6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Direct Measurement of Inter-Story Drift Displacements of Scale Model Building in Shake Table Tests

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ABSTRACT
The authors' research group has recently invented a non-contact type of sensing device of directly measuring the inter-story drift displacements for building structures. That sensor obtains the time histories of two dimensional drift displacements during a seismic event. This kind of sensor had been a long-wanted device but was not available until the recent development of these sensors. Utilizing an opportunity of participating in the shake table test experiments of a scale building model at E-defense, the authors' group installed these developed sensors into that model building. Reporting those drift displacement results which the sensors measured from non-severe to severe seismic excitations, this paper demonstrates that the sensors could provide the structural engineers with useful and significant data for damage assessment at the primary stage in particular.

KEYWORDS: *Drift displacement sensor, Residual displacement, Health monitoring, E-defense, Cumulative plastic deformation response ratio.*

1. INTRODUCTION

It has been more than two decades since the world's first full-scale building implementation of active control scheme was achieved in Japan in 1989 [1]. This epoch-making event inspired the world-wide structural engineering research community to attempt to integrate a variety of modern, advanced technologies into civil engineering structures. This movement definitely altered the conventional boundary of the structural engineering field. Along with such a movement, the authors would say, the concept of "modern structural engineering" has been gradually established. Information technology, system control technology and sensor technology as well as the concept of "smart" or "intelligent" has not only become the keywords for that modern structural engineering, but are also becoming a necessary background and knowledge for the near-future structural engineers to learn. Smart structures technology plays the main role at the stage of such a modern structural engineering field. Actually, ANCRiSST has held international workshops focusing on the smart structures technology research and development for the last decade.

Smart health monitoring for civil structures is one of the major research categories for smart structures technology. Among a variety of health monitoring schemes, the establishment of efficient, effective and smart seismic damage assessment or diagnosis frameworks for building structures, soon after a seismic event in particular, is of great significance. If the assessment or diagnosis for the purpose of detecting building damage condition and places or judging how a building has been injured is focused on, the information on inter-story drift displacement data during a seismic event would help the engineers make such a judgement. There is a good example for how significantly the drift displacements would be helpful for the safety diagnosis; it is the Building Standard Law in Japan. Japan is, as widely known, located in one of the most severe seismic regions in the world. All of the buildings to be constructed in Japan should be designed based on severe seismic design philosophy specified by the Building Standard Law. The Law provides the structural engineers with multiple seismic design schemes. Most of buildings, however, are designed with such a scheme as to satisfy the criteria corresponding to two levels of seismic excitations. In the first level of seismic excitation, peak ground acceleration (PGA) of around 0.1G is accounted for, while in the second level PGA of around 0.4G is considered. During an earthquake of the first level, all of the major components consisting of a building structure are required to remain in the elastic range and, in addition, the inter-story drift displacements are required to be less than 1/200 of the corresponding story height. This means that if the drift angle is less than 1/200 in every story, the entire structure would stay in the elastic range and thus would not have any significant damage. In this regard, the drift displacement data could be a straightforward, direct index of providing useful information in conducting safety or damage assessment after a seismic event.

Those direct sensing devices for inter-story drift displacements which could be practically installed into a real building had not been available until the authors' research group invented such devices. The drift displacement sensors were manufactured for the purpose of real-size building implementation. In fact, those sensors have been installed into multiple stories of a real building at Kajima Technical Research Institute. All the information of the drift displacements can be seen on a display screen in one room in that building immediately after an earthquake. One of the beneficial points in dealing with such drift displacement data is in that even only the peak value data of drift displacements in multiple stories could be helpful to make a quick assessment of the building safety level. By utilizing an opportunity of shake table test experiments at E-defense, the sensors were installed into all the stories of a one-third scale structural model representing a eighteen-story steel building [2]. In this experiment, the drift displacement data were successfully obtained for a variety of seismic excitation levels [2]. Based on the obtained data, this paper extends discussions in regard to the relationship between the drift displacement responses and damage occurrence/condition.

