A DATA DRIVEN METHODOLOGY FOR ASSESSING IMPACT OF EARTHQUAKES ON THE HEALTH OF BUILDING STRUCTURAL SYSTEMS

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Abstract

A data-driven approach for post-earthquake posting of buildings is presented. The approach is based on the analysis of residuals obtained by subtracting the measured responses from reference signals that reflect the behavior of the healthy system. The residuals are used to compute two indices from which the impact of the motion on the structure is assessed. One index measures the extent of nonlinearity and the other looks at changes in structural characteristics after the strong motion part of the record is over. Results obtained for a number of buildings taken from the CSMIP database suggest the approach may be suitable for automated posting.

Introduction

An item that has come to the forefront of the earthquake engineering agenda is assessing the state of health of structural systems after violent ground motion. The matter is of significant practical and economical importance given that assurance of structural safety is required before structures can be reoccupied following a major earthquake. At the present time post-earthquake assessment of structural health is based on visual inspections [1].

Although use of sensor data to asses the impact of earthquakes on structural systems is appealing, the idea has proven difficult to implement successfully. Work on using instrumental data to asses the impact of earthquake motion has been mainly focused on looking at the evolution of “effective fundamental period” [2,3,4]. The basic premise being that elongation of the “effective period” during the motion is an indication of softening and, therefore, of damage. The approach, which suffers from the fact that the feature used cannot be objectively defined (since there is no “effective period” at a given point in the response of a nonlinear system), has not proven robust in real applications.

This paper presents a new strategy to characterize the impact of earthquake motions in buildings. The approach is based on contrasting the measured response with the response of a fictive system whose behavior reflects the characteristics of the system in its reference (healthy) state. The responses of the reference state are computed through a partial observer model that is formulated using data from a non-damaging event. While the details of the observer are best explained in the body of the paper, the scheme essentially operates as a sequence of maps connecting each channel to all the others. The paper presents the mathematical support of the technique and illustrates its application in detail in the context of one particular case using real data. In addition, a summary of results for a number of building-earthquake pairs taken from the CSMIP database is also included.

The Basic Scheme in Open Loop Operation

Assume that data from a non-damaging event is available and that this data is used to obtain a map from input to output. The map can take various forms, in the time domain, for example, it could be specified in terms of the matrices of a state-space realization or in the form of a weighting sequence description (pulse response) or perhaps in an ARX model where the auto-regression part leads to a particularly concise representation. Assume that at a later time the structure is subjected to another earthquake and the formulated map, together with the new measured input, is used to estimate the output. If the structural response to the current earthquake is linear and the map is accurate (for the reference state) one anticipates that the measurements and the predictions will be in good agreement. If, on the contrary, the structure experiences significant nonlinearity the measurements and the estimates from the map will not match and the discrepancy provides a useful characterization of the nonlinear behavior experienced (the important issue regarding discrimination between nonlinearity and permanent damage is commented on later). Indeed, at each channel one has two curves: 1) the measured signal and 2) the estimate of what the signal "would have been" if the response was governed by the structural properties that prevailed during the non-damaging event used to formulate the map. The scheme outlined is depicted schematically in fig.1, where we refer to it as the Open Loop Model to emphasize that the path in the analytical estimates is from input through the model to the output.

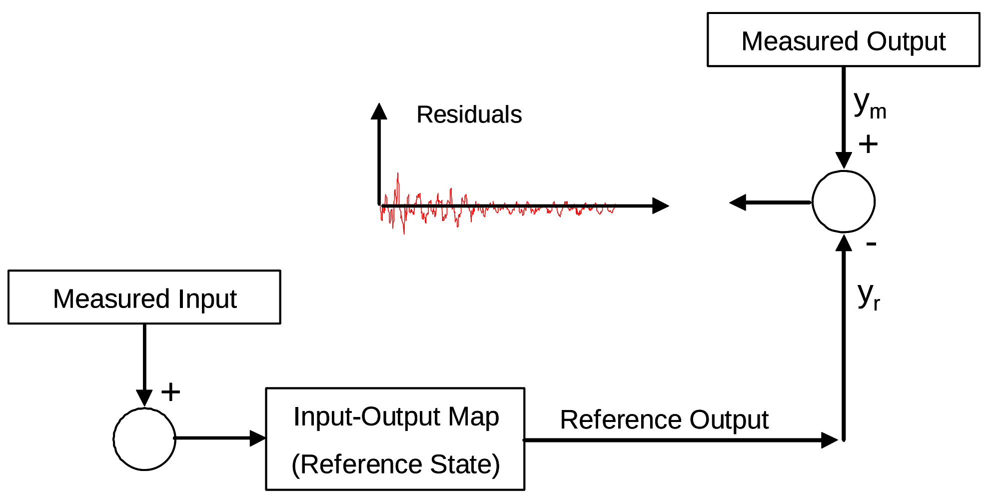

Fig.1 Computation of residuals using a basic open loop scheme

Factors Limiting the Accuracy of the Open Loop Scheme

Accuracy in y_r in fig.1 means that the response that is estimated by using the input-output map is a good approximation of the response that "would have been" measured if the structure had retained the properties that prevailed during the non-damaging event. A number of factors, however, conspire to produce non-negligible residuals, even when the response to the new motion does not induce damage (and this holds even in steel structures, where one cannot use the argument of variations due to different micro-cracking and so on). There are several factors that can contribute to making the residuals non-negligible for motions that do not induced damage but the most important one is the fact that the input-output (open loop) map reflects a *linearized* version of the compliance for the degrees-of-freedom (DOF) that are not prescribed at the soil-structure interface. Indeed, if one inspects the way the motion enters into the building from the ground it is evident that to perfectly isolate the structure from the soil and say "this collection of signals is the prescribed motion" and all the responses measured elsewhere are causally related to it, is a difficult proposition. The foregoing is not intended to imply that SSI is usually important (in a design sense) but simply that operating with a system that reflects compliance leads to a degradation in the level of accuracy that would otherwise be attainable if the map reflected only the properties of the structure.

