical components or structures, e.g. bridges, seashore structures and runway, et al [1]. Because of the complex stress distribution on structure surface, it is therefore a challenge for engineers and research scientists to predict the start of crack path, especially in the heterogeneous materials.

In recent years, a new kind of non-destructive testing technique, i.e. Digital Speckle Correlation Method (ab. DSCM), has been employed to measure the displacement, velocity, heat transfer and 2D full-field deformation monitoring of structural or composite surfaces [2-7]. DSCM can get full-field displacement by comparing two speckle images before and after deformation, and then the strain fields on concrete surface can be deduced from the lengthways and transverse displacements [8]. Comparing with those on homogeneous structure, the strain fields on surface of heterogeneous specimen under cyclic loading are more complicated, and they are affected by both load system and microstructure inside of the specimen. This kind of complicated strain field on the surface of specimen under flexural fatigue loading can not be obtained by normal testing methods. Owing to the compensation algorithm perfected in the correlative software and application of ultrahigh speed digital camera, DSCM method is also competent for analyzing the start of potential fatigue crack path by measuring the lengthways strain fields on global or local surface of concrete.

In this paper, prediction of potential crack path on surface of concrete under flexural fatigue loading was completed by using DSCM equipment and matched software program. The information needed for specimen and experimental method was presented in section 1. The experimental and analysis results were summarized in section 2 and discussed in section 3 in detail.

EXPERIMENTAL METHOD AND CONCRETE SPECIMENS

Experimental equipment and software

The 2D DSCM equipments are mainly consisted of five parts:

- Ultrahigh speed digital camera with 125 frames per second
- Camera viewer hardware and software
- Fiber optic illuminator used to illuminate the target surface of specimen
- Tripod used to fix the digital camera
- PC used to collect and analyze the speckle images

The matched analysis software is programmed and perfected by He Xiaoyuan, et al. and named UU©. Various compensatory algorithms were introduced in it. A schematic diagram of the DSCM system is shown in Fig 1.

In order to validate the quality and accuracy of DSCM system, an on-line dynamic strain collector SINOCERA® was also employed. The flexural fatigue experiment was implemented on a hydraulic servo fatigue machine with matched MTS controller and supervision software.

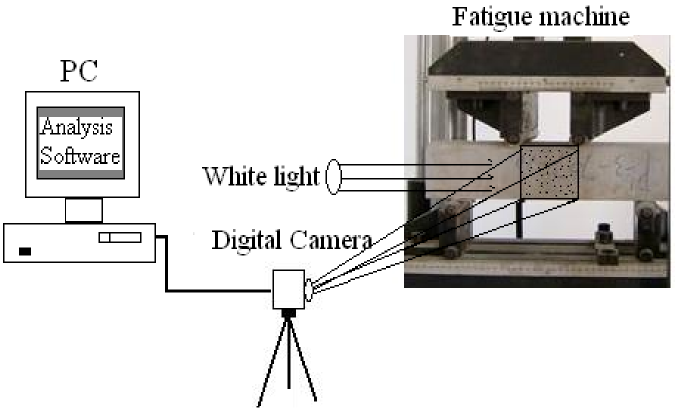


Fig. 1 Schematic diagram of the DSCM system

Concrete specimen and experimental preparation

The 42.5 Class Ordinary Portland Cement (OPC), commercial naphthalene water-reducing admixture, S95 grade ground granulated blast-furnace slag (GGBS) and Class ‾ fly ash (FA) were used in the mixes. The designed concrete strength grade was C50, and the slump of fresh concrete was controlled at 120±20 mm by adjusting the dosage of water-reducing admixture. The age of specimens were more than 90 days. The size of the prism was 100×100×400 mm^3 and the effective span was 300 mm under four-point flexural loading. The mix proportions and mechanical properties of two mixes are shown in Table 1 and 2, respectively.

The flexure fatigue tests were carried out in load control by using the constant amplitude of sinusoidal vibration with frequency of 10Hz. The nominal stress level was 0.75. A constant low to high load ratio was 0.1 in the present test program.

