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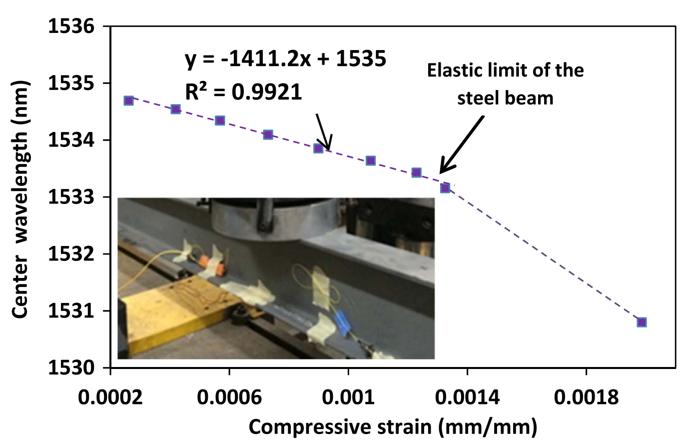

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Steel Beam Compressive Strain Sensor Using Single-Mode-Multimode-Single-Mode Fiber Structure

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Abstract: A steel beam compressive strain sensor using single-mode-multimode-single-mode (SMS) fiber structure is demonstrated. Parallel measurements are made using an electrical resistance (ER) strain gauge along with the SMS to sense the compressive strain on the steel beam. The ER strain gauge result shows that the steel beam has an elastic limit at a compressive load of 42 kN, as predicted via calculation. On the other hand, the SMS sensor is capable to detect the elastic limit by its significant increase in the slope of the peak center wavelength from compressive strain of 0.000261–0.001986 mm/mm. Moreover, the SMS sensor exhibits compressive strain sensitivity of −1411.2 nm/(mm/mm) from the initial load until it reaches the beam elastic limit.

Index Terms: Strain sensor, interferometer, steel elastic limit measurement.

1. Introduction

Optical fiber sensors have been widely used for measuring various physical, chemical, and biological parameters. They are compact, responsive, sensitive, stable, and resistant to electromagnetic interference [1], [2]. They have also been recommended for new applications such as in structural monitoring of buildings [3], estimation of metal surface roughness [4], vibration tests [5], determination of the thickness of a transparent plate [6], etc. A fiber Bragg grating (FBG) based optical sensor is by far is the most common type of fiber sensor [7], [8]. However, it suffers from a narrow measurement range especially when used for strain sensing, and consequently requires a suitable mechanical arrangement to improve its measurement range and a complex interrogation system to achieve a high wavelength resolution. For instance Fernández-Valdivielso *et. al.* [9] have demonstrated a FBG wavelength change within 1557.8 nm to 1560.87 nm as the strain is varied from 0 $\mu\varepsilon$ to 5000 $\mu\varepsilon$. In recent years, a single-mode-multimode-single-mode (SMS) fiber structure has been proposed and demonstrated as a strain sensor as it generates a sufficient

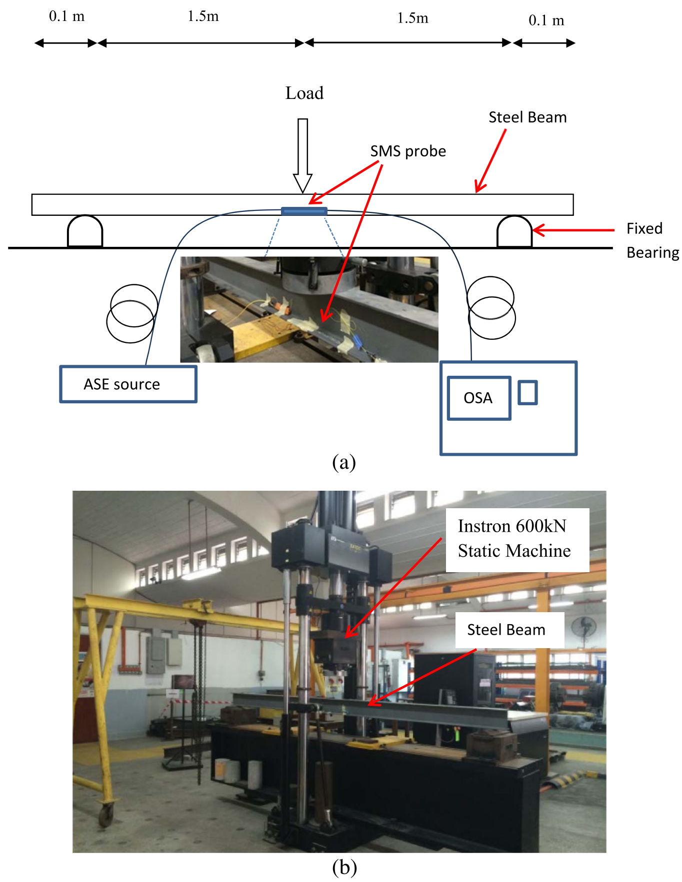

Fig. 1. Steel beam compressive strain sensor experimental setup. (a) Schematic diagram. (b) Image.