Work to reduce the residuals in cases where the structure behaves (essentially) as a linear system led to a modification of the open loop strategy which we have referred to as the Partial Observer (PO) model. In simple terms, the idea is that instead of thinking in the strict terms of input-output one can divide the available signals into a "predictor set" and a "target set" and use the predictors to anticipate the targets. As will be apparent from subsequent developments, the mathematical structure of the observer effectively eliminates the influence of compliance on the map, increasing the accuracy notably. Before we embark on describing the details of the PO model it is opportune to take a brief detour and comment on the matter of variability in the characteristics of the base motion.

Changes in Frequency Content

Implicit throughout the discussions presented in this section is the fact that the model identified during the non-damaging event "exists" in a bandwidth that is adequate for estimating the reference response to the subsequent inputs. Since the frequency content of the ground motion can change from event to event due to variations in source to site distance, focal mechanism and/or magnitude, difficulties from a potential dependency of the input-output map on the characteristics of the input may be problematic. Upon close examination, however, one concludes that no substantial problem is anticipated on this account. One reason has to do with the observer structure used to compute the reference response, and this will be best appreciated after the next section is completed. Another reason, however, has to do with the fact that the mapping is done in the time domain where, given that the structure starts vibrating from an (essential) at rest condition, many modes that may be poorly excited can be "viewed" during the early part of the response.

An alternative way to state the same thing is to note that although the Fourier spectrum may be very low at some frequencies when the complete motion duration is considered, the evolution to the final form starts from a wide band function, independently of the details of the input. This last point is illustrated in fig.2 which displays the evolution of the Fourier amplitude spectrum for a sine function with a 10Hz frequency, modulated by a box window whose width varies from ½ to 5 cycles. As expected, the Fourier transform becomes steep and narrow with a center at 10Hz as time increases but the envelope of the evolving spectra shows important non-zero amplitudes at all frequencies in the displayed bandwidth.

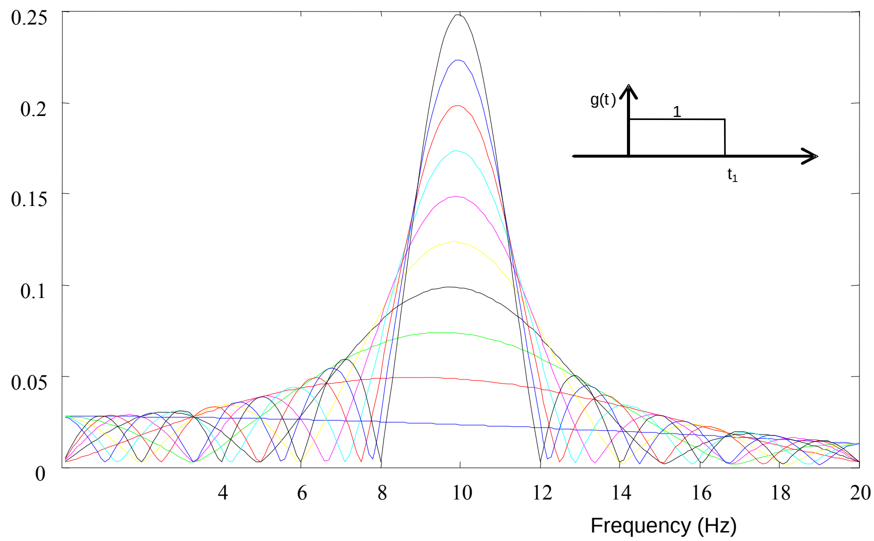

Fig.2 Evolution of the Fourier amplitude spectrum for the signal f(t) = sin(20πt).g(t,t_1) (10 plots corresponding to t_1 = 0.05, 0.1,.. 0.5 sec).

The Partial Observer Model

As noted previously, the problem with the open-loop model lies in fact that we do not have sufficient information on the input (to the non-interacting structure) to allow the computation of residuals that are as small as we would like in cases where there is no damage. In this section we present a solution to this problem based on the use of an "augmented input vector" which contains the input and some output signals. Assume we have a linear time invariant finite dimensional linear system with a state space parameterization in discrete time given by

$$x_{k+1} = Ax_k + Bu_k \tag{1}$$

$$y = C x_k \tag{2}$$

where we've taken the direct transmission term equal to zero because this happens to be the case when one is dealing with base excitation. In the previous expressions A, B and C are: the system, input to state influence, and state to output mapping matrices, in discrete time, and *x* is the state vector. In the order presented these matrices belong to R^{NxN}, R^{Nxr} R^{mxN} R^{Nx1}, where N is the order of the system and *r* and *m* are the number of inputs and outputs respectively.

