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LASER BASED INTERSTORY DISPLACEMENT MEASUREMENT FOR STRUCTURAL HEALTH MONITORING OF TALL BUILDINGS

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ABSTRACT: Interstory displacement measurement is a critical parameter for monitoring the structural health and integrity of engineering structures. Several techniques are available to measure the interstory drift such as Global Positioning Systems (GPS), accelerometers, photosensitive detectors, LVDTs, etc. However, each of these methods has limitations in terms of accuracy, cost, installation, signal conditioning etc. A novel laser sensor based *in situ* interstory drift measurement setup is proposed in this study where the laser sensors are mounted in the structure to measure interstory drift. The laser beam is incident on an inclined reflector surface to measure vertical displacement. The reflector surface is mounted in the floor while the laser is mounted at the ceiling. The inclined surface is then used to measure the interstory drift which is essentially the difference between the floor and the ceiling displacement in a building during an event. Using this principle, laser sensors can measure horizontal movement in large structures. The novel method does not require any additional reference structure used in other laser based measurement techniques. Also, it is free from numerical errors present in acceleration based measurement. In addition to that, it is also not susceptible to urban canyon effect as in GPS based measurement system. The proposed laser based measurement setup is experimentally tested with reduced scale earthquake profiles. It was obtained that the proposed method provides the accuracy between 6-14% which is comparable with the traditional measurement systems.

1. Introduction

Structural health monitoring of civil infrastructures such as buildings, bridge piers, towers etc. are critical since the service lives of many of these structures have either passed or are very close to their end (Skolnik and Wallace 2010, Shan et al. 2011). The actual structural behavior of multistoried buildings may differ from their predicted behavior based on simple analytical or idealization assumptions (Hoi et al. 2013, Park et al. 2007). Additionally, the structures which have experienced a small earthquake event, may not sustain the designed earthquake limit at future events. To assess the structural integrity and serviceability of these structures during and after an event, some dynamic parameters such as vibration, displacement, maximum interstory drift ratios etc. should be carefully monitored (Hoi et al. 2013). One of the key parameters in structural health monitoring of buildings is to measure interstory drift (ISD) which can be an important indicator to the level of damage in a building after an earthquake. Also, based on the ISD ratio, the building can be classified as serviceable, safe or unsafe. Typically, according to the building code, the ISD ratio should not pass 2.5% (NRC 2005). In this article, a new measurement setup is presented to measure the interstory drift and results are compared with the existing techniques.

Acceleration based interstory drift measurement is a popular choice for assessing structural damages at different locations in buildings (Shan et al. 2011). One of the key reasons for this type of measurement is because of its easy installation of sensors. However, using this method is inaccurate due to physical measurement limitations. The double integration required for extracting position from acceleration produces errors for long term measurements (Skolnik and Wallace 2010). Hence, alternative measurements such as linear variable differential transducer (LVDT), global positioning system (GPS), and laser based measurements are also investigated by researchers to reduce measurement error (Hoi 2013, Park et al. 2007, Chen et al. 1998). Skolink et al. used LVDTs to measure interstory drift and compared his technique with acceleration based displacement measurements (Makarios 2012). The limitations of LVDT measurements are: 1) difficult setup, 2) slack in wire and 3) inaccurate small displacements (Skolnik and Wallace 2010, Makarios 2012). Celebi et al. (2004) applied global positioning systems (GPS) to obtain the drift ratio of structures (Skolink et al. 2008). However, the cost associated with GPS based measurement increases with the level of accuracy desired. In addition to that, the GPS based technique suffers due to obstructed signal transmission, low data sampling rate, satellite visibility, and GPS data processing effects. In addition to that, GPS installed at the lower levels of tall buildings are affected by 'Urban Canyon effect' where the GPS signal is obstructed due to neighboring tall buildings (Matsuya 2010). Dai et al. developed a rapid measurement method to compute the horizontal drift using Augmented Reality (AR) visualization, GPS and photogrammetry surveying techniques (Makarios 2012). They developed a close-range photogrammetry algorithm to obtain spatial information from images and calculated the interstory drift geometrically to measure damages of buildings. This method suffers from the same problems as mentioned in GPS measurement such as 'Urban Canyon effect' as well as the error in camera lens correction to calibrate the displacement with the image processing. Laser based displacement sensors are often used to measure the interstory drift in vibrating structures where the laser sensors are mounted on a reference frame shown in Hoi et al. 2013. Although, this method provides accurate measurement of interstory drift, it requires a reference frame to mount the laser sensors. This limitation restricts the use of laser sensors in lab based measurements only.

