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Drift displacement data based estimation of cumulative plastic deformation ratios for buildings

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Abstract. The authors' research group has developed a noncontact type of sensors which directly measure the inter-story drift displacements of a building during a seismic event. Soon after that event, such seismically-induced drift displacement data would provide structural engineers with useful information to judge how the stories have been damaged. This paper presents a scheme of estimating the story cumulative plastic deformation ratios based on such measured drift displacement information toward the building safety monitoring. The presented scheme requires the data of story drift displacements and the ground motion acceleration. The involved calculations are rather simple without any detailed information on structural elements required: the story hysteresis loops are first estimated and then the cumulative plastic deformation ratio of each story is evaluated from the estimated hysteresis. The effectiveness of the scheme is demonstrated by utilizing the data of full-scale building model experiment performed at E-defense and conducting numerical simulations.

Keywords: inter-story drift displacement; hysteresis; cumulative plastic deformation ratio; E-defense

1. Introduction

During these two decades many engineering fields have been drastically altering their conventional boundaries. That is also the case in the structural engineering field. The first active

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control scheme implementation of a building structure in 1989 (Kobori *et al*. 1991) opened the door to smart structures technology integrating a variety of advanced techniques such as sensor, automatic control, information technologies, etc. This movement has been bringing a remarkable paradigm shift to the civil engineering field.

Based upon such a background, structural health monitoring has greatly appealed the attentions of structural engineers. For building structures, structural monitoring would be conducted based upon the daily and emergency vibration data sensing. These data records could provide useful information on how healthy or unhealthy, how safe or dangerous for continued use or stay the structure is. The significance of such health monitoring is demonstrated by recent accidents such as the ceiling board collapse at Sasago Tunnel (Kutsukake 2014) and the bridge fall-down in USA (www.ntsb.gov/investig ations/summary/har0803.htm). In addition to the preventing of these kinds of accidents mainly resulting from the time deterioration, it is also of great importance to establish the diagnosis scheme of building structures after a seismic event. With the establishment of such a scheme, it could be promptly judged which stories, or which structural elements if possible, are damaged. Such information would lead to the judgment of the appropriateness of continuous use or stay of building.

Most schemes for building health monitoring focusing on the diagnosis after a seismic event have been constructed with either accelerometers or velocity sensors. For instance, the schemes of Saito (1998), Nitta and Nishitani (2003) and Shinagawa and Mita (2013) were constructed based on the usage of accelerometers, and the scheme of Nakamura and Yasui (1999) was based on velocity sensor measurement. For the judgment of possibly-damaged building condition, however, inter-story drift displacement data could be more direct indices than acceleration and velocity response data. According to the Japanese Building Standard Law, most of the buildings in Japan are designed so as to satisfy the requirements of two levels of seismic excitations: Levels 1 and 2. Level 1 is such a medium level of earthquake input that the design base shear is 20% of total building weight for the typical situation; and Level 2 is such a large level of seismic input that induces the base shear equivalent of the total weight of building. During such Level 1 seismic event, all the stories of a building are required to remain in the elastic range and have the inter-story drift angles less than 1/200. These requirements indicate that if the drift angle is smaller than 1/200, the story would not deviate from the elastic range.

It would not be impossible to calculate the drift displacements from the acceleration or velocity data. However, the numerical integral calculations of displacements from acceleration or velocity data are not a trivial task. No numerical integral calculation technique is available which can manage to reach the accurate displacement results for any situation. For the case of shake table tests, the displacement responses of either a full- or small-scaled model building can be gauged with laser displacement sensors set up outside of the shaking table. For full-scaled or close-to-full-scaled model buildings, linear voltage transducer (LVT) type of sensors have been employed quite often. LVT is a typical displacement measurement sensor of contact type, and is set up so as to measure the relative displacement between two steel vertical elements: one hangs from the upper floor slab or beam and the other stands up from the lower. These two elements are needed to be close to perfectly-rigid as much as possible. However, this measurement system would occupy a large space and thus the sensor set-up is not practical at all for real buildings.

In this respect, the authors would say that non-contact type of direct measurement sensors for inter-story drift displacements were a long-wanted device. On such a background, the authors' research group has developed two kinds of non-contact type drift measurement sensors (Matsuya *et al*. 2010a, Matsuya *et al.* 2010b, Matsuya *et al*. 2011, Kanekawa *et al*. 2010), with which the drift displacement time histories can be obtained. The sensors have been already recognized to have the measuring range and frequency resolution fitted to the vibration of a normal building structure. When excitation test experiments were conducted using a real building with an on/off switching mechanism of braces, the developed sensors successfully traced the resulting residual displacement from the forced on/off switching of the braces during the excitations, which is hardly traced via numerical integral calculations of acceleration or velocity data (Hatada *et al*. 2010).

The authors' group (Hatada *et al.* 2013) has presented a structural element based damage detection scheme integrating the three dimensional (3D) push-over analyses utilizing the measured drift displacement data. This damage detection scheme, however, needs the detailed information on structural elements of a building in question for performing the 3D analysis.

This paper proposes a simple scheme of estimating story cumulative plastic deformation ratios (CPDRs) utilizing the drift displacement data, which aims at providing useful information toward a prompt safety judgment or assessment soon after a seismic event. Mainly from the data of inter-story drift displacements, the story hysteresis loops are estimated and then the story CPDRs are evaluated. (In regard to the simple estimation of story hystereses, the authors' group (Matsui *et al*. 2012) has already presented the framework.) Other than the drift displacement data the presented scheme only needs the ground floor seismic acceleration data. It does not need any prior information or push-over analysis of a building. After showing how accurate story hysteresis loops are obtained using the data of experiments already conducted at E-defense, the validity of the scheme of obtaining CPDRs is demonstrated by numerical simulations. The values of CPDRs are significantly helpful in judging the story-based building damage state.

