Structural Monitoring Scheme Based on Directly Measured Inter-story Drift Displacement Response Information

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SUMMARY:
The authors' research group has developed a noncontact type of sensors for the direct measurement of inter-story drift displacements of a building subjected to seismic excitation. The information on the seismically induced drift displacements would provide very significant evidence in evaluating how severe damages in which stories occur after, or even immediately after the seismic event. This paper presents a drift displacement measurement based diagnosis scheme to identify to which story and how the damage occurs. The presented scheme requires only relatively simple computations. The data to be used are just the drift displacements for all the stories other than the ground motion acceleration data. It is demonstrated that, with those data utilized, satisfactory hysteresis for every story can be estimated even if the measurement noise exists.

Keywords: drift displacement, hysteresis, structural health monitoring, damage detection

1. INTRODUCTION

Many engineering products have been altering their conventional definitions and boundaries by integrating the recent development of modern sensing and microprocessor technologies. To give a good example, recent motor vehicles have been more and more acquiring human beings like characteristics. The microprocessor integrated into such motor vehicles would determine whether or not an automatic brake should be applied based on the sensing of the distance to the preceding vehicle. In addition to this kind of automatic brake system, today's motor vehicles employ a variety of mechanisms integrating the sensor-and-microprocessor technology combination. These motor vehicles are called "smart" vehicles. Having such a trend of these days, the Merriam-Webster Dictionary International Edition (2004) provides the modern interpretation to the word *smart*; it is "containing a microprocessor for limited computing capability." Other than smart vehicles, there are many engineering products with the word *smart* prefixed. Smart phones are one of those examples. They are totally beyond the conventional image of telephones. They are not only a device for making a call any more but also a device for exchanging e-mails, obtaining a variety of information from the web-sites all over the world, and even working as a mobile personal computer.

Now the term *smart* has become one of the most important keywords representing modern engineering products. Smart structures and systems in the civil engineering field are those structures and systems which contain the function of self-sensing, self-computing, self-decision-making, self-diagnosis, and/or self-control. Integrating certain type of sensors and microprocessors, smart structures could monitor their own behaviors and make diagnosis of how good or how bad their own "health" conditions are, or could take certain action to conduct the response control to seismic or wind excitations. In conducting either health monitoring or response control, sensor plays a very important role. To promote the research on smart structures technology and its international collaboration, an international networking organization named ANCRiSST (Asia-Pacific Network of Centers for Research in Smart Structures Technology) has been established. Under the umbrella of this network, a number of international workshops for smart structures technology have been already organized and held in several countries. The workshop *ANCRiSST 2008* was held in Tokyo, Japan (Nishitani et al. 2008).

As above-mentioned, structural monitoring is one of the major research topics for smart structures technology. A variety of responses or outputs are to be measured in conducting structural health monitoring at the practical stage. In fact, it has been reported by Nitta et al. (2010) and Nishitani et al. (2011) that a kind of position sensitive detector (PSD) sensors were implemented in a full-sale steel structure building model at the opportunity of large shaking table test and the successful damage location detection was accomplished. It has been widely recognized that, among those responses, the inter-story drift displacement of a building structure could give a direct index in making the judgment of building health condition during or after a seismic event. However, non-contact type of direct measurement device for such a drift displacement did not use to be available, although contact type of devices, such as device utilizing a linear voltage transducer (LVD), are available. In most cases, instead of displacements, accelerations or velocities are measured. If the data of drift displacements are needed, certain computation process should be added to obtain the displacement from the measured data of velocities or accelerations. However, such computation requires certain techniques to derive the accurate drift displacement information. On such a background, the research group of this paper has developed non-contact type of sensors for inter-story drift displacements of a building (Kanekawa et al. 2010a, 2010b; Matsuya et al. 2010a, 2010b).

Applying the developed sensing devices to an actual steel structure building, several members of this research group have made experiments of drift displacement measurement (Hatada et al. 2010). In addition, these newly developed sensors have been practically implemented into a recently completed office building and a research laboratory building. Owned by one of the largest construction companies in Japan, both of the buildings are located in Tokyo. These developed sensing devices can measure directly the time history of drift displacements during various levels of seismic events. The information on the seismically induced drift displacements would provide very useful and significant evidence to structural engineers for the evaluation of which story or stories are damaged and how severe, moderate or little damages occur soon after the seismic event. These devices have an advantage of the conventional LVD type of measurement device in terms of its set-up and space occupancy.

