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A CRITICAL ASSESSMENT OF INTERSTORY DRIFT MEASUREMENTS

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ABSTRACT

Interstory drift, the relative translational displacement between two consecutive floors, is an important response quantity and indicator of structural performance. The structural engineering community would benefit well from accurate measurements of interstory drift, especially where structures undergo inelastic deformation. Unfortunately, the most common method for obtaining interstory drifts; double integration of measured acceleration, is problematic. Several issues associated with this method (e.g., signal processing steps and sparse instrumentation) are illustrated using data from shake table studies and an extensively instrumented building. Some alternative contact and non-contact methods for obtaining interstory drift are then presented.

Introduction

Interstory drift ratio (IDR), defined as the relative translational displacement between two consecutive floors divided by the story height, is an important engineering demand parameter and indicator of structural performance. Several aspects of structural engineering would benefit well from accurate measurements of IDR, especially for structures undergoing inelastic deformations. One particular area, for example, lies in the intersection of structural health monitoring (SHM) and performance-based earthquake engineering (PBEE), such as the PEER (Pacific Earthquake Engineering Research) methodology. The primary goals of SHM are to detect damage before it reaches a critical state and to enable rapid post-event assessment. PBEE provides the potential framework to establish these goals through monitoring key response quantities, like IDR (Naeim and Hagie 2005 and Celebi 2004). Unlike classical SHM which might track changes in modal and/or model parameters (via system identification and/or model updating), performance-based SHM addresses key uncertainties like nonlinear responses, which are inherent in the empirical nature of fragility functions. Fragility functions, from within the PEER methodology, are used to quantify uncertainty associated with response-damage relationships by mapping engineering demand parameters (EDPs) to damage measures (DMs). In turn, DMs are empirical parameters describing the level of damage in structural or non-structural components (e.g., concrete cracking). It is clear that understanding the EDP-DM relationship for a given assembly is fundamental to successful implementation of performance-based SHM. It turns out that IDR is by far the most common EDP in currently available and proposed fragility functions (FEMA-445 and ATC-58). This stems from the fact that IDR has been shown to correlate best (as compared to other response quantities) with observed damage of structural and some non-structural components (Algan 1982).

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In design, limits on IDR are used to ensure structural performance at acceptable deformation levels by limiting p-delta affects and damage to non-structural components. Story drift limits, such as those imposed by IBC 2006, are based on consensus judgment aimed towards a reasonable measure of safety required so that seismic elements can perform as expected. This becomes especially important in some cases, such as tall buildings and/or flexible moment-resisting frames, where drift limits, as opposed to the usual strength-capacity ratio, often control structural designs. In linear elastic design procedures, story drift limits are applied to elastic design drifts that are amplified based on the structural system to account for inelastic deformations. Measurements of IDR within the nonlinear range can provide validation of code amplification factors and their applicability over various structures. For nonlinear design procedures, no deflection amplification is needed and the drift limits are somewhat relaxed, especially for tall buildings. Again, measurements of IDR within the nonlinear range can provide validation of these code prescriptions that are as of now, based on engineering judgment and experience.

By far the most common method for experimentally obtaining full-scale IDR is by numerically integrating acceleration data, twice. One reason for this is the robustness of accelerometers and the widespread availability of acceleration data provided by large seismic networks such as the California Strong Motion Instrumentation Program (CSMIP). Unfortunately, there are a host of issues present in this process which are described in the next few sections.

Interstory Displacements from Acceleration Data

The path from measured acceleration to interstory displacements; Fig. 1, contains several processes, some of which can be subjective. The major steps described here include; double numerical integration, static condensation, and if necessary, interpolation.