Table 1 – Comparison errors between various methods

Methodology	Comparison with	Maximum error (%)	Reference
PSD	Laser distance meter	15%	Matsuya et al. 2010
Phototransistor Array	Actual displacement	9%	Kanekawa et al. 2010
LVDT	Local measured acceleration	20%	Skolnik et al. 2008
Terrestrial Laser Scanning	Strains measured	10%	Park et al. 2007
Photogrammetry Assisted Measurement	Actual displacement	14%	Dai et al. 2011
Laser crosshair projection	Micro-positioning stages	12.5%	Bennett et al. 1996

Matsuya et al. (2010) proposed the sensor system with three LED sources mounted on the ceiling and three position sensitive detectors (PSDs) with focusing lenses mounted on the floor to calculate relative interstory displacement and the local inclination angle (Celebi et al. 2004). The lenses assist in focusing the LED into a particular element of PSD. When the LED is displaced, the PSD generates voltage signal related to the change in ceiling displacement. Similarly, for inclination another pair of LED/PSD is used. Although, the proposed system provides both inclination and displacement with the LED/PSD pairs, the practical implementation of this method is yet to be proven (Matsuya et al. 2010). Kanekawa et al. proposed a sensor system including a laser light source, a photo scattering plate and a phototransistor (PT) array to measure the relative inter-story displacement of building structure (Li et al. 2013). The system was assessed experimentally with a shaking table. The method shows that for low frequency (≤ 5 Hz), the relative error is negligible. However, the performance degrades with higher frequency (>10 Hz).

A new method was developed using laser crosshair projection on four PSDs to obtain interstory drifts in building (Bennett and Batroney 1996). A prototype system was constructed to evaluate the accuracy and practicality of the purposed method. In comparison with LVDTs, this method is less complex, more cost-economic, and more immune to measurement noise. However, the method was not tested under real earthquake simulations. In summary, the errors obtained from various methods have been illustrated in Table 1. Overall, the range of relative error is in between 9% and 20% for various techniques.

2. Laser based in situ measurement technique

Typically laser based measurements detect the distance/displacement to a target plate that moves perpendicular to the laser beam as shown in Fig.1. Depending on the type of laser measurement employed, either absolute displacement, q, or relative displacement Δq of the target plate attached to the moving body is obtained. To implement this displacement measurement technique, laser sensors are usually mounted on a stationary reference frame. Although it is a common practice to use a reference frame to measure the ISD, this is not practical in a number of civil engineering applications such as interstory drift measurements, bridge pier displacement measurements etc.

