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Dynamic Characterization of Sub-Scaled Building-Model Using Novel Optical Fiber Accelerometer System

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Abstract This paper presents the damage assessment of a building structure by using a novel optical fiber accelerometer system. Especially, a sub-scaled building model is designed and manufactured to check up the feasibility of the optical fiber accelerometer for structural health monitoring. The novel accelerometer exploits the moiré fringe optical phenomenon and two pairs of optical fibers to measure the displacement with a high accuracy, and furthermore a pendulum to convert the displacement into acceleration. A prototype of optical fiber accelerometer system has been successfully developed that consists of a sensor head, a control unit and a signal processing unit. The building model is also designed as a 4-story building with a rectangular shape of 200 × 300 mm of edges. Each floor is connected to the next ones by 6 steel columns which are threaded rods. Basically, a random vibration test of the building model is done with a shaker and all of acceleration data is successfully measured at the assigned points by the optical fiber accelerometer. The experiments are repeated in the undamaged state and the damaged state. The comparison of dynamic parameters including the natural frequencies and the eigenvectors is successfully carried out. Finally, the optical fiber accelerometer is proven to be prospective to evaluate dynamic characteristics of a building structure for the damage assessment.

Keywords: Optical Fiber Accelerometer, Damage Assessment, Building Structure, Dynamic Characteristics

1. Introduction

Nowadays, just to cite an example, architectural heritage has to be available for several activities connected with the modern economy, but also has to be visited for its cultural and artistic value. However, while the conservation related economy is currently booming world-wide and huge investments are being encouraged and made to ensure the conservation, the sensitivity to research required to improve and establish reliable interventions. Particularly, the general attention is focusing on activities aimed at maintaining an acceptable level of structural safety over time: continuous and planned interventions are fundamental to reduce costs and to have a complete restoration. For this goal, the most relevant physical parameters related with the safety of the structure have to be continuously observed and evaluated: this means monitoring, which is a task concerning safety and risk management.

The building monitoring is not related just to a time problem. Perhaps, it is true that it could be the principle reason but it is impossible not to speak about earthquake damage. It is evident that for a real well-known structural behavior there is the need of a permanent analysis of data. In fact, a health monitoring system started getting strong attentions in Japan after the 1995 Hyogo-Ken Nanbu (Kobe). Earthquake in which more than six thousands people were killed and forty thousands buildings were destroyed. As was the

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case of the Northridge Earthquake, many steel buildings suffered severe damages mainly at their beam-column joint. In most cases, it was not possible to find the correct degree of damages by a simple eye-inspection of the structure surface because there were no major visible damages on the surface of fire-protection material and surely a late monitoring was not so efficient. This fact prompted strong demands in real-time nondestructive assessment systems for buildings.

In recent years, considerable effort has been directed towards the development of optical accelerometers in order to monitor and measure accurately vibrations in a strong electromagnetic field environment where traditional sensors based on piezoelectric or capacitive working principles are not efficient[1-4]. In complex industrial installations such as hydroelectric power plants, a permanent monitoring program of the wearing parts in rotating machines is absolutely required to predict mechanical failures which mean long stoppages and high replacement costs[5]. While changes in the vibration spectrum of a part over the course of time give information on its degree of wear, the monitoring can be achieved by continuously comparing the spectrum given by a sensor compared with the spectrum recorded at the starting up of the machine. The same technique can be used for a monitoring based on the damage inspection on bridges or other types of building. However, new ideas are being continuously developed and tested to have the best method which has to be also low-cost and efficient.