A Full Observer Model

It is appropriate to begin by developing what we refer to as a Full Observer (FO) model. Adding and subtracting to the state recurrence the output multiplied by some gain, G, one gets

$$x_{k+1} = (A - GC)x_k + [B\ G]\begin{Bmatrix} u_k \\ y_k \end{Bmatrix} \tag{3}$$

which, with obvious notation can be written as

$$x_{k+1} = \overline{A}x_k + \overline{B}\,\nu_k \tag{4}$$

Following the sequence in eq.4 for k = 1,2,3, etc one can find an expression for the state at step k in terms of the state at zero and the compound input ν_k from k = 0 to k-1 which, upon substitution into eq.4 gives

$$y_k = C\overline{A}^k x_0 + \sum_{j=1}^{k} \overline{Y}_j v_{k-j} \tag{5}$$

where the Markov parameters of the FO model, $\overline{Y}_j$, are given by

$$\overline{Y}_j = C\overline{A}^{j-1}\overline{B} \tag{6}$$

Assuming the pair $\{A,C\}$ to be observable there is a gain G that renders $\overline{A}$ nilpotent so, for some exponent $k \geq p$, $\overline{A}^k = 0$ and, taking the initial condition as zero one can write

$$\begin{bmatrix} y_{1,1} & y_{1,2} & . & y_{1,\ell} \end{bmatrix} = \begin{bmatrix} \overline{Y}_1 & \overline{Y}_2 & . & \overline{Y}_p \end{bmatrix} \begin{bmatrix} \nu_0 & \nu_1 & . & \nu_{\ell-1} \\ 0 & \nu_0 & . & \nu_{\ell-2} \\ . & 0 & . & . \\ 0 & 0 & . & \nu_{\ell-p} \end{bmatrix} \tag{7}$$

or, introducing obvious notation

$$y = \overline{Y}V \tag{8}$$

where $V \in R^{(m+r)p \times \ell}$ is Toeplitz and ℓ = number of the last time station considered. Taking ℓ sufficiently large the matrix V can be made wide and the least square solution for the Markov parameters of the FO model is

$$\overline{Y} = V^{*}y \tag{9}$$

where * stands for pseudo-inversion.

From Observer Markov Parameters to Markov Parameters

A last piece of background needed before introducing the Partial Observer (PO) model is clarification of the connection between the FO Markov parameters and the Markov Parameters

(MP) of the original system, which we designate as Y. The MP connect the input to the output and are given by eq.6 with $\overline{A}$ and $\overline{B}$ replaced by A and B, namely

$$Y_j = CA^{j-1}B \tag{10}$$

From a physical perspective Y_j is a matrix containing, in column *q*, the measurements at all the *m* output sensors due to a unit pulse applied at the q^{th} input. Because of their slow decay, the MPs are best computed from the Markov's of the FO in a recursive fashion. The governing expression is [5]

$$Y_k = \overline{Y}_k^{(1)} + \sum_{j=1}^{k-1} Y_j \overline{Y}_{k-j}^{(2)} \tag{11}$$

where the superscript (1) refers to the first *r* columns of $\overline{Y}$ and the subscript (2) to the remaining *m* columns (recall that *r* is the number of inputs and *m* the number of outputs).

Response in Terms of Markov Parameters

In terms of the MP the response can be expressed as

$$y_k = \sum_{j=1}^{k} Y_j u_{k-j} \tag{12}$$

Note that the representation of the output as function of the input and the output at a finite number of prior steps (eq.6) is the vector form of the widely used ARX structure. Likewise, the representation in eq.12 connecting the output exclusively to prior inputs is the weighting or pulse response sequence representation.

The Partial Observer Model

Consider eq.2 with the output signals partitioned into two sets with the *t* and the *p* superscripts suggesting *target* and *predictors*, namely

$$\begin{Bmatrix} y^t \\ y^p \end{Bmatrix} = \begin{bmatrix} C^t \\ C^p \end{bmatrix} x_k \tag{13}$$

defining

$$\overline{Y}_j^t = C^t \overline{A}^{j-1} \overline{B} \tag{14}$$

one can write

$$y_k^t = \sum_{j=1}^{k} \overline{Y}_j^t v_{k-j} \tag{15}$$

We now indulge in a bit of mental gymnastics. Consider a fictive system with an "augmented input vector" given by

$$\nu_k^t = \begin{Bmatrix} u_k \\ y_k^p \end{Bmatrix} \tag{16}$$

and output given by y^t. Reviewing the previous definitions one concludes that, for this system, eq.14 gives the FO Markov parameters and, consequently, the MP of this fictive system, Y^t, can be obtained from eq.11 by replacing $\overline{Y}$ with the appropriate partitions from eq.16. The output at the target set given the Markov parameters and the predictors in eq.16 is then

$$y_k^t = \sum_{j=1}^{k} Y_j^t \nu_{k-j}^t \tag{17}$$

Eq.17 predicts the output at an arbitrarily selected set of channels (the *t* set) using the augmented input of eq.16. It's opportune to note that the form in eq.17 is not autoregressive, since there is no intersection between the signals in the right and the left side of the equal sign, and it is not a weighting sequence either (in the traditional sense) because the right side includes not only the input, but also part of the output. The form in eq.17 is what we refer to as the Partial Observer (PO) model.