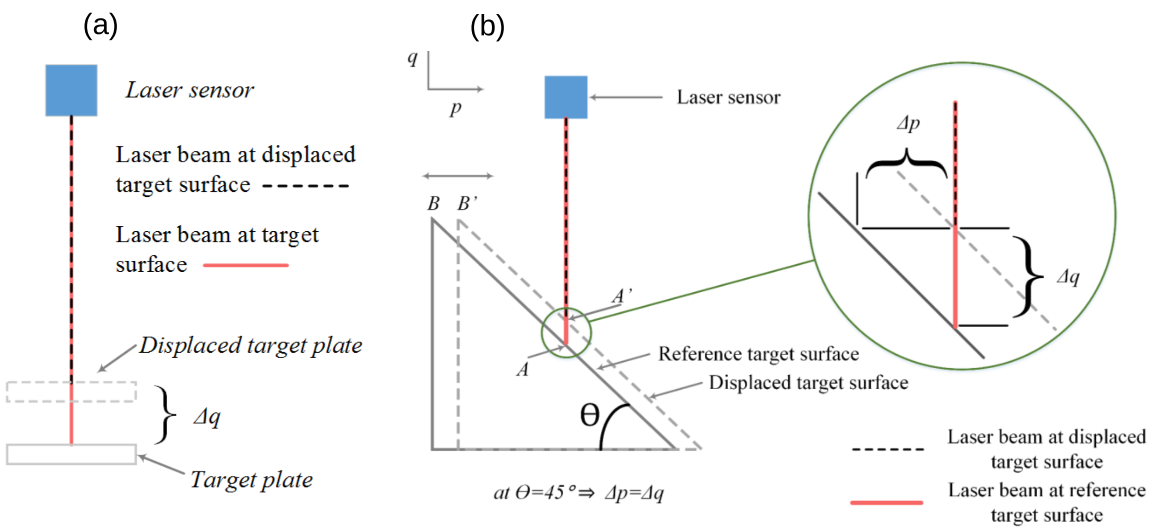

Figure 1(a) Traditional laser based displacement measurement (b) Proposed laser based displacement measurement

In this article, a new *in situ* laser based displacement measurement technique is presented. This measurement setup eliminates the requirement of a rigid stationary frame which is required for the traditional laser measurements. Fig.1(b) demonstrates the principle of this *in situ* laser based displacement measurement. Instead of a flat target plate, an inclined surface is proposed in the measurement setup. The inclined surface has the following benefits: 1) it can be used as a mechanical lever to amplify the displacement, and 2) it allows a 90° rotation between the direction of movement and direction of the laser based measurement. Due to the second benefit, the requirement of a stationary reference frame is eliminated and an *in situ* measurement is made possible. Fig.1(b) shows that the movement of the target surface in p direction from B to B', leads to a change in the point of reflection from A to A' in the q direction. The laser measures the change in the q direction due to the target surface movement in the p direction. The angle of the target surface can be adjusted to amplify the displacement. The relation can be found as follows:

$$\Delta q = \Delta p \times \tan \theta \qquad (1)$$

where, θ is the angle of inclination of the target surface. For an equal displacement in both p and q direction, $\theta = 45^{o}$. For example, to amplify the displacement in the q direction by 2 times, the value of the $\theta = 63.44^{o}$.

3. In Situ Interstorey Drift Measurement

In this section, an *in situ* interstory drift measurement setup is proposed based on the principle discussed in the previous section. Interstory drift can be defined as the difference between the displacements of two consecutive floor levels due to the base displacement of the structure (Skolnik and Wallace 2010). For example, to measure the ISD between level 3 and level 2, individual displacement of each level 3 and level 2 are measured and subtracted from each other. The interstory drift between level 3 and level 2 is denoted as ISD_{23}. Traditional laser based interstory drift measurement setups require a reference frame to mount the laser sensors to. Displacement of each level is measured using a dedicated laser sensor and a subtracted value provides the interstory drift of two subsequent floors as shown in Fig.2. This measurement procedure is reasonable for a small scale frame in a lab environment. However, for a large full scale building, constructing a reference frame is not practical. In addition, the reference frame will not stay stationary during events such as earthquakes or strong winds.