2. SIGNIFICANCE OF INTER-STORY DRIFT DISPLACEMENT SENSING AND SENSING MECHANISM

The direct sensing of inter-story drift displacements has a potential of opening the door to totally different damage detection or monitoring schemes for building structures from the conventional velocity/acceleration measurement based schemes. Combining the measured data of drift displacement time histories and a forcibly displaced three-dimensional push-over analysis with those data could construct a framework of structural element based damage detection for a building structure [3]. In addition to such a framework, the authors' group has also recently presented a scheme of estimating the values of story-based cumulative plastic deformation response ratios of a building mainly utilizing the obtained drift displacement time histories [4]. Even without combining any additional, non-trivial calculation or process such as push-over analysis or integrating skillful derivation of the cumulative plastic deformation response ratios, the drift displacement time histories themselves could provide the engineers with significant data in making early or pre-precise estimation of the story damage conditions. From the primary or early stage diagnosis point of view, only the time history data of drift displacements should be useful. This kind of simple framework without any complex calculation process involved would lead to a "practicing structural engineers-friendly" scheme. Those frameworks which can be conducted without any detailed information on story masses or structural components involved may be required, in particular, shortly or soon after a seismic event. In this regard, a damage assessment scheme with only the measured data utilized should be constructed. For the purpose of constructing a simple diagnosis scheme based on only the data of drift displacement time histories, the paper discusses the relationship between the drift displacement data and damage condition of each story utilizing the experimental data of a one third scale model steel building.

Another benefit of the direct measurement of inter-story drift displacements is that the drift displacement sensors can detect residual displacements resulting from severe seismic excitation. The residual displacement magnitude of each story, if such a displacement exists, could indicate that there would be certain damage in that story. With the obtained data, in that case, the engineers could recognize which stories would be damaged. Such residual displacements, however, can be never calculated through the numerical integral computation of measured velocity or acceleration data.

Prior to the main discussion, it is explained in the following how the developed sensor can measure the inter-story drift displacement. The authors' group has developed two types of drift displacement sensors. One is

“Position Sensitive Detector” sensor (PSD sensor) [5, 6, 7] and the other is “Photo-Transistor” sensor (PTr sensor) [8]. These two kinds of sensors have quite similar mechanisms to measure the data. Both sensors consist of two units: units of light source and light receiver. The measurement mechanism is briefly illustrated by considering PSD sensor. The light source unit of Light Emitting Diode (LED) and light receiver unit are set beneath the upper floor slab and on the lower floor slab, respectively. The latter unit is composed of a collecting lens and a photodiode with Positive, Intrinsic and Negative semiconductors combined (PIN photodiode). With the photo-emissive effect, the LED light reaching the PIN photodiode through the collecting lens causes the electron movement in the photodiode and thus-caused electron movement induces electric current flows in the opposite direction of electrons in the photodiode. If the light receiver is right beneath the LED light source, the current flows at the right- and left-hand sides of the photodiode would be identical. If the photodiode recognizes the difference of the induced current flows between the both sides, such a difference would indicate the relative location of the light source to the light receiver. This relative location would be the inter-story drift displacement.

3. EXPERIMENTAL SCALE MODEL BUILDING AND EXPERIMENTS

Experiments employing a one third scale model of eighteen-story steel building were conducted at E-defense in December, 2013 [9]. The model building is a moment-resisting frame structure with a total height of 25.3 m and total weight of 4179 kN. All of the floor plans from the first (ground) to the eighteenth floors are identical. The plan has three spans with 2.0 m each in the longitudinal direction (X direction) and one span of 5.0 m in the transverse direction (Y direction). All the columns are box-shaped steels of 200 mm x 200 mm, while the beams were H-shaped steels with a beam height of 270 mm and a flange width of 85-95 mm in the X direction and a beam height of 250 mm and a flange width of 125 mm in the Y direction. This scale model building was subjected to seismic excitations only in the X direction. The first mode natural period of the scale model building was 1.15 s in the X direction. The drift displacement sensors have been installed into all the stories from the first to eighteenth.

Table 3.1 Seismic excitations and responses for shake table tests

Case number	${}_pS_V$ values at periods of 0.8–10 s [m/s]	Maximum drift angle (Story location)	2nd Maximum drift angle (Story location)	3rd Maximum drift angle (Story location)
1	0.40	1/172 (2nd)	1/185 (3rd)	1/199 (13th)
2	0.81	1/94 (2nd)	1/99 (3rd)	1/104 (4th)
3	1.10	1/80 (2nd)	1/83 (3rd)	1/83 (4th)
4	1.10	1/85 (4th)	1/86 (2nd)	1/89 (5th)
5	1.80	1/56 (2nd)	1/57 (3rd)	1/58 (4th)
6	1.80	1/53 (10th)	1/53 (11th)	1/54 (9th)
7	2.20	1/47 (10th)	1/47 (11th)	1/48 (2nd)
8	2.50	1/36 (2nd)	1/41 (3rd)	1/46 (11th)
9	3.00	1/26 (2nd)	1/29 (3rd)	1/36 (4th)
10	3.40	1/16 (2nd)	1/17(3rd)	1/19 (1st)
11	3.40	Over sensing range	Over sensing range	Over sensing range
12	4.20	Over sensing range	Over sensing range	Over sensing range
13	4.20	Over sensing range	Over sensing range	Over sensing range
14	4.20	Over sensing range	Over sensing range	Over sensing range

