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Damage identification method for continuous girder bridges based on spatially-distributed long-gauge strain sensing under moving loads

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ABSTRACT

A novel damage identification method for concrete continuous girder bridges based on spatially-distributed long-gauge strain sensing is presented in this paper. First, the variation regularity of the long-gauge strain influence line of continuous girder bridges which changes with the location of vehicles on the bridge is studied. According to this variation regularity, a calculation method for the distribution regularity of the area of long-gauge strain history is investigated. Second, a numerical simulation of damage identification based on the distribution regularity of the area of long-gauge strain history is conducted, and the results indicate that this method is effective for identifying damage and is not affected by the speed, axle number and weight of vehicles. Finally, a real bridge test on a highway is conducted, and the experimental results also show that this method is very effective for identifying damage in continuous girder bridges, and the local element stiffness distribution regularity can be revealed at the same time. This identified information is useful for maintaining of continuous girder bridges on highways.

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1. Introduction

In recent years, the security of the traffic infrastructure, especially for bridges, has attracted increasingly attention. Bridges can experience structural deterioration as a result of aging, overloading or lack of proper maintenance. The ability to monitor the structural health of existing bridges is crucial for avoiding sudden bridge collapses, which lead to losses of lives and economic losses. Consequently, the structural health monitoring technology has rapidly developed [1–3].

The existing health monitoring systems and methods are primarily designed for long-span bridges [4–6]. By using various sensors, such as accelerometers and strain gauges, it is possible to quantify the response of the structure to static and dynamic loads, to estimate the distribution of extreme loads [7], to identify damages and to estimate the remaining structural capacity [8]. Vibration-based damage identification (VBDI) methods primarily depend on the change in structural parameters for determining whether structural damage has occurred, and the frequency, mode shapes, and mode damping ratio are typically selected as damage indices. Other damage indices include modal flexibility, modal stiffness, modal strain energy, and frequency response function. Extensive literature reviews on VBDI have been reported by Sohn [9] and Goyal [10].

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Although a number of such damage identification strategies have been explored, VBDI techniques still face practicality challenges. The existing methods are based on the traditional accelerometers, strain gauges and displacement meter, and the structural information obtained using these sensors is either too "macro" or too "local" to identify local damage [11]. Strain, as a local measurement has been verified to be more sensitive to damage. However, traditional strain gauges cannot effectively reflect the influence of damage unless the gauges are covering the damaged region.

Traditional sensors typically possessing a usually short service life are vulnerable to electromagnetic interference and need to be changed frequently. Fiber Bragg grating (FBG) sensors have begun to be widely used for civil structural health monitoring because such sensors are electromagnetic interference resistant, corrosion resistant, light weight, small in size, and easily installed [12]. The multiplexing capabilities of FBG sensors enable many sensors to be installed on a structure with minimal wiring. Villalba applied the optical fiber distributed sensing to health monitoring of concrete structures [13]. Lima et al. [14] presented a structural health monitoring system for one historical building structure, which was based on fiber Bragg gratings. Nineteen FBG displacement sensors and five FBG temperature sensors were used to monitor of the most important points of the structure.

Todd demonstrated the sensing capabilities of FBG sensors by installing a number of sensors on a steel girder in a bridge [15]. Schulz reported the application of long- gauge FBG sensors for monitoring civil structures [16]. Wu and Li developed a feasible implementation of distributed long-gauge FBG sensing techniques to use the strain distributions throughout the full or critical regions of structures to detect damage [17,18]. Hong et al. [19,20] investigated the evaluation of bearing capacity and identification of damage based on the distributed strain mode, and the mode macro-strain was selected as a damage index. However, as is the displacement mode, the strain mode is a relative value. The results from different data during short period of time may be different, which will have a certain influence on damage identification.

Compared with the monitoring method for long-span bridges, most of the existing highway bridges are using manual detection. Although manual detection can directly evaluate the apparent damage of bridges, this approach has some problems: (1) because of the growing number of bridges, the efficiency of manual detection is too low and the cost is too high; (2) manual detection can only detect apparent damage, and potential damage cannot be detected; and (3) manual inspection requires the use of a bridge inspection vehicle, which will occupy the corresponding lanes and affect the flow of normal traffic.

The main purpose of this paper is to investigate how to rapidly and effectively monitor highway bridges without affecting normal traffic. First, the areas distribution regularity of the long-gauge strain of the continuous girder bridge was studied, and the distribution regularity of the area of long-gauge strain history was obtained: when a vehicle passes the monitored span, the area of the strain history of the monitored span is a parabolic distribution; when a vehicle passes other spans, the area of the strain history of the monitored span is a linear distribution.

If the stiffness of the monitored element changes, there will be an obvious bulge at the location of the damaged element in the area distribution curve, and this phenomenon can be directly used for the damage identification in continuous beam bridges. The local stiffness distribution and the potential damage can be obtained in a timely manner, and the long-gauge strain history of the monitored span when a single vehicle passes the span is required in this method. Numerical simulations and real bridge tests have confirmed the validity of this method.

2. Theoretical background

As shown by Ojio and Yamada, the strain influence line is used primarily for vehicle load identification [21]. However, it is not suitable for bridge damage identification because the information obtained by traditional point strain gauge is too "local". Traditional strain gauges cannot reflect the information of damage effectively unless covering the damaged region coincidentally. In this section, the damage identification for continuous girder bridges was studied based on a method which combined the strain influence line and long-gauge strain sensing technology. The relationship between the damage and the area of long-gauge strain histories was investigated. According to influence line theory, the strain can be calculated using Eq. (1)

$$\overline{\varepsilon_i(x)} = \sum_{k=1}^{n} P_k f(x - d_k) \tag{1}$$

where $\overline{\varepsilon_i(x)}$ is the average strain obtained by long-gauge strain sensors; $f(x)$ is the value of the influence line corresponding to the location of the axis; d_k is the distance from the kth axis to the first axis (d_1 = 0, the span is L, and the ith axle load is P_i); and x is the distance from the first axis to the left support. Then, Eq. (1) is integrated along the length direction of the structure:

$$\int_0^L \overline{\varepsilon_i(x)} dx = \sum_{k=1}^{n} P_k \int_0^L f(x - d_k) dx = \sum_{k=1}^{n} P_k \int_0^L f(x) dx \tag{2}$$

in which $\int_0^L f(x)dx$ is the area of the strain influence line at the location of x_i in the x-coordinate. As shown in Eq. (2), the integral value of the strain along the length direction of the structure can be calculated if the influence line function $f(x)$ is known. For continuous girder bridges, the strain influence line function cannot be expressed by a specific function. For

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