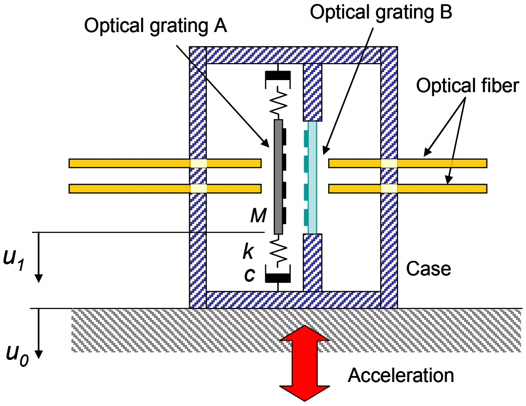
This paper focuses on the application of a novel optical fiber accelerometer system which uses Moiré-fringe phenomena[6,7]. This sensor system has great potentialities for deployment in the field to monitor the structural integrity and safety of large-scale civil infrastructure systems such as utility lifelines, highways bridges and buildings. Particularly suitable applications are in environments where conventional electric accelerometers cannot be used due to strong electromagnetic interference(EMI), electric spark-induced explosion risk and cabling problems. The novel optical fiber accelerometer represents a novel integration of an optic phenomenon (Moiré fringe) and optical fibers to achieve a robust performance in addition to its immunity to electromagnetic interference, easy cabling and multiplexing capability. All of these make the proposed sensor ideal for applications in civil infrastructure monitoring impossible to achieve by conventional sensors.

In this paper, the optical fiber accelerometers are applied to a sub-scaled building-model for its damage assessment. A shaking table test is carried out to check the dynamic behavior of the model with the optical fiber sensors. From the test, the natural frequencies are found to be changed due to the damage. Moreover, the mode shapes as well as eigenvectors are also analyzed in order to find the change of the dynamic characteristics. Finally, the optical fiber accelerometer is proven to be prospective to evaluate dynamic characteristics of a building structure for the damage assessment.

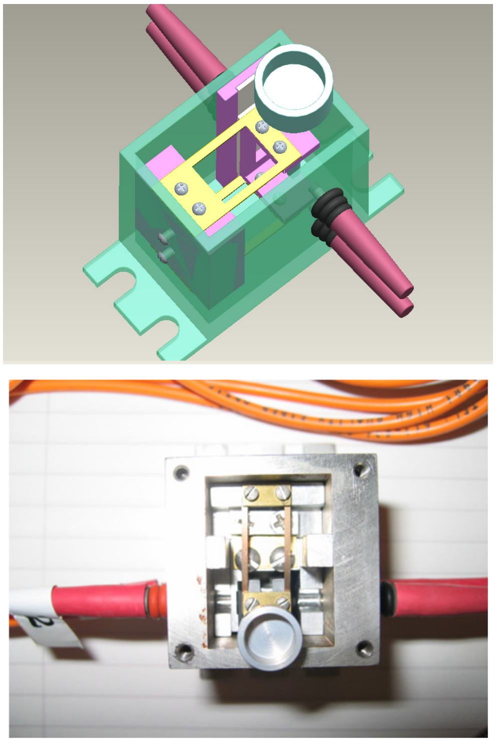
2. Optical Fiber Accelerometer System

The proposed accelerometer head contains a pendulum that can be modeled as a single-degree-of-freedom dynamic system with a mass *m*, a spring stiffness *k* and a damper *c*, as shown in Fig. 1(a). Particularly, two optical grating panels are attached to the mass and to the sensor case respectively and two pairs of optical fiber cables are aligned perpendicular to the optical grating panels to measure the relative displacement (u_o-u_I) between the grating panels. By using optical fibers, electric components can be excluded from the sensor head. Additionally, Fig. 1(b) shows the actual sensor head to understand the optical fiber accelerometer sensor.

Because one optical grating is attached to the mass of the sensor while the other is fixed to the sensor casing, the relative displacement of the two optical gratings is the same as the displacement between the mass and the sensor casing. When two optical gratings consisting of alternating parallel transparent and opaque strips (i.e. “rulings”) are overlaid, light will either be transmitted (when the transparent regions coincide) or be obstructed (when they do not coincide). If the rulings on one grating are aligned at a small angle relative to those on the other, then the loci of their intersections will be visible as dark Moiré fringes running approximately perpendicular to the rulings.



(a) Conceptual design of Moiré fringe based optical fiber accelerometer



(b) Optical fiber accelerometer sensor head

Fig. 1 Conceptual design and actual sensor of Moiré fringe based optical fiber accelerometer

In theory, the relative displacement between the two gratings can be measured by tracking the Moiré fringes as they pass through one point. However, observing the Moiré fringes at only one point yields no information regarding the direction of their movement, which is necessary to determine the direction of the relative movement of the two gratings. The direction can be determined as well as the amplitude of the displacement by tracking the fringes at two points which are separated by a quarter of the fringe width. Finally, the relative displacement can be converted into the external acceleration by using natural frequency and damping ratio of the single-degree-of-freedom system.