Employed seismic excitations are chosen by accounting for the case of the simultaneous occurrence of Tokai, Nankai and Tonankai earthquakes, i.e. Tokai-Nankai-Tonankai consolidated type of earthquake. They are simulated based on a response spectrum by assuming that the site is in Aichi Prefecture, Japan [9]. The duration is around 460 s. Table 3.1 shows these seismic excitations with different power. The second column indicates what the pseudo velocity response spectrum (${}_pS_V$) values corresponding to the building natural periods of 0.8 to 1.0 s. (The ${}_pS_V$ values are of around the same magnitude in the range of 0.8 s to 1.0 s.) This pseudo velocity response spectrum is calculated by dividing the value of absolute acceleration response spectrum by the corresponding natural circular frequencies. The peak ground acceleration of the earthquake for Case 1 with ${}_pS_V$

equal to 0.4 m/s is around 3.0 m/s^2. By accounting for the one-third scale model experiments, the time scales of all the waveforms have been compressed to be $1/\sqrt{3}$ of the original. The third column shows the maximum values of inter-story drift angles measured by the installed drift displacement sensors and locations of their occurrences. The third and fourth columns indicate the second and third maximum drift angles among all of the stories. The damage condition corresponding to each seismic excitation is presented in Table 3.2.

Table 3.2 Damage conditions for Cases of seismic excitations [9]

Case number	Damage condition
1	Elastic behavior; No damage recognized
2	Partially plastic at beam ends of 2nd to 4th floors
3	Partially plastic at beam ends of 2nd to 7th floors; Partially plastic at column bottoms for 1st story
4	Partially plastic at beam ends of 2nd to 7th floors; Partially plastic at column bottoms for 1st story
5	Plastic hinges at beam ends of 2nd to 14th floors; Sign of cracks at beam ends of 2nd to 5th floors
6	Plastic hinges at beam ends of 2nd to 14th floors; Cracks at beam ends for 2nd to 5th floors
7	Fractures at beam ends of 2nd floor
8	Fractures at beam ends of 2nd and 3rd floors
9	Fractures at beam ends of 2nd to 5th floors
10	Local buckling at column bottoms for 1st story
11	Increased local buckling at column bottoms for 1st story
12	Fractures at all beam ends of lower five stories; Fractures at column bottoms for 1st story
13	Same as above
14	Same as above

4. DISCUSSION BASED ON DRIFT DISPLACEMENT MEASUREMENT DATA TOWARD SIMPLE DAMAGE CONDITION ESTIMATE

The relationship between the damage condition for each story and measured drift displacement data is discussed. Even very simple processing of the measured data of the above mentioned experiments provides the structural engineers with useful information toward a simple damage condition assessment.

In Cases 11-14, as indicated in Table 3.2, structural engineers would visually recognize how the building has been damaged. In those situations, without any processing data, it would be clearly identified even where about the damages. For that reason, the data for Cases 11-14 are excluded in the following discussion. Fig. 4.1 displays the peak value distributions of the measured inter-story displacements for Cases 2, 5, 7 and 10. The distributions of Cases 2 and 10 are apparently different from those for Cases 5 and 7. In fact, as specified in Table 3.2, only small damage has been found in Case 2 and severe damage such as the local buckling of the columns in the first story has been observed in Case 10. However, the structure was less severely damaged in Case 5 than in Case 7, although significant difference in the peak value distributions is not recognized between Cases 5 and 7. From the damage assessment point of view, it would be important to distinguish the damage condition, either less severe or quite severe, for the situations such as Cases 5 and 7.