2. Inter-story drift displacement sensors

As mentioned in Introduction, the authors' group has developed two types of drift displacement sensors: one is referred to as PSD (position sensitive detector) sensor (Matsuya *et al*. 2010a, 2010b, 2011) and the other is PTr (photo-transistor) sensor (Kanekawa *et al*. 2010). The basic philosophy of measurement mechanism is quite similar to each other. The invented sensors are composed of two units: light source and light receiver units. In regard to PSD sensor, Fig. 1 schematically illustrates the sensor set-up. The configurations of the light source and receiver units for PSD sensor are briefly explained. The LED (Light Emitting Diode) light source is set beneath the upper floor slab and the light receiver unit is on the lower floor slab. The light receiver unit is composed of a collecting lens and PIN photodiode (consisting of Positive, Intrinsic and Negative semiconductors).

The measurement is conducted in the following way. The LED light going through the collecting lens reaches the PIN photodiode. Due to the photo-emissive effect the electrons in the photodiode start to move and then such movement of electrons induces electric current flows in the opposite direction of electrons in the photodiode. The photodiode, recognizing the difference of the induced electric current flows between the right- and left-hand sides, finds where the light source is located relative to the light receiver unit. The information of the light source location relative to the photodiode provides the time history data of inter-story drift displacements.

The developed sensors are mainly for a shear structure type of building. For a bending-deformation dominant type of building such as high-rise building, the measured data should be appropriately dealt with so as to take out the necessary information.

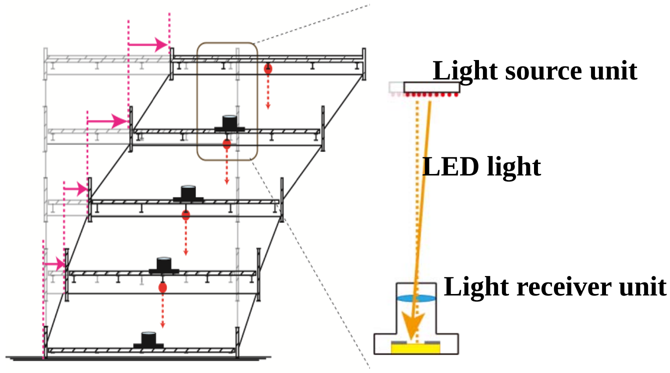


Fig. 1 Schematic illustration of drift displacement sensor

3. Estimation scheme of story hystereses and cumulative plastic deformation ratios

3.1 Estimate of story hystereses with inter-story drift displacement data

Compact for implementation, the developed drift displacement sensors do not occupy much space. Actually, the sensors were installed into a recently completed five-story building in Kajima Technical Research Institute and have started the measurement. In regard to the drift displacement data, even only the peak values could lead to a rough judgment of a building health condition. However, with the information on story hysteresis and cumulative plastic deformation ratio, more precise judgment on structural health can be conducted. In this subsection, it is presented how to estimate story hysteresis loops under the assumption that the sensors are implemented into every story of a building together with an accelerometer on the ground floor.

For hysteresis estimation, many identification-based methodologies have been proposed. Some of them are, for instance, Peng and Iwan (1997), Köylüoglu *et al.* (1997), Zhang *et al.* (2002) and Loh *et al.* (2011). In addition, Takewaki, Nakamura and Yoshitomi (2012) published a book of overviewing system identification techniques with the focus on structural health monitoring. Whereas these methodologies are rather for researchers, this paper aims at a "structural engineers-friendly" methodology for building health monitoring. For this reason, a presented scheme of estimating story hysteretic loops does not involve any identification process.

In a hysteresis loop, the vertical axis represents story shear force, while the horizontal axis presents drift displacement. The time histories of the drift displacements are directly measured with the PSD sensors. They provide the horizontal axis values and thus the information in regard to the story shear forces is needed for estimating the hysteresis. For the purpose of determining the vertical axis value based on the drift displacement data, the following steps are taken. Step (i): the double differential of the drift displacement data with respect to time is conducted to get the inter-story acceleration; Step (ii): accumulating those acceleration data from the first story to the story in question leads to the relative acceleration to the ground; Step (iii): adding the ground floor acceleration data to the acceleration data obtained in Step (ii) provides the story absolute accelerations; and Step (iv): the story shear force is obtained by multiplying thus-obtained story absolute accelerations by the corresponding story mass value and summing up such values from the top to the story in question. The flowchart of the procedures is shown in Fig. 2.

Unlike the numerical integral calculations, the numerical derivative calculations of displacements need no particular technique. In addition, as discussed more specifically in Section 5, the accurate story mass information is not necessarily needed in the presented scheme for evaluating story-based cumulative plastic deformation ratios.

3.2 Estimate of cumulative plastic deformation ratios

With the story hystereses obtained from the drift displacement measurement data, cumulative plastic deformation ratios (CPDRs) are estimated. The information on the story CPDRs would provide the structural engineers with significant data in judging a building health condition. In this respect, CPDR based judgment is not only for researchers but also practicing engineers. Hence, the authors would say that the presented scheme is a “practicing engineers-friendly” framework.