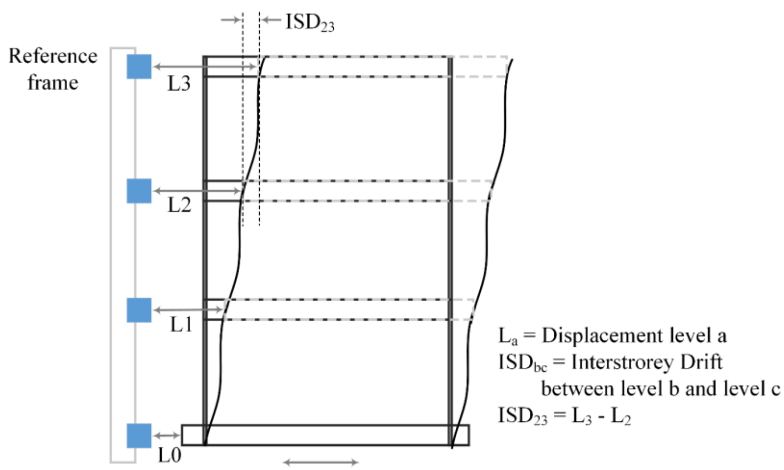

Figure 2: Traditional measurement of interstory drift

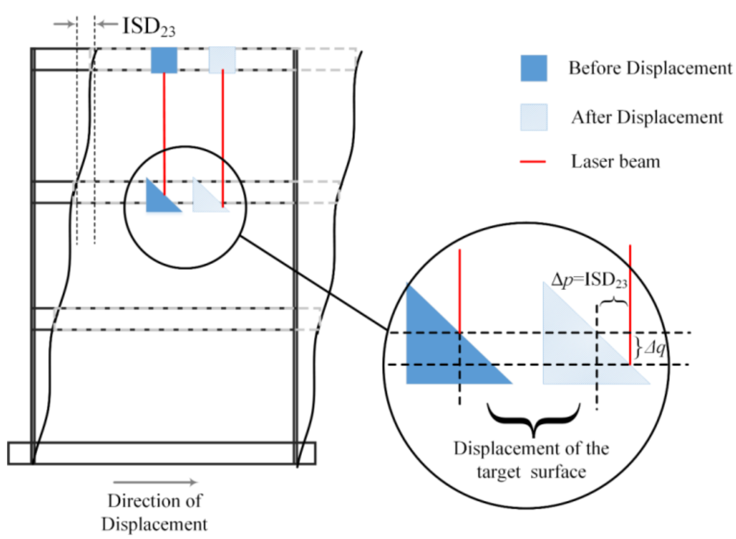

Figure 3: Proposed measurement of interstory drift

4. Experimental Setup

To experimentally validate the proposed technique, a scaled model (1:15) of a three-story, two-bay aluminum building frame was constructed and tested under simulated earthquake ground motion. A biaxial shake table was used to excite the base of the building. The shake table has two motors connected to a lead screw. The base is rested on the frame which is connected to the lead screws in both x and y direction. The table positions in both the directions are measured using encoders and used for feedback control. The shake table velocity and the overall distance traveled in the x and y directions are the limiting factors to provide a real earthquake motion. As a result, the Northridge and Kobe earthquake profiles were scaled for the shake table input as shown in Fig.4. Displacement input profiles were created from the earthquake acceleration profiles and used as inputs for the shake table. The reference input earthquake displacements are verified with the position encoder values. Matlab/Simulink environment was implemented to operate the shake table using the DSpace real-time interface. The table parameters are presented in Table 2.

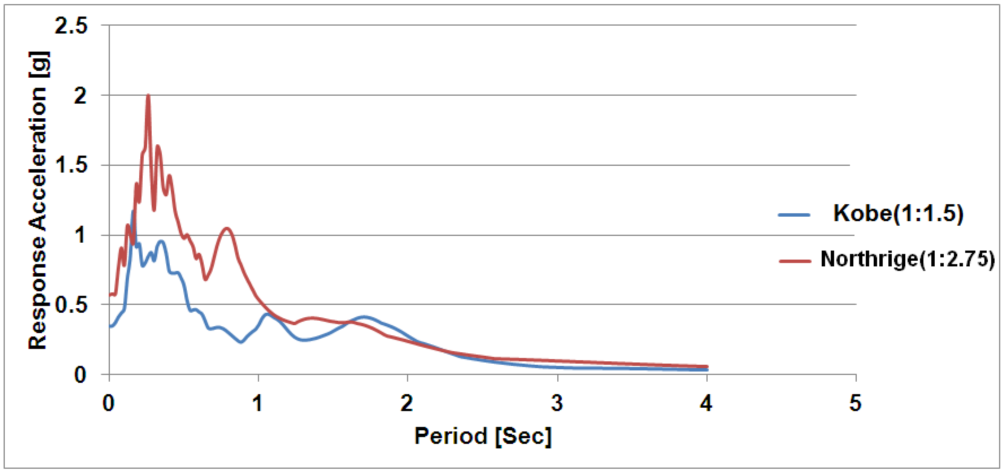

Figure 4. Ground motion spectra for y- and x-directions for Kobe and Northridge earthquakes used