A prototype of optical fiber accelerometer system was successfully developed, which consists of a sensor head, a control unit for driving the sensor head and a signal processing unit. The sensor head consists of a pendulum with a mass, a spiral spring, and an air damper, together with two glass gratings (pitch=200 μm) and two pairs of optical fibers(62.5/125 μm multimode optical fiber). The sensor head is linked to the control unit by using the two optical fiber cables. The control unit provides the light source to the sensor head through two optical fiber cables and detects the intensity variation of the light transmitted through the two optical gratings. Finally, two raw optic signals, which come from two optical fiber cables, are used in the signal processing unit for calculation of acceleration.

3. Sub-Scaled Building Model

In this paper, a sub-scaled building model is designed and manufactured to check up the feasibility of the optical fiber accelerometer for structural health monitoring. This little model is not built to be a real scaled building but only to simulate a plausible behavior. It is designed as a 4-story building with a rectangular shape of 200×300 mm of edges. Each floor is connected to the next ones by 6 steel columns which are threaded rods (#10 for those between the basement and the first and between the first and the second floors; #8 for the other ones). Every threaded rod is connected to two beams by nuts that are well fixed simulating rigid joints. The beam is an L-shape aluminum angle (1/16 thickness). The floor is well simulated by wooden plate of 17 mm of thickness which is connected to the two beams in the longest edges. Furthermore, the plates connect the two metal frames of the building model. The mass is constituted by 4 rectangular steel blocks of 4 kg each, glued on the geometrical center of every story. Fig. 2 shows the final product of the sub-scaled building model designed and manufactured in this paper.

Additionally, the model is simply damaged by unscrewing two nuts in the basement columns of the position edge as shown in Fig. 3. These two nuts in the undamaged configuration are utilized to fix the columns to the aluminum beam of the first floor.

4. Dynamic Tests

This section describes in details dynamic experiments done in the laboratory on the building model. A shaking table test is carried out to check the dynamic behavior of the model with the optical fiber accelerometers. From the test, the natural frequencies are found to be changed due to the damage. Moreover, the mode shapes as well as eigenvectors are also analyzed in order to find the change of the dynamic characteristics.

In the dynamic test, a random vibration test is done all with a shaker(APS Dynamics, model 113) as shown in Fig. 2. In this test, the objective is to identify the main natural frequencies and the frequency ranges to be investigated. As shown in Fig. 4, two points are assigned for sensing those in every story, and three accelerations are measured with respect to three directions during the shaking. Two sets of tests are repeated with respect to the direction of the shaking as like x-direction and y-direction. Moreover, a set of 12 signals (plus

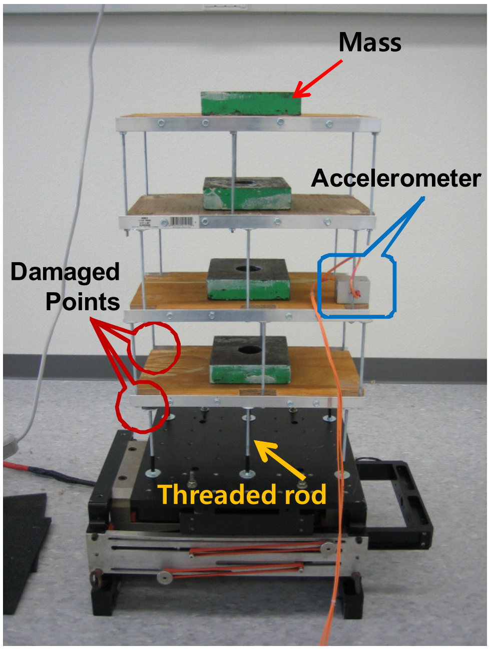


Fig. 2 4-story building model

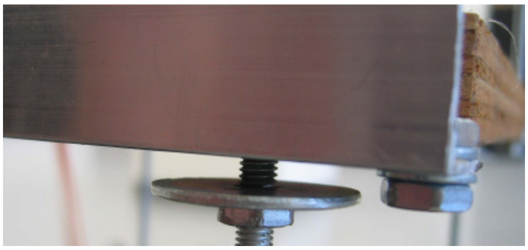


Fig. 3 Induced damage at the basement column of the position edge

the basement one) is acquired making also an average of the resulting FRFs(frequency response functions).