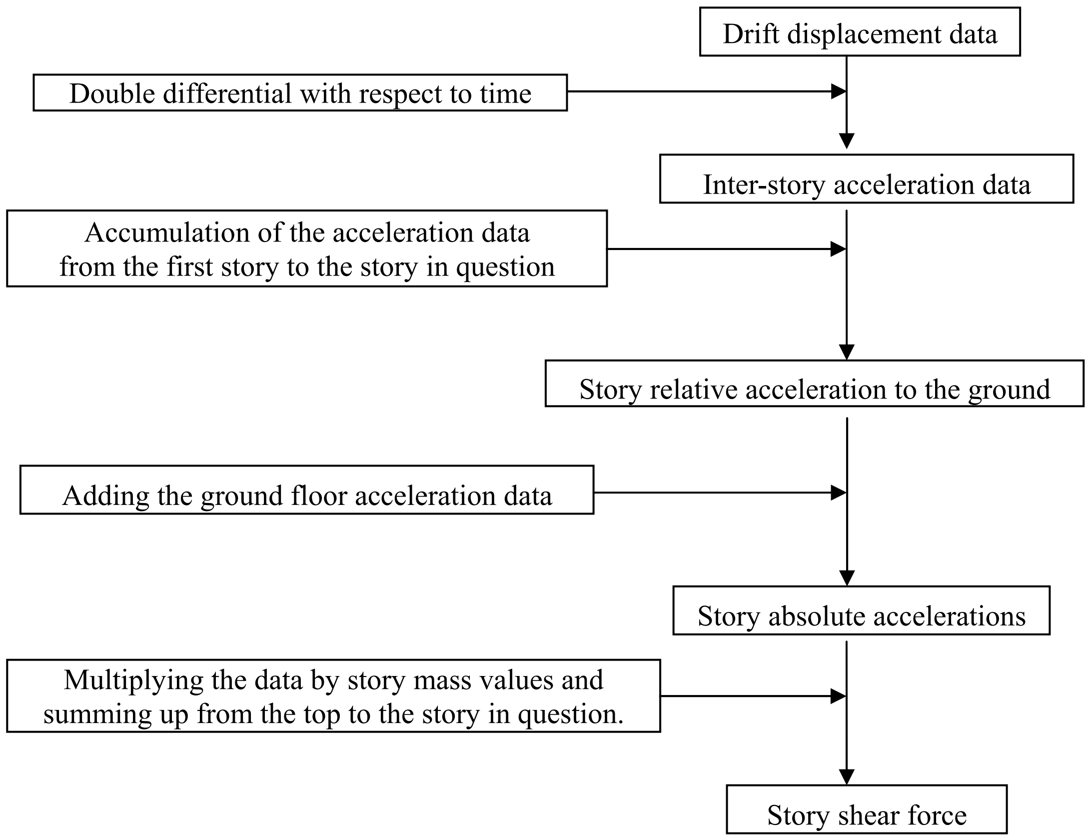


Fig. 2 Flowchart of estimation of story shear force from drift displacement data

The cumulative plastic deformations are the accumulation of the plastic deformations after exceeding the yield displacement. Then, CPDR would be directly calculated by dividing such accumulated plastic deformations by the yielding displacement.

Instead of the above direct calculation, herein, CPDR can be alternatively evaluated based on the area of hysteresis loops. By firstly accumulating the hysteretic areas and then dividing those accumulated areas by the product of the yield displacement and yielding force values, CPDR is obtained by

$$CPDR = \frac{\sum a_m}{\delta_y \cdot f_y} \tag{1}$$

where a_m: area of mth cycle hystersis loop; δ_y: yield displacement; and f_y: yield force. In conducting this calculation, the numerator does not include those hystersis loops of which the peak displacements do not reach the yield displacement .

For the case of idealistic hysteresis with a ductility factor of 1.2, for instance, as shown in Fig. 3, in which y and k, respectively, denote the yield displacement and initial stiffness coefficient. The area of the hysteresis loop in this case is 0.8 $k \cdot y^2$ and thus the division of 0.8 $k \cdot y^2$ by the product of y and ky leads to 0.8. This is identical to the value obtained directly by dividing the accumulated plastic deformation, 0.8y, by y. This alternative way would be much simpler and more appropriate than the direct CPDR calculation, in particular, in the practical situations of dealing with complex hysteretic loops during a real seismic event. It would be a complicated task to apply the direct method to real, complex hysteretic loops.

As already mentioned, it is the purpose of the paper to simply estimate the CPDR of each story toward the safety assessment. However, it is beyond the purpose to judge the overall safety or damage condition of an entire building based upon those story CPDR data. This sort of discussion is the next step.

