Crack Propagation Analysis for Fatigue Test and Monitoring by Fiber Optical Sensor

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1. INTRODUCTION

Fatigue crack is the most common one that causes damage to structure and impairs its service life. Crack may occur in structural steel due to various condition during fabrication and environmental effects. Not all cracks grow to critical level and causes catastrophic failure. Sometime it is difficult to arrest the crack but information is required for precaution to avoid loss of valuable lives and costly structural retrofit. For this purpose monitoring is essential so that we can alert for preparation to replace or strengthen the existing structure.

In this experimental study cyclic tensile loading is performed to initiate and propagate crack from a notch tip then measured by ultrasonic scanning for analysis. C-scan images of ultrasonic scanning gives crack developed length and rate of crack propagation. F&S Inc.'s absolute measurement system AFSS-PC software with EFPI (Extrinsic Fabry-Perot Interferometer) sensor with co-located electrical strain gages (Kyowa) used for strain measurement. Fiber optic sensor provides several advantages over their electrical counterparts, as high bandwidth, small size, lightweight, geometrical flexibility and inherent immunity to electromagnetic interface. Optical fiber sensor (FOS) and conventional electrical strain gage sensor (SGS) attached near notch tip for monitor strain variation due to loading. For integrity analysis, crack propagation measurement, estimation of remaining life cycles and strain sensing system from optical sensors were taken into account and it comes out as an smart system for evaluation and monitoring of fatigue crack propagation.

2. EXPERIMENTAL

2.1 Specimen Details The experimental program included a number of SS400 steel Y-shaped V- and round notched specimen of thickness 25mm and different notch angle and slit width used for cyclic loading. Detail geometrical dimension, loading direction and sensor location are shown in Fig.1.

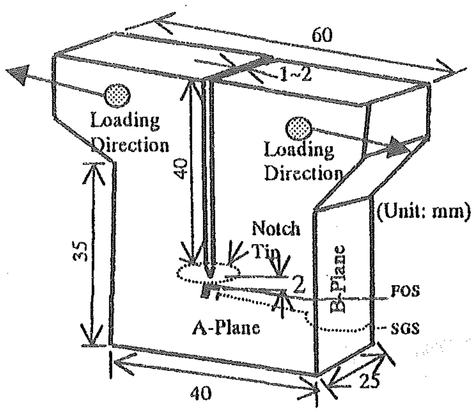

Fig.1 Test Specimen

2.2 Fatigue Loading The fatigue loading were performed with hydraulic equipment of survo-pulser unit that subjecting the specimens to tensile loading. Before loading all specimens were scanned to get image of notch tip area. Then sinusoidal wave cyclic loading performed under constant load range of 5.0KN~1.0KN and of frequency 10Hz~15Hz. During loading after predetermined cycles interval C-scan image and strain data were measured. During strain measurement interrupted the normal loading and strain data measured at various loading frequency of 0.10Hz, 0.25 Hz and 2.0Hz at predetermined cycle interval.

2.3 Ultrasonic Scanning Ultrasonic scanning performed under water with a piezo-electric transducer of 0.952 mm diameter and 80 mm focal length all over the experiment. Water used here as couplant to improve energy transfer. Ultrasonic waves emitted from transducer are reflected from the specimen interior received as electric signals and amplified by ultrasonic receiver. Automatic scanning control system has scanning range (mm) of 500(W)× 500(L)× 250(D), scanning pitch of 0.005~9.95 mm and scanning speed of 10~150 mm/sec scanned on predetermined area. Reflection echoes from the selected location of the specimen recorded by Digital Storage Oscilloscope (DSO) of frequency range up to 300 MHz, sampling speed of 500 mega samples per second and vertical resolution of 10 bit.

