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Experimental study on damage detection at bolted joint using frequency response function

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ABSTRACT

Structural steel members are connected by the bolts among them. There are a few cases that the structural performance is governed by bolted joints. This work considers a damage identification to detect damage due to bolt loosening at bolted joint based on measured frequency response function (FRF) data. The damage identification approach is performed by the only FRF data collected through impact hammer test. Two types of measurement sensors of accelerometer and strain gage are utilized to evaluate the bolt loosening and their experimental results are compared. The FRF data sets in the neighborhood of the first resonance frequency are transformed to the proper orthogonal modes (POMs). It is shown that the bolt is loosened at the region to represent the abrupt change of the POMs. The validity of damage detection method at bolted joint due to bolt loosening is illustrated in the experimental tests.

1. INTRODUCTION

Steel structure is a structure which is made from organized combination of structural steel members designed to carry loads and provide adequate rigidity. Connections of steel structure are designed more conservatively than members because they are more complex than members. It indicates that the structural performance should be more sensitive to the joints than the members. If the structural performance of steel structure is deteriorated, it is related to the joints rather than the existence of damage in the longitudinal direction of steel members.

Bolted joints are one of the most common elements in steel structure design and bolts provide the required axial forces on them. The type of connection designed has an influence on member design and the member forces in structure are determined

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depending on the connections to be pinned, rigid or semi-rigid. The damage due to joint loosening belongs to the local performance deterioration of joint bolts. Milanese et al. (2008) introduced frequency and time domain signal processing techniques to detect damage in a bolted composite structure. Pilipchuk et al. (2011) experimentally studied the influence of cracking damage on the dynamic response of T-joint structures to find a proper visualization for the developing damage that can be used for on-line health monitoring of real marine structures. Rahmatalla et al. (2013) presented the use of vibration-based damage detection approaches as local methods to quantify damage at critical areas in structures. And they provided a transmissibility concept and damage-detection algorithm that show potential to sense local changes in the dynamic stiffness between points across a joint of a real structure. Caccese et al. (2004) focused on experimentally quantifying changes in bolt load of composite/metal hybrid connections due to viscoelastic creep and/or environmental effects. Todd et al. (2004) investigated whether modal analysis is an appropriate tool for detecting bolted joint degradation on a simple beam bolted to supports. Nichols et al. (2004) examined the functional relationship between data gleaned from locations on either side of the connection using nonlinear predictive models as a function of bolt loosening. Rutherford et al. (2007) presented the application of a non-linear feature identification technique for structural damage detection in the form of autoregressive coefficients in the frequency domain autoregressive model with exogenous inputs.

This work performs the experiments to detect damage due to bolt loosening at bolted joint by measured FRF data only. Two types of measurement sensors of accelerometer and strain gage are utilized to evaluate the bolt loosening and their experimental results are compared. The FRF data sets in the neighborhood of the first resonance frequency are transformed to the POMs. The loosened bolt is tracked by the POM curves depending on measured sensors. The validity of damage detection at bolted joint due to bolt loosening is illustrated in the experimental tests.

2. FREQUENCY RESPONSE FUNCTION

FRFs relative to the reference location of the stationary accelerometer or strain gage are measured. The measured data are collected as FRF which is defined as the ratio of the displacement mode of a system to its excitation force. The FRF response data can be experimentally obtained by the roving of measurement sensors or impact hammer. The FRF can be expressed as a function of the cross and auto spectra, which can readily be obtained from most multi-channel data acquisition systems. The cross spectrum is computed by multiplying the Fourier spectrum of a measured response by the complex conjugate of the Fourier spectrum of a known input:

$$G_{xy}(\Omega) = F_x(\Omega) F_y^*(\Omega) \tag{1}$$

where $G_{xy}(\Omega)$ denotes the cross spectrum, $F_x(\Omega)$ the Fourier spectrum of a measured response, and '*' is the complex conjugate. The auto spectrum is computed by multiplying the Fourier spectrum of the input by the complex conjugate of itself.

$$G_{yy}(\Omega) = F_y(\Omega) F_y^*(\Omega) \tag{2}$$

where $G_{yy}(\Omega)$ represents the auto spectrum. The FRF is then defined as the ratio of the cross and auto spectrum.