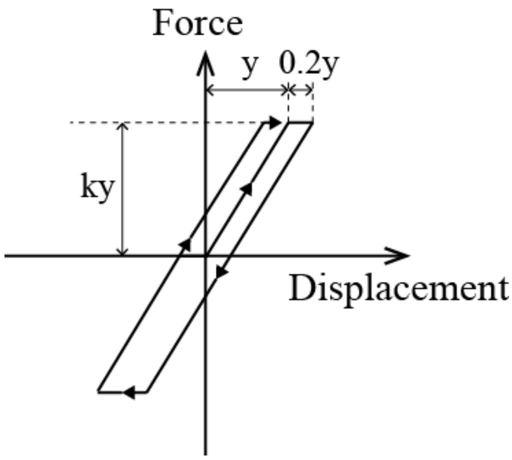


Fig. 3 Idealized hysteresis loop

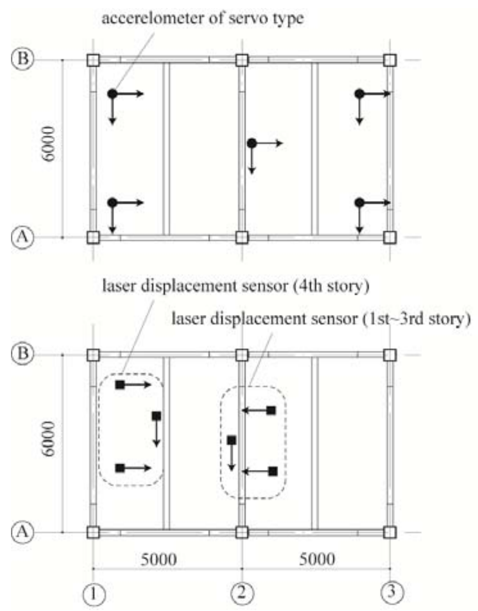


Fig. 4 Plan of model building with sensor locations

4. Validity of estimated story hystereses based on drift displacement data

Utilizing the experimental data available at the web-site of E-defense (https://www.edgrid.jp), the hystereses of a full-scaled four story steel building are, first of all, estimated with the above-presented scheme. The experimentally obtained data of "Full collapse experiments of steel building structure" performed in September 2007 is utilized, which are accessible via the web-site (https://www.edgrid.jp/lists/download_pubfile/0703). The full scale experimental model is a moment-resistant frame building with one-bay (6 m) frame in the shorter direction and two-bay frames (5 m for each) in the longer directions. The plan of this building is shown in Fig. 4. The further details are found at the above website. Fig. 4 also indicates the locations of implemented servo type accelerometers and laser displacement sensors. Although the displacement data in this experiment were not measured by the developed drift displacement sensors but the laser displacement sensors, they are herein utilized to demonstrate how effectively the presented scheme based on the drift displacement measurement works out to give quite accurate hysteresis loops. For comparison, those hystereses which are calculated with the directly measured acceleration data combined are also presented. In Figs. 5 and 6, respectively, the time histories of the directly measured accelerations and drift displacements are exhibited. The input excitation for this case was the JR Takatori earthquake observed during the 1995 Kobe earthquake with the peak value normalized as 60% of its original.

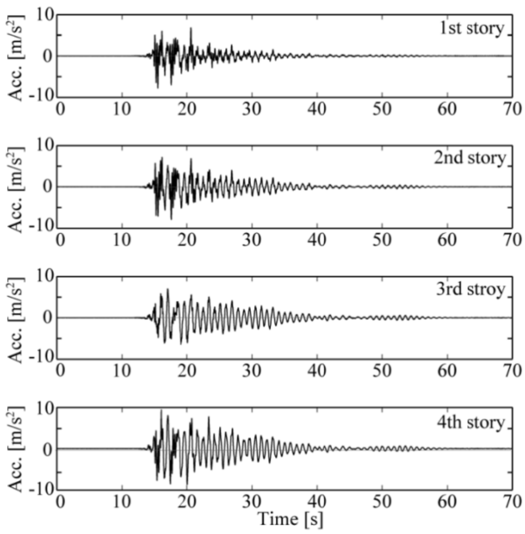


Fig. 5 Directly measured acceleration time histories

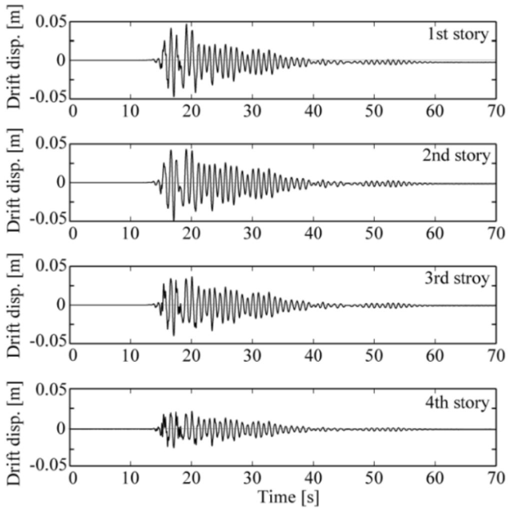
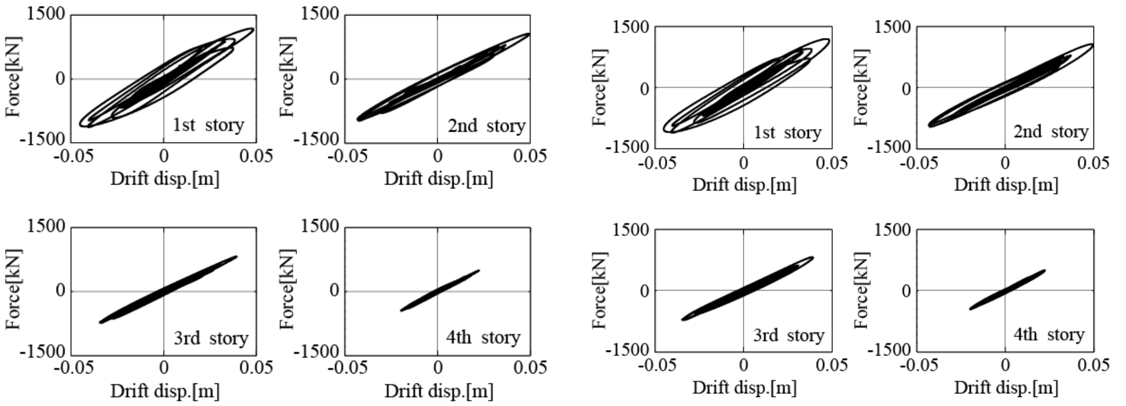


Fig. 6 Inter-story drift displacement time histories

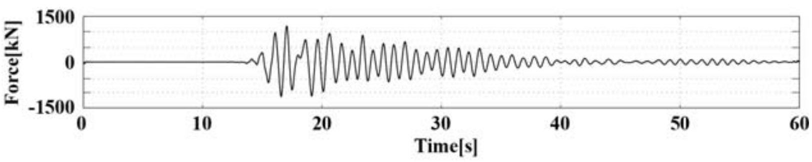
The hysteresis loops estimated by the proposed scheme are shown in Fig. 7(a). In calculating the differentiated acceleration from the displacement data, a low-pass filter of cutting the frequency components over four times the natural frequency of the model building has been applied twice: it is applied firstly to the measured drift displacement data and secondly to the calculated acceleration data. The estimated hystereses, shown in Fig. 7(a), are found to agree fairly well with the ones obtained from the combined use of the directly measured acceleration and displacement data, which are presented in Fig. 7(b). This agreement demonstrates that the presented scheme based on the drift displacement information works well in estimating the hysteresis loops.