Observer Structure

The result in eq.17 can be viewed in terms of the observer like structure depicted schematically in fig.3

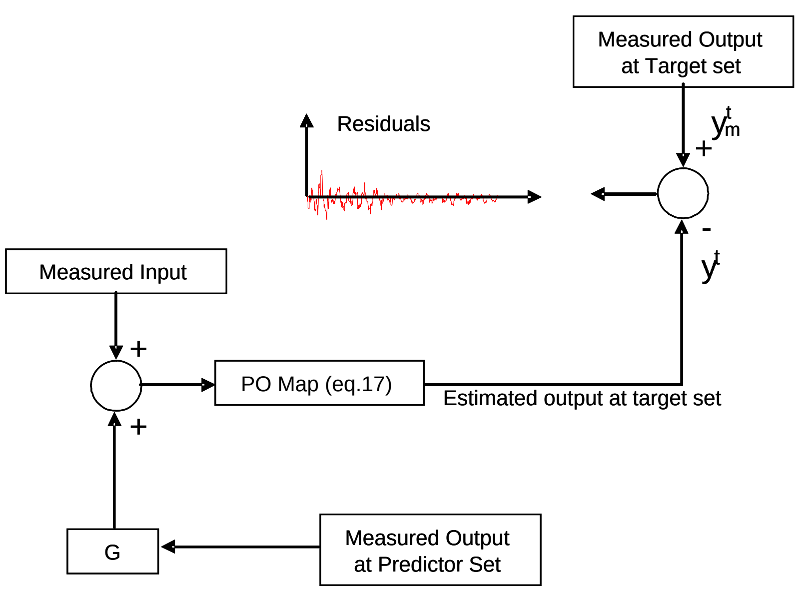

Fig.3 Schematic illustration of the Partial Observer Scheme

At this point it should be apparent why the target channels are not included in the predictor set. Namely, we wish to control the effect of unmeasured inputs and to isolate SSI effects but otherwise allow the target channels to respond freely - namely:

The target output obtained from the observer is the response that the linear system of the reference state would have if subjected to the measured inputs and to prescribed motions equal to the measurements at the channels in the predictor set.

Selection of the Target and the Predictor Sets

Given that the fundamental objective of the "feedback" from y^p is to isolate the effect of unmeasured base motions it appears that the channels in the lowest instrumented level of the building are a good choice for this set. In this scheme damage occurring between the foundation and the first instrumented level would be addressed by switching the y^p and the y^t sets, although one anticipates that in this case the foundation effects would be less effectively isolated.

Another possibility is to place all the channels in the predictor set, except for one at a time, which is treated as the target and to proceed by formulating one map for each channel. This alternative maximizes isolation of the structure from SSI and any unmeasured disturbances but also reduces sensitivity of the residuals to inelastic behavior. A review of the mathematical developments of the previous section shows that the formulation of all the maps can be done directly from the FO Markov parameters and, as a consequence, the computational burden in this alternative is not much larger than in the first case.

In deciding between the two alternatives we contemplated one more factor, namely, the fact that the dynamics of the model in the second alternative are simpler than in the first because each channel that is moved to the predictor set eliminates two eigenvalues from the system matrix of the "augmented input" system. Given that this simplification adds to robustness, and that robustness is of the essence, we opted for the second alternative.

On the Selection of p

The only user decision in the approach to obtain the PO model is the selection of the number of non-zero observer Markov parameters (p) in eq.7. Notwithstanding minor caveats because of details in the inter-step behavior of the input, in an ideal situation of noise free data the value of p does not need to be larger than the order of the system divided by the number of output measurements.

In a realistic noisy environment, however, a more useful result is that the product of p and the number of outputs is the maximum number of modes that can be identified if the Markov parameters of eq.10 are used in a realization algorithm. Given that the number of system modes that can be extracted from real data is not too large, when the objective is to compute frequencies and mode shapes the typical approach is to specify p such that $p{\times}m$ is larger than what experience shows can be reasonably computed and then proceed to separate computational modes from system modes [6]. This last step, i.e., the discrimination between system and computational modes, however, is a difficult problem for which no entirely satisfactory solution is currently available (although major gains appeared to have been made in the last couple of years with the introduction of the POLYMAX technique [7,8].

In any event, the point to stress here is that in our application there is no pressing need to "clean out" computational modes since these have very small contributions to the map and prove immaterial in the evaluation of residuals. In the current automated implementation of the PO model we've taken $p=2*NS$, where NS is the number of stories of the building. In the unlikely event that the maps obtained are not sufficiently accurate with $p=2*NS$ (gauged with metrics that compare the measurements with the predictions in the reference state) the value is increased until the criterion is satisfied. If $p > 30$ seems necessary for an accurate map this is taken as an indication of anomalies, namely, either the structure is behaving with significant nonlinearity, which invalidates the selected record as reference motion, or there are faulty sensors in the set.

Comparison of Open Loop with PO Model

Before proceeding to examine the processing of the residuals it is useful to illustrate how the predictions of the PO model are significantly more accurate than those from the open loop system for realistic operating conditions. For this purpose consider the 6 story building at CSMIP station #24370 (Burbank). We focus attention on channel #3 which is located on the roof and is oriented in the E-W direction. Assume that two identification models are obtained using data taken from the response to the Whittier Earthquake of 10/01/1987. The first model is the open loop model that predicts the output in channel #3 using the excitation at the base and the second is the PO model. The measured response is compared in Fig.4b with the open loop prediction and in Fig.4a with the PO model – the improved accuracy of the PO model is evident.