In detail, there are two steps. The first step is to measure all of acceleration in the undamaged state. The optical fiber accelerometer is attached at the assigned point with the assigned direction as shown in Fig. 2 and Fig. 4. Then, the optical fiber accelerometer is connected to the light control unit which is composed of LED(light emission diode) and PD(photo diode). In addition, the signal line is also connected to the computer in which a signal processing software is installed to calculate actual acceleration with raw signals. Finally, the shaker is operated to generate random vibration. During the vibrating, the optical fiber accelerometer measures the vibration of the building model. The same experiment is repeated on every assigned point as shown in Fig. 4.1. The second step is in the damaged state where two nuts are released to simulate the damage condition as shown in Fig. 3 and Fig. 4. The same experiments as in the undamaged state are repeated in the damaged state to compare the dynamic characteristics in two states.

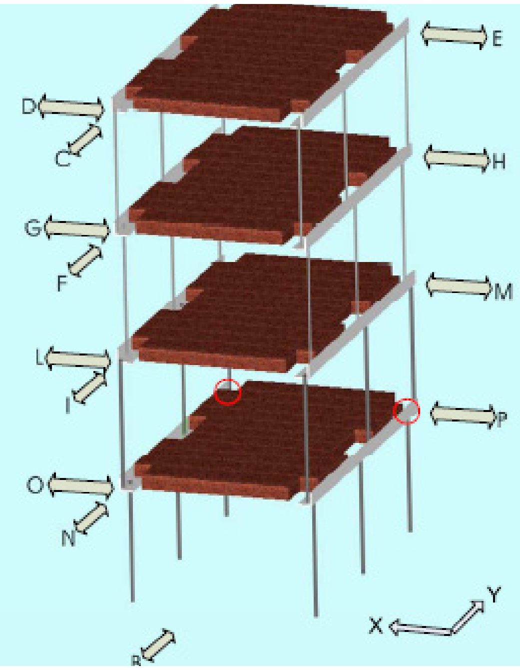


Fig. 4 Sensors disposition with localization of damaged joints

First of all, a random vibration is utilized to check the FRF peaks. To eliminate the shaker inaccuracy, the power spectrum of each channel is divided by the power spectrum of the vibrating table. To compare the dynamic characteristics of undamaged state and damaged state, the accelerometer is moved test after test to get time histories in the same positions and directions as before.

The followings are the final results which are plotted in Fig. 5 - 7. These graphs are also the representatives in the 2nd story and the others are omitted because all the graphs have similar behaviors. As shown in figures, the FRFs in the undamaged state are different from those in the damaged state. The mode frequencies are localized and a left shift is easily found for the plots.

From this first important part of testing, natural frequencies and modal recognition are well determined for both situations of undamaged and damaged, as it is shown in the Table 1.

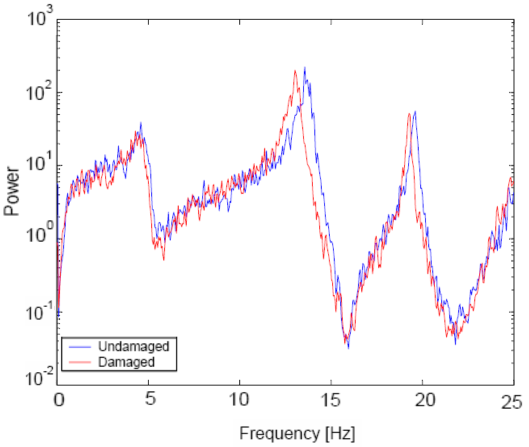


Fig. 5 FRF comparison between the undamaged state and the damaged state in I-direction (Y-direction shaking)