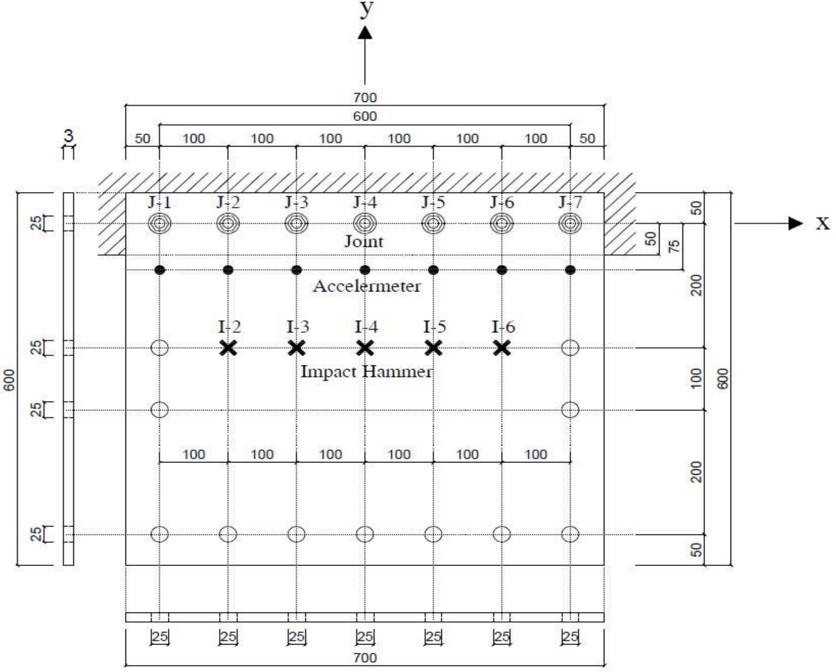
$$H(\Omega) = \frac{G_{xy}(\Omega)}{G_{yy}(\Omega)} \tag{3}$$

where $H(\Omega)$ denotes the FRF to be collected experimentally. If strain gages are utilized as measurement sensors, the strain frequency response function (SFRF) data are expressed in the similar form as Eq. (3).

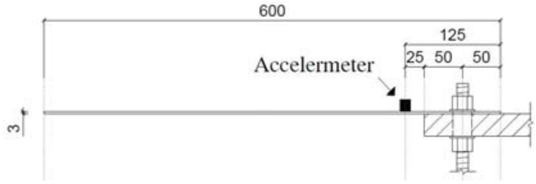
Feeny and Kappagantu (1998) observed that the POMs represent the normal modes of vibration in undamped and lightly damped systems. A set of FRF response data collected within a given frequency range is transformed to the POMs. The POM associated with the greatest proper orthogonal value (POV) is the optimal vector. If the eigenvalues are normalized, they represent the relative energy captured by the corresponding POM. The eigenvalue reflects relative kinetic energy associated with the corresponding mode. This work utilized the POM corresponding to the first POV extracted from the FRFs collected in the neighborhood of the first resonance frequency.

3. EXPERIMENTS

The validity of the damage detection method based on the POMs extracted from measured FRF data was investigated in detecting the location of loosed bolt at bolted joint. Two types of measurement sensors of accelerometer and strain gage were utilized for evaluating their applicability.



(a)

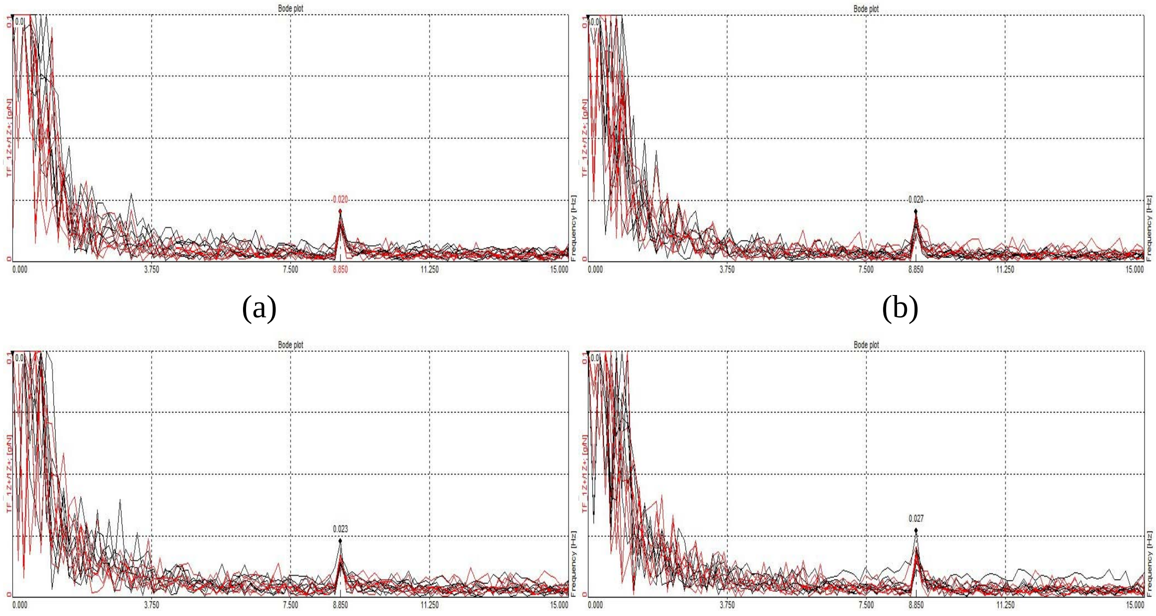


(b)