2.4 Fiber Optic Sensor and Absolute Measurement System The extrinsic Fabri-Perot interferometer (EFPI) sensor head and a schematic diagram showing functionality of the absolute fiber-optic support system (AFSS-PC) shown in Fig.2. The AFSS-PC sensor system employs a broadband light-emitting diode (LED) as the optical source. A single mode fiber (λ = 1300 nm) is used as the input/output fiber, and a multimode fiber used as reflector, from an air gap that acts as a low-finesse Fabry-Perot cavity. The far end of the hollow core tube is fused to the multimode fiber. The hollow core tube is attached to a single mode fiber with high temperature epoxy adhesive. The gage length is defined by the distance between the fused region and the left end of the tube minus the length of epoxy wicks up into the tube. Light is sent down the input/output optical fiber to the sensor head where it is modulated by the Fabry-Perot cavity inside the EFPI and the properties of the light are changed by the Fabry-Perot cavity. Although multiple

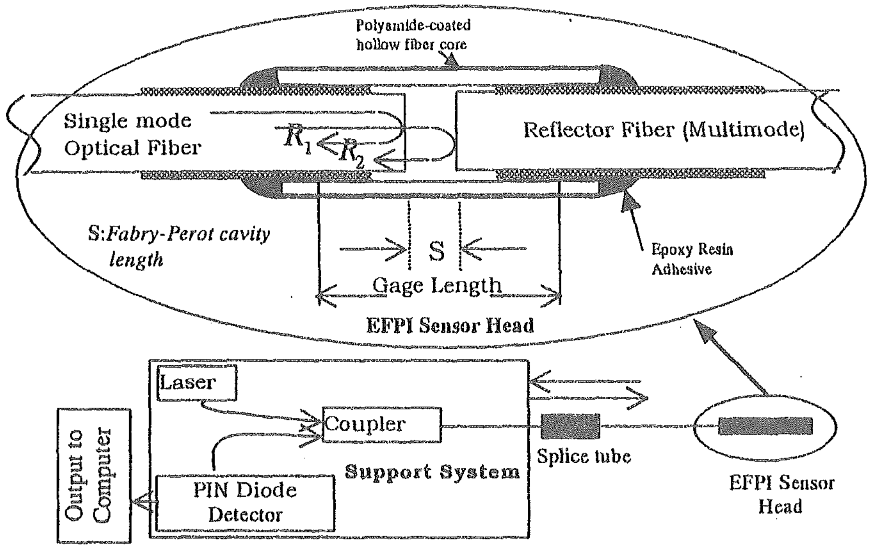

Fig.2 Schematic of the EFPI Sensor and AFSS-PC Support System

reflection occurs within the air gap, the effect of these reflections is negligible. As the test material is strained the silica tube, and hence the air gap, changes in length which causes a change in the phase difference between the reference reflection and the sensing reflection. This changes the intensity of the light and spectral properties that monitored at the output arm of a coupler. A simple algorithm is used to determine the Fabry-Perot cavity length, s, from the optical signal returned from the EFPI sensor Head.

AFSS-PC can be operated in three measurement modes, Strain, Relative Displacement and Absolute displacements. The system has refresh rate of DC - 5 Hz, strain resolution of 1μstrain and displacement range of 30 to 300μm. Strain is the current EFPI gap displacement subtracted from the zero point gap displacements in micrometer.

3. EXPERIMENTAL RESULTS

3.1 Crack Propagation Analysis from C-scan Images Ultrasonic C-scan image is the plotting of a collection of gated amplitudes of ultrasonic A-scan signals which are expressed as time vs echo amplitude. In this scan mode images of defects and other interior conditions are displayed with 16grades of color display. A cracked portions which has a lower density and lower refractive index from the surrounding material. C-scan images color is directly proportional to