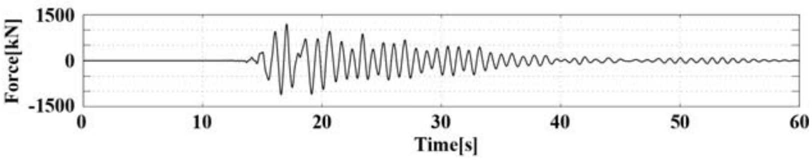
(a) Estimated hysteresis loops

(b) Hysteresis loops derived with measured acceleration data combined

Fig. 7 Comparison of story hysteresis loops



(a) From displacement differential-based calculation



(b) From measured acceleration data

Fig. 8 Comparison of shear force time histories

In addition to Fig. 7, Fig. 8 presents two kinds of time histories of the first story shear forces: (a) is obtained from the displacement differential-based calculation; and (b) is from the measured acceleration data. The two time histories are also in very good agreement, which indicates that the values corresponding to the hysteresis vertical axis is correctly estimated.

In the practical situation, unlike the full-scale model shake table test situation, even accurate story mass information is difficult to obtain. Most likely, there are some uncertainties involved in the mass information. The story mass contains live load values which are difficult to accurately evaluate in practice. In addition, it would not be a trivial work to obtain even the structural element mass values without any structural design documents available. Despite that, the estimating of story hysteresis loops herein is the step prior to estimating the story CPDRs. If accurate (or nearly accurate) *shape* of the hysteresis is obtained, CPDRs should be satisfactorily evaluated by Eq. (1). The errors in the story mass information affect only the vertical axis values in drawing the hysteresis loop but do not necessarily deform the hysteresis itself. This fact is significantly related to the calculating processes of CPDRs and will be specifically discussed in Section 5 which will conduct the numerical simulations of eight-story building.

5. Numerical simulations for story cumulative plastic deformation ratios

This section discusses the proposed scheme of deriving the cumulative plastic deformation ratios (CPDRs) for the purpose of story-based damage assessment. Based on the obtained story hysteresis loops, CPDRs are estimated by the scheme specified in 3.2. The presented scheme presumes no structural design specification document available, because it aims at a prompt judgment of how close to the dangerous limit a story would be soon after a seismic event. All the calculation processes could be computer-programmed from the data measurement to the calculation of story CPDRs. The available data are, as repeatedly mentioned, the inter-story drift displacement of each story and the ground acceleration. The hystereses during a seismic event are not likely to be as idealized as the purely theoretical situation. For instance, even the yielding force values corresponding to the yield displacement are not always the same in the practical case. With such a case accounted for, story CPDRs are estimated utilizing the four-story building experimental data of E-defense and conducting the numerical simulations of an eight-story model building.

Firstly, CPDRs are estimated based on the hysteresis loops for the full-scale model building experiment of E-defense obtained in Section 4. As far as the accurate values of yield displacements are concerned, the estimated hysteresis loops would not provide any information, in particular without the structural design specification documents. For this reason, CPDRs are herein calculated assuming that the yield displacement of each story is 1/130 of the story height. Fig. 9 compares the two results: one is calculated based on the hystereses obtained by combining the measured acceleration and drift displacement data for each story (indicated as “w/ story accel. data” in the figure) and the other is by using only the drift displacement data for each story (indicated as “w/o story accel. data” in the figure). The two results of CPDRs provide the similar tendency of which story is likely to be more severely or earlier damaged than other stories, although the two kinds of CPDR results have differences of about 0.5 for all the stories. The yield force values corresponding to the yield displacement are not always the same in this case, and thus the average value of them is employed in estimating the estimating CPDRs.

In conducting numerical simulations, an eight-story steel model building represented by a lumped mass model is employed. The model parameters are given in Table 1. It is assumed that the story heights are 3.5 m, and the initial and second yield displacements are, respectively, 1/130 and 1/100 of the story height for all the stories. Nonlinear seismic response analyses are conducted utilizing this lumped mass model (8DOF model). The damping proportional to the stiffness matrix is employed with a damping ratio of 2%. The drift displacements obtained by the simulation are regarded as the measured data of the drift displacement PSD sensors. The employed seismic inputs are El Centro NS component, Taft EW component and Hachinohe EW component with two kinds of peak acceleration values, 4 and 7 m/s^2.