Fig. 1 Experimental plate with loosed bolt and accelerometers(unit: mm):
(a) plan view, (b) side view

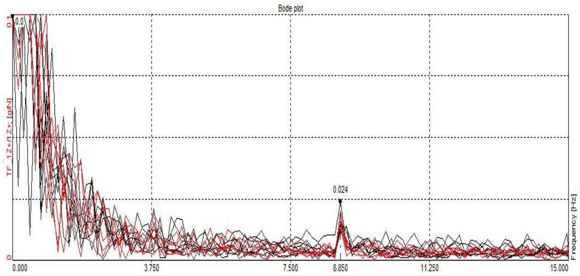
The dimension of plate for this experiment is $700 \times 600 \times 3\mathrm{mm}$ and a plate end at $\mathrm{y} = 50\mathrm{mm}$ is connected with the support by seven bolts of 25mm diameter in the x-direction as shown in Fig. 1. The other ends are free. A torque wrench is a tool u+sed where the tightness of bolts is crucial and used to precisely apply a specific torque to a bolt. The full torque of the bolt joint measured at the end joint was $50\mathrm{N} \cdot \mathrm{m}$. As a damage scenario, the torque of the loosed bolt at the joint J-2 of seven bolt joints was established as $20\mathrm{N} \cdot \mathrm{m}$.

The first test was performed using the accelerometers. The accelerometers were installed at the top of the plate at 75mm in the negative y direction of the bolt. An impact hammer hit at a stationary point of five locations (I-2 to I-6) in Fig. 1, and the corresponding modal displacements were simultaneously measured by uniaxial accelerometers at seven different locations (J-1 to J-7). And the impact hammer moved to the other point, the same test was repeated and each data set was collected. The experiment was conducted using DYTRAN model 3055B1 uniaxial accelerometers



(a) (b)

(c) (d)



(e)

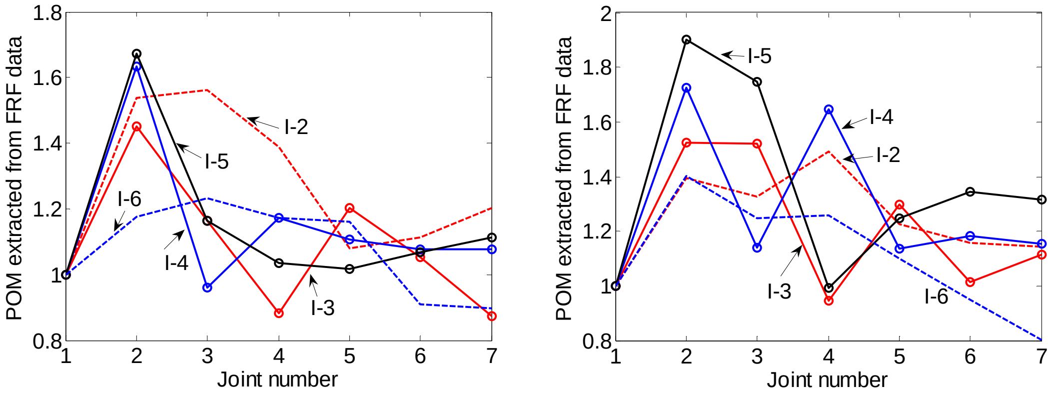
Fig. 2 FRF receptance curves depending on the impact location:

(a) I-2, (b) I-3, (c) I-4, (d) I-5, (e) I-6

along with a miniature transducer hammer Brüel & Kjaer model 8204 for the excitation of the system. The data acquisition system was a DEWETRON model DEWE-43. The FRFs were simultaneously measured at each frequency.

Figure 2 represents the FRF receptance curves describing the displacements at seven different accelerometer locations due to the impact at five different locations. It can be observed that the first resonance frequency locates at 8.85Hz regardless of the impact locations. Twenty-one FRF data sets within the frequency range of 7.324-10.376Hz including the first resonance frequency were extracted to estimate the POMs.