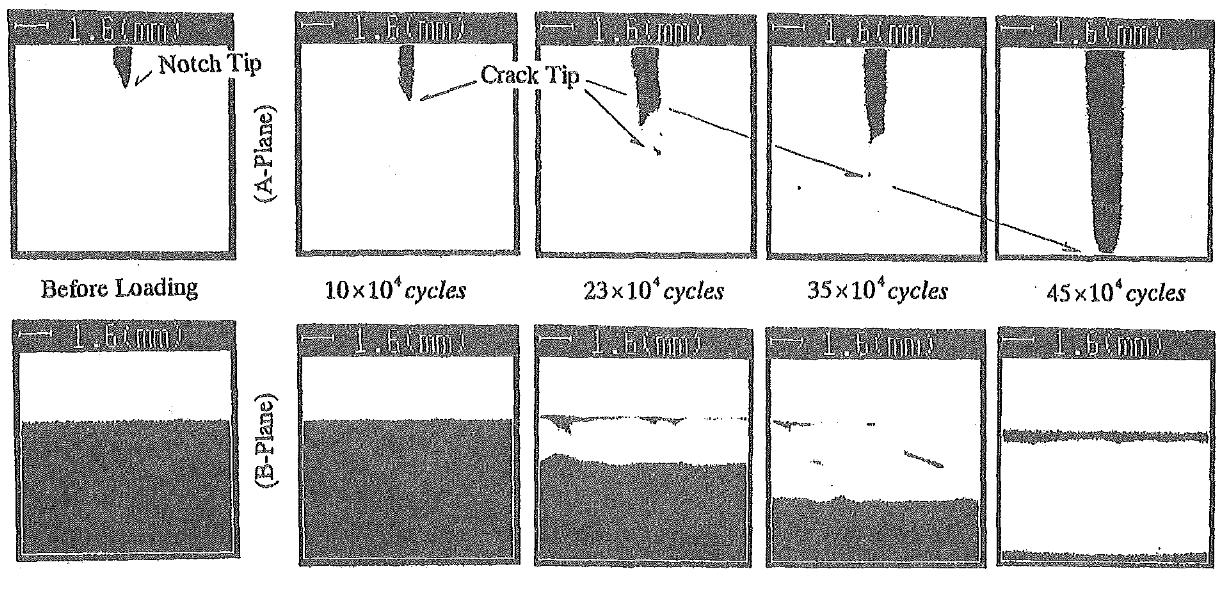

Fig.3 C-scan Images of Specimen No.2-1

the flaw amplitude compared to a given amplitude within a certain range. The focus of the transducer adjusted on center position and 2~3 mm far from the notch tip then scans over predetermined area of 10mm × 10mm for specimen No.1 and 2. For black and white images echo amplitude data areas where echo amplitude is high are displayed in white and areas where echo amplitude is low are displayed in black. Again areas where time of flight data is long is displayed in black and where time of flight data is short is displayed in white. C-scan images of before and after loading are shown in Fig.3. Images for scanning on plane A where crack length elongated and became sharp due to increase of loading cycles. Scanning on B-plane was done to observe image parallel to direction of crack propagation plane. From the images of different planes rate of progress of crack propagation is observed. Interior rough and undulated surface of fatigue crack is effecting on the scattered image. 3-D representation of crack tip area displayed from time of flight data of reflection echoes are shown in Fig.4. Images here are two dimensional array of pixels displayed by 200×200 (mm) size of 8 bit per pixel. Crack propagation direction and tip from different angles can be shown here by rotation. Hence comparing the before and after loading images crack length, depth and crack propagation rate could be calculated.

3.2 Fatigue Damage Analysis The fatigue life of a specimen is defined as the number of cycles to failure at a given loading range. Crack length measured from crack tip elongation of C-scan image vs loading cycles, N plotted as damage accumulation curve is shown in Fig.5. Notch tip elongation is always observed in the beginning as after 10×10^4 cycles, and with further cycling it would propagate rapidly towards the plastic zone leading to its final collapse. For calculating stress concentration factor original notch dimension and stress concentration chart [5] considered. The higher values of stress concentration factor causes lower fatigue life, which also depends upon the notch dimension, physical and chemical properties of specimen materials. Fracture occurs when the n/N ratio reaches to unity. Load ratio vs Log N curve is shown in Fig.6. This result follows the conventional linear damage rule. More experiment with a number of specimens is needed to improve accuracy of measurement. Measured life cycles and stress concentration factors for different specimens are shown in Table.2.