As referred to in the above, accelerometers or velocity measurement sensors have been used mostly at the practical stage of structural health monitoring. The displacement data, if needed for any reason such as for the damage detection or diagnosis, would be obtained through the process of numerical integration of measured acceleration or velocity data. Despite that, in some cases or even quite many cases, it would be a non-trivial task to obtain the accurate displacement time history with the aid of the numerical integration. In this respect, the sensor devices which can measure directly the drift displacement without involving any integration process are the one which is expected to fill a long-felt want in the field of structural monitoring and damage detection.

Having the above-mentioned background of the current states of structural health monitoring, this paper presents a drift displacement based scheme to identify in which story or stories and how damage would occur at a building structure soon after the seismic excitation. In the presented scheme, the employed computations are rather simple. The scheme is demonstrated to be effective even in the case relatively large measurement noise is involved into the data obtained by the inter-story drift displacement sensors. The purpose of this research is to present a scheme to find which story has been damaged during a seismic event, not to find which structural elements in which story/stories have been damaged. In this regard, the presented scheme is for making prompt diagnosis immediately after or even during the seismic event.

2. INTER-STORY DRIFT DISPLACEMENT SENSORS

2.1 Significance of Inter-story Drift Displacement Measurement

Actually, in conducting structural design of a high-rise building in most cases in Japan, the ratio of inter-story drift displacement to the story height in each story is computed for specified seismic excitations. If the value of this ratio is less than one two hundredth in every story, the entire building would be regarded to remain in the elastic range. Therefore, if the ratio is far beyond one two hundredth, the story in consideration would be out of the elastic range. In this respect, the drift displacement information is of great importance for judging the health condition of the story of a building. For obtaining the inter-story drift displacement information without the noncontact type of drift displacement sensor utilized, there have been practically two ways to be employed: one is to use a contact type of device such as LVT based device; and the other to conduct the numerical integration of either the measured acceleration or velocity data with respect to time. However, neither of them lacks precision for the following reasons.

In using a device integrating an LVT element, the LVT element is set up so as to connect, in the horizontal direction, the two bars with the lengths of about a half of the story height: one hangs down from the upper floor slab of a story and the other stands up on the lower floor slab. During a seismic event, LVT would measure the distance between the two oscillating bars. If these two exhibit the perfect rigid body motion, LVT would measure the precise inter-story drift displacement. However, both of the bars actually exhibit vibrations like cantilever beams, and thus the data obtained by LVT are not the accurate inter-story drift displacement, involving the effect of two bars' cantilever-like motions. In addition, this type of devise has the following disadvantage from the practical implementation point of view; the set-up of the devise would occupy a large space in the three dimensions and thus the device would not be fitted to the implementations in many stories at the practical stage of measurement. Therefore, it is mainly used at the opportunity of real-size model building experiments to obtain the reference data to be compared to the data measured by different types of sensors.

On the other hand, the difficulty with respect to the integration based scheme for deriving the drift displacement is in regard to the numerical integration. As above-mentioned, it is not a straightforward task to utilize the numerical integration of acceleration or velocity time history for the purpose of obtaining the displacement data. No matter which data, either acceleration or velocity data, may be utilized, the measurement of the different location time histories should synchronize with each other prior to the integration to derive the precise drift displacement through the integration process, because the drift displacement would be obtained by subtracting the numerically integrated time history of the lower floor from that of the upper floor. In addition, the integral computation itself may lead to miscalculation. It is well known that with the ordinarily conducted integration of the acceleration or velocity data the computed displacement time history would be likely to have gradually increasing discrepancy from the zero line with the processing of integration.

Accounting for the above-mentioned situation regarding the significance of direct drift displacement measurement, it can be said it would be of great advantage to develop a noncontact type of practical sensor devise of directly measuring the inter-story drift displacement.

2.2 Development of Inter-story Drift Displacement Sensors

As briefly mentioned in INTRODUCTION, the authors' research group has developed two types of noncontact sensors which can directly measure the time history of inter-story drift displacement in a building. With only the data measured by a sensor unit (either type) installed in a story, the drift displacement of that story can be obtained. Both types are comprised of a light source element and a focusing lens element.