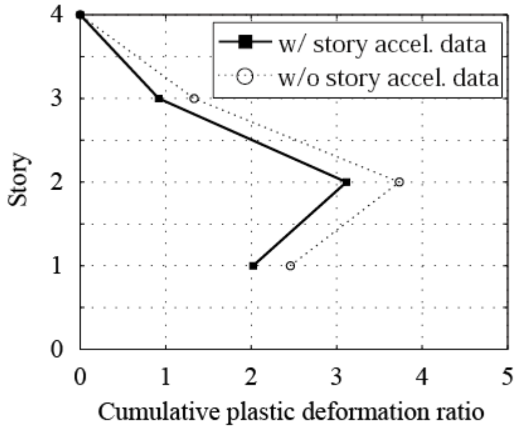
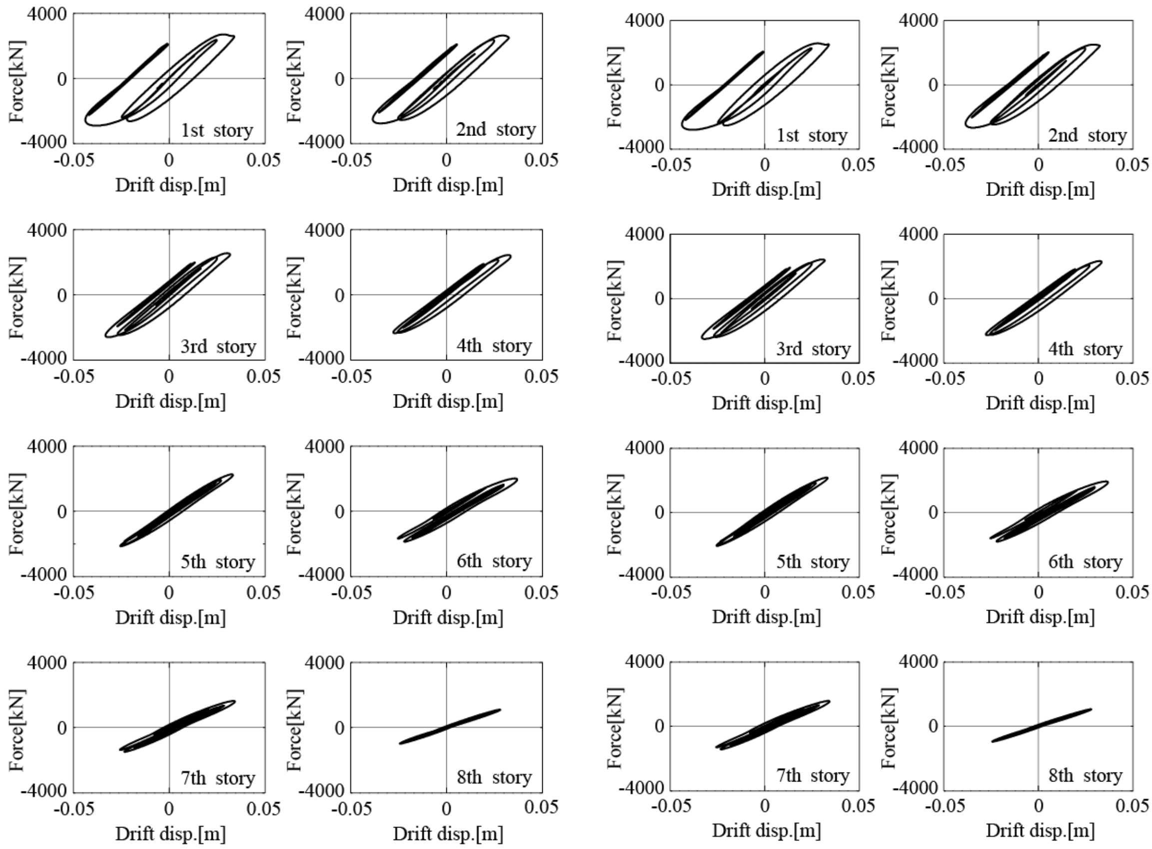
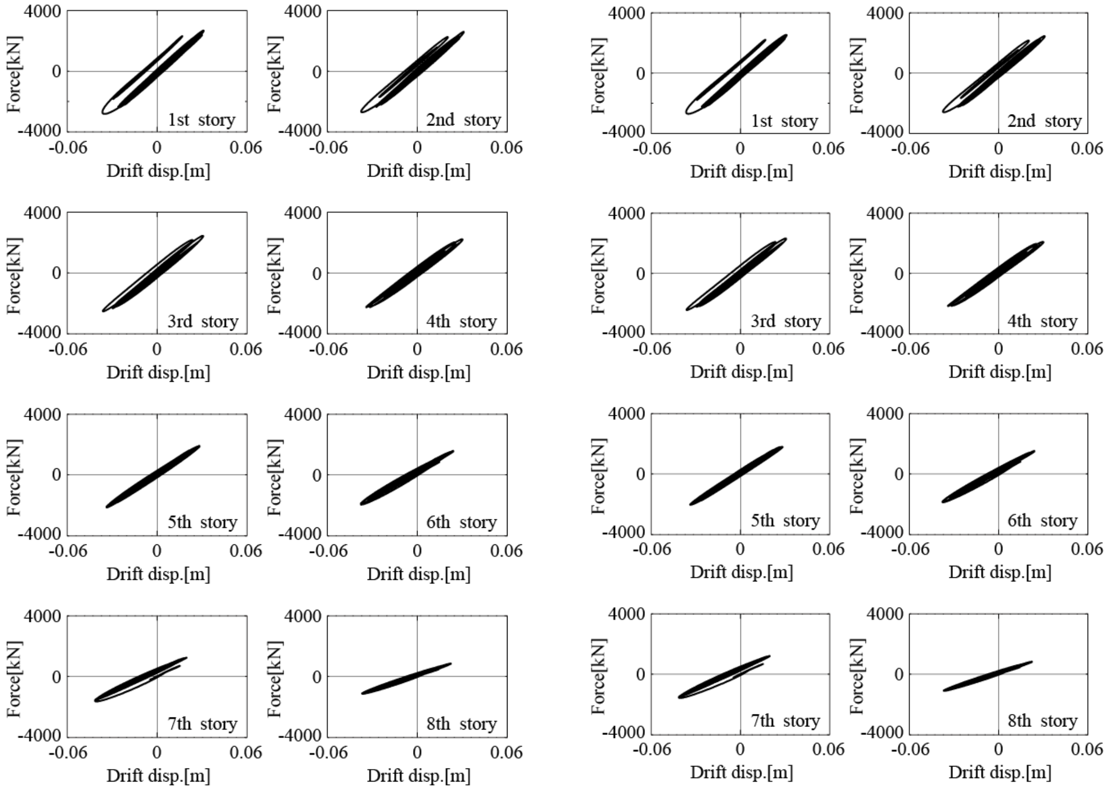


Fig. 9 Comparison between two CPDRs from actual and estimated hystereses



(a) Estimated hysteresis loops (b) Accurate hysteresis loops

Fig. 10 Comparison of story hysteresis loops for eight-story building (El Centro NS with peak acceleration of 7 m/s^2