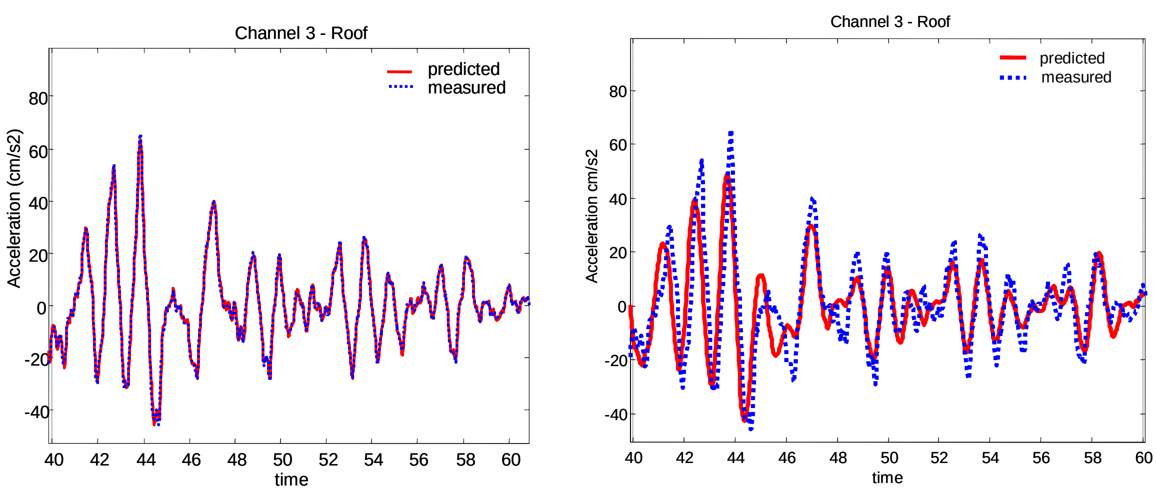

Fig.4 a) PO model predictions b) Open loop model

Residuals

The objective of the work reported here was to provide a post-earthquake automated health assessment compatible with the current ATC-20 posting scheme. To attain this objective there is a need to reduce the time histories of the residuals to metrics that can be used in a classification scheme. After exploring various alternatives we settled on two scalars, η and κ, in particular

η - is a measure of the total deviation of the measured response from linearity. Based on the aggregate of the numerical results examined η < 0.20 is proposed as equivalent to the ATC-20 posting INSPECTED.

κ - is a parameter used to differentiate inelastic response with no permanent damage from cases where the structure does not revert back to the original state after the strong motion ceases. Computation of κ is relevant only when η > 0.20.

The previous metrics are defined by

$$\eta = \gamma_{t=t_{max}} \Big|_{\text{max over all channels}} \tag{18}$$

$$\kappa = \frac{S_e}{S_r} \Big|_{\text{max over all channels}} \tag{19}$$

where

$$\gamma(t) = \frac{\int_0^t \varepsilon^2 dt}{\int_0^{t\,max} y_m^2 dt} \tag{20}$$

$$\varepsilon = y_p - y_m \tag{21}$$

where, y_p = output predicted by the PO model (for the channel in question); y_m = measured output and t_{max} = total duration of the earthquake record.

The numerator in eq.19 is the average slope of the curve given by eq.20 computed after it reaches 95% of its final value. The denominator is the slope of a line joining the 10% to the 90% values of the function in eq.20 for the earthquake used to generate the PO model. It's worth noting that the denominator (S_r) would, ideally, be an estimate of the initial slope of the same curve used to compute the numerator (prior to the onset of inelastic action) but this definition does not prove practical because the time available to ascertain this average slope is too small to ensure robustness.

Instrumental Automated Posting

In keeping with the objective, the information from the PO model has been mapped to the three group scheme adopted in the ATC-20 posting procedure [1]. The resulting Instrumental Automated Posting (IAP) approach, as tentatively defined, is summarized in Fig.5.

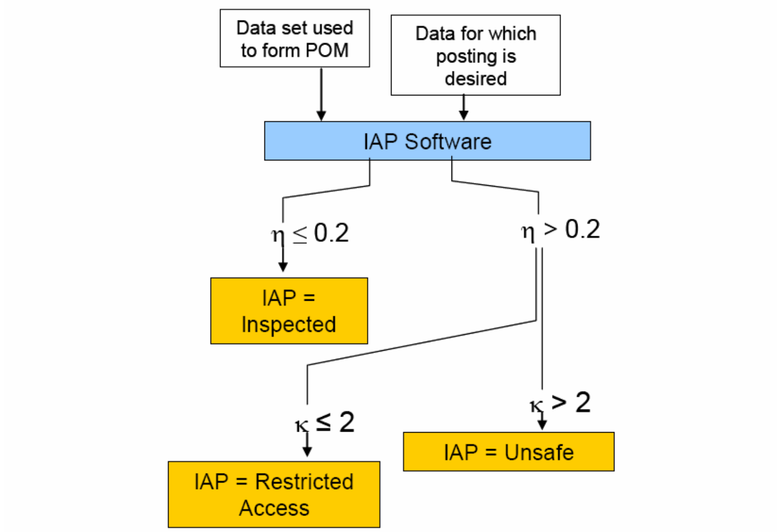

Fig.5 Instrumental Automated Posting Scheme

Detailed Illustration

We illustrate the procedure by looking at the well known Van Nuys 7-story Hotel. As shown in fig.6, the structure has 16 sensors. The impacts of two earthquakes on the building are investigated: one is the Big Bear earthquake of 1992, which did not produce any damage, and the other the Northridge earthquake of 1994 which induced significant damage.