One type of sensor utilizes a light emitting diode (LED) array as a light source element. The details of this sensor have been reported in Matsuya et al. (2010a, 2010b). The sensor is comprised of LED array element and position sensitive detector (PSD) element. PSD element works as focusing lens. The LED array is set up on the lower side of the upper floor, while the PSD element is set up on the upper side of the lower floor. This sensor mechanism of obtaining the drift displacement is as follows: the LED array moves together with its connected floor movement; the movement of LED array is focused by the lens of the PSD element, and then the focused light is projected onto the central part of the photo-sensitive region. The time history of drift displacement can be thus obtained by this sensor, without any involvement of integration kind of computation after the measurement. Aiming at measuring the displacement of base-isolators, this sensor has been implemented in a base-isolated office building located at the center of Tokyo.

Instead of LED array for the sensor mentioned in the above, another type of sensor uses a laser light source (Kanekawa et al. 2010a, 2010b). Phototransistor array is used as the focusing lens element. The fundamental mechanism is as follows: the laser light beam from the upper floor is scattered through certain process; the scattered laser light brightens the phototransistors on the lower floor; and the center position among the phototransistor array is determined by comparing the intensity of the laser light at each phototransistor. Several units of this sensor have been installed in plural number of stories at the recently completed building for the technical research institute of one of the Japanese top construction companies.

3. STORY HYSTERESIS EVALUATION BASED ON DRIFT DISPLACEMENT DATA

The information obtained by the developed drift displacement sensors would directly give an idea of how severely or little at which story in a building has been damaged immediately after a seismic event. In addition to that beneficial information, if the story hysteresis loops would be obtained, it could be of a substantial help toward the deeper insight into the story damage detection or damage assessment. A health monitoring scheme is herein presented in which the hysteretic loop of each story is estimated mainly with the drift displacement measurement data.

The time histories corresponding to the inter-story drift accelerations are computed with the double differentiation of the drift displacement data. Although the numerical integration would have certain discrepancy from the zero line, the numerical differentiation in general is much less troublesome. The proper accumulation of the computed drift accelerations (from the differentiation) along with the ground surface acceleration would lead to the estimation of the absolute acceleration of each story. Then, the resulting shear force from the seismic excitation would be computed based on these absolute acceleration data. The hysteretic loop of each story can be obtained by combining the time histories of shear force and drift displacement.

In the following, numerical simulations are conducted by presenting how simply the hysteretic loops can be estimated mainly with the measured inter-story drift displacement data. A shear structure model of four-story building is considered. The employed data are shown in Table 3.1.

Table 3.1. Data for the numerical simulation model

Story	Mass (t)	Initial stiffness (kN/m)	Initial yield displacement (10^{-2} m)	Second yield displacement (10^{-2}m)
Fourth	53.6	38,042	0.70	0.98
Third	53.6	61,419	0.70	0.92
Second	53.6	78,942	0.75	0.92
First	66.3	93,720	0.80	1.10

Each story is assumed to have a tri-linear hysteresis; thus it has the initial, second and third stiffness coefficients. For the first story the second and third stiffness coefficients are, respectively, 23% and 2% of the initial stiffness; for the second story they are 29% and 4%; for the third story they are 38% and 6%; and for the fourth story they are 46% and 6%.

It is further assumed that: the model building has such a viscous damping proportional to the stiffness matrix as to give the first modal damping coefficient of 2%; it is subjected to the 1940 El Centro earthquake (NS component) with the peak acceleration of 3.0 m/s^2; and all of the inter-story drift displacements are measured along with the ground surface acceleration during a seismic event.

In Fig. 3.1 the drift displacement time histories for all the stories are presented. The data involve the measurement noise with S/N ratio of 20 dB. This value of S/N ratio has been determined by processing the experimentally-measured data obtained from the drift displacement sensor (the sensor using phototransistor array) in the case of sinusoidal excitation. Fig. 3.2 provides the real hysteretic loops for the first to fourth stories, all of which are unknown at the actual stage. The following numerical example demonstrates how satisfactory hysteresis loops are obtained only with the drift displacement data other than the ground surface acceleration.

