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SYSTEM IDENTIFICATION AND RESPONSE PREDICTION OF NONLINEAR STRUCTURAL SYSTEMS

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ABSTRACT

This paper is concerned with the system identification of nonlinear building structures subjected to strong ground motion. Practical conditions of instrumentation are considered to define the strategy of identification of actual structures. A simplified model of structural behaviour is used to represent the real behaviour of the system. In addition, a suitable response prediction algorithm based on the system identification results is introduced. The system identification and the prediction methods are used in a numerical example using simulated records of structural response. A stationary extended Kalman filter is used as identification technique. A good correlation between recorded signals and predicted response is found.

KEYWORDS

System Identification; Structural Response Prediction; Nonlinear Systems.

INTRODUCTION

Structural systems under dynamic loading usually exhibit hysteretic behaviour when the response becomes inelastic. Earthquake records constitute a valuable source of information concerning the dynamic behaviour of structures. System identification of full-scale nonlinear structures subjected to high-intensity earthquakes, is an interesting subject, affected by severe difficulties. First of all, the behaviour of nonlinear structures is complex, and trying to represent that behaviour with a theoretical model is difficult; on the other hand, we do not count with enough information about seismic structural response under real conditions, because in practice the number of instruments used to record the response of a system is usually much smaller than the number of degrees of freedom.

Several models have been proposed to describe the hysteretic behaviour of structures excited beyond the elastic range. Otani [1] has revised some of them. These models range from relatively simple but not very realistic models to some very sophisticated representations in which the interpretation of the loading and unloading rules is somewhat obscure. So far, none of the proposed models has gained wide acceptance among the researchers and no model has proven entirely satisfactory using actual seismic data. Practical conditions in structural system identification force engineers to use simplified models. In this paper a simplified model of structural behaviour is proposed, which is consistent with the amount of information on structural response. The proposed model is basically an equivalent linear model whose properties vary with time, in order to account for the degradation of the stiffness of the structure, as a function of relative displacements and accumulated damage (fatigue).

Explicit expressions are found for the variation of stiffness and equivalent viscous damping with respect to relative displacements and accumulated damage. A response prediction algorithm that uses the mentioned expressions and calculates the system response to other excitations is introduced.

SIMPLIFIED NONLINEAR STRUCTURAL MODEL

As a consecuence of using only a few instruments on a particular structure, it is neccesary to represent that structure by a simplified system according to the number and location of the instruments. During strong ground motion, each "block" or subsystem presents a hysteretic behaviour, which for the purposes of this paper is described by the secant stiffness (peak to peak) of each hysteretic half-loop of the deformation response of any member or subsystem of the structure of interest. For a typical softening hysteretic system the stiffness decreases and the area of the hysteretic loop increase (fig. 1) when the absolute value of the deformation increases. Damage accumulation may lead to narrowing of the hysteretic loops and, therefore, to a reduction of their area.

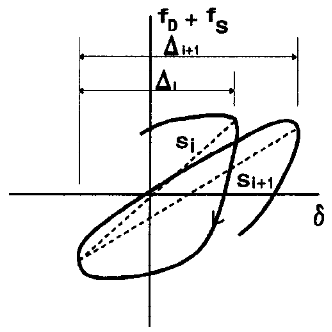

Fig. 1. Secant stiffness concept.

The model proposed here is a combination of a linear equivalente model (fig. 2) and a set of expressions for the variation of equivalent stiffness and viscous damping in terms of deformation amplitudes and fatigue effects.

The equivalence criteria adopted follow the ideas originally proposed by Jacobsen [2], but they are incorporated into an integral system identification and response prediction framework: the structural properties of a simplified model and their variation laws with respect to some important response caracteristics are identified and used later in a structural response prediction algorithm. On the basis of observations (fig. 3), the following functional forms are proposed for the variation of structural properties with respect to response caracteristics:

$$S = So * e^{(a\Delta^{r} + bD^{s})} \quad (1)$$

$$C = C_o*(1 + a\ln(1 + \Delta^r))*(1 + b\ln(1 + D^s)) \tag{2}$$

Here, S and C, are instantaneous values of equivalent stiffness and viscous damping respectively. Δ is the half-cycle amplitude of the deformation response, D the accumulated damage and So, Co, the tangent initial values of S and C for small deformations in the undamaged structure. D is a function of the values of the amplitudes of previous half-cycles of deformation:

$$D = \sum_{i=1}^{N} \Delta_i^{\,m} \tag{3}$$

a, r, b, s and m are coefficients to be determined in the system identification process.