Then, the time durations of exceeding certain threshold levels are presented. Together with the horizontal lines indicating the threshold of drift angle of 1/100 both in the positive and negative directions, Fig. 4.2 shows the time histories of drift displacements of the second story, as an example, for Cases 2 and 7. The differences in those durations due to the powers of seismic excitations are recognizable. For the purpose of making quantitative discussion, Fig. 4.3 shows the stories' total durations beyond the drift angles of 1/150, 1/125 and 1/100 for Cases 2, 5, 7 and 10. When setting the threshold level to be 1/50, which case is not shown in Fig. 4.3, the crossing of that level occurred only at the lower four stories during the excitation of Case 10, but never occurred at any story during the excitations of Cases 5 and 7, although Case 7 caused quite severe damage to several beams and columns. On the contrary, when employing 1/150 and 1/100 as the threshold levels,

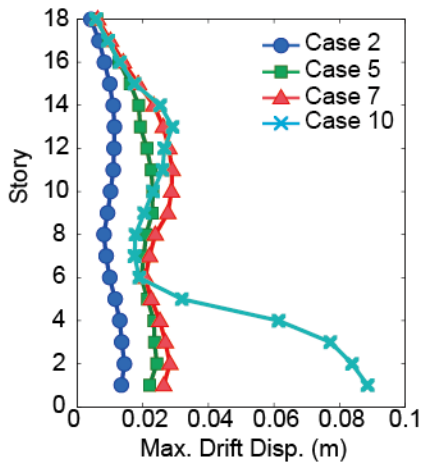

Figure 4.1 Maximum drift displacements

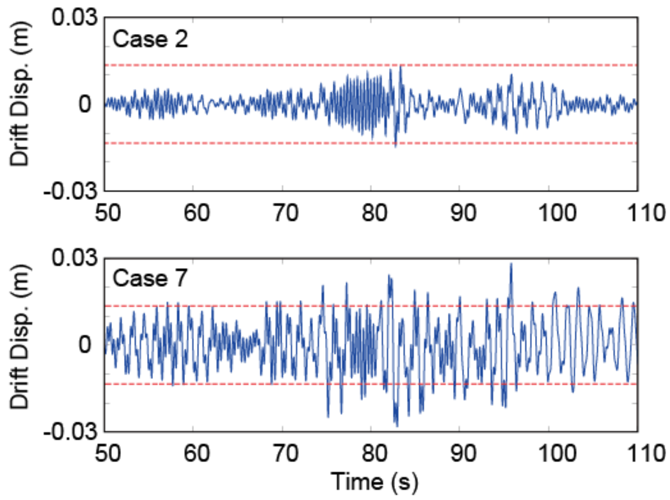

Figure 4.2 Part of drift displacement time histories of second story for Cases 2 and 7 with 1/100 threshold level

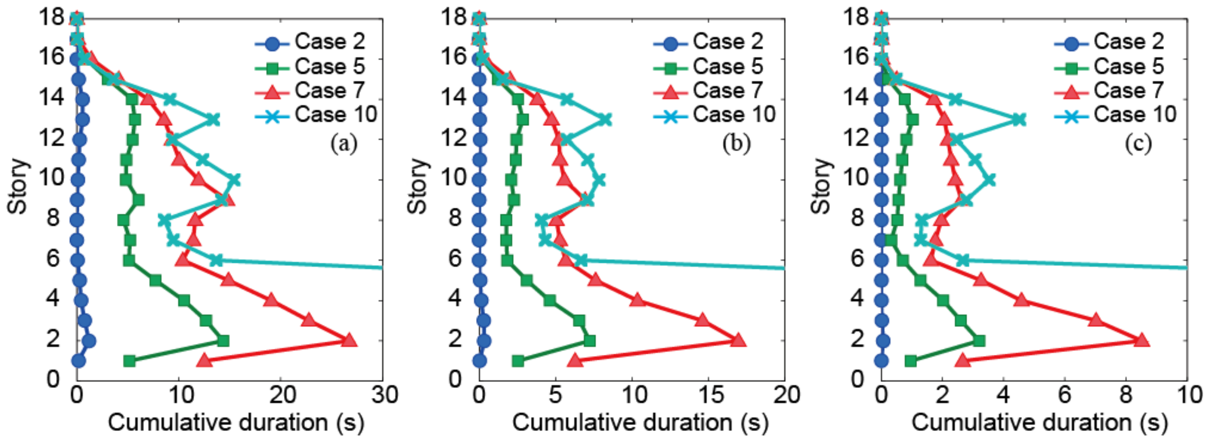

Figure 4.3 Cumulative durations of exceeding drift angle thresholds of (a) 1/150, (b) 1/125 and (c) 1/100

