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TESTING R/C SPECIMENS BY A SUBSTRUCTURE-BASED HYBRID EARTHQUAKE LOADING SYSTEM

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SUMMARY

This paper presents an application of substructure – based on – line hybrid tests for computation of inelastic earthquake response of integral structures. The part of a structure expected to behave strongly in nonlinear range is experimentally tested to determine its restoring – force characteristic , while the remaining part of the structure is included in the model analytically. A series of reinforced concrete (R/C) multistory shear building frames were analyzed for earthquake response in which the first story restoring – force characteristics were measured directly from on – line experimental tests. Experimental results show that relatively strong earthquake ground motion induced significant nonlinearity in the first – story sections for these frames with relatively stiff upper stories, which in turn affected the overall response computed for the integral structures.

INTRODUCTION

In an on – line hybrid procedure for a single degree of freedom (SDOF) model, the equation of motion is formulated with analytically prescribed inertial and damping properties, and fed on – line with experimentally measured restoring forces. The resulting equation is then numerically integrated for a specified ground motion to solve for subsequent displacements to be imposed by an actuator on a test specimen. It has been effectively used to study stiffness deterioration process of virgin (ref.1) and repaired R/C specimens (ref.2), to develop and verify a stress – strain based model of R/C elements subjected to earthquake – induced bending and varying axial loads (ref.3).

In earthquake – resistant design, structures are expected to survive severe earthquakes by sustaining inelastic deformation without significant strength degradation in certain critical regions. A difficult part of pure analytical investigations is the modeling of strongly nonlinear behavior of the critical regions which could seriously affect the accuracy of the overall response values computed. On the other hand, size and scale of prototypes modeling the complete structure may have to be compromised in order to be accommodated in testing facilities. Actual overall behavior of these structures with localized nonlinearities could be economically and efficiently analyzed by extending on – line hybrid procedure of SDOF systems to multi – degrees of freedom (MDOF) systems incorporating substructuring concepts.

SUBSTRUCTURE – BASED HYBRID EARTHQUAKE RESPONSE ANALYSIS

In the developed substructure – based on – line hybrid procedure, a structure is divided into analytical and experimental substructures. Analytical substructure (s) is comprised of members whose behavior can be analytically modeled, while the critical member (s) whose behavior is expected to be extensively nonlinear is experimentally tested and treated as experimental substructure (s).

Fig.1 shows a three degrees-of-freedom lumped-mass model with nonlinearity assumed to be confined to element # 1 while elements # 2 and # 3 are assumed to remain elastic. Dynamic equilibrium at any time (t) is formulated for each lumped-mass body, as follows :

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{Bmatrix} \ddot{\delta}_1 \\ \ddot{\delta}_2 \\ \ddot{\delta}_3 \end{Bmatrix}_t + \begin{bmatrix} c_1+c_2 & -c_2 & 0 \\ -c_2 & c_2+c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{bmatrix} \begin{Bmatrix} \dot{\delta}_1 \\ \dot{\delta}_2 \\ \dot{\delta}_3 \end{Bmatrix}_t + \begin{bmatrix} k_2 & -k_2 & 0 \\ -k_2 & k_2+k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix} \begin{Bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{Bmatrix}_t + \begin{Bmatrix} rf_1 \\ 0 \\ 0 \end{Bmatrix}_t = \begin{Bmatrix} p_1 \\ p_2 \\ p_3 \end{Bmatrix}_t \tag{1}$$

Or, in condensed matrix form :

$$[m]\{\ddot{\delta}\}_t+[c]\{\dot{\delta}\}_t+[\tilde{k}]\{\delta\}_t+\{rf\}_t=\{p\}_t \tag{2}$$

where $\{\ddot{\delta}\}_t$, $\{\dot{\delta}\}_t$, $\{\delta\}_t$ = acceleration, velocity, and displacement vector, respectively, at time (t) ; [m] = diagonal matrix of lumped masses ; [c] = damping matrix ; $\{p\}_t$ = excitation force vector at time (t).
In eqn.2, the stiffness matrix $[\tilde{k}]$ contains only the the stiffness properties (assumed linear in this case) of elements # 2 and # 3. For nonlinear element # 1, restoring force resulting from the imposed displacement will be directly measured from an on-line test and fed into the restoring-force vector.