Table1. Mix Proportions of concrete (kg/m^3)

Series	OPC	GGBS	FA	Water	Coarse Aggregate	Fine Aggregate	Water-reducing Agent
PL1	230	0	230	161	1104	676	2.3
PL2	92	368	0	161	1104	676	2.3

Table2. Mechanical properties

Series	Static flexural strength (MPa)	Standard cubic compressive strength (MPa)	Static flexural elastic modulus (GPa)
PL1	6.86	58.1	48.9
PL2	7.10	61.4	52.9

Before the tests, a piece of resistance strain grid, with length of 5mm, was pasted on the middle of bottom plane of specimen to implement the on-line inspection of the average strain during the cyclic loading. In order to obtain the stochastic and settled tiny round speckles on the target surface, one plane in middle section of specimen was painted very carefully by white and black spray-paints (Fig. 2). And the maximum diameter of the black speckle is less than 1 mm. The central section of specimen with 100×100 mm^2 area was chosen as the target surface of DSCM system.

EXPERIMENTAL RESULTS

Before the fatigue experiments, speckle images of concrete free of fatigue loading would be demarcated as reference by the following ones (Fig. 2). Thousands of digital speckle images were collected by camera with 512×512 pixels and stored in PC as bitmap files.

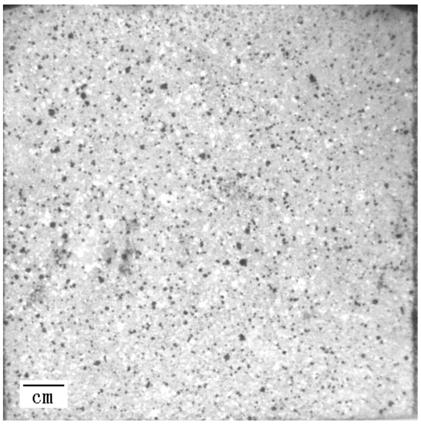


Fig. 2 Speckle image on target surface of specimen

The ultrahigh speed digital camera is quite sensitive to the tiny displacement of the target surface during the fatigue process. Therefore, by comparing two speckle images before and after deformation, the vertical deformation and strain fields would be received by the software UU$^{©}$. The real fatigue load pattern on the specimen was validated at first by the strain curve of one pixel and shown in Fig. 3. It is obvious that vibrant mode of target surface is as same as the fatigue load pattern, i.e. sinusoidal vibration. The lengthways deformation of target surface was presented in Fig. 4. And the global and local lengthways strain fields of the same target surface at the same fatigue cycle were deduced by the lengthways deformations of speckle images (Fig. 5~6). Those are useful for predicting the start of potential fatigue crack path on the surfaces of concretes.