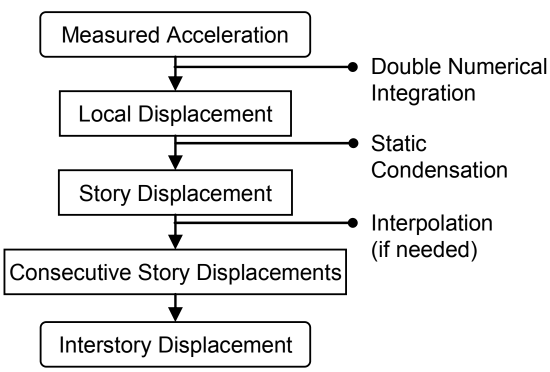

Figure 1. Signal processing steps.

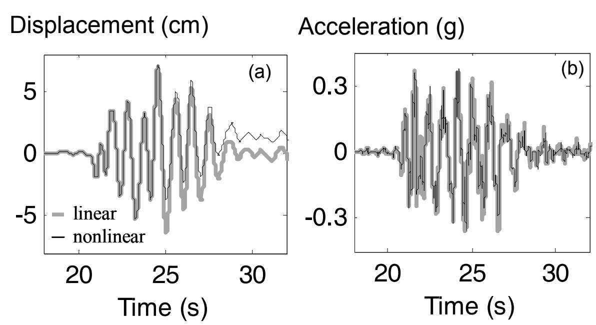

Figure 2. Displacement (a) and acceleration (b) time histories.

Double Numerical Integration

Obtaining displacements by double numerical integration of measured acceleration requires several delicate and sometimes subjective signal processing steps such as baseline correction, zero-padding, and band-pass filtering. Various SMIP agencies have established specific guidelines with respect to the order and extent that these steps be applied to both ground and structural accelerations (COSMOS 2009).

The first step is to improve the overall signal quality. This is achieved by a few well established sub-steps including initial baseline correction and low-pass filtering. Raw data are inevitably noisy and often have some nominally constant offset. Initial offsets are removed by subtracting the pre-event mean from the entire signal. Low-pass filtering is then applied to reduce the amplitude of noise typically present within a high frequency bandwidth. The benefit of low-pass filtering, effectively increasing the signal-to-noise ratio (SNR), should be balanced against the inevitable decrease in signal amplitude.

Beyond the initially constant one, smaller indiscernible baseline shifts in acceleration histories are exposed by numerically integrating to velocity and noting long-period drifts. These baseline shifts, which are generally not constant, have been attributed to many sources such as electrical and mechanical hysteretic effects (Iwan 1985), sensor misalignment and cross-axis effects (Wong and Trifunac 1977), tilt effects (Boroschek and Legrand 2006), and the quantization errors (Boore 2003). Usually, the offsets are small and high-pass filtering is sufficiently effective in their removal. In some cases, tailored corrections may involve piecewise fitting of polynomials to velocity traces and then subtracting the derivatives of these fits from the acceleration time series (Boore 2002). High-pass filtering is probably the most important step in processing strong-motion data. In preparation for this step, signal ends are conditioned by adding a pad of zeros to accommodate filter transients. In general, filter types and parameters (e.g., cutoff frequency) are chosen by trial-and-error and visual inspection of ensuing displacements. Special consideration is required when selecting filters that may induce phase delays which may devastate the synchronization of multiple channels. Another important issue stems from physically sound drifts and/or residual displacements. High-pass filtering is applied to remove suspect drifts in displacement histories, but some structures, such as base isolated and those undergoing inelastic deformations are expected to have some residual displacement.

To illustrate these issues, a simple test is performed using a shake-table in which displacement histories with and without a residual displacement are measured along with accelerations using three different commercially available accelerometers. The goal is to investigate the sensitivity of the displacement histories obtained via double numerical integration to the various required signal processes. Using three different transducers allows for the demonstration of how some signal processes are extremely sensitive to the individual signal acquired. In other words, we show how the same acceleration history simultaneously acquired by different high-quality transducers yield different displacements. Accelerometers used in this study include Kinemetrics' force balance accelerometer (ES-U), Measurement Specialties silicone MEMS-based (4000A), and PCB Piezotronics capacitive-based (3703G2FD3G). A 16-bit multiplex digitizer from National Instruments Inc. is used to sample (at 1kHz) and record data. In the interest of fairness, the effective resolution of each accelerometer/digital-channel is set to the same value of 30μg or 16bits over ±1g. The displacement response of a linear-elastic and inelastic-perfectly-plastic single degree of freedom structure to a scaled (in amplitude) 1994 Northridge record (CDMG station 24514) is simulated using a Newmark integration time-stepping method. The linear system has a fundamental period of 1s and a damping ratio of 5% of critical and the non-linear system has a yield force of 15% of the seismic weight. The measured linear and nonlinear displacement and acceleration histories are displayed in Figs. 2a & 2b.