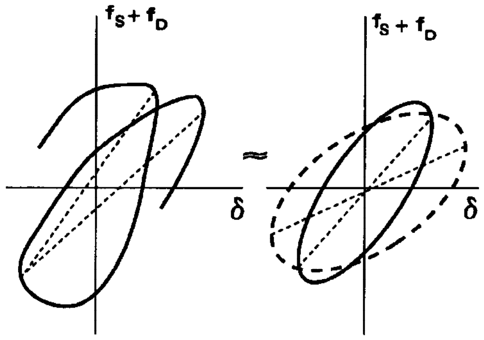

Fig. 3. Equivalence between models.

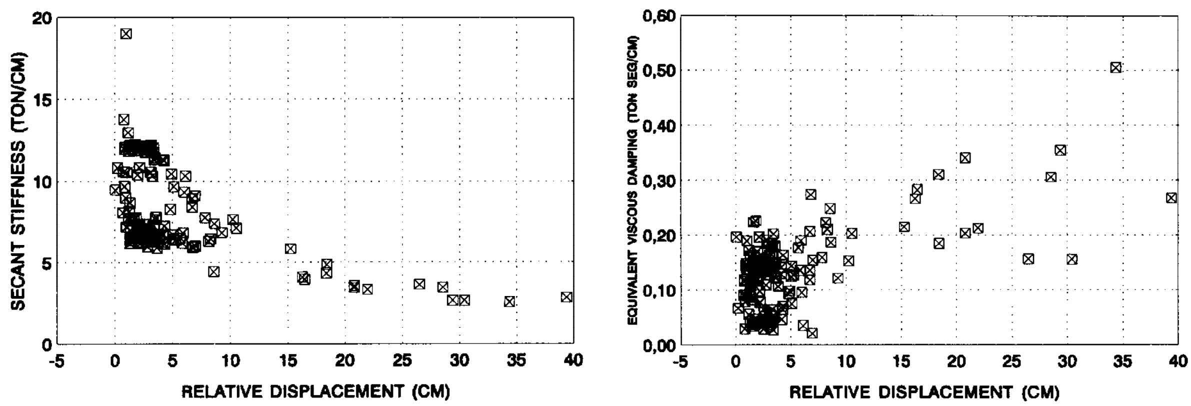

Fig. 3. Secant stiffness and equivalent viscous damping as related to relative displacements.

SYSTEM IDENTIFICATION

Experimental data are used to fit the parameters of the model, minimizing the error between recorded and predicted values of both secant stiffness and equivalent viscous damping. In this case, the experimental information for each half-loop consists of secant stiffness, area, relative displacement and accumulated damage. The system studied in this paper is a multistory building frame, instrumented with accelerometers that record the horizontal motion of several floors. For the purpose of identification, the system is represented by a shear-type system behaviour of the portions (or "blocks") of the actual system between instrumented levels. The mass matrix is condensed with respect to the traslational degrees of freedom of the instrumented floor levels.
The extended Kalman filter is used for identification of the parameters *a* and *b*. The dynamic and measurement equations of the extended Kalman filter are as follows.

$$\begin{pmatrix} a \\ b \end{pmatrix}_{half\text{-}loop_i} = \begin{pmatrix} a \\ b \end{pmatrix}_{half\text{-}loop_{i+1}} \tag{4}$$

$$h_{half\text{-}loop_i} = \begin{pmatrix} S \\ C \end{pmatrix} = \begin{pmatrix} S_o * e^{(a\Delta^r + bD^s)} \\ C_o * (1 + a\ln(1+\Delta^r)) * (1 + b\ln(1+D^s)) \end{pmatrix} \tag{5}$$

Extended Kalman filter expressions are omitted, but they are available in refs. 3 and 4. The parameters *m*, *r*, and *s* can be identified by succesive minimization of the error, fixing two of them and varying the other. A flowchart for the system identification procedure is shown in fig. 4.