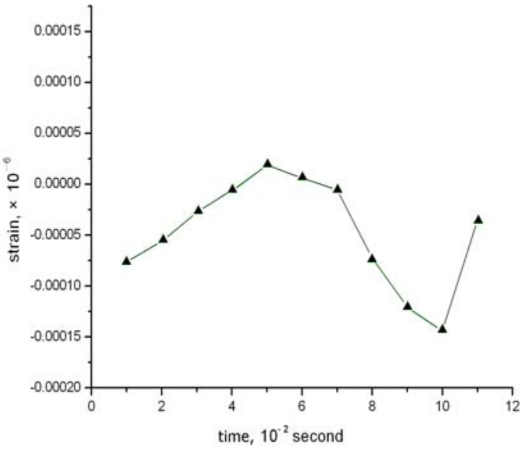


Fig. 3 Vibrant pattern of one pixel

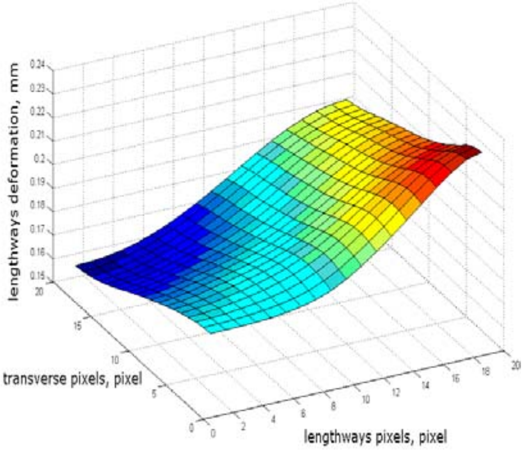


Fig. 4 Lengthways deformation of target surface

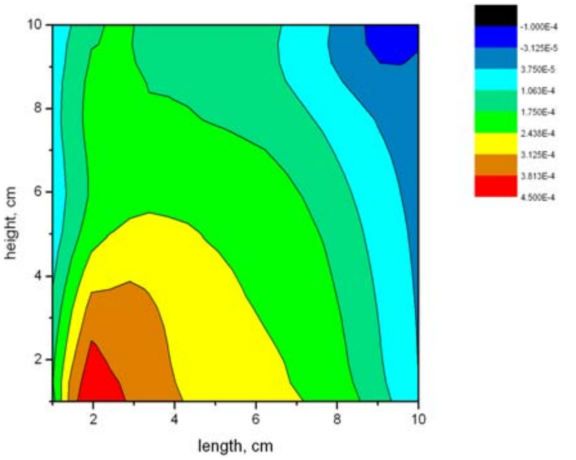


Fig. 5 Global lengthways strain field

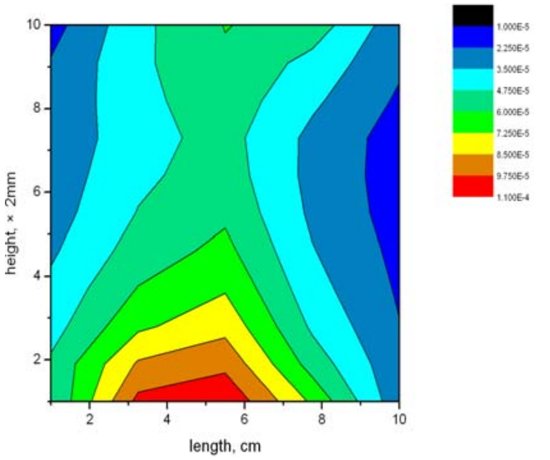


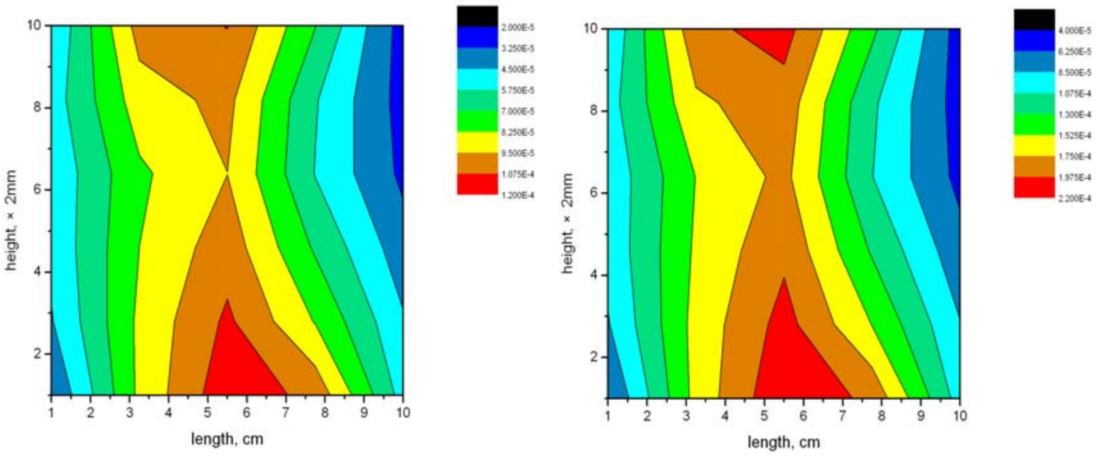
Fig. 6 Local lengthways strain field

DISCUSSION

To validate the feasibility and reliability of DSCM system in prediction of potential fatigue crack path, thousands of speckle images at different fatigue cycles were analyzed. It is well known that the emergence of fatigue crack is mainly controlled by the maximum fatigue stress. The local stress centralization on the central section of specimen under four-point flexural fatigue loading is the inducement of crack start. But the 2D stress field on specimen surface is impossible to be measured by testing apparatuses. Fortunately, the global and local strain fields on target surface can be received by DSCM system. In addition, the local strain field is more accurate than the global one to reflect the development of local stress centralization.

When specimens were under the maximum fatigue load, the lengthways strain fields of them at early phases and before the emergence of potential cracks were shown in Fig. 7 and 8. The crack paths on target surfaces of them were presented in Fig. 9.