As noted earlier, the first step in post-processing aims to improve signal quality by removing the pre-event mean and applying a low-pass filter. Fig. 3a shows the first few seconds of measured acceleration (without mean removed) and the corresponding root-mean-square (RMS) amplitude of noise (with mean removed) before and after applying a 4^{th} order 25Hz low-pass zero-phase Butterworth filter. Note the difference in quality of the signal for the various sensors. The best of the three studied here being the Kinemetrics uniaxial EpiSensor (ESU) with an initial RMS noise amplitude of 421μg reduced to 58μg after filtering. The observed noise likely comes from multiple sources including electrical (radio interference) and mechanical (shake table hydraulic system). Decreasing the cutoff frequency would further decrease the RMS noise amplitude, but at some point, the overall signal amplitude would begin to suffer. This can be seen by zooming-in near a local peak as in Fig. 3b where, even with a cutoff frequency of 25Hz, it may be argued that some signal content is being smoothed out.

The next step is high-pass filtering to remove baseline shifts in the acceleration that lead to long period drifts in velocity and displacement histories, Figs. 4a & 4b. It is immediately obvious that these histories, which are linear and thus should start and finish at zero, are not correct. As mentioned earlier, the selection of filter type and parameter is somewhat subjective. Here, we focus on the cutoff frequency of a 4^{th} order zero-phase Butterworth filter. Nominal cutoff frequencies are selected by comparing the resulting displacements to the measured displacements in Fig. 2a. Fig. 5a shows the SNR, defined in Eq. (1), of the resulting displacement histories

$$SNR = 20 \log (RMS_{sig} / RMS_{err}) \quad (1)$$

where RMS_{sig} and RMS_{err} are the RMS values for the signal and error. The nominal cutoff frequencies correspond to that which maximizes the SNR. As expected, the ESU accelerometer provides the highest SNR; nearly 40dB, which is equivalent to a noise amplitude that is just over 1% of the signal amplitude. The MEMS accelerometer achieves 20dB, or amplitude of noise that is 10% of the signal. The nominal frequencies range from 0.1 to 0.3Hz and appear to be inversely proportional to noise amplitude. This can also be seen in Fig. 5b which depicts the FFT of the unfiltered (dotted lines) and band-pass filtered accelerations – recall high-pass filter (25Hz) was applied earlier. This figure also depicts the sensors' susceptibility to whatever it is that causes the baseline shifts. Of the likely causes mentioned earlier; hysteretic effects, sensor misalignment, cross-axis sensitivity, tilt, and quantization, we can rule out the last three. This is because the shake table imparts linear motion (no cross-axis) of a rigid steel mass (no tilt) and all sensors have the same effective resolution.

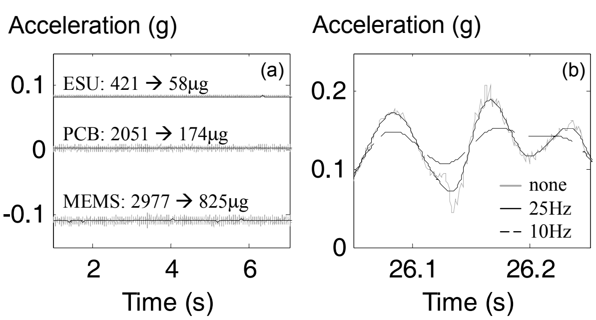

Figure 3. RMS noise amplitude of pre-event accelerations (a) and example data smoothing (b).