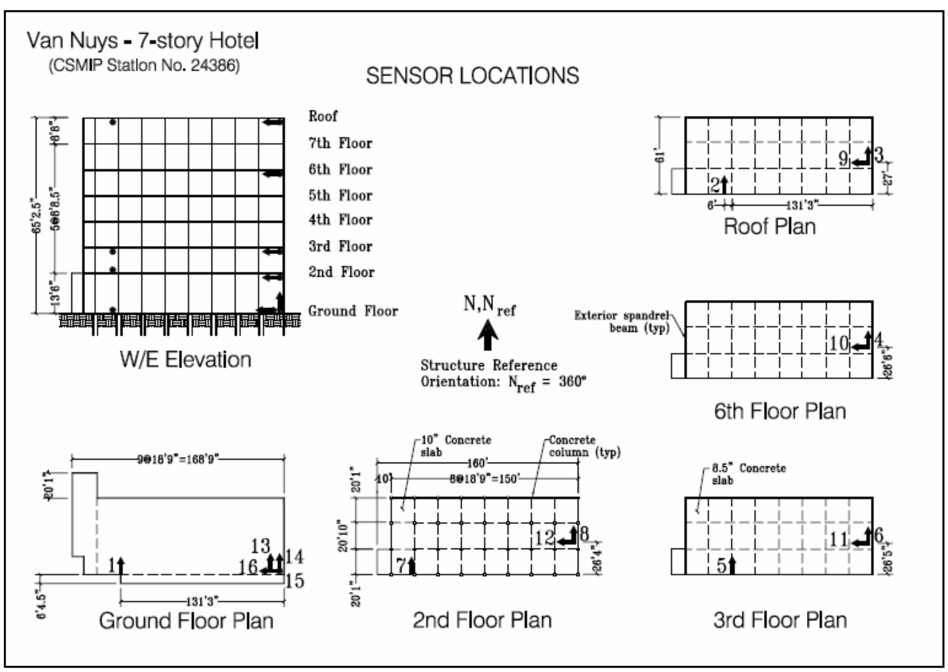

Fig.6. Schematic illustration of building and sensor location (taken from CSMIP web site)

Formulation of the PO Model

To PO model is formulated using the Landers Earthquake of 1992. For this earthquake the maximum base acceleration recorded was 0.06g, and the maximum acceleration elsewhere in the structure was 0.19g, which are modest values and thus damage is not anticipated and none was observed.

Case 1. Big Bear, 1992.

The maximum recorded base acceleration for this motion is 0.03g, and the maximum structural acceleration 0.06g. The intensity of shaking is, therefore, significantly smaller than that induced by the Landers motion used to generate the PO model. Fig.7 shows a comparison between the measured and predicted response at the channel where the largest residual is obtained (ch.12-1st Floor). As can be seen, the residual is very small and one would conclude (by inspection) that there was no damage in the response to this event – which was the case. In terms of the IAP outlined in fig.5 one finds η = 0.06 which is well bellow the 0.2 cutoff so the structure is classified as INSPECTED.

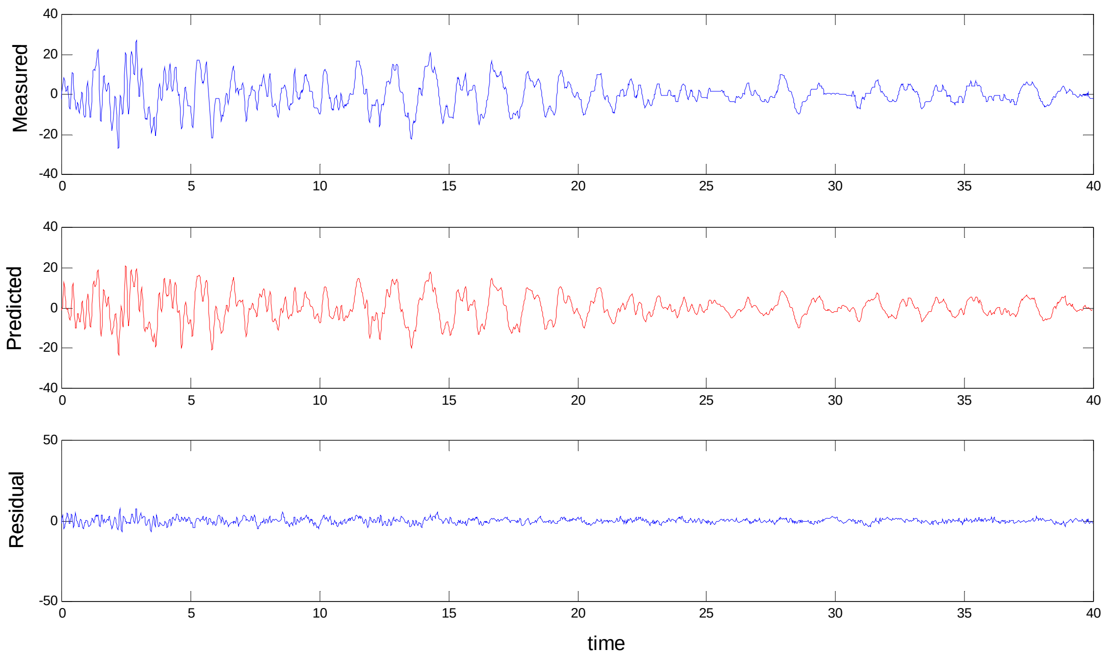

Fig. 7. Comparison of Measured and POM reference accelerations (cm/s^2) at channel 12 during Big Bear.

