Piezoelectric strain-based member-level health monitoring for a large scale steel frame test bed

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ABSTRACT: This paper introduces a case study on the application of a strain-based local damage detection method to a large scale steel frame test bed. Local damage on individual members was detected by a novel damage index that was extracted from a comparison of strain responses between undamaged and damaged states. In vibrational testing, strain responses were measured using wireless piezoelectric strain sensing.

Test Structure and Measured Data

The test bed was a five-story steel frame that was located in the structural laboratory at Disaster Prevention Research Institute, Kyoto University (Fig. 1(a)). At the second, third and fifth floors, beams in the longitudinal direction and columns were connected to joints using removable steel connections, i.e., four links at the flanges and one pair of links at the web (Fig. 1(c)). There were twelve removable connections at beam ends (i.e., B1 to B12) in each longitudinal frame (see Fig. 1(b)). By removing the links, fracture damage was simulated (see Fig. 1(d)). The details of the test structure were reported by Kurata et al. [1].

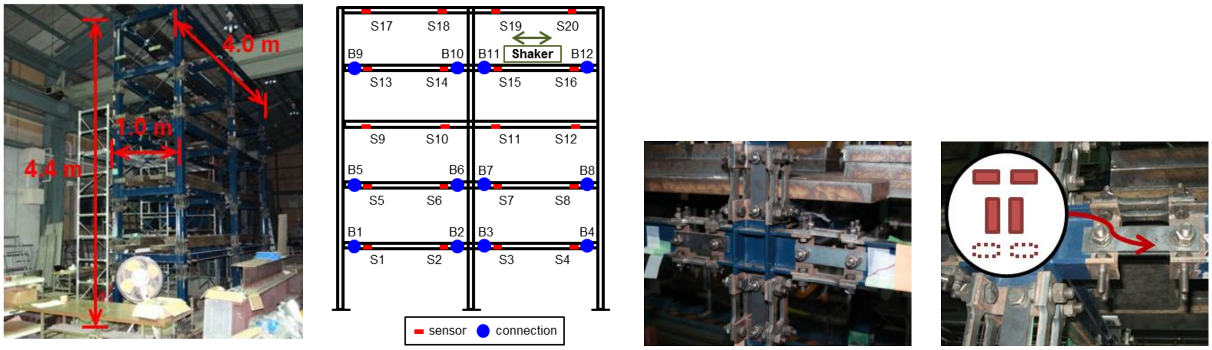
The strain measurement system that consisted of twenty polyvinylidene fluoride (PVDF) sensors (i.e., S1 to S20) (LDT1-028k, Measurement Specialties, VA, USA) interfaced with *Narada* wireless sensing units (Civionics, LLC, CO, USA) was deployed on one longitudinal frame of the five-story frame test bed (Fig. 1(b)). All sensors were attached with strong adhesive on one side of the bottom flange of beams at 330 mm away from the center line of columns.

The test bed was excited at the fifth floor using a modal shaker (APS-113, APS Dynamics) that was fixed to the steel mass plate by four machine bolts. For each structural condition, the steel frame was excited in the longitudinal direction using three loadings: (1) ambient excitation (AmbE); (2) small amplitude white noise (WN1); and (3) relatively large amplitude white noise (WN2). In the structural laboratory, the level of ambient excitation mainly caused by ground microtremor was around 0.49 cm/s^2 in RMS at the top floor. When the two white noise excitations with the frequency range of 1-50 Hz were input for the undamaged condition, the acceleration responses of the top floor were 3.32 and 8.45 cm/s^2 for WN1 and WN2 in RMS, respectively.

In each measurement, a strain time history was measured for 75 sec with a sampling rate of 100 Hz. Fig. 2 shows the dynamic strain responses at the undamaged condition in voltage and their amplitude spectra at the beam of the second floor (S2 in Fig. 1(b)) under three excitations.

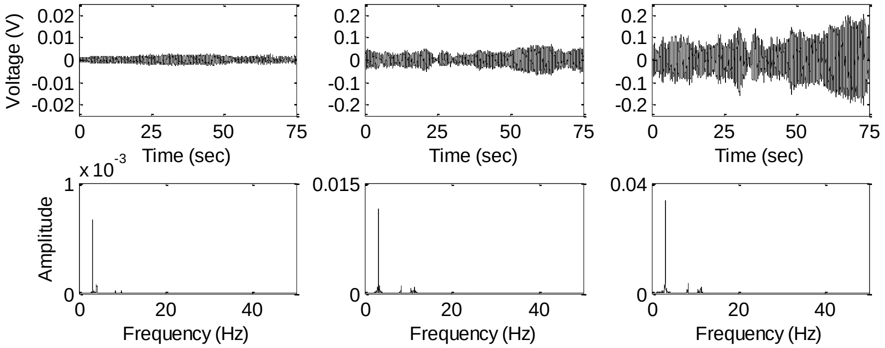
SHM Methodology and Results

The strain-based local damage detection method was originally presented by Kurata et al. [1] and Li et al. [2]. Fig. 2 illustrates the conceptual scheme of the local damage detection method. As shown in the schematics, a wireless piezoelectric strain sensing system that consisted of a dense array of PVDF sensors interfaced with *Narada* wireless sensing units was developed for measuring the strain responses of beams at undamaged and damaged conditions. The sensing system, including a reference sensor and detecting sensors, is deployed to monitor pre-identified damage-prone beams. The reference sensor is used to eliminate the effects of the excitations. The detecting sensor near probable damage is used to detect the local damage. A strain-based damage index was derived from a comparative study of strain responses between undamaged and damaged conditions. The notable feature of the damage index was that the index is independent of external excitations and vibrational modes.