bandpass spectral response for a given wavelength range [9]–[11]. It can be used as either a stand-alone sensor or an edge filter that interrogates an optical sensor such as an FBG. Since an SMS fiber structure is much easier to fabricate than an FBG, a sensor based on an SMS fiber structure will be more economic than the one based on an FBG.

Recently, optical fiber sensors have also gained interest among researchers for their application in the long-term health monitoring of civil structures due to their durability, stability, and insensitivity to electromagnetic (EM) interference [1]. The majority of optical fiber monitoring systems are not designed to measure displacement of a structure but to gauge strain within the structure. For instance, FBGs can be attached to rock bolts for long-term strain and temperature measurements [8]. In this paper, we propose to use an SMS fiber structure instead of an FBG to measure compressive strain and of a steel beam. This technique offers the advantages of a much simpler configuration, ease of fabrication, and wide measurement range. Moreover, in order to validate the experimental data, a parallel measurement will be made along the beam with a strain gauge method to measure the compressive strain. The proposed SMS sensor is also able to measure a compression strain up to the elastic limit of the steel beam at 1325 $\mu\varepsilon$.

2. Experimental Setup

The experimental setup for the steel beam compressive strain sensor is shown in Fig. 1. An Instron universal testing machine with a 600 kN static load capacity is used to apply the compressive load at the center of the 3.2 m steel beam (Universal Beam 150 UB 14.0). The beam is simply supported over a clear span of 3 m on fixed roller bearings, with an overhang of 0.1 m at the ends as shown in [see Fig. 1(a)]. The ER strain gauge is fixed to the top surface of the

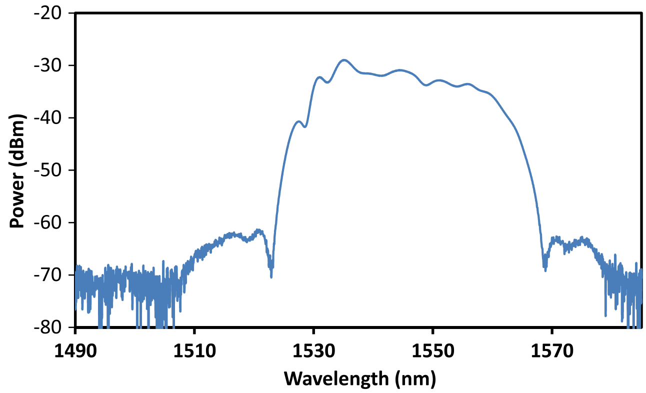

Fig. 2. SMS bandpass filter interferometer spectrum at 10 kN compressive loading.

bottom flange of the beam at mid-span position using a superglue or cyanoacrylate adhesive. Thermoplastic adhesive is then used to cover the top part of the gauge with the help of hot glue gun. A data logger is used to read and record the strain values. An initial load of 10 kN is applied and gradually increased at the rate of 2.5 kN/min. A straight SMS fiber structure with the multimode fiber of length 8 cm is attached in a similar fashion on the lower surface of the steel beam, as shown in the inset of Fig. 1(a). In the experiment, the center of the SMS is vertically aligned with the position of applied load. The MMF has a step-index profile with a core diameter of 105 μm and is fused spliced with 2 SMF-28 fibers to form the SMS structure. Amplified spontaneous (ASE) source at C-band wavelength is used as a light source while optical spectrum analyzer (OSA, Aritsu MS9710C) is used to capture the spectral change at the output of the sensor, as shown in Fig. 1(b). The ER strain gauge and the SMS sensor measurement were simultaneously recorded for comparison. The elastic limit of the steel beam can be calculated by

$$P = \frac{4M_{\max}}{L} \tag{1}$$

where P is the yield load, $M_{\max}$ is the maximum bending moment, and L is the distance between supports. Since the steel beam has a maximum bending moment, $M_{\max}$ of 31625 Nm and the distance between the two fixed bearings is 3 m, it is expected to reach its elastic limit at a compressive load of 42.2 kN. The load is applied from10 kN up to 44 kN. The experiment is conducted at room temperature in an enclosed laboratory which the temperature is regulated to be around 25 °C by air conditioners.