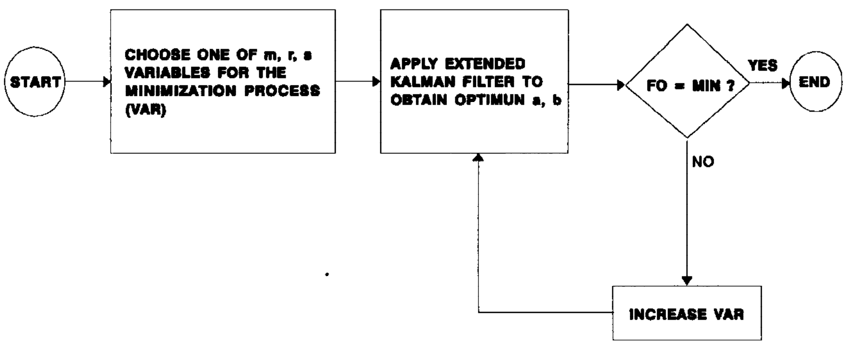

Fig. 4. Flowchart for system identification procedure.

PREDICTION

In order to predict the response of the system using the results of the system identification process, the actual system is replaced by a linear equivalent system with time-varying properties. The initial values of the small-amplitude tangent stiffness and equivalent viscous damping are known. At a given instant the parameters of the simplified model are not known in advance, because they depend on the response itself. Therefore, we proceed by iteration: we propose tentative values, which are modified by means of a locally iterated extended Kalman filter, until the optimun structural properties are obtained. The response prediction method works in time windows. A flowchart for the described prediction procedure is shown in fig. 5.

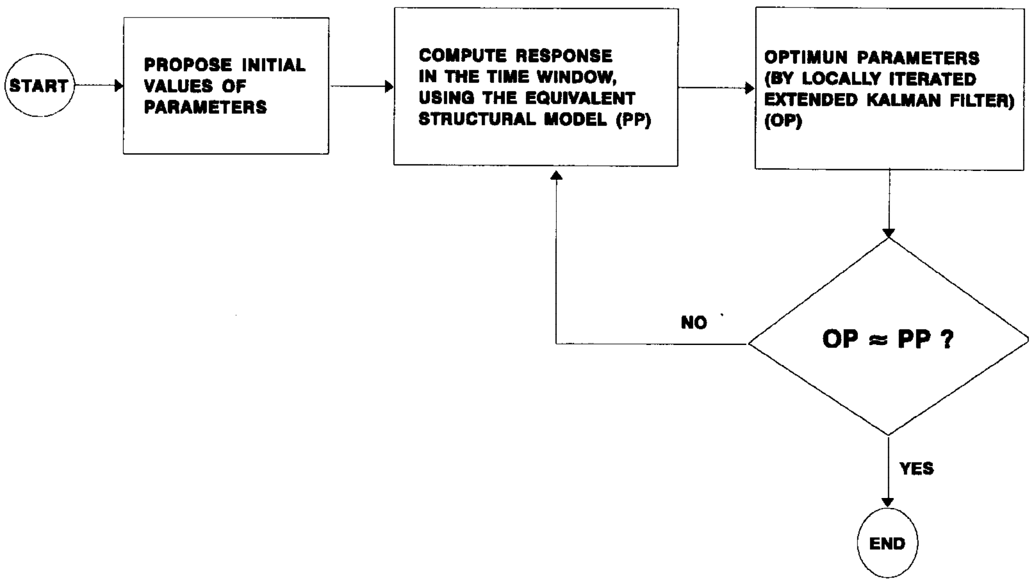

Fig. 5. Flowchart for response prediction procedure.

NUMERICAL EXAMPLE

In order to validate the proposed system identification and prediction methods they were applied using simulated data for a 10-story reinforced concrete building model (fig. 6). The reinforced concrete model was excited with the Mexico SCT-EW, Sep.19.1985 earthquake (fig. 7) scaled by a factor of two. Records of the response were obtained by using the DRAIN-2D program [5].