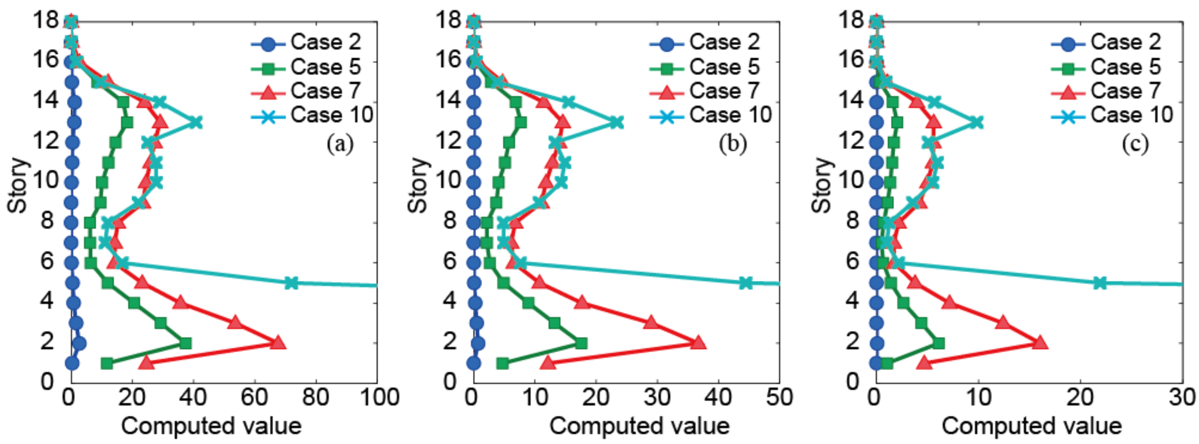

Figure 4.4 Pseudo-CPDRRs for drift angle thresholds of (a) 1/150, (b) 1/125 and (c) 1/100

difference between Cases 5 and 7 is clearly recognizable in Figs. 4.3 (a) and (b) in terms of the magnitudes of duration. However, in both Cases, the same tendencies can be recognized if the horizontal axis values are, intentionally, not concerned (although Case 7 exhibits 2 to 2.5 times larger values than Case 5).

In order to derive an index corresponding to a certain physical quantity, the summation of the peak values of exceeding the set threshold among the values during every single duration is estimated in Cases 5 and 7 for the threshold levels of 1/150, 1/125 and 1/100. These values, if divided by the threshold level, which is the assumed yielding displacement, would be indices to have certain relationship with cumulative plastic deformation response ratio (CPDRR). With such a simplified calculation framework, Fig. 4.4 displays the values corresponding to CPDRR, where those values are referred to as pseudo CPDRR even though they do not necessarily correspond to CPDRR. Fig. 4.4 (a), (b) and (c) present those values corresponding to the situations of the drift angle threshold levels of 1/150, 1/125 and 1/100, respectively. In Fig. 4.4 (a), it is found that several stories have values of more than 20 and the second and third stories have values of over 50 and 60 for Case 7, while they have values of 40 and 30 for Case 5. When setting 1/125, even the largest value is less than 20 for Case 5 and the values at the second and third stories have 40 and 30 at the second and third stories for Case 7. However, for the threshold level of 1/100, most of the values are much less than 20 for Cases 5 and 7 and even the largest value found at the second story for Case 7 is a little less than 20. It is said that a story could be severely or quite severely damaged with CPDRR of around 40. Accounting for the above-mentioned fact, the demonstrated values could be treated as pseudo CPDRR with the threshold of 1/125, as far as the experimental test results of this scale model are concerned. The presented simplified estimation of the values with some relation to CPDRR could be utilized to assess a primary or first stage damage assessment.

5. CONCLUSIONS

This paper has, first of all, presented the significance of direct measurement of inter-story drift displacement responses during a seismic event and then has briefly shown the mechanism of the invented sensing device of these drift displacements. Having an opportunity of joining the shake table test experiments at E-defense in December, 2013 with an eighteen-story scale-model building, the authors' group installed the drift displacement sensors into all the stories of that model building. For the purpose of constructing a simplified scheme of story-based primary damage assessment, the time durations of exceeding certain threshold levels and simply estimated values with some correspondence to the values of cumulative plastic deformation ratio (CPDRR) have been presented. It seems that the distributions of those values could explain the resulting damage conditions of each story by choosing appropriate threshold levels. Further investigation is needed with more effective usage of the obtained data of the experiment toward the construction of a simplified yet effective damage condition assessment scheme fitted to "structural engineer friendly" purpose. The development of drift displacement measurement based health monitoring scheme would lead to next generation damage assessment methodologies.

AKCNOWLEDGEMENT

This research is partially supported by the Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). The advices of Dr. I. Ohdomari and Dr. S. Shoji (Waseda University) and Dr. I. Matsuya (Nagaoka University of Technology) on the development of the sensors are greatly appreciated.

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