The adding of double-differentiated results of the measured displacement data would lead to the hysteretic loops for all the stories. Although the accurate mass data of all the stories are needed to obtain the actual story shear forces, they are, in general, not available in the practical situation. For the purpose of reflecting that fact, the simulation employs those mass values which have some discrepancy from the accurate mass values presented in Table 3.1. The employed values are $0.8m_1$,

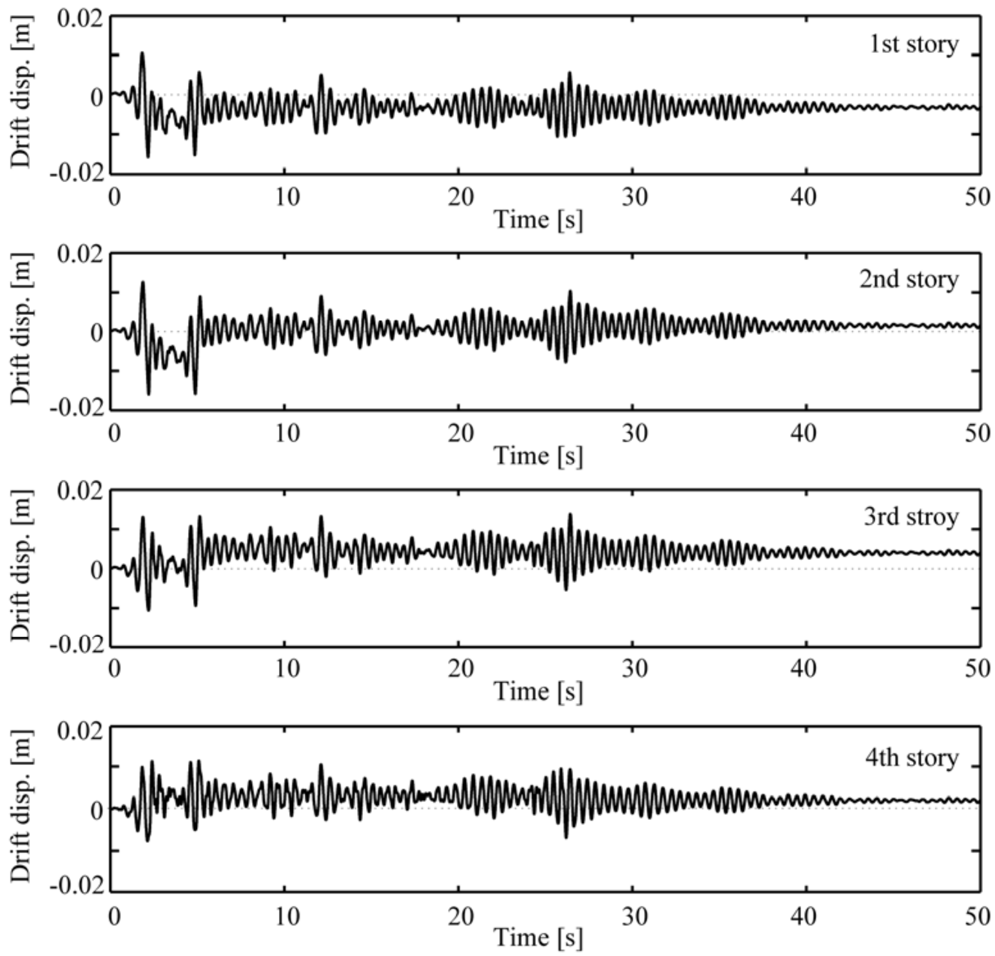

Figure 3.1. Drift displacement time histories

$1.2m_2$, $0.9m_3$, and $1.1m_4$, with m_1, m_2, m_3, and m_4 denoting the real mass values from the first to fourth stories. The obtained hysteresis shapes, shown in Fig. 3.3, are quite similar to the results in Fig. 3.2, although they are estimated using the inaccurate information with respect to the mass values and the drift displacement data with the measurement noise involved.

