(126) ANALYTICAL FORMULATION AND LOADING CONTROL PROCEDURE IN SUBSTRUCTURED HYBRID LOADING TEST

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INTRODUCTION Most on-line hybrid tests (pseudodynamic tests) had been conducted on complete prototypes of structures. However, inelastic deformations in structures during strong earthquakes are often confined to some localized regions. By incorporating substructuring concepts into the basic form of on-line hybrid test, only the critical regions need to be fabricated and tested with the rest of the structure analytically modeled.

A complete structural system is considered to be divided into analytical substructures and experimental substructures. Portions of the structure that are as yet difficult to model mathematically are taken as experimental substructures. The remaining portions are taken as analytical substructures in which presently available analytical models are used to describe their restoring-force characteristics. For the experimental substructure, restoring-force information is directly measured from a specimen loaded to its current deformation state. A brief flowchart of the substructured hybrid loading test procedure is shown in Fig. 1.

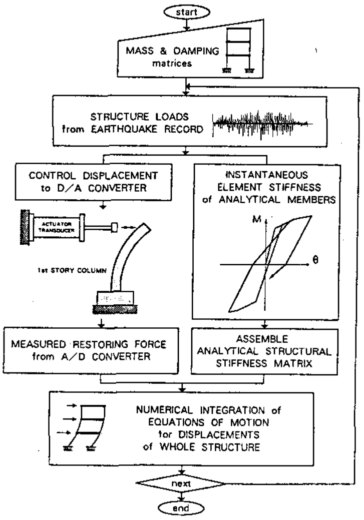

Fig. 1 Substructured Hybrid Test Procedure

In spite of its evident advantages, very few actual implementations of substructured on-line hybrid method have been done. Most of these tests were conducted to demonstrate the feasibility and concepts of substructured on-line hybrid technique. Two of the main reasons for the limited implementation of substructured on-line hybrid methods are: (1) lack of general loading system capable of subjecting a loaded specimen under any general deformation state; (2) numerical accuracy and stability problems.

In order to extend the applicability of substructured hybrid tests, a 3-D.O.F. general in-plane loading system has been devloped and implemented at the Earthquake Engineering Laboratory, Civil Engineering Department, Kyoto University. This paper will present the current implementation of substructured hybrid test using this loading system for testing columns and seismic isolators.

ANALYTICAL FORMULATION The procedure of computing inelastic earthquake response in a substructured hybrid test is very much similar to conventional analytical procedure, except for the contributions of the experimental restoring forces which may simply be treated as a subroutine for describing the hysteretic load-deformation characteristics of those experimental substructures. The equations of motion of a nonlinear inelastic structural system may be expressed as follows:

$$[M]\{\ddot{u}\}_{t+\Delta t} + [C]\{\dot{u}\}_{t+\Delta t} + \{R_f\}_{t+\Delta t} = \{P\}_{t+\Delta t} \tag{1}$$

In an on-line hybrid test method, the restoring force vector $\{R_f\}$ is measured from a specimen loaded to its current deformation state. For substructured hybrid test, the equations of motion may be similarly expressed as in Eqn. 1. But, the contributions into the restoring-force vector $\{R_f\}$ come from both analytical models and measured restoring forces from the loaded specimen. Hysteretic models (Bilinear, Takeda, 3-parameter, ...) are used to model the inelastic response of the analytical substructures.

NUMERICAL INTEGRATION SCHEMES Using the conditionally stable explicit integration method in substructured on-line hybrid tests of a MDOF system would necessitate extremely small integration time intervals in order to satisfy the required numerical stability criterion. This requirement is especially stringent in systems such as structural frame where the axial and rotation D.O.F.s are very much stiffer than the lateral ones. A class of so-called mixed integration methods originally developed for finite-element analysis of structure-fluid interaction has been found to be suitable for substructured hybrid tests [Nakashima et al, 1990; Dermitzakis and Mahin, 1985].

Belytschko and Mullen [1976] proposed an implicit-explicit node-by-node partitioning, while Hughes and Liu [1978] presented an element-by-element partitioning scheme. An explicit integration scheme is employed in the stiff subdomains, while an implicit integration scheme is used in the remaining flexible subdomains. Park [1980] presented a unified partitioning procedure which can incorporate the above two pioneering schemes and introduced a D.O.F. by D.O.F. partitioning scheme which can be applied to separate computationally the D.O.F.s exhibiting low frequencies from those exhibiting high frequencies. Belytschko, Yen, and Mullen [1979] presented a subcycling procedure in which different time steps are used in different partitions. All of the above procedures involve partitioning of the structural system in which appropriate procedures are used in each partitioned subsystem. Later, Plesha and Belytschko [1985] introduced a constitutive operator splitting method for nonlinear transient analysis (based on an earlier proposition by Hughes, Pister, and Taylor) in which the material constitutive law is split into a constant history-independent relation (implicit portion) and a variable history-dependent relation (explicit portion).