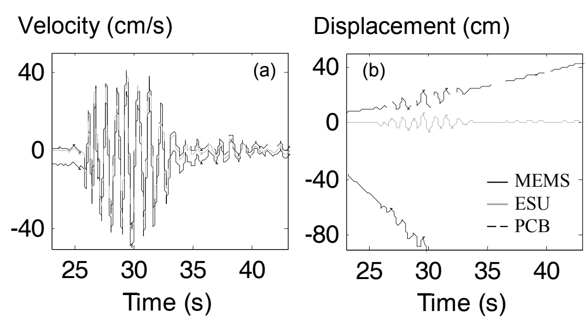

Figure 4. Velocity (a) and displacement (b) histories from linear acceleration responses.

The difference between measured displacement histories and those obtained via numerical integration are shown in Fig. 6a for the linear response and Fig. 6b for nonlinear. The disparity in error traces from sensor to sensor is an unfortunate result; however, no comment can be made as to which is good enough since that depends on the intended application and cost. Thus it appears that even with delicate application of post-processing tools such as low- and high-pass filtering; displacements may be subjective. Furthermore, it is nearly impossible to accurately capture nonlinear responses such as residual displacements by measuring acceleration. This is due to the required high-pass filtering step which effectively removes long period drifts. Indeed, some researchers have been able to partially recover permanent displacements in some cases where displacements are also measured directly; for example, in buildings with GPS sensors on the roof (Celebi 2002). In this case, however, specific baseline corrections are performed in lieu of high-pass filtering. Neglecting the problem with residual displacements, and given casual acceptance of linear structural displacements derived from accelerations, the next step(s) to obtain IDR may require static condensation and vertical interpolation. Several related issues emerge here that stem from sparsely instrumented buildings.

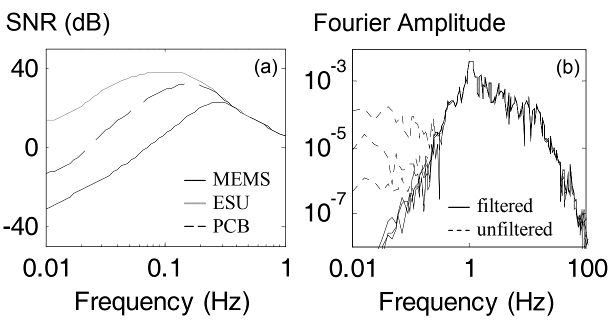

Figure 5. Cutoff frequency (a) and FFT of acceleration histories (b).

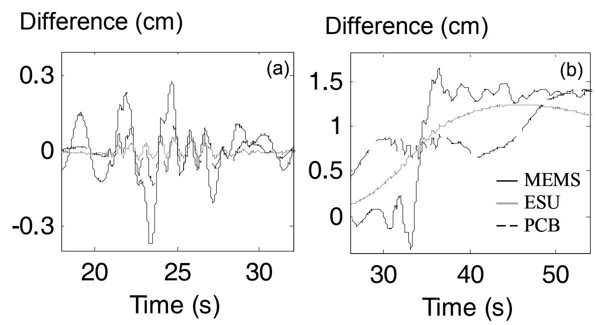

Figure 6. Difference between measured and calculated liner (a) and nonlinear (b) displacements.

Sparse Instrumentation

When considering the dynamic behavior of buildings, the assumption of rigid diaphragms substantially simplifies structural analyses. In design, floor systems are permitted to be idealized as rigid if span-to-depth ratios are less than 3 and no large discontinuities exist. Under this assumption, the structural systems' degrees of freedom (DOF) are reduced to three in-plane per floor; two orthogonal translational (u_0 and v_0) and one torsional (θ_0). The relationship between local translational acceleration at any given point on a floor (u_i and v_i) and the story motions (u_0, v_0, and θ_0) is described in Eq. (2);

$$u_i = u_0 - y_i\,\theta_0 \quad \& \quad v_i = v_0 + x_i\,\theta_0 \tag{2}$$

where x_i and y_i are the signed coordinates of the i^{th} point with respect to the control node at which the story motions are being defined. Thus, in order to experimentally obtain IDR for a given story, a minimum of six channels are required; three on two consecutive floors. Unfortunately, very few structures are this extensively instrumented. Most often only two horizontal channels are available and thus, torsional responses are not. In this case, one could still obtain the translational drift, but it is local drift and only valid at the sensor location. This is because torsion can lead to a substantial amplification (or reduction) of translation, especially at slab edges.