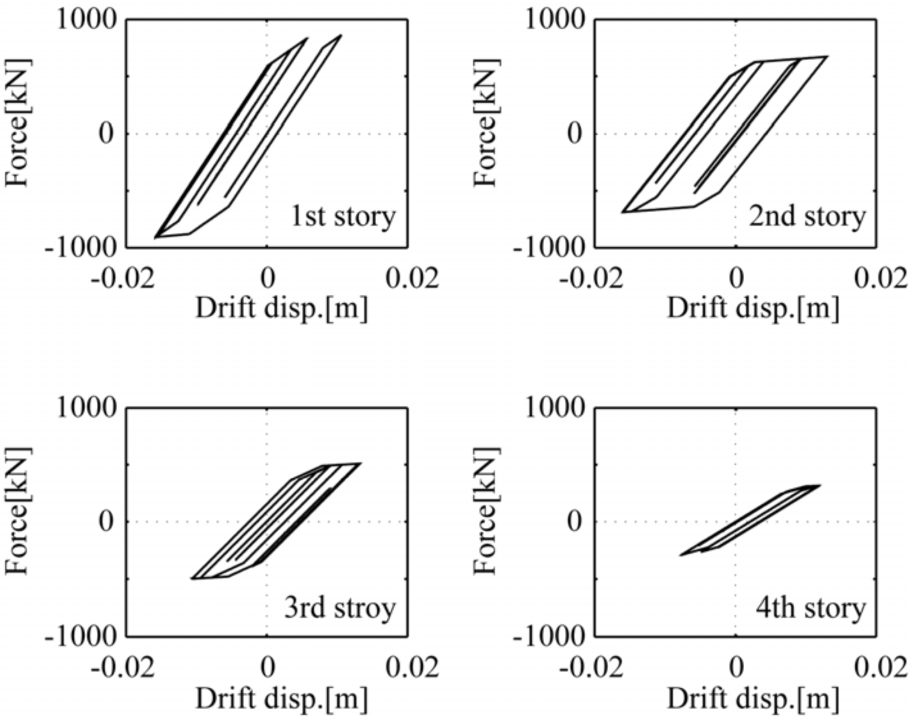

Figure 3.2. Right hysteresis loops

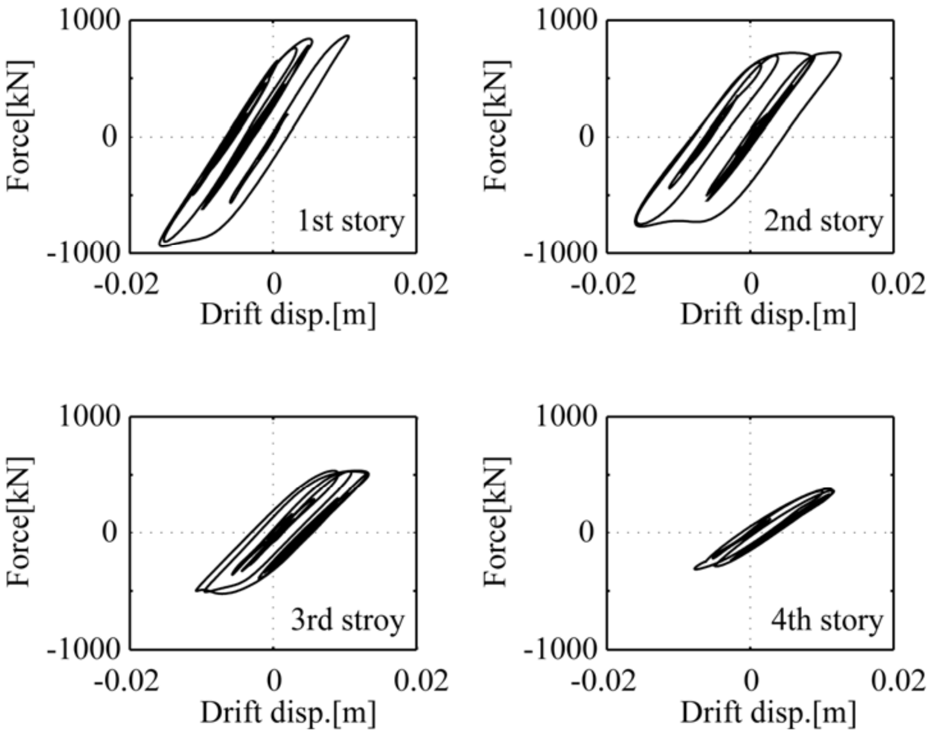

Figure 3.3. Estimated hysteresis loops

In calculating the above hystereses, the effect of the measurement noise involved into the original displacement data has been removed or undermined in the following way. First of all, all the original measured displacement data go through a low-pass filter in the frequency domain such as to cut off the wave components in the range of frequencies five times larger than the first-mode natural frequency of the building. They are herein referred to as the filtered drift displacement data. Those filtered drift displacement data are double-differentiated, with the inter-story drift acceleration time histories obtained. The combining of thus obtained accelerations leads to the story absolute accelerations. Prior to the construction of the hysteretic loops, the calculated absolute accelerations are made to go through another low-pass filter. The employed low-pass filter is to cut off the wave components for the range of frequencies four times larger than the building natural frequency. Combining such calculated acceleration data together with the filtered drift displacement data, the hysteretic loops are finally constructed.

For the purpose of ensuring the validity of the presented procedure for removing or undermining the effect of measurement noise, the case involving larger measurement noise of S/N ratio 10 dB is examined. Fig. 3.4 demonstrates the comparison of the constructed hystereses with the right hystereses for the first to fourth stories. The red solid lines represent the constructed hysterses, while the black solid lines represent the right ones. Both of the hystereses are found to be satisfactorily in good agreement with each other. Accounting for the purpose of constructing the hystereses, the hysteretic shapes are important rather than the absolute values of the longitudinal axis in the hysteretic loop. In this regard, the presented scheme is effective even in case of relatively large measurement noise involvement.