While all of the above procedures have been directed toward the solution of very large coupled-field interaction problems, the partitioning schemes lend themselves very amenable to substructured hybrid test procedure. Whereas implicit integration is used mainly for the stiff partitions in numerical analysis of coupled-field interaction problem, the suitability of mixed methods for substructured hybrid tests is that explicit integration can be used for the determination of the current deformation state of the experimental substructure. Hughes-Liu member partitioning scheme had been used in several cases of substructured hybrid tests and studies [e.g., Dermitzakis and Mahin, 1985; Nakashima et al, 1990] probably due to its natural adaptation to the member substructuring step in a substructuring hybrid test. The first mixed method by Belytschko and Mullen [1976] is also applicable to substructured on-line test and had been used in numerical studies [Nakashima et al, 1990]. Taking advantage of the popularity of the central difference integration scheme in hybrid tests, the subcycling technique may be worked to simplify programming and computational efforts. The DOF-by-DOF partition may be used to complement member partitioning scheme [Park, 1980] in which each element or subdomain is further partitioned into DOF's exhibiting low frequencies from high frequencies. The study of mixed integration methods is still a very active field of interest and it is expected that more useful schemes may be adapted for substructured hybrid tests.

Nakashima et al [1990] compared the 3 integration techniques (Belytschko-Mullen, Hughes-Liu, and OS methods) adapted for substructured hybrid test and has found that the constitutive operator splitting (OS) method is the most effective to substructured on-line hybrid tests in terms of both solution stability and accuracy. The OS method has been frequently used for substructured hybrid tests in Japan for the most recent tests based on the merits studied by Nakashima et al [1990]. It is adapted in the current implementation of this substructured hybrid loading test system used in the testing of steel box bridge piers presented in Yamada et al [1991(b)].

To implement the OS algorithm, Eqn. (1) is expressed as follows:

$$[M]\{\ddot{u}\}_{t+\Delta t} + [C]\{\dot{u}\}_{t+\Delta t} + \{R_f\}_{t+\Delta t}^{linear} + \{R_f\}_{t+\Delta t}^{nonlinear} = \{P\}_{t+\Delta t} \tag{2}$$

$$[M]\{\ddot{u}\}_{t+\Delta t} + [C]\{\dot{u}\}_{t+\Delta t} + [K]\{u\}_{t+\Delta t} + (\{R_f\}_{t+\Delta t} - [K]\{\tilde{u}\}_{t+\Delta t}) = \{P\}_{t+\Delta t}$$

An explicit trapezoidal rule for the predictive displacement vector is given by:

$$\{\tilde{u}\}_{t+\Delta t} = \{u\}_t + \Delta t\{\dot{u}\}_t + \left(\Delta t^2/4\right)\{\ddot{u}\}_t \tag{3}$$

On the other hand, an implicit trapezoidal rule (Newmark method with $\gamma = 0.5$ and $\beta = 0.25$)

$$\{u\}_{t+\Delta t} = \{\tilde{u}\}_{t+\Delta t} + \left(\Delta t^2/4\right)\{\ddot{u}\}_{t+\Delta t} \tag{4}$$

$$\{\dot{u}\}_{t+\Delta t} = \{\dot{u}\}_t + (\Delta t/2)\left(\{\ddot{u}\}_t + \{\ddot{u}\}_{t+\Delta t}\right) \tag{5}$$

Substituting the displacement and velocity expressions given above into Eqn. (2),

$$\{\ddot{u}\}_{t+\Delta t} = \frac{\{P\}_{t+\Delta t} - \{R_f\}_{t+\Delta t} - [C]\{\dot{u}\}_t - [C](\Delta t/2)\{\ddot{u}\}_t}{([M] + [C]\Delta t/2 + [K]\Delta t^2/4)} \tag{6}$$

It has been shown [Plesha and Belytschko, 1985] that the OS integration method is unconditionally stable for materials with decreasing stiffness (hysteresis is of 'softening' type).