Eqn.2 is numerically integrated to get displacement responses at subsequent solution steps. Using the central difference numerical integration scheme, displacements at the next subsequent time step (t + Δ t) vector is obtained.

$$\left(\frac{1}{\Delta t^2}[m]+\frac{1}{2\Delta t}[c]\right)\{\delta\}_{t+\Delta t}=\{p\}_t-\{rf\}_t - \left([\tilde{k}]+\frac{2}{\Delta t^2}[m]\right)\{\delta\}_t-\left(\frac{1}{\Delta t^2}[m]-\frac{1}{2\Delta t}[c]\right)\{\delta\}_{t-\Delta t} \tag{3}$$

Note that $\{\delta\}$ at time (t + Δ t) is obtained explicitly based on input acceleration value at the current time step and the calculated response values of the previous two steps, including the measured value of restoring force generated by imposing δ_1 of time (t) on a specimen modeling only the critical member of the integral structure.

The central difference scheme has a stability limit of $\omega\,(\Delta t) <= 2$, where ω is the highest frequency of the structure. Several investigators (e.g., ref.4) have suggested the use of an explicit-implicit mixed integration method. In this paper, however, the central difference is chosen for simplicity to solve practical frame models satisfying the stability criterion.

The main procedure of substructure-based on-line hybrid response analysis is summarized in the flowchart shown in Fig.2.

STRUCTURAL MODEL, SPECIMEN, AND TEST SET-UP

In this and subsequent related works, a range of structural and ground motion parameters have been used to study energy-dissipating demands on critical first-story columns and the effect of the induced nonlinearities on the overall response of integral structures. Two structural models to illustrate substructure-based hybrid on-line response analysis are presented here. The first structural model is a three-story one-bay frame that is hinge-supported at the base (Fig.3a). Girders are assumed rigid and carry floor weights of 3.5 tons, 3.0 tons, and 2.0 tons in the first, second, and third floor, respectively. Analytically prescribed story stiffnesses of the upper stories are both 0.374 ton/mm for the 2nd and 3rd stories. These assumed values of stiffnesses are intended to give a relatively stiff upper stories. The restoring-force characteristics of the first story columns were directly measured from an on-line test. But, for eigenvalue analysis to determine natural periods and mode shapes of the structural model, story stiffness of 0.233 ton/mm was used, corresponding to initial elastic stiffness of the first story members. Natural periods are given as follows: T1 = 0.44, T2 = 0.15, and T3 = 0.10 seconds.

The second structural model is a five-story one-bay frame that is also hinged at the base (Fig.3b). Rigid girders carry weights of 4.5 tons, 3.8 tons, 3.8 tons, 2.0 tons, and 1.8 tons in the 1st, 2nd, 3rd, 4th, and 5th stories, respectively. Analytical story stiffnesses are given as follows: 0.374 ton/mm for the 5th and 4th stories, and 0.623 ton/mm for the 3rd and 2nd stories. A first-story stiffness of 0.233 ton/mm is used for eigenvalue analysis. Natural periods of the model are given as follows: T1 = 0.61, T2 = 0.22, T3 = 0.13, T4 = 0.09, and T5 = 0.08 seconds.

Damping coefficients are specified at 5% of each critical modal damping for both structural models. Both structures were subjected to 30 seconds of the N-S component of the El Centro earthquake scaled to 0.5g.

All first-story columns are assumed identical and were modeled with 150mm by 200m R/C cantilever specimens 1.634m long. Concrete compressive strength using 100mm x 200mm cylinders was 480 kg/cm^2. Longitudinal reinforcement consisted of four 13mm deformed bars with specified yield strength of 3500 kg/cm^2. Transverse reinforcement consisted of 5mm rectangular ties spaced at 40mm for 400mm of the potential plastic hinge region and continued at 100mm spacing for the remaining length. The specimen was securely fixed to the reaction floor and loaded laterally at its tip.

The system controller is a microcomputer whose main task includes: (1) performs the numerical integration; (2) sends displacement control signals to the hydraulic servo-actuator through a D-A (digital-to-analog) converter; and (3) receives measured restoring-force feedback values through an A-D (analog-to-digital) converter. Hysteretic response was continuously monitored in the CRT screen, and progress of visible cracking could be observed because of the slow rate of loading.