3. Results and Discussion

The output comb spectrum from the SMS structure at 10 kN load is shown in Fig. 2. The output suggests that the SMS fiber structure has a bandpass spectral response with its peak at around 1535 nm for the wavelength range. The bandpass response is a result of multimode interference and recoupling within the SMS fiber structure. As observed, the comb spectrum has a fixed peak-to-peak spacing of about 4 nm. This shape characteristic depends highly on the interference between the light modes that propagate in the MMF section of the SMS. When the compressive load is applied, the steel beam is bent along the MMF section of the SMS. In consequence, the relative phase difference between the propagation modes is changed due to the non-symmetrical refractive index distribution in the MMF when the fiber is bent. This causes interference shifts and the change of the output spectrum from the SMS. In the experiment, the length of MMF was fixed at 8 cm due to its convenient to be spliced with the SMF-28 fibers. As the length of MMF increases, this increases the number of spatial mode beating in the MMF thus the transmission spectrum comb pattern will become more prominent. However, from our observation, this does not significantly influence the sensitivity of the sensor. The thermal

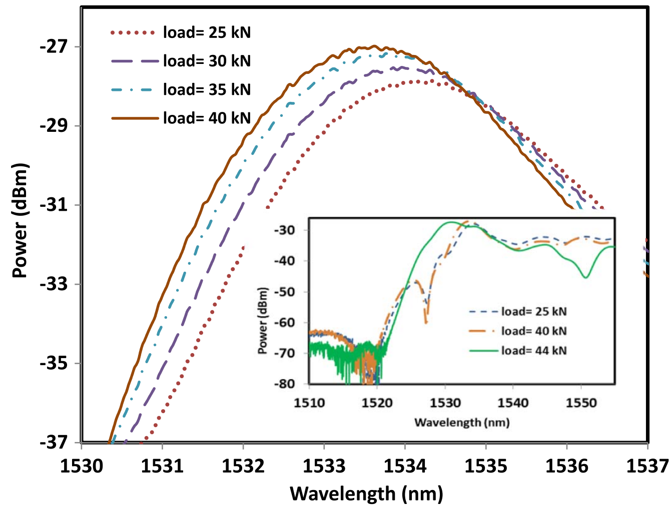

Fig. 3. Peak bandpass spectra at different compressive loading within a span of 7 nm. (Inset) Spectra within a larger span of 50 nm.

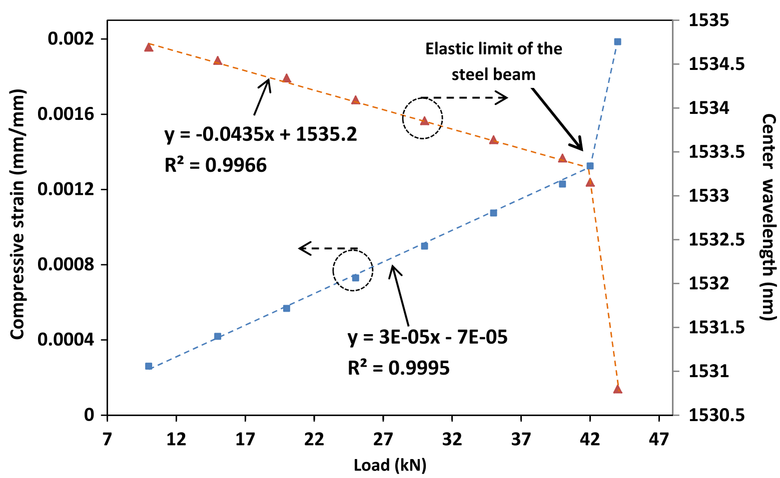

Fig. 4. Compressive strain and peak center wavelength at different amount of compressive loading.

stability of the sensor is high since the temperature sensitivity of the sensor is measured to be around −0.0069 nm/°C.

