13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2700

A DATA DRIVEN APPROACH TO IDENTIFY DAMAGE INDUCED BY EARTHQUAKES

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SUMMARY

A data driven methodology for the evaluation of earthquake induced damage on civil engineering structures in presented. The main features of the approach are: (1) identification of a collection of mappings containing transmissibility between sets of channels for the nominally healthy state of the system and (2) computation of differences between the predicted signals at the various channels and the measured ones during a potentially damaging event. The transmissibility maps are obtained in an entirely data-driven fashion using measurements obtained from non-damaging events. The technique is found effective in identifying which recorded motions have induced damage and which have not in a 7-story concrete structure located in Van Nuys, CA.

INTRODUCTION

An item that has recently come to the forefront of the earthquake engineering agenda is assessing the state of health of structural systems after violent and potentially destructive ground motion. The mater is of significant practical importance given that assurance of structural safety is required before structures are reoccupied after a major earthquake. At the present time, post-earthquake assessment of health is based on visual inspections [1]. Needless to say, the cost and time needed to execute visual inspections depends on how much effort is dedicated to access regions that contain important structural components and are hidden from view. Given the very large number of structures that are exposed to severe excitation when an urban area is subjected to an earthquake, inspections base on little more than overall appearance are often all that can be done in the time scale of a few hours or days following the motion. As the hidden weld fractures that occurred during the Northridge earthquake clearly showed, these cursory inspections have severe limitations.

A strategy that has great potential for post earthquake safety assessment is the use of measurements obtained from sensors. Although this idea is immediately appealing, there are many difficulties in transferring the concept to an approach that can operate robustly in the conditions encountered in practice. Some facts worth noting from the outset are:

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- Structures are only partially instrumented; a typical situation is to have instrumentation at the base, the roof, and perhaps one or two intermediate floors.

- Full characterization of the input is difficult. The lack of a full characterization of the input derives from several sources. One that can be easily resolved is lack of sufficient sensors to estimate rocking. A much more difficult one, however, is the fact that the forces that come from interaction of the structure with the soil along basement walls contribute to the input and cannot be readily measured.

- Measurements are noisy.

- Last but not least in the list is the fact that damage is a generic term used to describe a perception on the state of a system but is not a directly measurable quantity. A large fraction of the effort in developing the framework reported here was spent on the selection of a feature whose connection to damage is as transparent as possible.

It is convenient to divide possible features used to predict damage into two categories: 1) those that can be measured directly and 2) those that are computed, estimated or inferred from measurements. For example, the maximum acceleration at a given sensor or maximum strain in a steel rebar (if measured directly) belong to the first category while base shear obtained from a few measured accelerations (obtained by estimating all the non-measured accelerations and using estimated weights) belongs to the second. Features that belong to the first category eliminate estimation errors and are thus desirable.

Conceptually it is important to differentiate between features that are correlated with damage through a priori knowledge about the system and those features where the connection is more transparent. For example, if one could measure the size of the largest crack opening in a concrete column during an earthquake and found it to be, say 1/4", the conclusion would be that severe damage occurred. Note that this conclusion is independent of whether the column was designed in one way or another because the crack width is, itself, one of the faces of damage. On the other hand, if one looks at the elastic spectral ordinate for the recorded motion at the estimated period of the system the value only has meaning because of the way that structures are built but not because there is any "intrinsic" damage information in it. The objective here is not to imply that a priori knowledge about thresholds should be discarded but rather to emphasize that there is a conceptual difference between measuring a direct expression of damage like a crack and inferring damage from a quantity that is not an expression of distress.

The strategy for assessing damage described in this paper operates exclusively with measured signals and operates with a feature that has a strong component of intrinsic damage information. In particular, the approach uses data from small events to formulate transmissibility state-space mapping between sensor channels for the nominally healthy state and extracts information on the damage state from residuals between the predictions of these maps and the signals measured during a large event.