For illustration, the plot of γ as a function of time for channel 12 is depicted in Fig. 8.

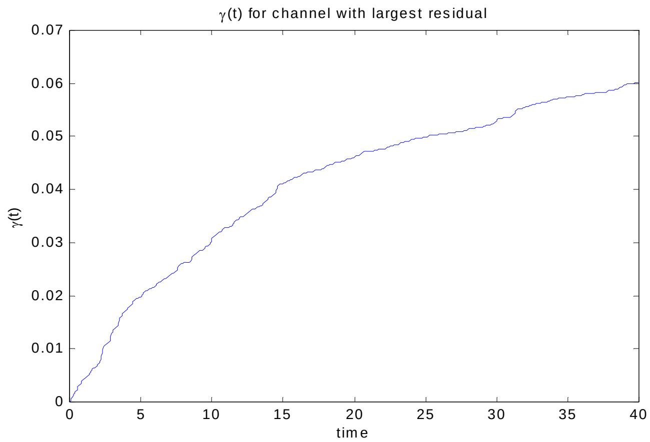

Fig. 8. γ for channel #12.

Case 2. Northridge Earthquake, 1994.

The maximum recorded base acceleration for this earthquake was 0.49g and the maximum recorded acceleration on the structure 0.59g. The measured and the PO model reference response at the channel where the largest residual is obtained (ch.9-roof) are depicted in fig.9. The value of η proves to be 0.55, which is significantly larger than the threshold (0.2) bellow which no damage is anticipated. Given that the methodology indicates that the building has suffered significant nonlinearity one proceeds to determine if the nonlinearity led to permanent changes in stiffness. In the IAP approach this is done by looking at the parameter κ which, in this case proved to be 20.33, which is much larger than the threshold of 2 below which the structure would be assumed to have suffered nonlinearity but no substantial permanent damage. For the (η,κ) pair obtained, namely (0.55, 20.33) the IAP leads to a classification of UNSAFE which, of course, is consistent with the field observations.

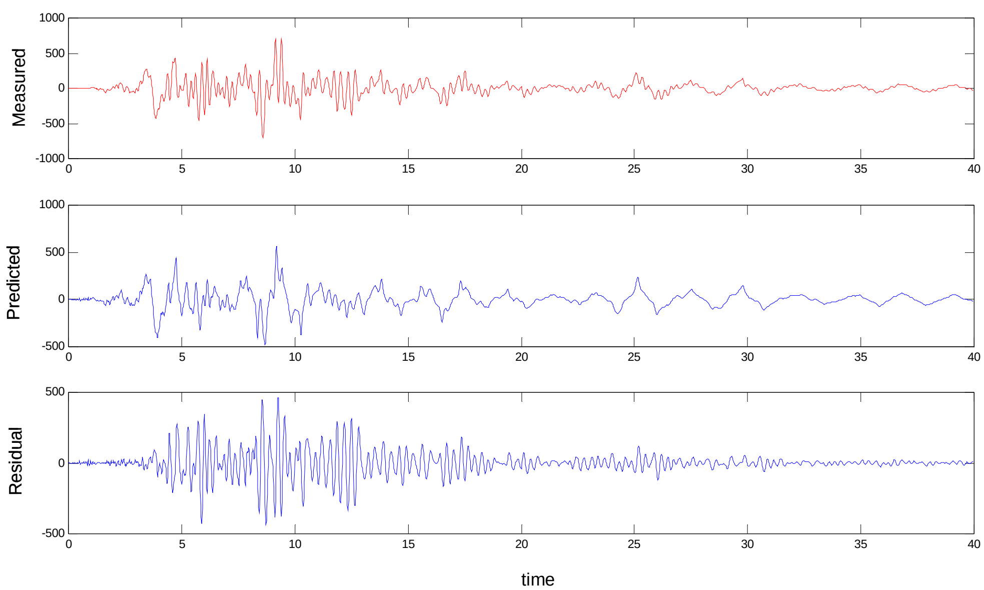

Fig. 9. Measured and PO model reference acceleration (cm/s^2) in channel 9 during the Northridge Earthquake

Other Buildings from the CSMIP Database

The same procedure described previously has been applied to several other buildings of the CSMIP database and the results are, to the best knowledge of the writers, in agreement with the empirical observations from the field in all cases. Table1 presents results for five structures for which explicit post earthquake assessments have been reported [9,10].

Table 1. Summary of IAP results for 5 buildings taken from the CSMIP database

Building	Earthquake used to formulate POM --------------------- Earthquake investigated	PGA (PSA) In g's	η	κ	IAP
Sherman Oaks 13-story commercial building Station# 24322 Concrete	Whittier 1987	0.15 (0.17)	0.03		
	Northridge 1994	0.46 (0.90)	0.29	0.95	Restricted Access
Van Nuys 7-story hotel Station# 24386 Concrete	Landers 1987	0.06 (0.19)	0.02		
	Northridge 1994	0.47 (0.59)	0.55	20.33	Unsafe
Los Angeles 17-story residential building Station# 24601 Concrete	Landers 1992	0.05 (0.21)	0.02		
	Northridge 1994	0.26 (0.58)	0.03	NA	Inspected
Burbank 6-story commercial building Station# 24370 Steel	Whittier 1987	0.05 (0.22)	0.07		
	Northridge 1994	0.35 (0.49)	0.59	0.30	Restricted Access
Los Angeles 52-story Station# 24602 Steel	Landers 1992	0.05 (0.17)	0.06		
	Northridge 1994	0.15 (0.41)	0.14	NA	Inspected