Fig. 3 shows the peak spectral change at different loading measured at OSA resolution of 0.05 nm and span of 7 nm. The bend in the MMF section has a significant influence on the mode distribution in the SMS fiber structure, which in turn will have a profound effect on the overall transmission characteristics of the SMS structure. It can be inferred from the figure that the peak wavelength of the interference comb spectrum shifts to a shorter wavelength as the load grows from 25 kN to 40 kN. In addition the peak power also increases with load increment. In the experiment, measurements were also taken at a span of 50 nm, as shown in the inset of Fig. 3. The inset indicates that the pattern of interference spectrum completely changes as the load increases from 40 to 44 kN.

The compression strain and the peak of interference wavelength are also measured using a data logger and OSA, respectively, for different amount of load and the result is illustrated in Fig. 4. At the initial load of 10 kN, the OSA and ER strain gauge show a peak center wavelength of 1534.693 nm and a compressive strain of 0.000261 mm/mm, respectively. As the load is increased, the peak wavelength shifts to a shorter wavelength while the compression strain linearly

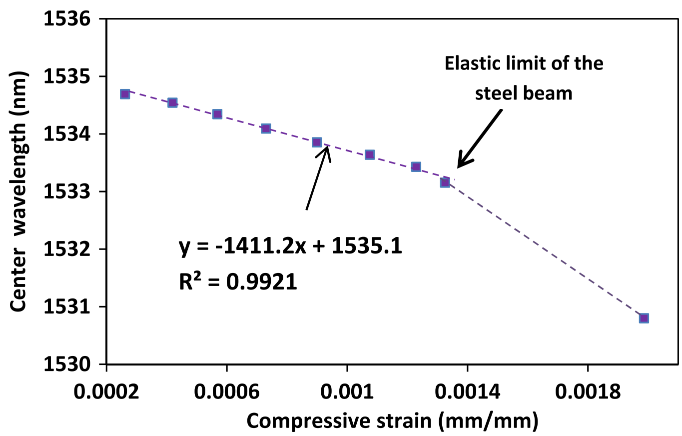

Fig. 5. Relation between the peak center wavelength and the compressive strain.

increases. A total wavelength shift of 1.26 nm is obtained with a sensitivity of 0.0435 nm/kN from the initial loading to 40 kN. Above the load of 40 kN, the compressive strain curve shows a radical change to a higher slope in an exponential manner with a compressive strain of 0.001986 mm/mm obtained at the maximum load of 44 kN. It is noted that, at the load of 42 kN, the steel beam is predicted to reach its elastic mode limit as calculated. From the compressive strain curve, the increased change of compressive strain slope above 42 kN explains the radical change in the mechanical property of the steel beam, indicating that the elastic mode limit has reached at this load.

On the other hand, the peak center wavelength curve has a greater slope from a loading of 42 kN to 44 kN as well. Changes for both curves are well matched to the applied load which proves that the SMS sensor is able to measure the steel beam compressive strain with good sensitivity and linearity. In the inset of Fig. 3, a significant change in the spectral shape and peak center wavelength is detected as the amount of load reaches 44 kN. This indicates that the amount of loading is above the elastic limit of the steel beam. Fig. 5 shows the relation between the peak bandpass spectrum and the amount of loading. It exhibits a linear curve with a slope of −1411.2 nm/(mm/mm) and linearity of more than 99% until the elastic limit of the steel beam. From Figs. 4 and 5, at yield load of 42 kN, it is shown that the beam experiences compressive strain of 0.001325 mm/mm. Then, when compressive load of 44 kN is applied the strain changes to 0.001986 mm/mm. The large change of strain from the load of 42 kN to 44 kN, as compared to any other transition of loading, is due to the fact that the beam strength and rigidity have weakened. As calculated, the elastic mode limit is estimated to be around 42.2 kN. Beyond this applied load, the beam has exceeded its linear characteristic of modulus of elasticity; hence greater change of strain can be experienced by the beam. This is good agreement by the observation in Fig. 5, where the large change of the strain is reflected as well by the large change of wavelength shift.

4. Conclusion

An SMS fiber sensor is shown to be able to measure a steel beam compressive strain from an initial value of 0.000261 mm/mm to the final value of 0.001986 mm/mm. The steel beam achieved its elastic mode limit as per calculation and strain gauge measurement at compressive load of 42 kN or at compressive strain of 0.001325 mm/mm. On the other hand, the SMS sensor is able to detect the elastic limit by its significant slope change of the peak center wavelength from a compressive strain of 0.001325 mm/mm to 0.001986 mm/mm. From a wide range values of compressive strain (0.000261 mm/mm to 0.001325 mm/mm), the SMS sensor exhibits linear sensitivity of −1411.2 nm/(mm/mm).

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