TEST RESULTS AND COMMENTS ON GENERAL APPLICABILITY

Fig.4 shows the time histories of column deflections (or interstory drifts) for the 3-story model. Dotted traces indicate responses if all columns are assumed to remain elastic throughout the excitation. These indicate small deformations in the upper stories as intended due to relatively stiffer upper stories. However, maximum deformation of about 29 mm in the 1st-story columns early during the strong phase of the excitation (at about 2. sec) should have precipitated extensive inelastic deformation, which would accordingly alter the responses in all other stories computed using all-elastic assumption.

The bold traces in Fig.4 show the time histories of column deflections computed using substructure-based hybrid earthquake response analysis. The hysteretic response of the tested specimen is given in Fig.5a, showing a plot of measured restoring forces versus imposed displacements. The time history of the displacements imposed on the specimen is that shown in Fig.4c, resulted from a step-by-step solution of Eqn.3. Strong nonlinearity is induced in the first-story columns. Most of the input excitation energy were absorbed through hysteretic damping by the first-story columns, resulting in much reduced column deformations in the upper stories (Fig.4a and Fig.4b). Thus column deformations in the upper stories are within elastic ranges as modeled.

Similar observations can also be made of the five – story model. Time histories of column deformations are shown in Fig.6. Maximum 1st – story column drift of about 108 mm corresponds to about 6.6% of story height and yet the specimen didn't collapse due to well – confined concrete in the plastic zone . As shown, extensive inelastic deformation in the first – story columns resulted in much reduced column deformations in the upper stories. Severe stiffness deterioration in the 1st – story columns further accentuated the relatively – flexible first story and the relatively – stiff upper stories. Fig.5b shows the hysteretic response of the specimen strongly favoring one side, initiating strain – hardening of steel at deformation of about 40 mm and leaving a permanent deformation of about 60 mm.

The frames used practically models a structure with stiff upper stories and a soft first story. During strong earthquakes, inelastic deformations should be sustained at the critical sections without significant strength degradation, as embodied in earthquake – resistant design philosophy. This type of model in which nonlinearity is confined to certain critical sections is efficiently analyzed by substructure – based on – line hybrid response analysis.

In this paper, 2 specific frame models were analyzed to illustrate substructuring concepts applied to on – line hybrid procedure, making use of a simple cantilever set – up of tested specimens. The concepts of substructure – based on – line hybrid response analysis outlined earlier, however, is broadly applicable to a wider class of MDOF models with different combinations of analytical modelling and different arrangements of test specimens and actuators.

CONCLUSIONS

Structures in which certain critical sections are designed to dissipate intense earthquake energy through extensive hysteretic damping are efficiently and economically analyzed by substructure – based on – line hybrid earthquake response analysis. For this type of structures, extensive nonlinearities might be induced in some critical sections, which could drastically affect the overall response of the integral structure.

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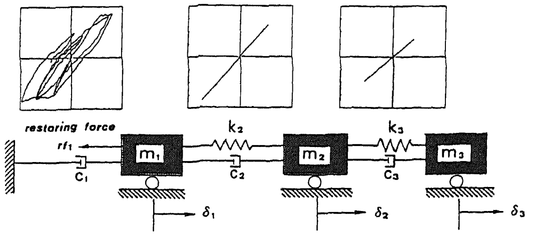


Fig.1 A 3 d.o.f. lumped-mass system with nonlinearity confined to element #1

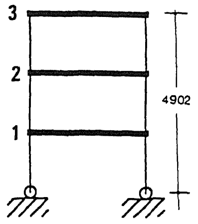
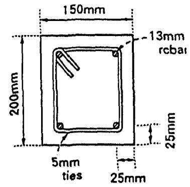
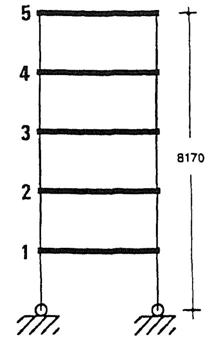