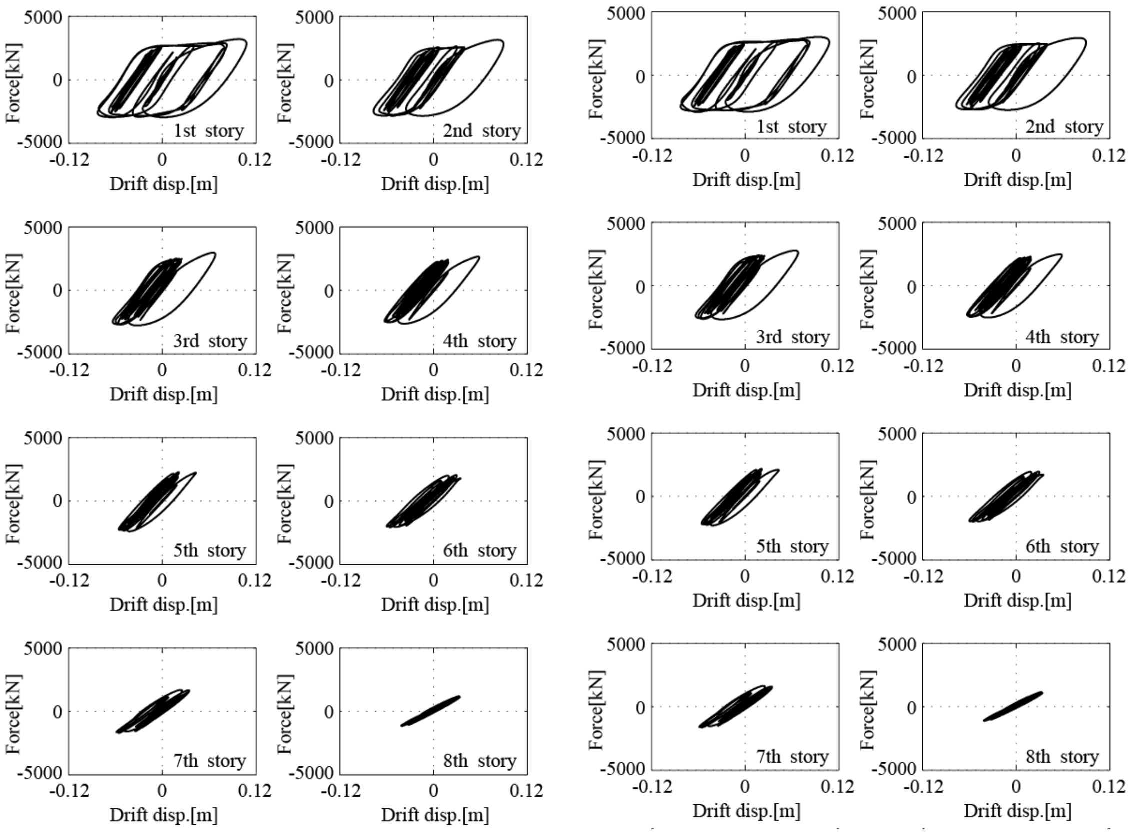
(a) Estimated hysteresis loops (b) Accurate hysteresis loops

Fig. 11 Comparison of story hysteresis loops for eight-story building (Taft EW with peak acceleration of 7 m/s^2

Figs. 10-12 compare the estimated and accurate hystereses for the case of three different seismic excitations with peak accelerations of 7m/s^2. The "accurate" loops are obtained using the simulated story shear forces and drift displacements. In calculating these estimated hysteresis loops, the measurement noises with S/N ratio of 26 dB have been added into the simulated drift displacement data. To those noise-added data, that low-pass filter explained in 3.1 has been applied.

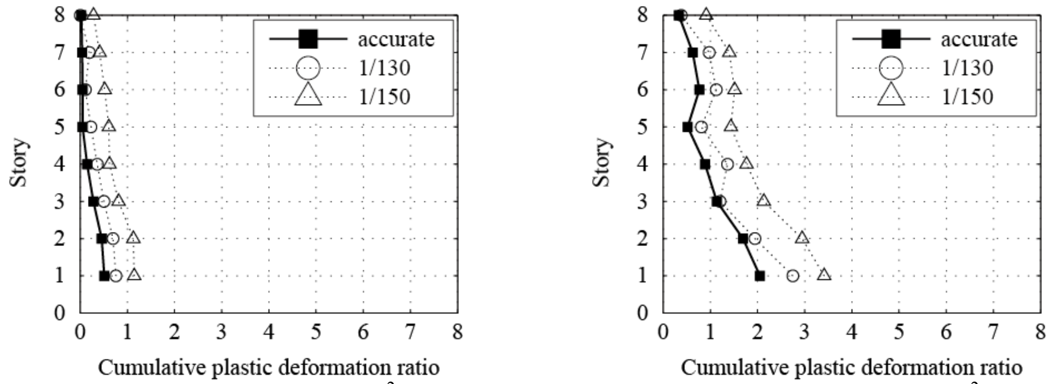
In estimating the vertical axis values for hysteresis loops, the story absolute acceleration data multiplied by the corresponding mass value are accumulated for the stories above the story in question. However, there is no established way for obtaining or estimating accurate story mass values in the real situation. With such a situation reflected, the mass values for all the stories are assumed to have the identical values of 550 t. These assumed mass values could bring about more or less deviated values from the right ones in the vertical axis for the hysteretic loop. From the CPDR estimation point of view, even in such a case, the absolute values on the vertical axis are not expected to affect the estimate of CPDRs very much as long as CPDRs are calculated as the ratio of hysteresis area to the product of yielding displacement and force. In other words, CPDRs could be estimated fairly well unless the shape of an estimated hysteresis is deformed. As far as the hysteresis shapes in Figs. 10-12 are concerned, the estimated hysteretic loops are in very good agreement with the accurate loops and even the vertical axis values for the estimated loops do not appear different from those for the accurate loops.