(a) (b) (c) (d)

Fig. 1. Steel frame test bed: (a) overview; (b) beam connections and sensor location; (c) removable steel connection; (d) simulated damage [1]



(a) (b) (c)

Fig. 2. Measured data at S2: (a) AmbE; (b) WN1; (c) WN2

Fig. 3 shows the damage index results for the undamaged and damaged cases under three different excitations. At the undamaged condition, the variation of the damage index was less than 7% for all the input excitations (Fig. 3(a)). Fig. 3(b) shows the results for the damaged case A where the entire bottom flange links were removed at B2 near S2. The damage index of −60% at S2 clearly indicates the existence of severe damage at B2. In addition, the damage index of +18% at S3 also indicates damage at nearby connections. With the removal of both the web and the flange links at B2 in the damaged case B, the damage index at S2 decreased by 90%, indicating severe damage at B2 (Fig. 3(c)). In addition, small difference in the damage indices for the damage under three excitation inputs implies a weak dependency of damage index on the characteristics of the external loading.

Lessons Learned

This paper presented an application of the local damage detection method to a five-story steel frame test bed. The developed wireless strain sensing system showed excellent performance for monitoring the dynamic strain in the steel structures under small amplitude vibrations and even ambient excitations. In addition, the damage index values clearly indicated the existence and severity of the damage, which would enable the quantification of fracture damage in steel frames. Nonetheless, as the local damage detection method was derived from the bending moment of individual members, it is not effective for small damage that slight changes the inner forces sustained by the damaged elements.

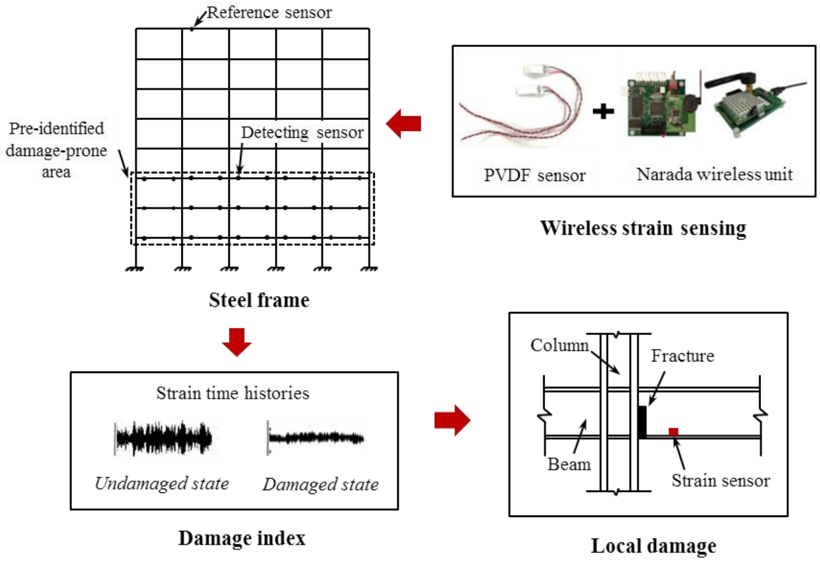
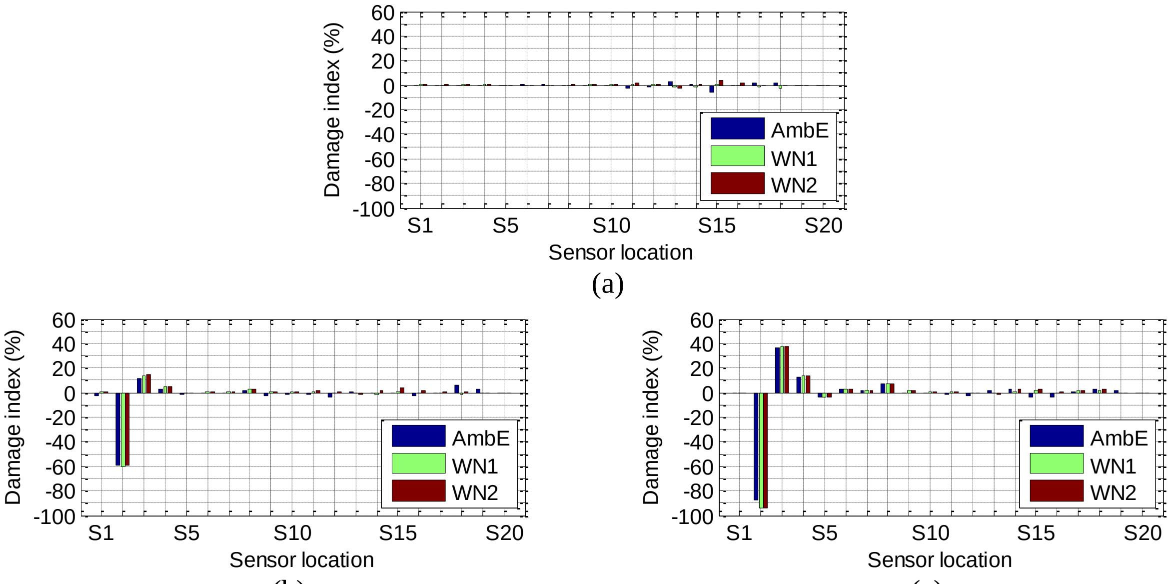


Fig. 3. Scheme of local damage detection method



(a)

(b)

(c)

Fig. 4. Damage index: (a) undamaged case; (b) damaged case A; (c) damaged case B

References

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