Another sparse instrumentation issue is missing floor-to-floor motions which require vertical interpolation. An effort to evaluate error in IDR due to this issue first came from Naeim and Lee (2005) while developing the 3D building response visualization program; CSMIP-3DV. CSMIP-3DV provides measured responses of about 80 instrumented buildings (as of 2004) to significant earthquakes for general research and educational purposes. Because CSMIP instrumented buildings typically have sensors installed at a limited number of floors, displacements at floors in between instrumented floors are approximated. Naeim and Lee proposes two types of interpolation schemes; linear and cubic spline. Typically, linear interpolation is appropriate for base-isolated buildings or sub-basement levels whereas cubic spline interpolation may be better suited for floors above ground. Naeim and Lee first used the above interpolation scheme to establish virtual sensors to account for floors that have less than three channels. Then, given story motions on select floors, interpolation was repeated to fill-in the remaining floors. To verify this approach, real sensor data was simulated as if missing. Although no quantitative results are presented, the authors noted 'remarkably accurate estimates in maximum displacements' and some deviation 'from intermediate response values particularly in [the] high frequency portions'.

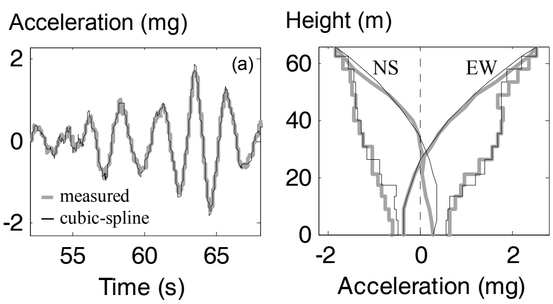

Figure 7. Measured and interpolated acceleration history (a) and peak floor accelerations (b).

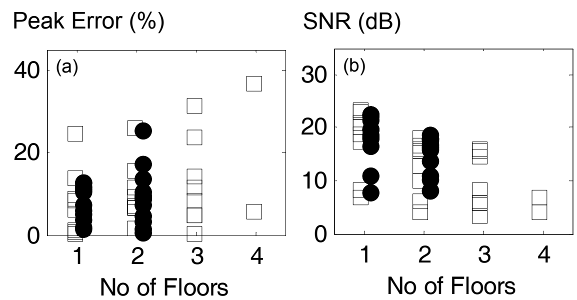

Figure 8. Error in peak value (a) and SNR (b) as a function of distance to nearest floor with sensors.