THE APPROACH

To illustrate the essential features of the proposed approach consider the schematic illustration shown in the Fig.1. In the top left portion of the figure a system is depicted, subjected to a multi-component earthquake motion at time t_1. It is assumed that the motion at t_1 is such that the system behaves in a quasi-linear fashion throughout the excitation. From the measured data obtained at

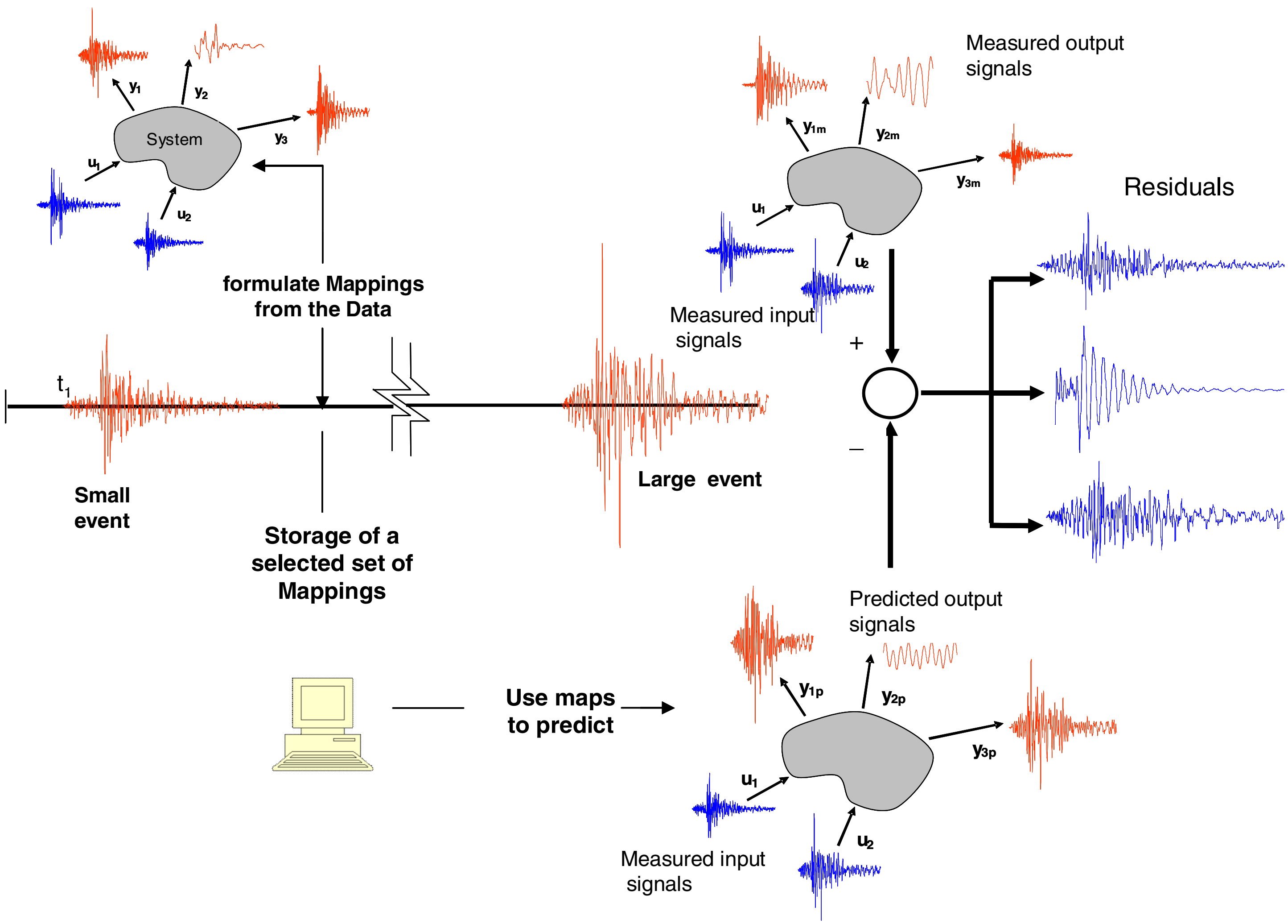


Fig.1 – Schematic Illustration of Strategy

all the available sensor locations, a collection of transmissibility maps between selected sets of inputs and outputs channels is obtained and stored electronically. At a future date, which is designated as t_2 in the figure a larger earthquake strikes and there is interest to answer, exclusively from the data, the following two questions: 1) was there significant inelastic behavior during the response and 2) if there was, did the structure recuperate much of it's initial stiffness after the motion decreased in intensity.

We begin by predicting the response of the nominally healthy system (y_p) using all the measurements and the transmissibility maps previously stored. Since the actual response (y_m) is measured, the difference between the two can be obtained – we refer to this time history signals as residuals. The residuals in the schematic illustration shown are depicted on the left portion of Fig.1. It's important to note that the residuals computed as described are rigorously defined quantities (in the sense that there is an underlying exact value) – this is in contrast with quantities such as "effective period" which depend on the window of time used as well as on the techniques and assumptions used to compute it [2,3] (given that there is no underlying exact value for the nonlinear response).