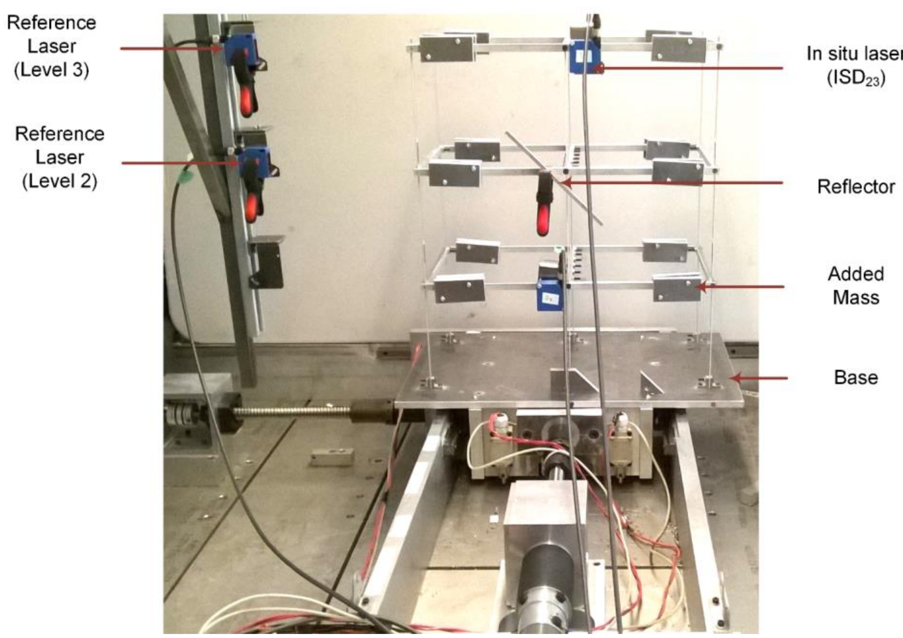

Figure 5. Experimental test setup with shake table

The frame was built with thin columns and thick beams to mimic the rigid floor motion. Additional masses (1 kg) were attached in each level to facilitate larger displacement. The base plate of the frame is rigidly attached to the shake table. Fig.5 presents the frame and the shake table. Two reference laser sensors (Wenglor CP35MHT80) were used to measure the interstory drift using the traditional method (shown in Fig.2) while one *in situ* laser sensor was used to measure the displacement using the proposed setup (Fig.3). In the results section, the reference laser measurement is compared with the *in situ* laser measurements and the % error of the proposed setup is presented with respect to the reference measurement. Table 3 provides the parameters of the aluminum frame under test.

Table 2 – Shake table parameters

Parameters	Value	Units
Travel in X-direction	720.34	mm
Travel in Y-direction	491.74	mm
Lead screw pitch	6.35	mm/rev
Peak Acceleration in X and Y axis	2.2	g
continuous Acceleration in X and Y axis	0.29	g
Max velocity	8890	mm/min

5. Results

The interstory drift measurements are calculated using the reference laser sensors and *in situ* laser measurement setup. The drift is calculated from the difference in the displacement of two consecutive levels. The *in situ* laser based measurement setup directly measures the interstory drift. The error percentage is calculated from the difference between reference measurement and *in situ* measurement. Eq.(2) presents the interstory drift calculation from the absolute displacement of the levels as follows:

$$ISD_{23ref} = abs(L_3 - L_2) \qquad (2)$$

where $ISD_{23\ in\ situ}$ is the interstory drift between level 2 and level 3 and L2 and L3 are the absolute displacement of the levels. The percent error calculation between the traditional and proposed method is shown is Eq.(3).

$$\mathrm{error}_{23(\%)} = \frac{ISD_{23ref} - ISD_{23\ in\ situ}}{\mathrm{MAX}(\mathrm{abs}(ISD_{23ref}))} \times 100\% \qquad (3)$$

where, $ISD_{23\ in\ situ}$ is the interstory drift measurement using *in situ* laser measurement setup.

Table 3 – Small scale (1:15) frame parameters

Parameters	Value	Units
No of columns	6	mm
Heights of each floor/bay	200	mm
Width of each bay	250	mm
Width of the building	500	mm
Breadth of the floor	200	mm
Width of the column	12.74	mm
Thickness of the column	1.6	mm
Base plate area	625*250	mm^2
Mass at each level	1	kg

The experiments are divided into two parts: 1) free vibration tests 2) simulated earthquake tests. In the free vibration test, the top of the building is provided with some initial displacement and released. The reference laser sensors provides the displacement of each individual level shown in Fig. (1) using Eq.(2). The newly proposed in situ laser sensors setup measures the ISD [as shown in Fig. (3)]. Fig. 6 presents the ISD response of the building along with the error percentages. The percentage of error is calculated using Eq. (3). The error percentages are 5.23%, 8.5% and 10.18% for ISD_{01}, ISD_{12} and ISD_{23}, respectively.