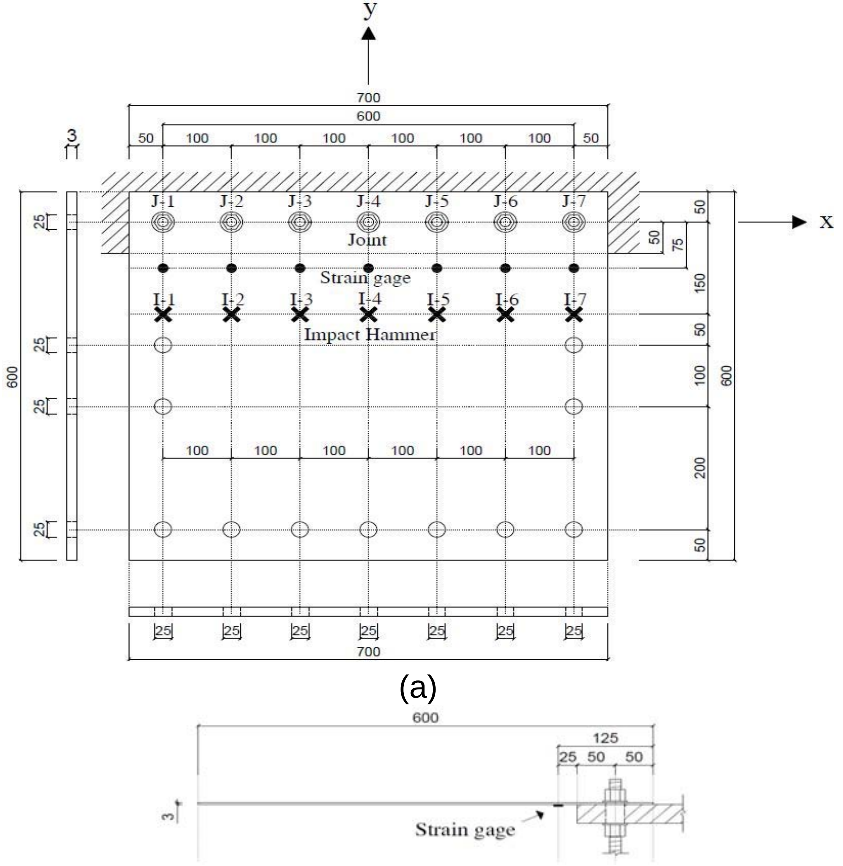
Figure 3 exhibits the POM curves. Each data set was normalized by the J-1 POM data. It is expected that the non-smoothness of the curves partially comes from the contaminated measurements including external noise. The joint damage due to bolt loosening can be observed by the POM curves. It is shown that the location to represent the abrupt change in the POM curve coincides with the loosened bolt position J-2. More explicit change when the impact hammer located at I-3, I-4 and I-5 rather than I-2 is displayed as shown in Fig. 3(a). The same experiment was repeatedly carried out, the POM curves were obtained as shown in Fig. 3(b) and the similar results were obtained. The abrupt variance in the POM curve located at the loosened bolt position except when the impact is performed in alignment with the damage location.



(a) (b)

Fig. 3 POM curves depending on the impact location:
(a) the first test, (b) the second test