A key feature of the procedure, hinted previously in the use of the term transmissibility, is the matter of connecting a set of channels that are treated as inputs (which contain input and output signals) to a single output. Before discussing the details associated with the selection of channels it is appropriate, however, to briefly review the basic idea in the formulation of state-space mappings from measured data.

STATE-SPACE REVIEW

A linear finite dimensional system subjected to a time varying excitation u(t), can be described by the following ordinary linear differential equation [4] :

$$M\ddot{w} + \zeta\dot{w} + Kw = b_2 u(t) \tag{1}$$

Where w is the displacement at the degrees of freedom, M, ζ and K are the mass damping and stiffness matrices respectively and b_2 is a vector describing the spatial distribution of the excitation u(t), taking;

$$\begin{aligned} x_1 &= w \\ x_2 &= \dot{w} \end{aligned} \tag{2}$$

and substituting into eq.1 results in:

$$\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}\zeta \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} + \begin{bmatrix} 0 \\ M^{-1}b_2 \end{bmatrix} u(t) \tag{3}$$

which can be written as;

$$\dot{x} = A_c x + B_c u \tag{4}$$

where x is the known as the state vector. Assuming that measurements y are taken and that these are linearly related to the state one can write:

$$y = Cx + Du \tag{5}$$

where $y = \ddot{w}$, $C = \begin{bmatrix} -M^{-1}K & -M^{-1}\zeta \end{bmatrix}$, and $D = M^{-1}b_2$ .The solution to eq.4 is given by;

$$x(t) = \int_0^t e^{A(t-\tau)} B_c u(\tau) d\tau + e^{At} x_0 \tag{6}$$

which can be substituted into eq.5 giving;

$$y(t) = \int_0^t Ce^{A(t-\tau)} B_c u(\tau) d\tau + Ce^{At} x_0 + Du \tag{7}$$

where x_o is the initial state. For sampled data the previous relations can be passed to the form;

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k + Du_k \end{aligned} \tag{8}$$

Where, if the input is assumed constant within the sampling interval one has $A = e^{A_c \Delta t}$, and $B = [A - I] A_c^{-1} B_c$. In the above discussion $u \in R^{rx1}$, $y \in R^{mx1}$, and $x \in R^{nx1}$, where m is the number of outputs, r the number of input and n the order of the system

MULTI- MAPPING CONCEPT

The fundamental step in the data driven methodology presented here is the ability to identify an accurate map between selected input and output channels. In this regard, the usual practice in the identification of civil engineering structures subjected to earthquake motion is to assign as input the base motion and as outputs the measurements obtained from sensors within the structure itself.