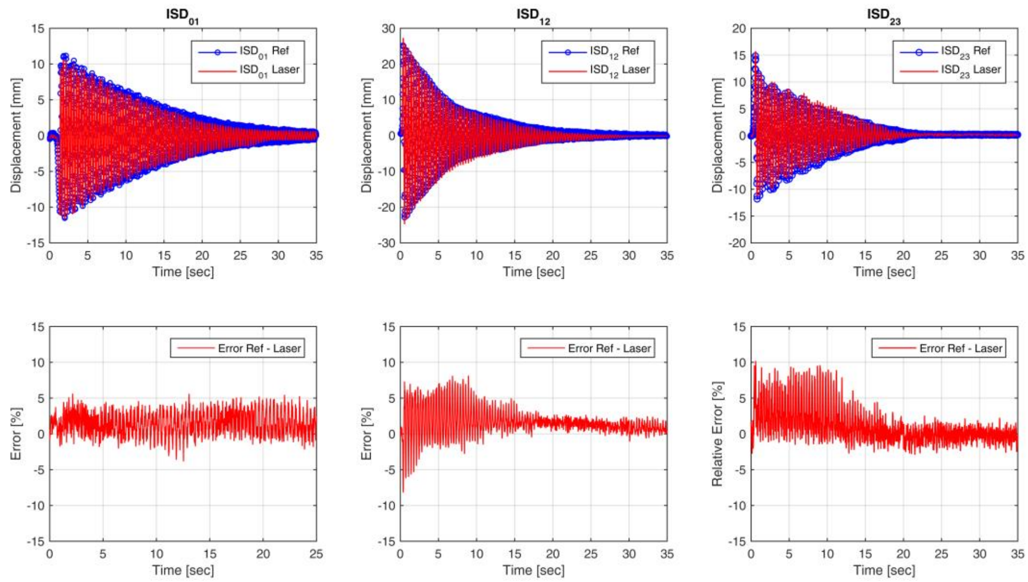

Figure 6: Free vibration tests for different levels and the error between reference measurement and laser based *in situ* measurement

Table 4.shows the maximum absolute errors (%) for the different initial displacements of ISD_{23}. It is noticed that overall errors decrease with increasing initial displacements. It started from 12% at 10.5 mm initial displacement and ended to 4.1 % for 45 mm. This table also illustrated the maximum ISD_{23} from 2.8 mm to 9.9 mm with respect to initial displacements.

Table 4 – Maximum absolute errors (%) for different initial displacements of ISD_{23}

Initial Displacement (mm)	Maximum ISD (mm)	maximum abs error (%) in ISD_{23}
10.5	2.8	12
22.22	5.1	4.8
29.5	6.6	5.8
37	9.1	4.5
45	9.9	4.1

For the simulated earthquake tests, the building frame is also tested with Northridge and Kobe earthquake motions using the shake table. Similar to free vibrations tests, *in situ* laser based ISD measurements are compared with reference laser based ISD for each level. Eqs. (2) and (3) were used to calculate error percentage for each of the earthquake profiles. The responses for both the measurements and the errors are presented in Figs. 7-8. Different parameters such as alignment of *in situ* laser sensors, reflector angle, resolution of the laser sensors etc. affected the errors and ISDs. Five sets of data have been collected for each levels and type of earthquake profiles experimentally in order to show the statistical deviation in the test results. Absolute maximum error (MAE) and the standard deviation (Std. Dev.) of the measurements for different ISDs are listed in Table 5. It shows that the maximum error occurs at minimum interstory drift at ISD_{23}. The error decreases with increasing values of ISD at other levels such as in ISD_{01} or ISD_{12}.