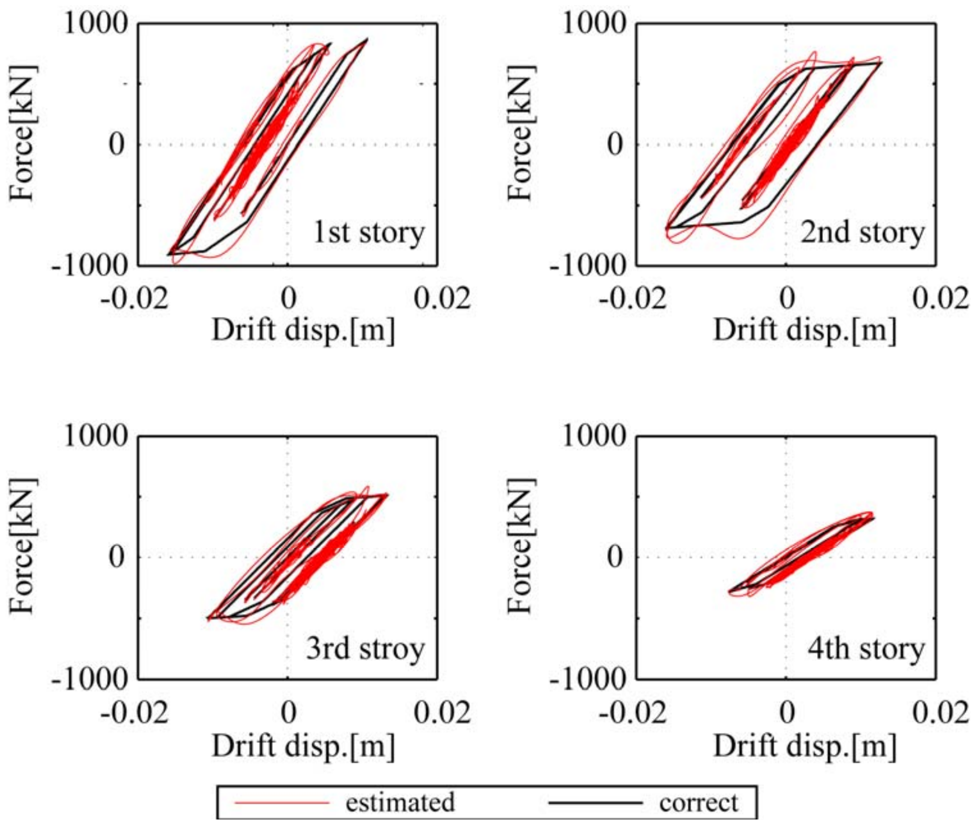

Figure 3.4. Estimated hysteresis loops from the data with S/N ratio of 10 dB

4. CONCLUSIONS

Noncontact type of inter-story drift displacement sensors have been developed by the authors' research group. Such devices were not available, although the drift displacement information would have become a direct and significant index for the scheme of damaged story detection i.e., how severe damage in which story would occur in the building. In a way the development of this kind of sensing devices is expected to fill a long-felt want in the field of structural monitoring. First of all, the significance and effectiveness of such a direct measurement of drift displacements have been discussed from the building health monitoring perspective. Secondly, for the purpose of getting deeper or further insight toward more accurate and clear recognition of the structural or story health condition, the obtained drift displacement data have been utilized to construct the story hysteresis loops during a seismic event. The information on the shape of hysteresis itself is rather important, and the hysteresis shape is of substantial help for the diagnosis of story damage state. It has been demonstrated that satisfactory story hysteretic loop shapes can be obtained mainly with the drift displacement data even in case the measured data involve rather large measurement noise and the accurate mass information is unavailable.

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REFERENCES

Hatada, T., Takahashi, M., Suzuki, Y., Matsuya, I., Kanekawa, K., Nitta, Y., and Nishitani, A. (2010). Measurement of relative story displacements by noncontact-type sensors on forced vibration test of an actual building, *AIJ Journal of Structural and Construction Engineering*. **75:653**, 1257-1264.

Kanekawa, K., Matsuya, I., Sato, M., Tomishi, R., Takahashi, M., Miura, S., Suzuki, Y., Hatada, T., Katamura, R., Nitta, Y., Tanii, T., Shoji, S., Nishitani, A., and Ohdomari, I. (2010a). An experimental study on relative displacement sensing using phototransistor array for building structures, *IEEJ Transactions on Electrical and Electronics Engineering.* **5:2**, 251-255..