To investigate the effects of interpolation over the vertical height of a building, the UCLA Factor Building, which has 16 stories, provides well suited data. The Factor building was instrumented with an embedded 72 channel accelerometer network following the 1994 Northridge earthquake by the USGS. Each of the 16 floors has four uniaxial accelerometers (2-u_i and 2-v_i) located around the perimeter. Over the past few years, the Center for Embedded Networked Sensing (CENS) has supported several upgrades and additional equipment. See Kohler (2005) and Skolnik (2006) for more details about the building, network and some related research. Here, data recorded during the 2004 Parkfield earthquake (Mw 6.0, 260 km away) is used to evaluate error in interpolated acceleration histories. First, story motions for each floor are calculated from the four uniaxial acceleration channels. Assuming that only ground, roof, and 9th floor motions are available, the remaining floors are interpolated with cubic-spline functions. Fig. 7a displays an example acceleration trace from interpolation compared to measured data. It can be seen that the overall behavior is captured quite well. Fig 7b compares the absolute peak acceleration of each floor (staircase lines) in addition to curves showing instantaneous floor acceleration at the moment of peak roof acceleration, for both NS and EW directions. As expected, the error increases as you move away from the floors with measurements; herein referred to as nodes. To better illustrate this, Fig. 8a shows the relative error in peak acceleration as a function of vertical distance (in number of floors) to the nearest node. In addition results from a 4-node scheme (measurements on floors 1, 6, 11, and 16) are also shown as black dots. In the 4-node case the farthest floor without sensors is only two away. Surprisingly, the increase in nodes does not help in reducing error in peak value for the floors that are at most 2 floors away. Fig. 8b shows a similar trend with surprisingly low SNRs. However, the acceleration data used here is quite small in magnitude (~1mg) making SNR highly susceptible to small errors. Nevertheless, some very small values (e.g. SNR<10dB) for floors directly next to (above/below) a node are especially worrisome.

Alternative Methods

Given the drawbacks associated with numerically integrating acceleration data and the additional issues related to sparse deployments, an assessment of alternative methods for obtaining IDR is warranted. Consequently, this section describes recent applications of several alternative methods, which are classified as either contact or non-contact. A summary of the advantages/disadvantages of each approach described herein is provided in Table 1.

Contact Methods

Presumably, the most straightforward way to obtain IDR is to directly measure the absolute displacement of each floor using a displacement sensor such as a Linear Variable Differential Transformer (LVDT). This, however, requires a rigid reference frame which is impractical for field deployments. The next logical step is to directly measure relative displacements (floor-to-floor) which can be done with an LVDT and a spring tensioned wire diagonally strung across a bay. This approach works reasonably well in laboratory set-ups at moderate scales, where results can be verified with external reference displacements (Skolnik 2008). However, it is less effective for actual buildings where the wire spans long distances and becomes susceptible to sagging (Yu 2008). Finally, this approach is impractical for deployment in buildings with occupants and typically numerous partition walls.

Another contact method for obtaining structural displacements includes the use of strain-sensitive fibers, usually embedded within concrete members. Many instrumented bridges and other structures are currently being monitored with fiber optics, and have been for 10 plus years. Unfortunately, there appears to be a void in the literature when it comes to successful application inside buildings with the intention of measuring interstory drift. Some of the main challenges currently being addressed include large dimensions, material heterogeneity and hostile construction environments (Ansari 2007). Additionally, monitoring systems that depend on embedded cables suffer from shortcomings associated with temperature gradients, debonding, and difficulty in installation and maintenance.

Non-Contact Methods

Current GPS technology can sample at 20Hz within a translational accuracy of ±1cm and has been successfully used to monitor roof displacements of tall buildings (Celebi 2002) and other long-period structures. Despite limited deployment capabilities (i.e., only available for roof installations) this system offers several advantages. One immediately obvious advantage is in the ease and unobtrusiveness of deployment. GPS sensors could also be used to verify displacements obtained by nearby accelerometers. Typical building deployments such as those detailed in Celebi (2002), require installations at reference stations. Difficulties associated here include nonideal locations with potential variations in ground motions as compared to the building site.

Following the lead from motion-tracking technology emerging from Hollywood studios, Wahbeh (2003) employed high-fidelity video cameras to track LED targets. The system deployed on the Vincent Thomas Bridge was able to track displacements over 450m down the length of the span. The bridge was already instrumented with several accelerometers (by CSMIP) which provided the researchers with comparable displacements via double integration and high-pass filtering. Issues such as flexible/rigid camera mounts susceptible to low/high frequency motion unfortunately plagued the test. Emerging image processing techniques (e.g., edge detection algorithms) together with advancing technology such as high resolution still-cameras (Fu and Moosa 2002) show promise for long-term monitoring of structural displacements.

Table 1. Summary of current and alternative approaches for measuring interstory displacements.