Figs. 13-15 compare the estimated and accurate CPDR values for the cases of El Centro, Taft and Hachinohe earthquakes, respectively, with peak accelerations of 4 m/s^2 in (a) and 7 m/s^2 in (b). These figures present two kinds of estimates for CPDRs based on Eq. (1): they set the yield displacements equal to 1/130 and 1/150 of the story height, respectively. The story shear forces corresponding to those displacements are regarded as the yielding forces in computing CPDRs with Eq. (1). The accurate data of yield displacements are not available in the practical situation, although the accurate results in Figs. 13-15 are obtained with them.



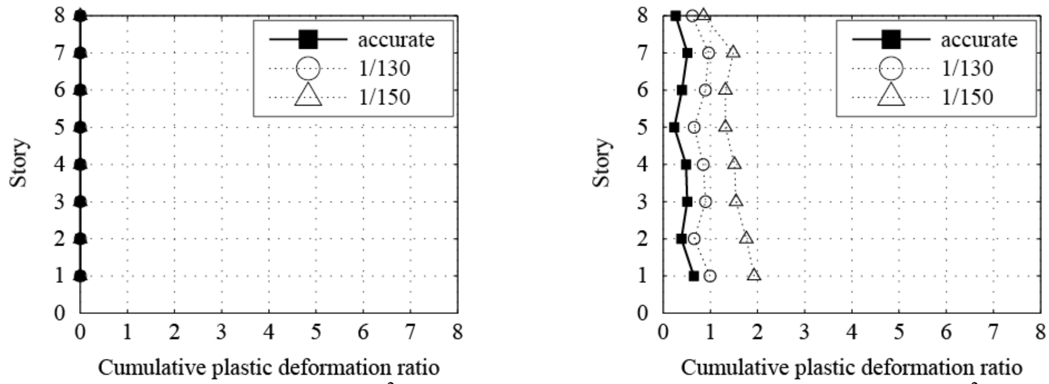
(a) Estimated hysteresis loops (b) Accurate hysteresis loops

Fig. 12 Comparison of story hysteresis loops for eight-story building (Hachinohe EW with peak acceleration of 7 m/s^2



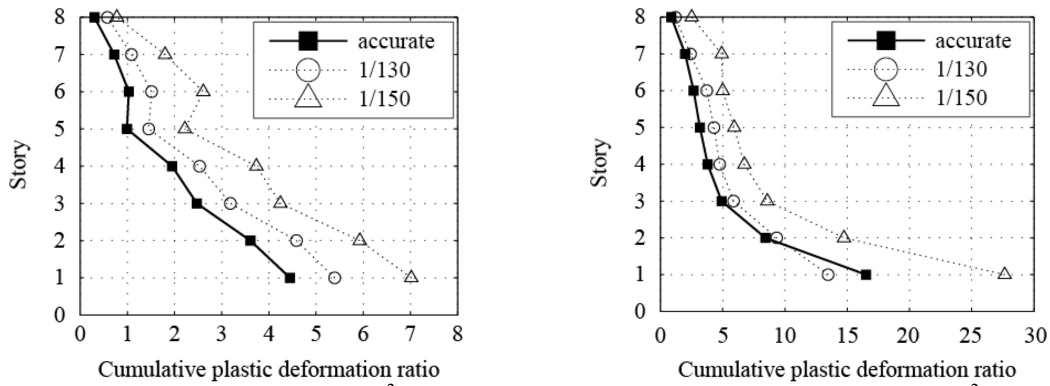
(a) Peak acceleration of 4 m/s^2 (b) Peak acceleration of 7 m/s^2

Fig. 13 Comparison of estimated and accurate CPDRs for El Centro excitations



(a) Peak acceleration of 4 m/s^2 (b) Peak acceleration of 7 m/s^2

Fig. 14 Comparison of estimated and accurate CPDRs for Taft excitations



(a) Peak acceleration of 4 m/s^2 (b) Peak acceleration of 7 m/s^2

Fig. 15 Comparison of estimated and accurate CPDRs for Hachinohe excitations

Figs. 13-15 indicate how CPDR values depend on the characteristics and magnitudes of seismic excitations. Every estimate of CPDR demonstrates the same tendency as the accurate CPDR. The absolute values of estimated CPDRs depend on how the yield displacement values are assumed. The smaller the yield displacement is assumed, the larger CPDRs become. For this reason, the estimated CPDRs are different from the accurate values but the estimated CPDRs provide the information on which story is likely to be more severely damaged, earlier damaged or have smaller margin to the ultimate limit than the other stories. It is said that the engineers should be concerned about the severe damage if CPDR is close to around twenty in general, although this critical value of CPDR is varied from case to case.

6. Conclusions

The authors' research group has developed direct measurement sensors of inter-story drift displacements. With these sensors the time histories of drift displacements can be obtained for a building structure. The sensors are of non-contact type and could be installed into an actually used building without occupying much space. Presuming the employment of these drift displacement sensors, this paper presents a rather simple yet effective scheme of estimating the story cumulative plastic deformation ratios (CPDRs) toward safety assessment. The indices of story CPDRs provide structural engineers with quite helpful information in judging the damage condition or remaining earthquake resistance capacity of the story soon after a seismic event. In this respect, the presented scheme could construct a "practicing engineers-friendly" framework.

The validity of the scheme has been demonstrated using the data of full-scale building model experiments performed at E-defense and conducting numerical simulations. The direct sensing of drift displacements has a great potential for constructing a new diagnosis schemes of building structures and for bringing a new paradigm-shift in the building structural health monitoring field.

Acknowledgments

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