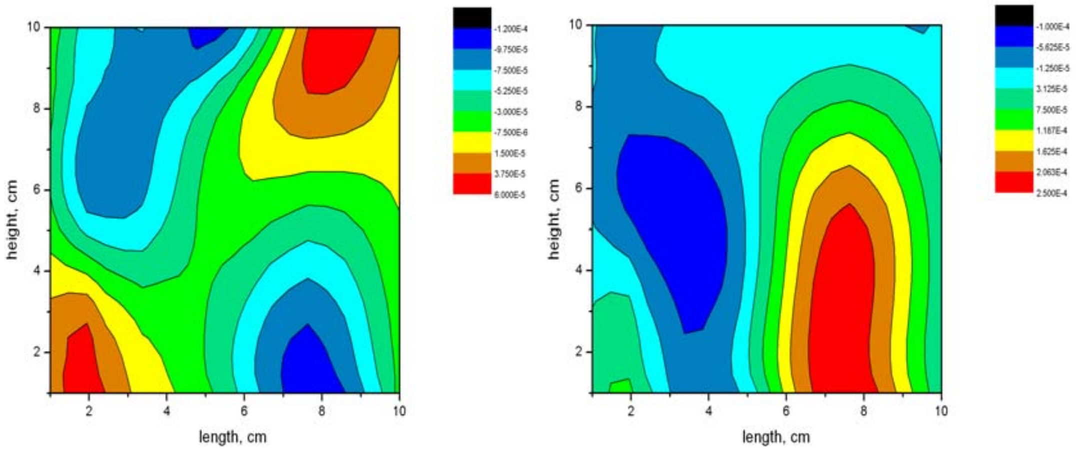
PL1 specimen fractured at the fatigue life of 131066 cycles and PL2 failed at the 30th cycles. The maximum local strains as developed as the increase of cyclic numbers. Furthermore, it can be concluded from these figures that the start of potential fatigue crack is consistent with the maximum section in the local strain field. Therefore, the potential fatigue crack path of specimen under flexural cyclic loading can be predicted by the local strain field of target surface at the initial numbers of cycles.



(a) at the 4200th cycles

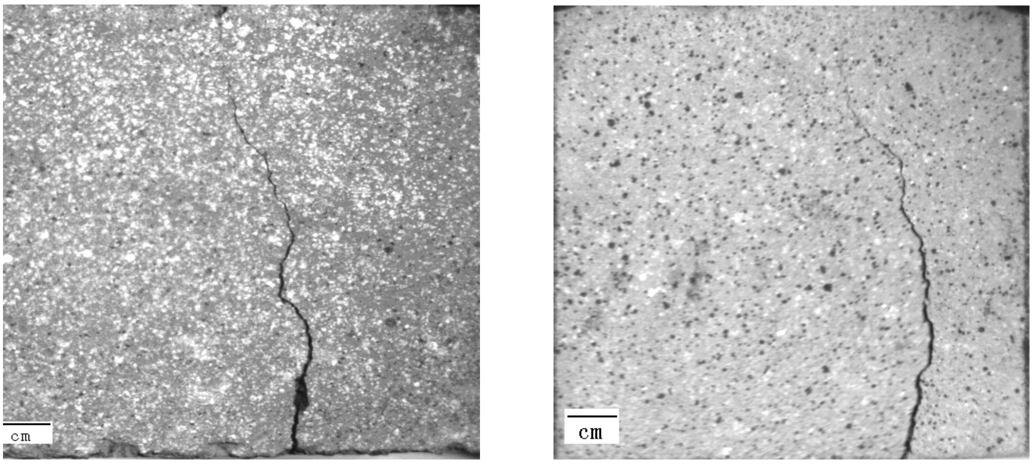
(b) at the 100100th cycles

Fig. 7 Local lengthways strain fields of PL1 specimen at different fatigue phases



(a) at the first cycle (b) at the 28th cycles

Fig. 8 Local lengthways strain fields of PL2 specimen at different fatigue phases



(a) PL1 (b) PL2

Fig. 9 Crack paths on the surfaces of PL1 and PL2 specimens

There are several factors which would affect the accuracy of strain fields on specimen surface, i.e. distribution and dimension of speckle, immobile of camera lens and optic illuminator, vibration and noise in surroundings, et al [9]. Therefore, in order to assure more precise results of strain fields on specimen surfaces, the fatigue testing circumstances should be still and clean.

CONCLUSION

DSCM system as a new non-destructive testing technique is accurate and effective in on-line prediction of potential fatigue crack paths of heterogeneous specimens under flexural cyclic loading. Especially, it is beneficial to the safety evaluation and structural design of critical components or structures in practice. In order to obtain precise analysis results by matched software UU©, several factors (e.g. uneven speckles, shift of lens, noise and vibration in surroundings, et al.) should be considered adequately during fatigue testing and analyzing process.

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