Approaches		**Advantages**	**Disadvantages**
Double integration of acceleration		Robust technology; Easy unobtrusive installation; Data widely available (SMIP)	Requires multiple sensors on two consecutive floors and substantial signal processing; Residual displacements unreliable
Contact	LVDT with bay-spanning wire	Measures displacements directly	Difficult and obtrusive set-up; Requires extra hardware; Small amplitudes unreliable
	Embedded Fiber optics	Embedded cables are unobtrusive	Embedded cables installed during construction are difficult to repair
Non-contact	GPS	Easy unobtrusive installation Commercially available	Roof displacements only; Interference in urban areas; Requires reference station
	Video / image tracking	Easy unobtrusive installation	Requires image processing; Requires frame of reference; Low resolution
	Photoelectric (direct transverse)	Unobtrusive installation	Expensive technology; Limited range; Susceptible to rotations
	Photoelectric (axial distance)	Easy unobtrusive installation Commercially available	Low resolution; Susceptible to rotations

Chen and Bennett (1998) published work on bench top studies where displacements and rotations were measured with a cross-hair laser and four 1D position sensitive photodiodes (PSD). Unfortunately, PSD technology remains fruitful within rather small-scale applications and thus only relatively small PSDs are produced. For example, the displacement range of the system developed by Chen and Bennett was limited to ±15mm. Building upon their work; a similar set-up was developed by Skolnik (2008) which provided a sensing range of ±50mm and 2D functionality. However, a critical issue was the systems' susceptibility to small rotations of the laser which translates to large displacements.

Many commercially available non-contact sensors discern the axial distance between a light emitting diode (LED) or laser and a target using a PSD (or similar light-sensing technology). Typically, these sensors work on some photoelectric effect such as triangulation or time-of-flight, whereas many others employ principles of optical interferometery (e.g, phase shift, Sagnac effect, diffraction grating, etc). And although non-contact axial distance tools have been widely used within the manufacturing industry with respectable accuracy for years, there is yet to be published literature with respect to civil structural applications. Non-contact distance sensors appear to have suitable measurement and frequency ranges, but suffer from poor resolution at moderate amplitudes. Presumably, measurements of axial distance suffer from large errors due to rotations similar to direct transverse approach previously described. However, considering advancing technology along with an increase in civil engineering interest, non-contact distance sensors may become a winning alternative for measuring interstory drift.

Conclusions

Accurate measurements of interstory drift, especially in the setting of inelastic deformation, could help advance emerging structural health monitoring approaches that rely on probabilistic damage detection tools (i.e., fragility functions) and validate several design code prescriptions (e.g. drift limits) that are currently based on engineering judgment and experience. The most common method for obtaining IDR is by double integration of acceleration data, which is widely available, thanks to large SMIPs. However, non-linear responses, especially those including residual displacements, are ultimately unreliable, since they may be indistinguishable from fictitious long period drifts due to unavoidable baseline offsets in acceleration histories. Additionally, the final displacements are highly sensitive to signal processing techniques, such as high-pass filtering which can be subjective. Furthermore, there are two additional issues related to missing data from sparsely instrumented buildings. First, with respect to calculating story motions, a minimum of three channels (one orthogonal and two non-coincident parallel) are required on every floor. If less than three are used, then only local drift at the sensor location is available, and thus, the peak story drift is most likely not. Secondly, if instrumentation is unavailable on a number of floors and vertical interpolation is used, the error can be substantial (10 to 20% in peak value and SNR of 10 to 20dB in this study) even for floors immediately adjacent to instrumented floors. For these reasons, an assessment of alternative methods for measuring IDR is provided.

Alternative methods that require contact between transducer and structure suffer from many limitations (e.g., dynamic interaction), and may not be practical for real buildings. Non-contact alternative methods, both transverse and axial distance measurement tools, offer real promise for directly measuring interstory drift in both the elastic and inelastic range, however, more research is needed to address issues such as minimum requirements for resolution, measurement range, and susceptibility to local rotation.

Acknowledgments

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