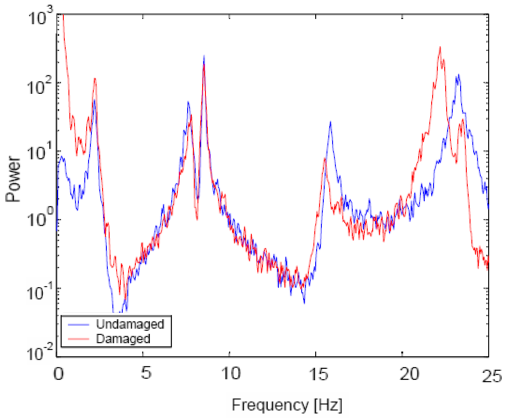


Fig. 6 FRF comparison between the undamaged state and the damaged state in L-direction (X-direction shaking)

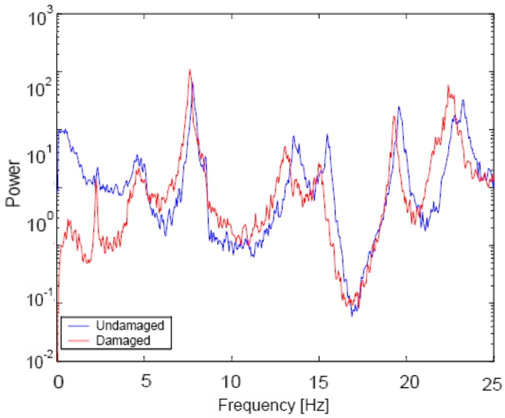


Fig. 7 FRF comparison between the undamaged state and the damaged state in M-direction (Y-direction shaking)

Table 1 Natural frequencies and modal recognition with dynamic tests

Undamaged Frequency [Hz]	Damaged Frequency [Hz]	Mode
2.24	2.22 (-0.89%)	I X-displacement mode
4.63	4.54 (-1.94%)	I Y-displacement mode
7.79	7.70 (-1.16%)	I Torsional mode
8.51	8.47 (-0.47%)	II X-displacement mode
13.56	13.02 (-3.98%)	II Y-displacement mode

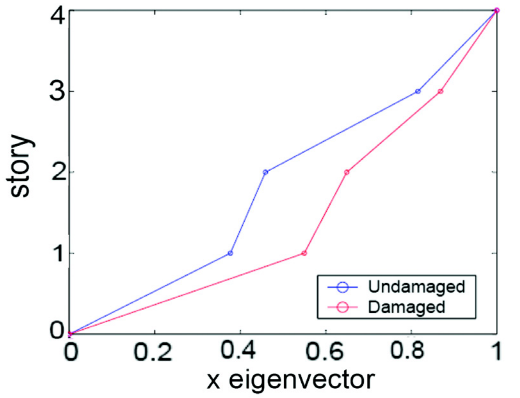
Table 2 Eigenvectors for the undamaged model

Story	I-X	I-Y	I-Torsional	II-X	II-Y
4	1.000	1.000	1.000	-1.000	-0.665
3	0.816	0.604	0.462	0.113	0.302
2	0.459	0.549	0.402	0.967	1.000
1	0.377	0.415	0.170	-0.101	0.521

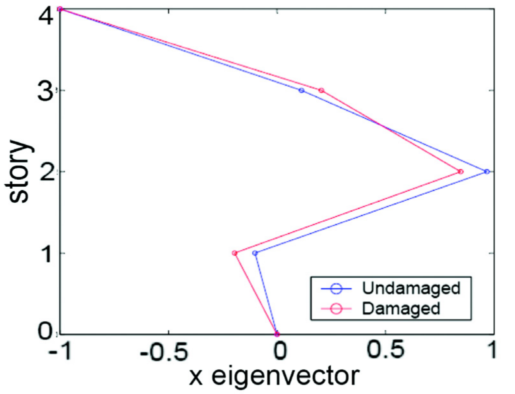
To find mode shapes directly from the FRFs, after having found the mode frequencies, the squared root of every value is made per each monitored point. The final result is displacement vectors which are normalized to have eigenvectors. Table 2 and 3 shows the results for the eigenvectors. Additionally, the eigenvectors are displaced in Fig. 8-10 in order to figure out the mode shape in detail.