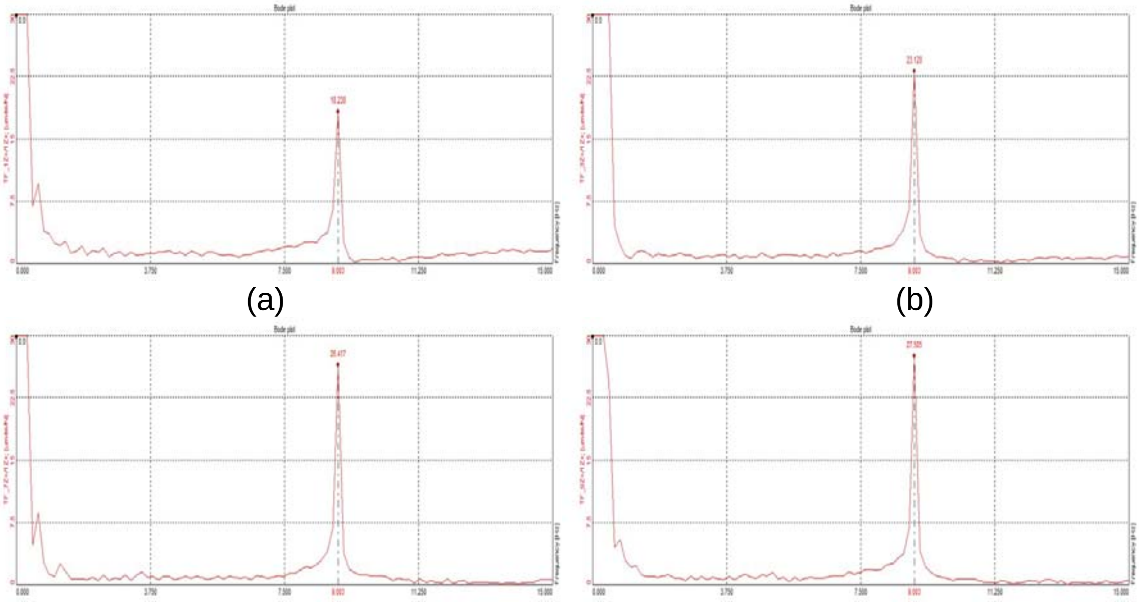
Another experiment was performed using strain gages as measurement sensor. The strain gages were bonded to the bottom of the plate at the same location as the accelerometers (Fig. 4). The impact hammer at each test is in alignment with the strain gage because it is utilized to measure the flexural performance. The strain frequency response functions (SFRFs) were simultaneously collected by the strain response and a disturbing force at the same x coordinates. A full SFRF data set was completed by seven impact tests. It is found in Fig. 5 that the first resonance frequency locates at 9.003Hz. Figure 5 represents the SFRF receptance magnitude curves. The first resonance frequency is a little difference in using the accelerometers and strain gages because the accelerometer has a mass unlike the strain gage. Twenty-one SFRF data sets in the neighborhood of the first resonance frequency were extracted to transform to the POMs. Figure 6(a) represents the POM curves obtained by two repeated experiments. The POM data at each position were independently obtained so that we cannot mention the damage information. Thus, in order to establish the relation of the



(a)

(b)

Fig. 4 Experimental plate with loosened bolt and strain gages (unit: mm):
(a) plan view, (b) side view



(a) (b)

(c) (d)

Fig. 5 SFRF receptance curves depending on the impact location:
(a) I-1, (b) I-2, (c) I-4, (d) I-5

POMs, the POM data were interconnected by their slopes. The damage exists at the bolt location to represent the abrupt change in the consecutive slopes. Figure 5(b) shows the slopes of the POMs. The consecutively abrupt change in the slopes between the locations 1 and 2, and the locations 2 and 3 is observed. Thus, we can recognize that the bolt loosening locates at the second bolt.

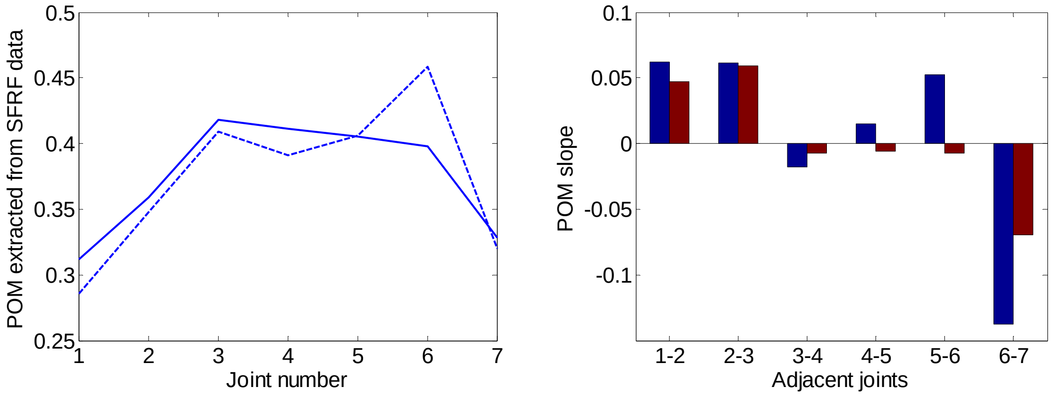


Fig. 6 POM curves when the strain gages are utilized as the measurement sensor:
(a) POM curves, (b) POM slopes

4. CONCLUSIONS

The purpose of this experimental work is to evaluate the health state of bolted joint due to bolt loosening using the FRF data collected by accelerometer and strain gage. The FRF data within the first frequency range are transformed to the POMs. It was shown that the location to represent the abrupt change in the POM curve coincides with the loosened bolt position in using the accelerometers as measurement sensor. The damage exists at the bolt location to represent the abrupt change in the consecutive slopes in using the strain gages as measurement sensor. It can be concluded that the POMs transformed from the measured FRF data sets by accelerometer and strain gage are utilized in detecting the joint damage due to bolt loosening at bolted joint.

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