Fig. 3a 3-story model



3c specimen cross section



3b 5-story model

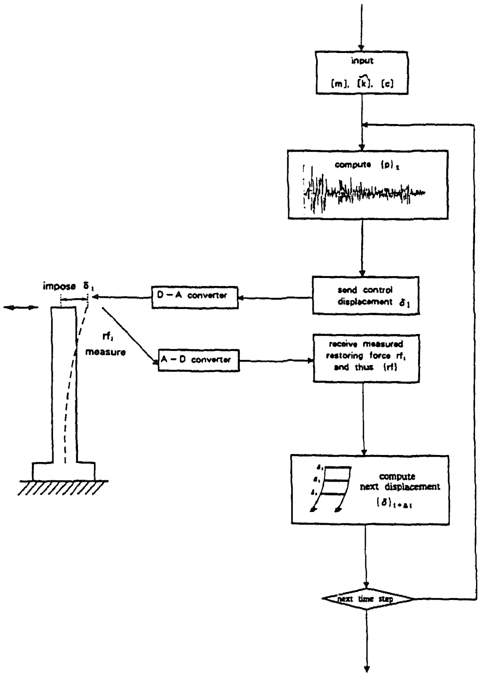
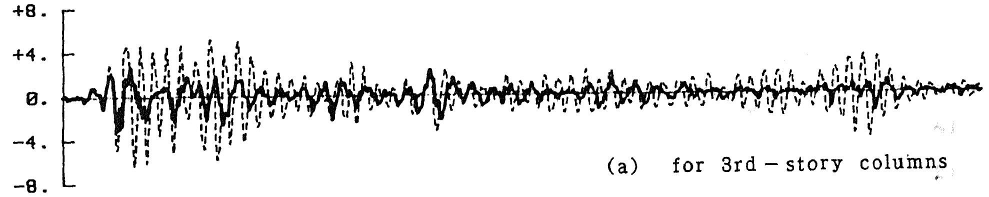
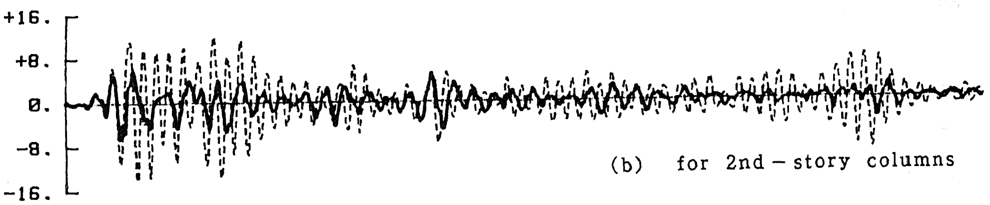


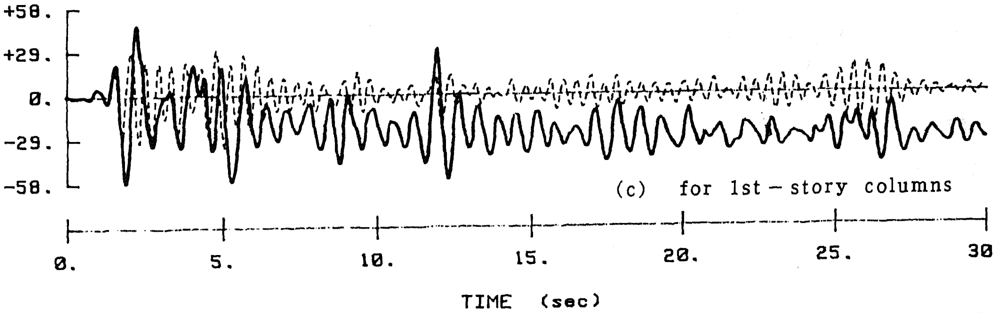
Fig.2 Main procedure of substructure-based on-line hybrid earthquake response analysis