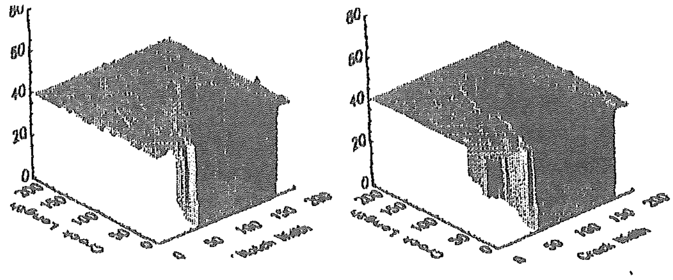

Fig.4 3D images from Time of Flight Data (Specimen No.1-1)

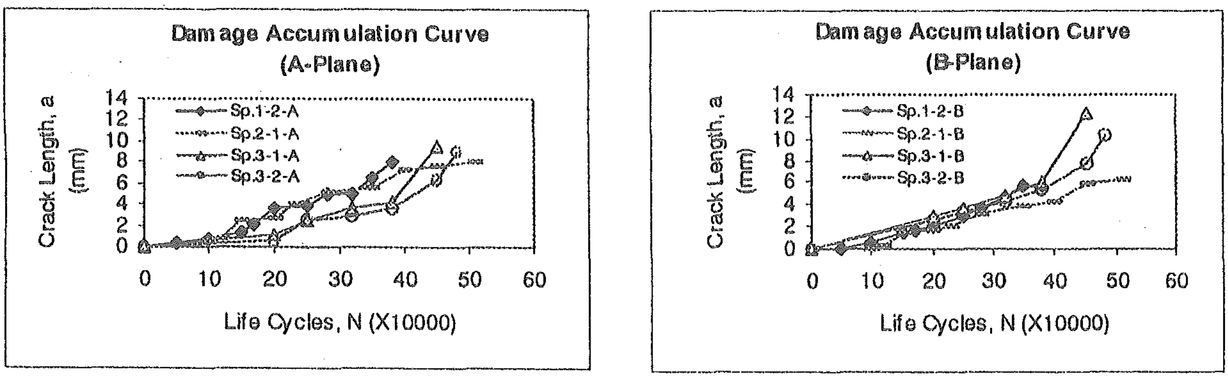

Fig. 5 Damage Accumulation Curve

4. STRAIN MEASUREMENT AND MONITORING

Fatigue loading and measurement procedure is described before. Preloaded Specimen No.2-2 is prepared for strain measurement and monitoring. Fiber optic and strain gauge sensor attached 2 mm far form notch tip on opposite side (Fig.1). By absolute measurement system (AFSS-PC) measured absolute displacement for static and cyclic fatigue loading of different frequencies and then absolute displacement data converted to strain data as microstrain. For loading at lower frequency maximum-minimum difference in absolute displacement is comparatively less than for higher frequency loading. Time vs absolute displacement data for different frequency are plotted in Fig.7. For cyclic sinusoidal loading strain variation is also in cyclic order and maximum-minimum data observed wide range of variation for higher frequency loading. For higher frequency load crack tip/notch tip expands and contracts in order to loading speed then FOS and SGS senses this fluctuation value and average data represents strain reading of the loading cycle. It is observed that by increasing loading cycle strain reading is also increased. After loading we monitored whether crack elongated or not by C-scan image. Here after 50000 cycles crack elongated about 1.2 mm (from C-scan image, Fig.8) and significant variation in strain reading is also observed.

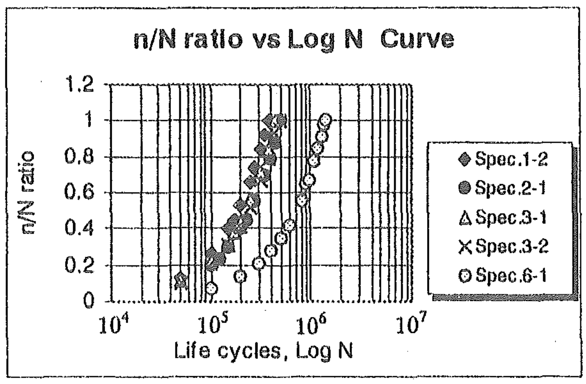

Fig.6 Load Ratio vs Life Cycles Curve

However the maximum strain range cause to failure for the specimen is still under experiment. Observing by ultrasonic scanning data crack tip propagation direction can be detected. The increasing loading cycle will gradually cause failure to the specimen. When the crack proceeds close to sensors sensing zone strain variation is observed. It is needed to set strain range, maximum elastic range and plastic zone before fracture for monitoring. The sudden jump in strain is seen