A 3-DOF GENERAL IN-PLANE LOADING SYSTEM   Substructured hybrid tests had been conducted for specimens under bending [Dermitzakis and Mahin, 1985] and bending with rotation [Tsutsumi et al [1990]. A 3-DOF general in-plane loading system capable of subjecting a specimen under combined axial, shear, and bending loads has been developed and implemented. The overall set-up of the test bed and test rig is shown in Fig. 2. One actuator (max. load 40.tf; max. stroke 125.mm) is attached horizontally to the reaction wall, while two others (both max. load 40.tf; max. stroke 50.mm and 125.mm) are hanged vertically from the overhanging reaction girder. A rigid load-transfer beam was fabricated to transfer displacements and forces between the actuators and the specimen. Universal joints consisting of swivel heads and swivel bases are attached to both ends of each actuator. The loading system has been used to test RC and steel box-girder columns [Yamada et al, 1991(b)], and high-damping rubber seismic isolators (Fig. 3) [Yamada et al, 1991(a)].

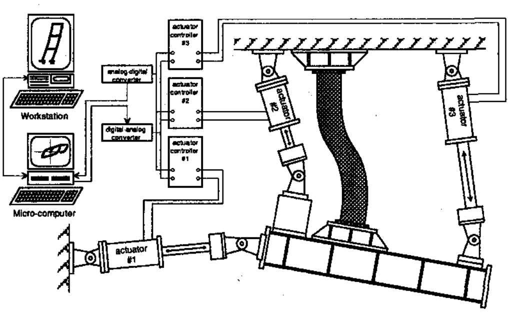

Fig. 2 Set-up for Testing Column

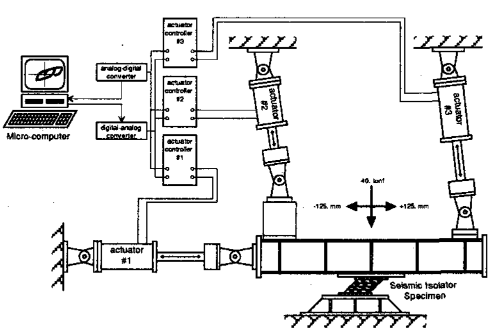

Fig. 3 Set-up for Testing Seismic Isolators

LOADING CONTROL PROCEDURE   The control computer used in these sets of experiments is a TEAC PS-9000 series 300 technical computer (manufactured by Yokogawa Hewlett-Packard) that is equipped with sophisticated interface programming control. An internal GPIB (IEEE 488 standard) interface bus is used to connect the analog-digital (A/D) converter, hard disks and other storage media, printers, pen plotters, and other peripherals. Digital strain reading device is also attached through the GPIB bus. Three channels of 12-bit digital-analog (D/A) converters are multiplexed through a Serial Output I/F module to the GPIO (General-Purpose Input/Output has 16 input lines and 16 output lines) interface in the control computer. In substructured hybrid tests, a Sony NEWS Workstation or a PC computer is connected by RS-232C serial interface to handle all the computational tasks, while the TEAC computer is solely devoted to controlling the actuators and other instruments.

General displacement pattern of the experimental substructure are transformed into deformation of an equivalent cantilever model. For a desired deformation state in the cantilevered specimen tip defined by $\delta_x, \delta_y, \theta_z$, the restoring forces P_x, P_y, M_z are to be determined. The procedure is outlined in the following: (1). Initial lengths of the actuator pistons are computed at the initial set position with the specimen tip O taken as reference origin; (2). Compute constant distances and orientations within a rigid body between specimen tip O and the respective positions of the pivot hinge of the swivel heads; (3). For a desired deformation state defined by $[\delta_x, \delta_y, \theta_z]$, locate the new position of the pivot hinge of the respective swivel heads; (4). From the computed new positions of the swivel heads, compute the changes in lengths in order for the piston to reach these new positions; (5). Find the actuator displacement control signals $\Delta_1, \Delta_2, \Delta_3$ and send commands to D/A converter; (6). Load cells inside the actuators measure the forces induced in the pistons F_1, F_2, F_3 and readings taken by A/D converters; (7). Specimen restoring forces P_x, P_y, M_z are computed based on equilibrium equations of the rigid transfer beam; (8). And finally, cantilever restoring forces are transformed into the required restoring forces at the member ends.

In the loading control procedure used, all computations of positions are taken with reference to a global set of axes with the origin at the initial tip position of the undeformed specimen. The geometrical problem of finite actuator lengths especially for precise control of specimen under combined axial, shear, and bending loads has been mentioned by Thewalt and Mahin [1987] in which a procedure of coordinate transformations was proposed.

CONCLUSIONS Using the 3-DOF general in-plane loading system, seismic isolators and columns had been tested. Combined with substructured hybrid loading test procedure, critical members can be tested under realistic loads and proper boundary conditions. Using restoring forces that are directly measured from a loaded specimen, inelastic earthquake response of the total structure can be reliably predicted.

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