Table 3 Eigenvectors for the damaged model

Story	I-X	I-Y	I-Torsional	II-X	II-Y
4	1.000	1.000	1.000	-1.000	-0.883
3	0.868	0.678	0.604	0.204	0.319
2	0.649	0.605	0.178	0.846	1.000
1	0.550	0.392	0.059	-0.195	0.674

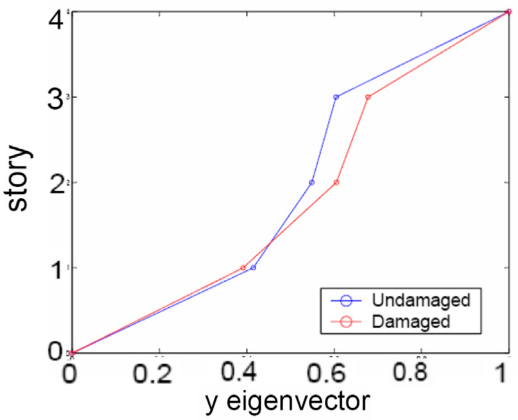


(a) I-X

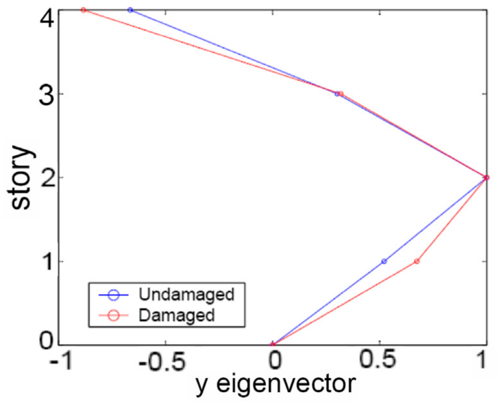


(b) II-X

Fig. 8 X-directional mode shape for undamaged and damaged model



(a) I-Y



(b) II-Y

Fig. 9 Y-directional mode shape for undamaged and damaged model

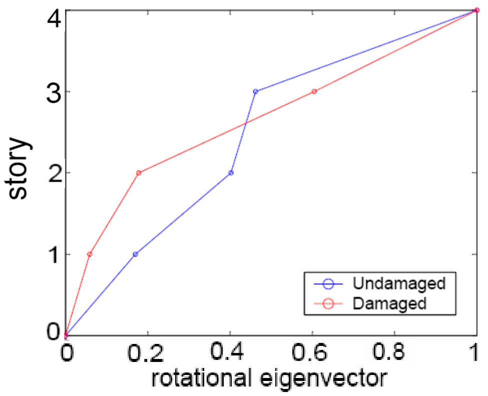


Fig. 10 I-torsional eigenvector

As shown in the previous figures and tables, the damage of the structure induces the reduction of the stiffness of the structure, and the decreasing of the natural frequencies. Especially, high order natural frequency is more sensitive to damage than lower one. As a result, the optical fiber accelerometer is proven to be available to evaluate dynamic characteristics of a building structure.

5. Conclusions

This paper presents the damage assessment of a building structure by using a novel optical fiber accelerometer system. Especially, a sub-scaled building model was designed and manufactured to check up the feasibility of the optical fiber accelerometer for structural health monitoring. The novel accelerometer exploits the Moiré fringe optical phenomenon and two pairs of optical fibers to measure the displacement with a high accuracy, and furthermore a pendulum to convert the displacement into acceleration. The building model was also designed as a 4-story building with a rectangular shape of 200×300 mm of edges. Each floor was connected to the next ones by 6 steel columns which are threaded rods. In order to simulate a damage condition, two nuts are released in the 1st floor. Several dynamic tests were carried out onto the building model in both situations of intact state and damaged one. From the random vibration test of the building model, natural frequencies and mode shapes were found and compared between in the intact state and damaged one. As a result, the frequency-decreasing in FRF was present due to the damage. Especially, high order natural frequency was more sensitive to damage than lower one. As a result, the optical fiber accelerometer is proven to be available to evaluate dynamic characteristics of a building structure.

Acknowledgement

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