No Prior Earthquake Available to Formulate the POM

A situation that can arise in practice is that there is no excitation to formulate the PO model. The first thing that comes to mind for resolving this situation is to generate the maps using the early part of the records, before the motion is strong enough to induce nonlinear response or damage. This option was explored and it was concluded that the available duration is usually too short to ensure an accurate map. Another alternative, of course, is to use the late portion of the records, after the strong motion ceases, so the response can be once again assumed to be essentially linear – to distinguish this model from the standard situation we refer to it as the LPO model (where the L is reminiscent of late). Needless to say, if the structure has suffered permanent damage the reference map is then the one for the damaged system. For the purpose of identifying the impact of the motion on the building the information lost in trading the reference model at the start for the one that prevails at the end is not much regarding the computation of η (the amount of nonlinearity) but the computation of κ is no longer feasible (at least in the standard fashion) because the average slope after the strong motion ends will always be small.

One could think or reversing the process to use the slope at the early part of the record to get κ but robustness becomes a problem due to the short time intervals involved. At the present state of development, if there is no prior reference motion, we limit the IAP to differentiating between INSPECTED and OTHER.

To offer some quantitative insight into the accuracy that can be attained with a PO model based on the later portion of the record we consider again the Van Nuys building but assume that at the arrival of the Northridge earthquake no prior data was available to formulate a PO model. Fig.10 shows, in the same plot, the LPO model predictions and the measurement at channel #9. As expected, the model matches the later part of the response and shows that the strong part of the excitation was not governed by the same map. The value of η for the results in fig.10 (which is the channel with the largest residual) is 0.51 – which is in good agreement with the 0.55 that was obtained when the Landers earthquake was used to formulate the PO model.

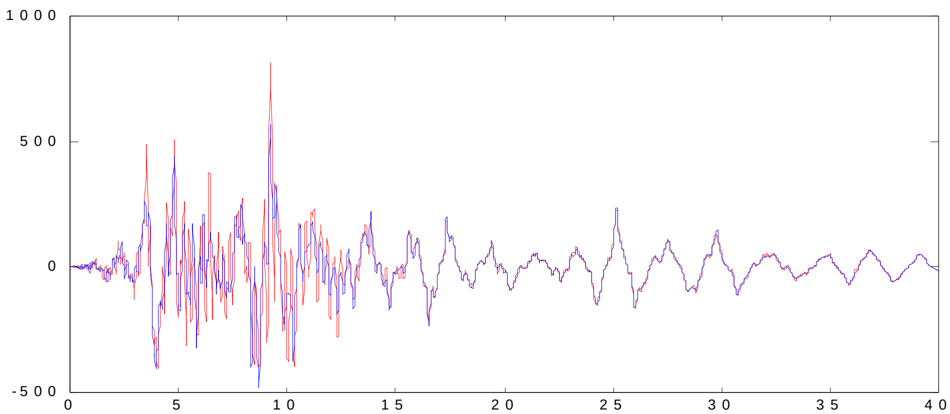

Fig.10. Comparison between measured (blue) and LPO model (red) in channel 9 (cm/sec^2)
Northridge Earthquake

Conclusions

The data driven approach to asses the impact of earthquakes presented here is based on a very simple concept, namely, if one has data from a non-damaging motion a map between the available channels for the healthy behavior can be established and this map can be used to determine the deviations from the reference in subsequent earthquakes. Needless to say, the key for success in this simple concept is connected with the ability to formulate an accurate map for realistic conditions. In this regard, a standard map operating in open loop proves to be less accurate than one would like, primarily because of SSI effects. One way to improve accuracy is by changing the open loop to an observer structure. The solution developed here, which has been designated as the Partial Observer model feeds the measured output channels that are not being predicted into the model that predicts the reference response. The lack of an autoregressive term ensures adequate sensitivity to nonlinearity.

One point that deserves explicit note and which was only briefly mentioned in the body is the fact that much of the robustness of the approach presented derives from the fact that the technique avoids the nemesis of most identification based procedures, i.e, the need to distinguish between computational and system modes. Indeed, in the real situation one faces high order dynamics, noise in all the signals and the inevitable fact that the structure is not viscously damped and perfectly linear, even when there is no damage. All of these facts (and many others not noted for brevity) combine to make the separation of actual system modes from computational ones a difficult problem for which no entirely satisfactory solution has been yet devised. Nevertheless, because the computational modes have a small contribution to the output the PO model can be formulated without a need to worry about this (otherwise potentially critical) matter.

A related issue also worth noting is the fact that the technique presented is not only devoid of heuristics but is insensitive to complications from high modal density, interacting closely spaced modes and all the other issues that can arise if one attempts to translate the map between the channels into a modal-model characterization.

We conclude by noting that the approach uses *all the available data,* does not call on any priory knowledge about the structural system and operates in a fully automated fashion. This last feature is one that we insisted from the outset, not because it is essential for practicality, but because it ensures against the malady of “we can find it when we know where it is”. Note that while the information from the residuals has been mapped to the ATC-20 posting, the residuals are rich in information and may allow a more refined classification, including perhaps indications on the localization of damage, if damage is identified.

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