# 論 文 の 内 容 の 要 旨

論文題目

Structural health monitoring of adhesive bonded single-lap joints in composite materials by fiber-optic distributed sensing system

（分布型光ファイバセンサを用いた複合材料シングルラップ接着継手の構造ヘルスモニタリング）

氏　　名　　寧　霄光

## Background

The use of adhesive-bonded joints especially in composite structures has been increasing in recent year for decent properties such like light in weight, less source of stress concentration and better fatigue properties. However concerns in practical applications, such as joint quality variety depending on manufacturing, and joint condition sensitive to environmental degradation, affect reliability and applicability of adhesive-bonded joints.

The common defects in adhesive-bonded joints, which can cause joint failure, such as cracks often occur in adhesive layer or at adhesive/adherend interface. The complex structure and poor disassembly of joint make the inspection and maintenance difficult. Comparing with the non-destructive inspection (NDI) techniques which are mainly used for on-ground inspection, the structural health monitoring (SHM) strategies suggesting real-time on-board monitoring and automatic structural condition assessment are considered more suitable to solve the problems in adhesive-bonded joints. Among the SHM techniques, optical fiber sensor (OFS) is promising for SHM of joints for its small sensor size and ability of distributed sensing.

## Objectives

The ultimate objective of this study is to develop an SHM method for adhesive-bonded joints using OFS sensing techniques. In order to achieve this, specific goals were defined and approaches were made as following:

(1). Study objects analysis and OFS technique development
(2). Dynamic strain distribution measurement in adhesive-bonded joint
(3). Damage detection and further applications

## Results and conclusions

### *Development of OFS sensing system for this study*

The long length FBG associated with distributed sensing system based on OFDR can achieve measurement with high spatial resolution of less than 1 mm, which is suitable for high precision strain measurement and damage detection in adhesive-bonded joint. And this sensing technique was employed in this study. In order to carry out dynamic measurement to achieve real-time strain measurement and damage detection of joint in service, the sensing system capable of dynamic measurement was designed based on requirements of this study. By system evaluation after manufacturing, the spatial resolution was less than 1 mm, and sampling rate of continuous measurement in about 24 hours was confirmed to be stable. The schematic of developed system is shown in Fig. 1.

### *OFS embedment in adhesive-bonded joints*

An embedment method of OFS for adhesive-bonded joints made of composite material was developed. By using this method, the long length FBG was successfully embedded into adhesive/adherend interface of an adhesive-boned single-lap joint made of unidirectional carbon fiber reinforced plastic (CFRP). During embedment process and the following tests, no strength loss of the joint or function loss of the sensor was found, and the embedment provided effective protection for FBG during measurement. The cross-section of CFRP adherend with embedded optical fiber is shown in Fig. 2.
Since the embedment location of FBG in CFRP adherend can be controlled and observed in this study, the three-dimensional finite element (FE) model of joint specimen with embedded FBG was built according to the real condition. By using this model, the detailed information in fiber

core of embedded FBG was obtained. Through comparison of analysis using detail FE model and old model, we believe that the detailed model with embedded FBG can evaluate the mechanical condition more accurately and help us to have the better understand on the FBG measurement.

*Dynamic strain distribution measurement in static and cyclic load tests*

The joint specimen with embedded FBG was subjected to static and cyclic load, the developed dynamic distributed sensing system was employed for dynamic measurement of strain distribution. The measurement accuracy was confirmed to be good both in static and cyclic load test by FEA. The FWHM center wavelength determination method showed the better spatial resolution, but the centroid method was employed in this study for dynamic measurement for the better stability for long-period measurement. The longitudinal strain distribution measured by embedded FBG and simulated by FE analysis at static load of 200 kgf is shown in Fig. 3.
The sampling rate of developed sensing was evaluated using the strain gauge sensing system as reference in cyclic load test. The constant phase difference growth rate in measurements by two systems was found, which means during measurement, the sampling rate of developed sensing system was as stable as the reference system.