Kanekawa, K., Matsuya, I., Sato, M., Nitta, Y., Tanii, T., Nishitani, A., Shoji, S., Ohdomari, I., Hatada, T., and Takahashi, M. (2010b). An experimental study on relative displacement direct sensing in real-time using phototransistor array for building structures, *The Fifth World Conference on Structural Control and Monitoring.* **USB:** Paper No. 216:1-7.

Matsuya, I., Katamura, R., Sato, M., Iba, M., Kondo, H., Kanekawa, K., Takahashi, M., Hatada, T., Nitta, Y., Tanii, T., Shoji, S., Nishitani, A., and Ohdomari, I. (2010a). Measuring relative-story displacement and local inclination angle using multiple position sensitive detectors, *Sensors.* **10:11**, 9687-9697.

Matsuya, I., Oshio, M., Fuji, R., Sato, M., Kanekawa, K., Takahashi, M., Miura, S., Suzuki, Y., Hatada, T., Katamura, R., Nitta, Y., Tanii, T., Shoji, S., Nishitani, A., and Ohdomari, I. (2010b). Noncontact-type relative displacement monitoring system using position sensitive detector, *AIJ Journal of Technological and Design.* **16:33**, 469-472, 2010.

Merriam-Webster, Incorporated. (2004). *Merriam-Webster Dictionary International Edition* (Paperback: Based on Merriam-Webster's Collegiate Dictionary, Eleventh Edition). Merriam-Webster, Springfield, USA

Nishitani, A., Spencer, B.F. Jr., Yun, C.-B., and Nitta, Y. (ed.). (2008). Proceedings of ANCRiSST 2008 (The fourth International Workshop on Advanced Smart Materials and Smart Structures Technology), JSPS, Japan.

Nishitani, A., Nitta, Y., Nagae, T., Ji, X., and Nakashima, M. (2011). PSD sensor based damage detection for full-scale model building experiments, *The 2011World Congress on Advanced Structural Engineering and Mechanics (ASEM11+).* **CD-ROM:** Paper ID 318-581:1-8.

Nitta, Y., Nishitani, A., Nagae, T., Ji, X., and Nakashima, M. (2010). Damage detection of beam-column joint in full-scale model building experiments, *Fifth World Conference on Structural Control and Monitoring.* **USB:** Paper No. 238:1-7.