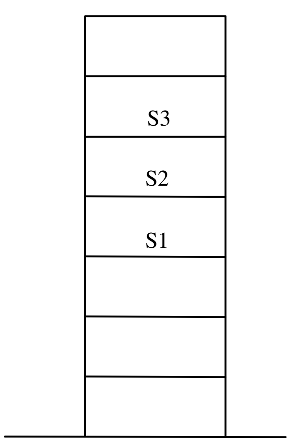


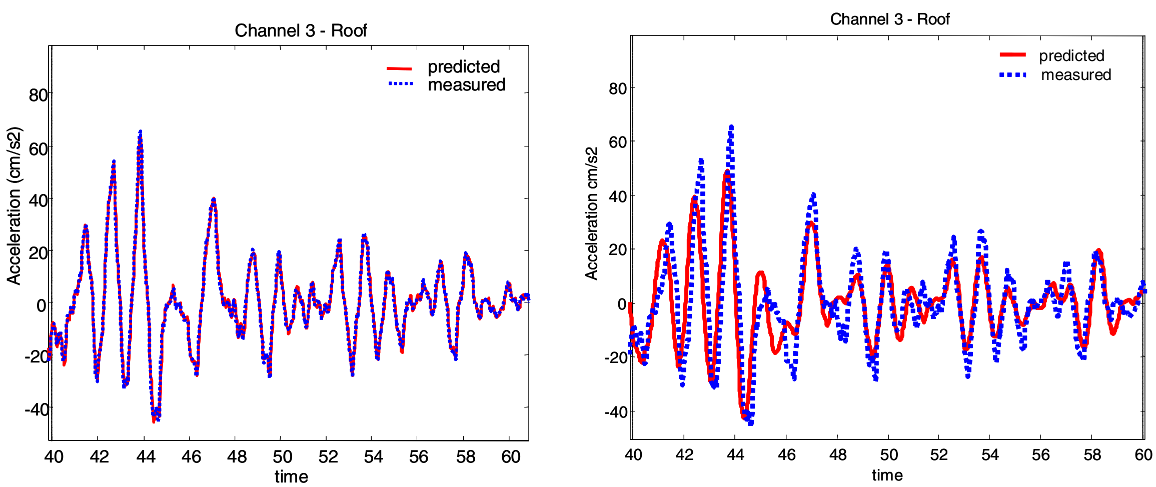
Fig. 2

In the ideal situation where the data is perfect (noiseless) and the system is perfectly linear one can compute a good map between the input and output. In the real situation, however, the data is noisy, the system is not perfectly linear (for the low excitation used to form the healthy map) and the input can't be entirely measured. Furthermore, the order of the dynamics connecting the input to all the output channels can be quite large and difficult to capture.

Nevertheless, provided that the system is invertively causal (no lag time between input and output) freedom to choose causes and effects exists. Although in reality there is some finite lag between input and output, for the frequency band of interest and the sampling rates used in earthquake applications these lags are negligible. The previous fact allows us to treat any output signals as inputs, which, in practice, can be used to drastically reduce the dimensionality of the important dynamics, allowing for dramatic improvements in accuracy. To illustrate the idea consider the frame shown in fig.2 and assume that measurements are available at the base and at locations S1, S2 and S3. If we use S1 and S3 as prescribed motions and form a state space mapping with them to predict S2 the dynamics will be quite simple since they are dominated by the two included floors only.

To illustrate the idea described previously in setting that is realistic consider the case of the Van Nuys, Holiday Inn Hotel (the information regarding the building and the earthquake records where obtained from the CSMIP web site). For this structure we form a basic map using data from the Landers earthquake of 1992 and is used to predict the response; no damage is anticipated so the structure behaves basically linearly. Fig. 3(a) shows a comparison between the predicted and the measured output in channel 3 (roof) when the base motions, along with all the remaining sensor measurements are used as inputs. In fig. 3(b) the same comparison is presented for the case where only the base motion is used as input. As is evident from the results, the improvement in accuracy is very significant – as a matter of fact, the accuracy in fig.3(a) is so good that for the scale shown it's difficult to distinguish between the measurements and the predictions.

It's worth noting that the invertible causality of the system used to augment the inputs is easily satisfied in buildings but could pose difficulties if the approach is attempted in structures that have a large surface expansion, such as long span bridges.



a) b)

Fig.3 a) Prediction using base motion and other output measurements, b) Prediction using base motion only

THE RESIDUAL

The residual ε is the difference between the predicted output (y_p) and the measured output (y_m) at any given channel, namely;

$$\varepsilon = y_p - y_m \tag{10}$$

While inspection of the history of the residual is instructive, for practical applications it is important to reduce the information to a few scalars that capture the essence of the information. While this is an aspect that is currently under development, the description presented next is illustrative of the type of processing that we're currently contemplating. Defining the running integral of the residual as γ one has:

$$\gamma(t) = \int_0^t \varepsilon^2 dt \tag{11}$$

A typical curve for γ, for a case where the structural characteristics do not recuperate after the strong motion is depicted in fig.4. Needless to say, since the duration where the impulse response function is significant is small for buildings (short memory) when the system recuperates its initial characteristics the third slope becomes close to the first. It's worth noting that the slopes ϕ are best normalized to account for the influence of the magnitude of the input (and this is easily done).