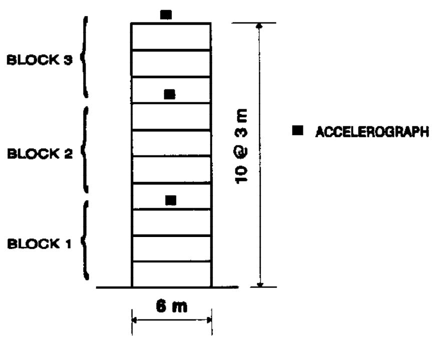

Fig. 6. 10-story reinforced concrete building model.

The reinforced concrete buiding model was designed according to RCDDF-87 Mexican Code. For analysis purposes the beams of the reinforced concrete model were represented by a stiffness-degrading Takeda model, and the columns by means of an elastoplastic model. Thus, the following expresions are adopted to represent the stiffnesses and viscous damping coefficients of the equivalent system

$$S = S_o * e^{(a\Delta + bD)} \tag{6}$$

$$C = C_o * (1 + a\ln(1+\Delta)) * (1 + b\ln(1+D)) \tag{7}$$

In this case, the value of D for a given block is represented by the maximun value previously attained by the relative displacement of that block. The values of the coefficients a, b obtained are reported in Table 1. In order to evaluate the efficacy of the response prediction method, the structural response to the EW component of the SCT record of the Mexico City earthquake of 1985 (fig. 7) was calculated by means of a conventional approach (actual response) and by the method presented here (predicted). The time histories of the response of floor 7 are shown in fig. 8. The values of actual and predicted secant stiffness are plotted versus displacement amplitudes in fig. 9.

Table 1. Parameters resulting from system identification

BLOCK	PARAMETERS			
	STIFFNESS		DAMPING	
	a	b	a	b
1	-0·0189	-0·0130	0·1209	0·5665
2	-0·0069	-0·0113	0·0163	0·5260
3	-0·0164	-0·0227	0·0133	0·8859

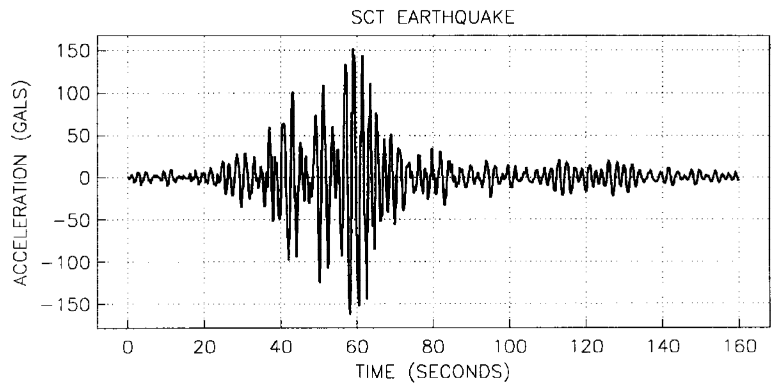

Fig. 7. Excitation used in the numerical example.