Table No.2

Spec. No.	Notch Angle	Slit Width (mm)	Notch Depth, t (mm)	Notch Tip radius, ρ (mm)	Stress Concentration Factor, K_t	Stress, σ_{max} Mpa	Life Cycles, N_f (× 10000)
1-1	45°	2	42.414	0.125	41.5	471.85	38
2-1	45°	1	41.201	0.110	42.8	455.39	51
2-2	45°	1	41.201	0.110	42.8	455.39	-
3-1	60°	2	41.732	0.150	37.6	411.72	45
3-2	60°	2	41.732	0.150	37.6	411.72	48
6-1	Round	1	42.000	1.000	15.5	166.65	143

After 7×10^4 cycles is the indication of crack tip deformation. Sometimes negative or compressive strain is observed which is may be due to strain response for bond performance between sensor and specimen or crack tip deformation nature.

5. CONCLUSION

Crack propagation in notched steel specimen due to cyclic fatigue loading monitored in this research. When actually crack initiated was difficult to detect though C-scan images gives some reliable information. From the damage accumulation curves and C-scan images it is clear that notch tip propagated. Images are amplified and are obtained from varying focal positions, so that it is approximate measurement of crack propagation length. Sharp crack tip and rough crack surface affects in the energy transmission of transducer and C-scan images. For optical sensor data measurement proper bond is a vital factor and it was carefully done. Both the sensors survived after loading and under water scanning. Crack propagation and strain variation depends upon load ratio and loading frequency. We persue this line of investigation by bringing new experimental evidence about fatigue crack evaluation specifically we simultaneously monitored applied loads, crack tip propagation length and strain variation. Taking these criteria into account the long term use of fiber optic sensor as structure integrated measuring device for remote online monitoring and early fatigue damage assessment will be possible.

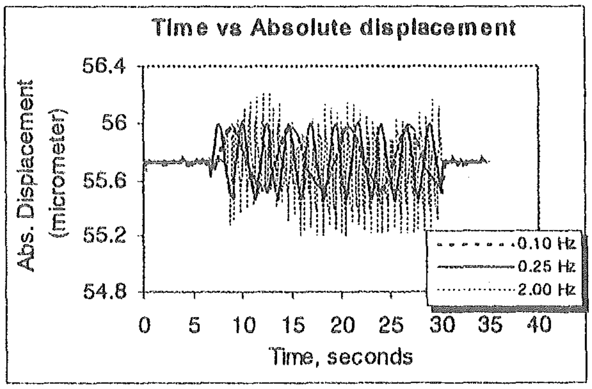

Fig.7 Fatigue Loading Frequency Curve

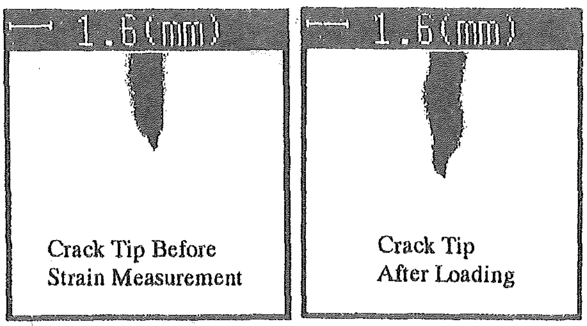

Fig.8 C-scan Image for Specimen No.2-2

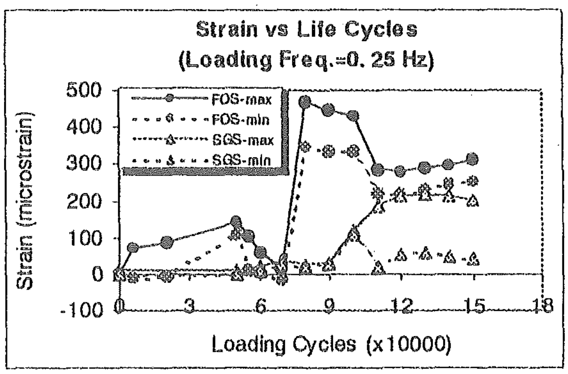

Fig.9 Measured Strain Comparison

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