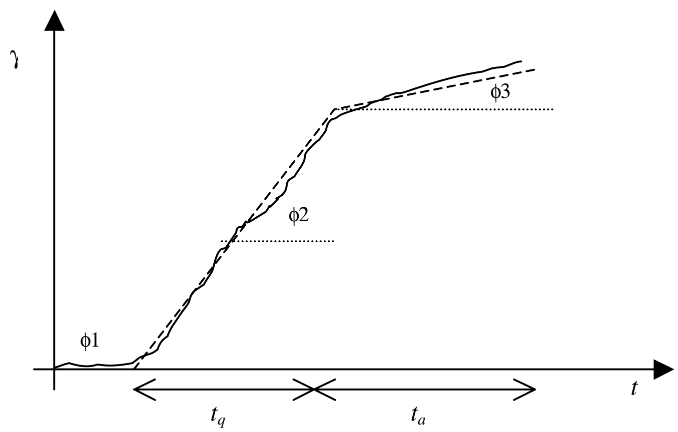


Fig.4 – Schematic Illustration for the Running Integral of the Residual

CASE STUDY

To illustrate the methodology described in a realistic setting, consider the Holiday Inn Van Nuys Hotel shown in fig.5). This building is a concrete building with perimeter frames, with base dimensions 151 x 63 ft, the structure was designed in 1965 and was instrumented in 1980. Measurements for 3 significant ground motions are available for this structure, namely: 1) Landers, 1992, 2) Big Bear, 1992 and, 3) Northridge, 1994. The location of available sensors and a general idea of the structural configuration appears in Fig.6 (taken from CSMIP web site). The Northridge earthquake induced significant structural damage in the perimeter frames in the longitudinal direction (E-W), [5].

Fig.5 Van Nuys – 7 story Hotel

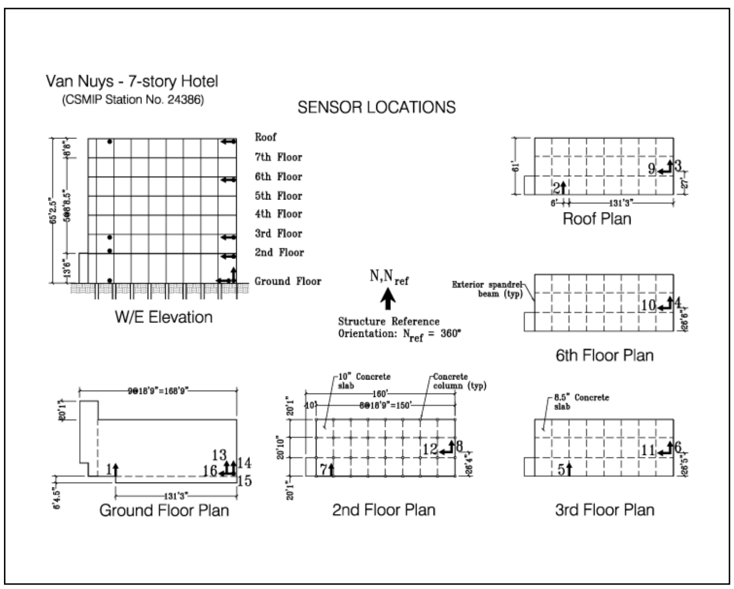


Fig.6 Sensor layout (from CSMIP web site)

<u>Results</u>

We used the Landers record to establish the maps for the nominally healthy system. The maps are then used to predict the response for the Big Bear record. For illustration we show the comparison between predictions and measurements for channel 9 in fig.7. As is evident, the agreement is excellent and we conclude that the building experienced no significant non-linearity or damage during the response to this earthquake – which is what happened in reality. Channels not shown yielded results similar to those in fig.7.

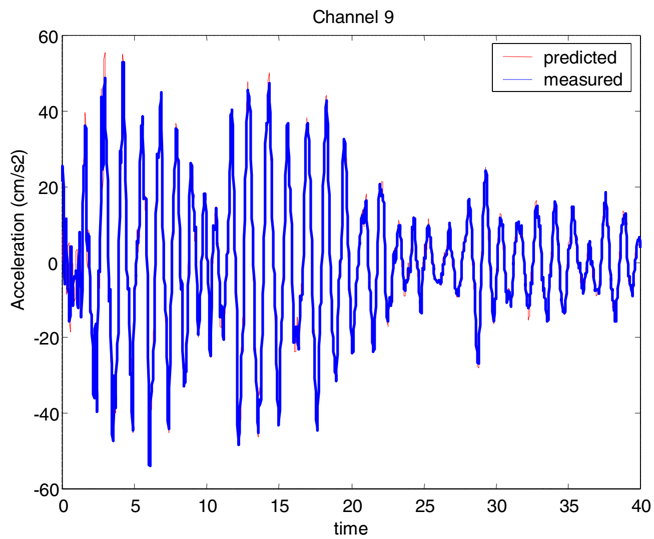


Fig. 7.Comparison between the Predicted and the Measured Response for the building in fig.6 subjected to the Big Bear earthquake

Fig. 8 shows the comparison between the predicted and the measured response in the case of the Northridge earthquake, also for channel 9. The figure is presented for a window of 10 seconds during the strong motion and for ten more after the strong motion ended to allow for enhanced clarity.