*Crack detection*

A crack detection method based on analysis of strain distribution in adhesive-bonded joint was proposed. In order to confirm the detection method, the cracks occurred in cyclic load test were estimated by strain distribution measured by embedded FBG, the estimation results were compared with microscope measurement, and the crack detection method was confirmed to be effective. The crack length of crack 2 in cyclic load test estimated based on strain distribution and measured by microscope is shown in Fig. 4.
The irregular FBG spectra around crack fronts were observed and discussed, as the result, the peel stress concentrated at overlap end and crack front when joint loaded in tension was not the main reason, and the main reason was considered to be the sharp strain variation in that area. The relation between strain growth rate and shape of irregular spectra was investigated, and the relationship was employed to estimate the crack length based on examining FBG spectra. The agreements of estimated crack length based on strain distribution and FBG spectra analysis were found to be good.

Future works

In this study, the dynamic distributed sensing system based on OFDR using embedded FBG has been used to measure strain distribution in adhesive layer of adhesive-bonded joint during static and cyclic load test. The measured information, strain distribution and FBG spectra, have been used to provide real-time detection of cracks propagated along adhesive/adherend interface. Besides these applications which have been proved feasible and effective, the further subjects were proposed in three aspects with preliminary discussions: adhesive-bonded joint manufacturing monitoring, fracture condition assessment of adhesive-bonded joint and crack area detection for adhesive-bonded joint.

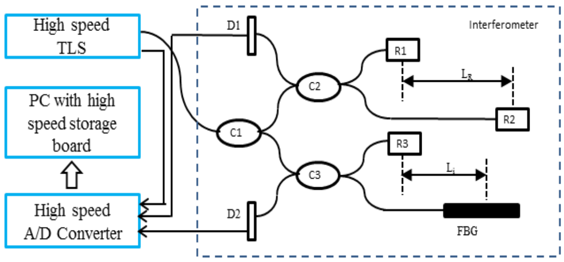


Fig. 1. Schematic of dynamic distributed sensing system based on OFDR

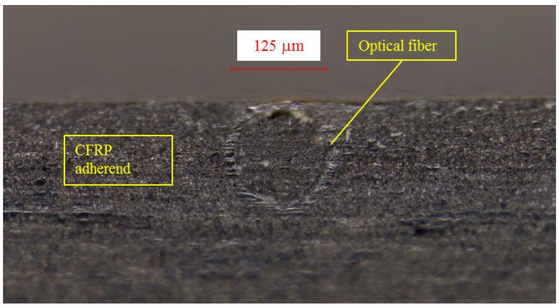


Fig. 2. Cross-section of CFRP adherend with embedded optical fiber

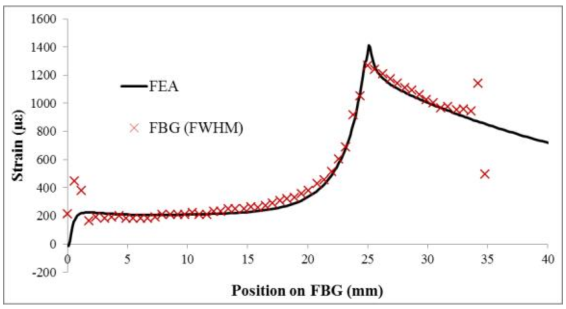


Fig. 3. The longitudinal strain distribution measured by embedded FBG and simulated by FE analysis

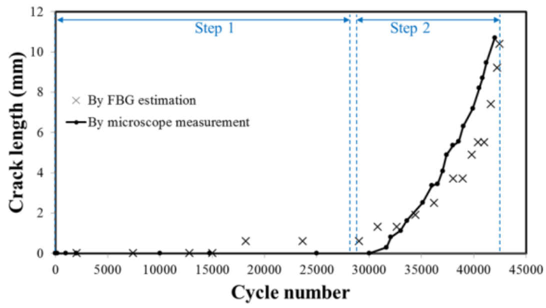


Fig. 4. Crack length estimated based on strain distribution and measured by microscope