(a) for 3rd-story columns

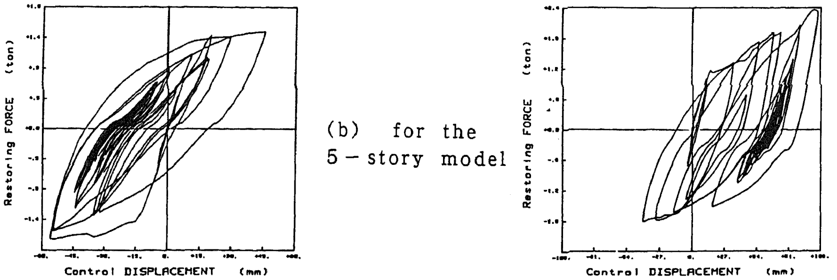


(b) for 2nd-story columns



(c) for 1st-story columns

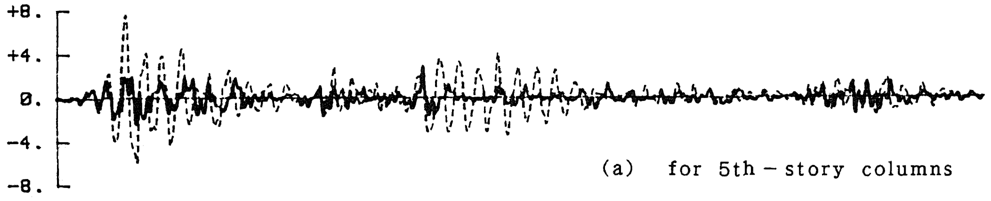
Fig. 4 Time histories of column deflections (mm) for the 3-story model.



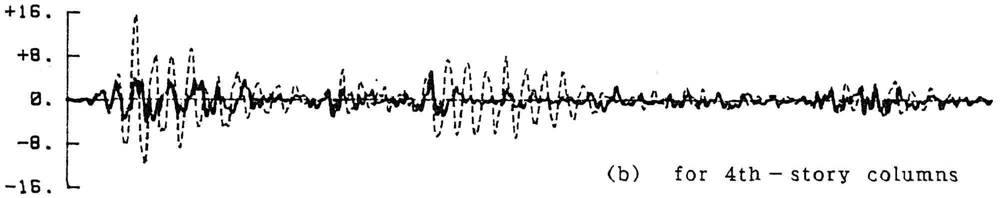
(a) for the 3 – story model

(b) for the 5 – story model

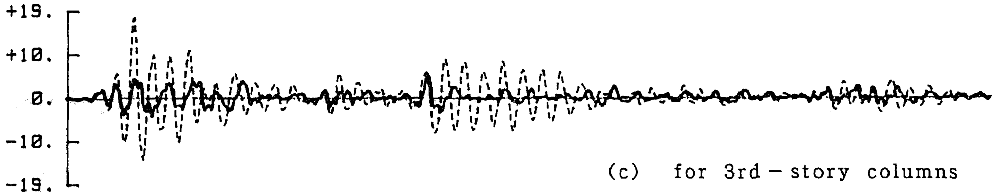
Fig. 5 Restoring force v.s. control displacement of tested 1st – story column



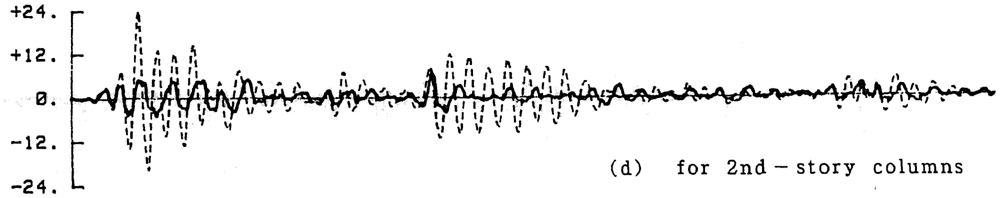
(a) for 5th – story columns



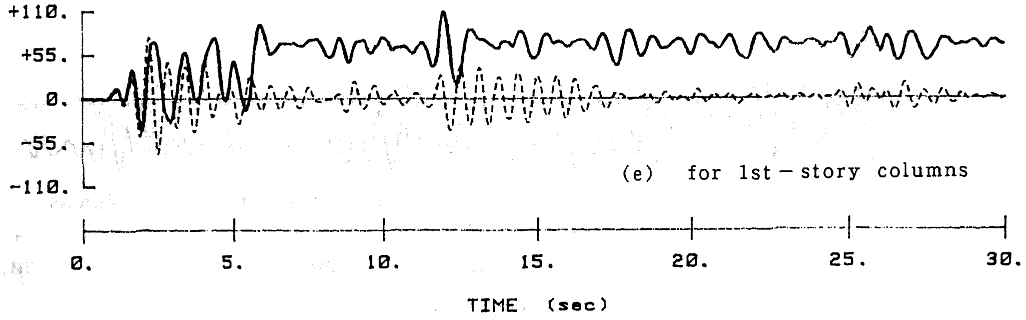
(b) for 4th – story columns



(c) for 3rd – story columns



(d) for 2nd – story columns



(e) for 1st – story columns

Fig. 6 Time histories of column deflections (mm) for the 5 – story model.