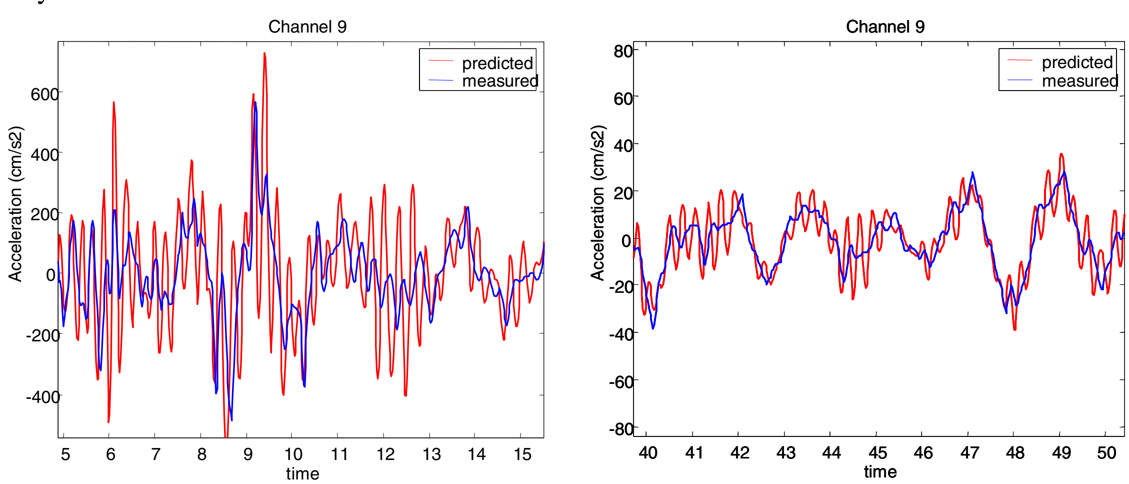
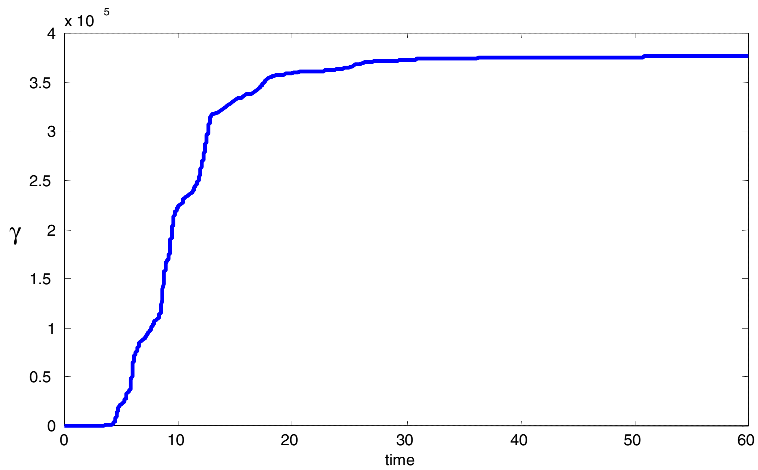


Fig. 8. Comparison between the Predicted and the Measured Response for the building in fig.6 subjected to the Northridge earthquake

A cursory inspection of fig.8 shows that this structure has responded to the Northridge earthquake in a very different manner than that which the nominally healthy system predicted (during the strong portion) and that the system does not recuperate its initial properties when the motion goes back to small amplitude.

Fig. 9 shows the normalized running integral of the residual (γ). The ratio between ϕ_3 and ϕ_1 is found to be around 4.25 times, indicating a significant change in system properties – which is in agreement with the heavy damage that actually took place.



$\phi_1 = 0.107$

$\phi_3 = 0.455$

Fig. 9. Running integral of the residual from the results in fig.8.

CONCLUSION

An approach that offers information on the effect of ground shaking on instrumented buildings, exclusively from the examination of the recorded signals is presented. The central feature of the approach is the computation of residuals between predictions obtained from maps representative of the healthy system and the actual measurements during the earthquake. While the need for a prior mapping can be viewed as somewhat restrictive, in practice this requirement is not an important limitation since small events occur with a frequency that is orders of magnitude larger than that of the strong ground motion. As a consequence, for most instrumented structures (or structures to be instrumented) one can expect to have data for formulating the required maps prior to the occurrence of a potentially damaging event. In any case, for the exceptional situations where the first ground motion experienced is sufficiently strong to be potentially damaging there is the possibility of obtaining a nominally healthy map from data in the early segment of the records or, alternatively, from data taken in the later portion (which are much longer and thus better for mitigating noise).

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