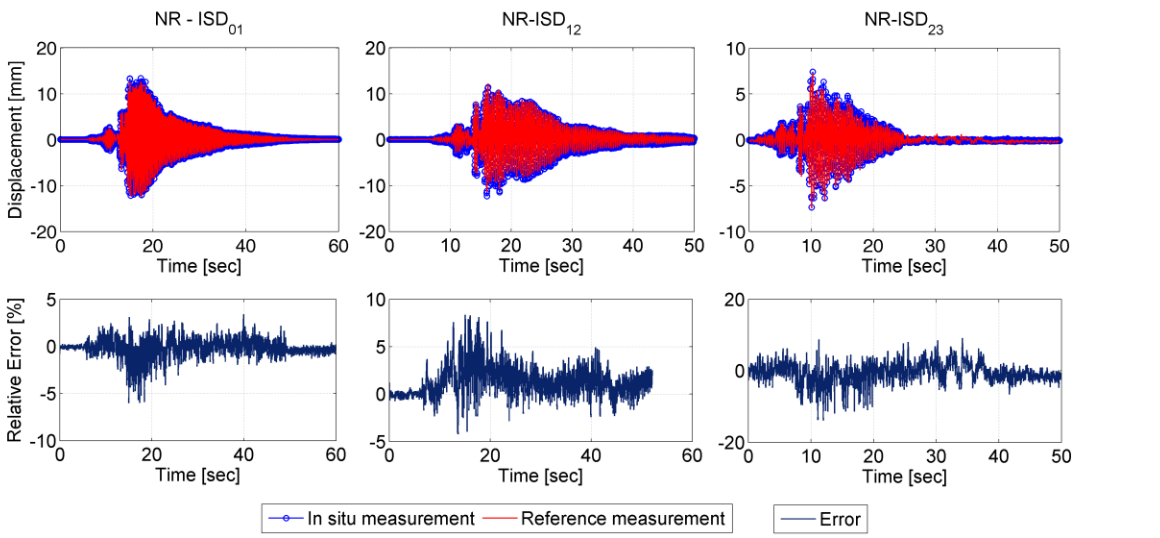

Figure 7: Interstory drift measurement at different levels under simulated Northridge earthquake

Table 5 – Percentage of error with respect to maximum ISD

Earthquake	ISD	Max ISD (mm)	Avg. MAE(%)	Std. Dev. Of MAE(%)
Northridge	ISD_{01}	12.88	7.34	0.68
	ISD_{12}	12.06	8.92	0.71
	ISD_{23}	7.73	14.21	1.02
Kobe	ISD_{01}	21.69	8.72	0.62
	ISD_{12}	17.37	8.27	1.09
	ISD_{23}	10.44	10.53	1.01