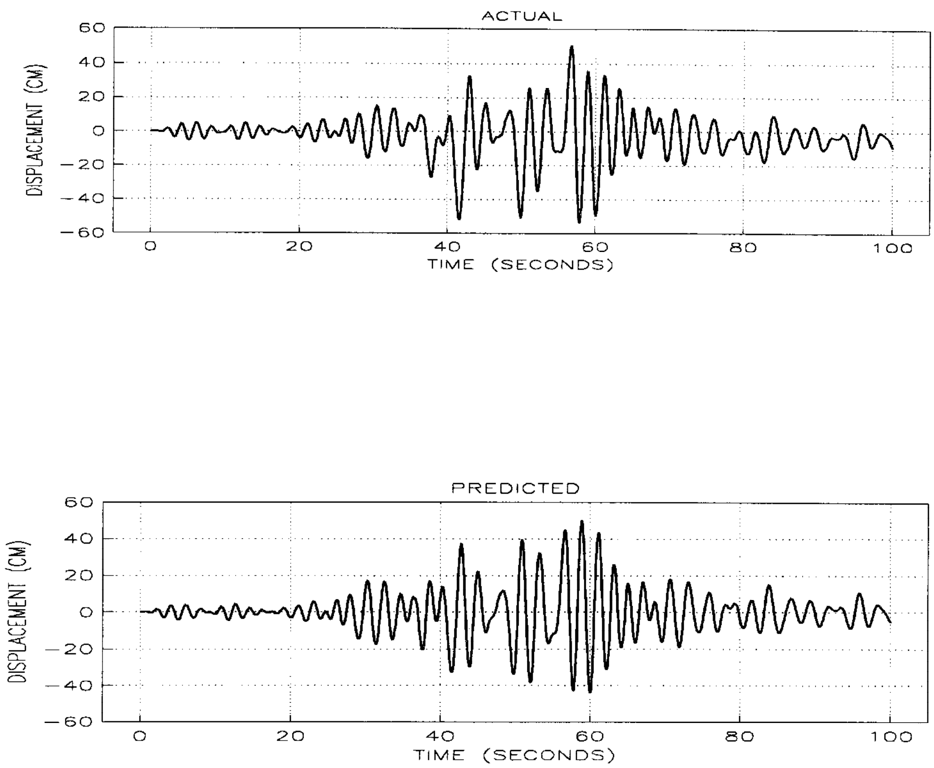

Fig. 8. Actual and predicted displacements of floor 7.

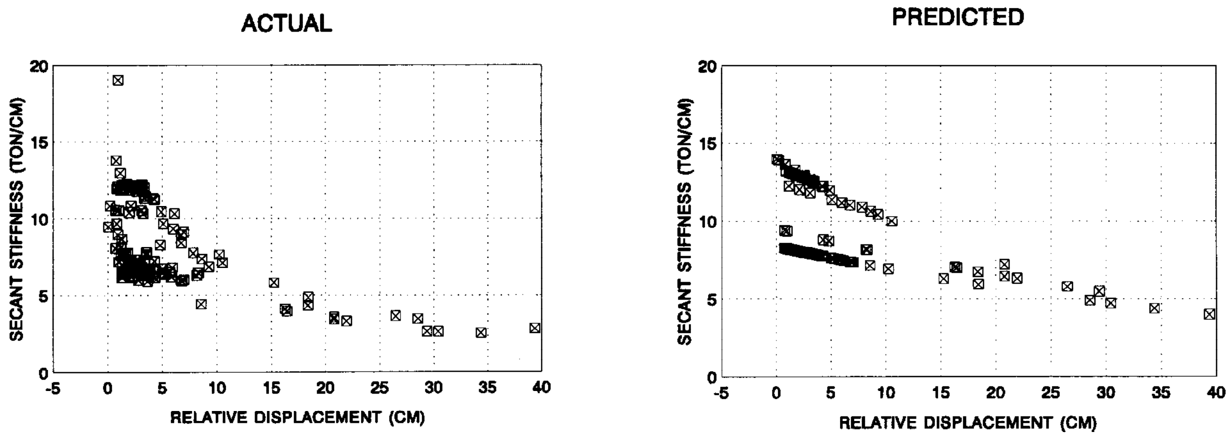

Fig. 9. Actual and predicted secant stiffness of block 1.

CONCLUSIONS

1. The limited size of the instrument arrays used to record the seismic response of structural systems for the purpose of identification of the parameters of their constitutive laws makes it neccesary to represent those systems by simplified models capable of preserving the basic features of the actual systems that are more significant for the purpose of response prediction.

2. Considerable efforts have been devoted to the development of system identification techniques that help to improve stability and convergence of the numerical methods used. More efforts are required in that area, as well as in one which is perhaps more important for practical applications, but which has received much less attention: the area of simplified equivalent models, capable of representing the variation of structural properties in terms of response amplitude and accumulated damage, to be applied in response prediction problems.

3. Use of the locally iterated extended Kalman filter in the prediction algorithm helps to improve stability and convergence of the response obtained with the simplified models mentioned above.

4. The results show a good correlation between recorded and predicted signals.

5. The method presented requires only small computational efforts, due to the fact that the system identification is based on global properties of hysteretic loops rather than on entire response histories.

6. The results presented here can be used in a next step to evaluate the structural reliability of systems under seismic excitation.

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