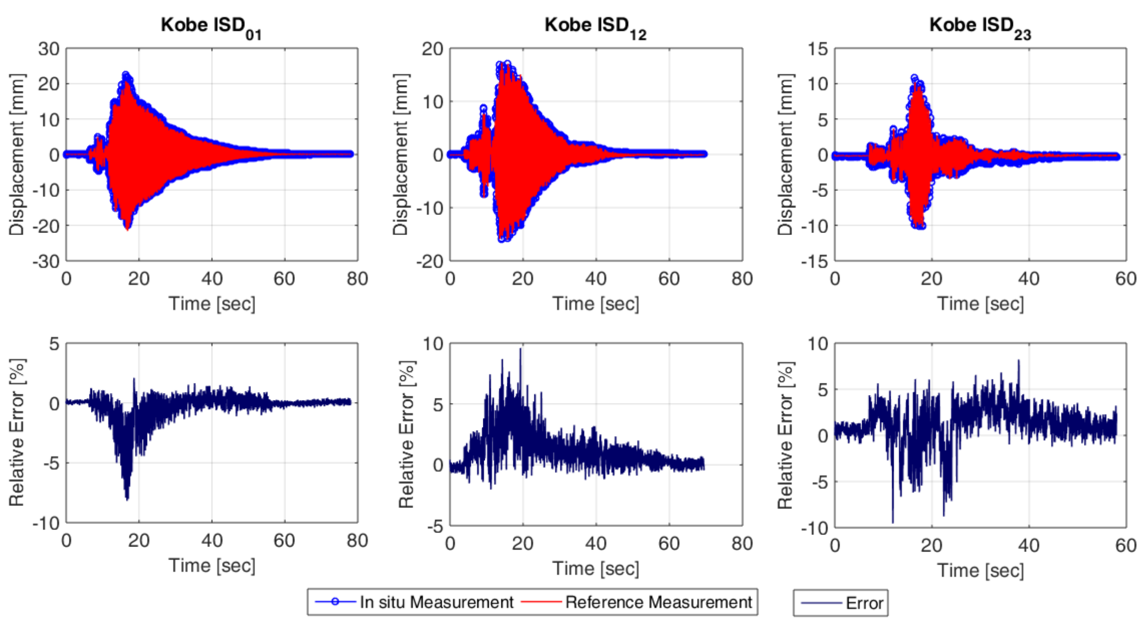

Figure 8: Interstory drift measurement at different levels under simulated Kobe earthquake

The errors are compared in Fig. 9 for both the earthquakes at different interstory drift levels. The trends show that the errors (%) increase with the decrease in the interstory drifts. It is noted from the Table 5, that the maximum interstory drifts occur at lower levels (ISD_{01} and ISD_{12}) where the error is small in comparison to higher levels (ISD_{23}). This is related to the accuracy of the laser sensors used in these tests. The resolution of the laser sensors is close to 0.05 mm which results in a minimum error of $\pm$0.05mm. Since the error percentages are obtained from the maximum ISD at each level due to the earthquake tests, they are dependent on the magnitude of ISD at each level.

In real civil structures, the interstory drift is at least three times larger than the obtained results in the tests. Hence, it is expected that for real applications, the errors of the interstory drift measurements will decrease. The results of the proposed measurement setup compares well with the other proposed methods shown in Table 1.

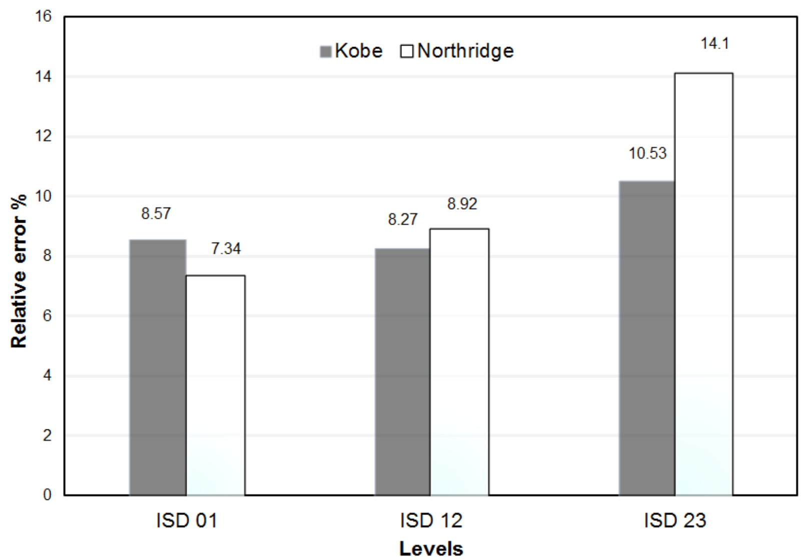

Figure 9: Error comparison among different levels at simulated earthquake ground motions

6. Conclusions

In the paper, a new method to measure the interstory drift in tall buildings is presented based on *in situ* laser sensors. An inclined reflecting surface is attached to the floor of one level while the laser sensor is mounted to the ceiling. The vertical displacement at the reflector surface due to the horizontal movement in the structure is cor related to the horizontal displacement of the floor in the building. The real-time earthquake response of each floor can be used to interpret the structural integrity at a post-earthquake event. The percentage errors obtained falls in the range of 6-14%. This is due to the limitation in the level of accuracy of the laser sensors used in the experiments. More accurate laser sensors will improve the ISD measurement. Also, the trends shown in the test results suggest that for large of displacements, the percent error becomes smaller. Hence, for real structures, in the presence of large interstory drift, the percent error will be smaller. The proposed technique can also be used to measure drift in bridge piers, windmills and other tall structures where drift measurement is challenging. In the future, the authors plan to implement these sensors in a full scale frame to measure the interstory drift for structural health monitoring and its algorithm development.

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