A 3-DOF GENERAL IN-PLANE LOADING SYSTEM
FOR INELASTIC EARTHQUAKE RESPONSE OF STRUCTURES

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Introduction   The main objective of this paper is to present the development of a general 3-DOF (degrees of freedom) in-plane loading system capable of subjecting a specimen to combined pattern of axial, lateral, and bending loads. Furthermore, the set-up has been designed to test columns as well as seismic isolators. The main motivation for this is to extend the applicability of substructured hybrid loading test to general types of structures. At the same time, the usual procedure of quasi-static cyclic loading tests can be extended to included more complex patterns of generalized loads.

3-DOF Loading System   The displacement pattern of a general frame member is defined by u_1, u_2, u_3 at A-end and by u_4, u_5, u_6 at B-end. Rigid-body motion is included in this general displacement pattern. A stable determinate configuration is chosen, analogous to that used in element flexibility matrix formulation of structural analysis. A cantilevered set-up is chosen in which the axial displacement δ_y, lateral displacement δ_x, and rotation θ_z at the column tip are to be controlled. Another possible stable determinate configuration in the theoretical sense is a simply-supported beam-column set-up. However, this is a not practical approach to implement since the two ends have to be rotational controlled along with the axial displacement at the roller support.

For the cantilevered set-up, global displacements of the general displacement pattern $[u_1, u_2, \ldots, u_6]$ are transformed into member deformations $[\delta_x, \delta_y, \theta_z]$ corresponding to a cantilevered specimen. Based on these imposed displacements, restoring forces for the cantilever $[P_x, P_y, M_z]$ are measured; and by force equilibrium, global restoring forces of the member $[F_1, F_2, \ldots, F_6]$ are obtained. These are contributing restoring forces of the experimental substructure to the structural restoring-force vector $\{R_f\}$.

The developed 3-DOF general in-plane loading system has been implemented at the Department of Civil Engineering, Kyoto University. One actuator (designated as actuator no. 1) is attached to the reaction wall, while two others (no. 2 and no. 3) are hanged vertically from the overhanging reaction girder. Load actuators no. 1 and no. 3 have maximum stroke of $\pm 125.$ mm and static load capacity of 40. tonf and 32. tonf when operated dynamically. Actuator no. 2 also has the same load capacity as the others, but has a maximum stroke of $\pm 50.$ mm.

A rigid load-transfer beam was fabricated to transfer displacements and forces between the actuators and the specimen. Rigid shim plates and spacer blocks are inserted to settle differences in lengths of the actuators and also to accommodate different sizes of specimens. 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 diverse types of specimens, such as RC and steel box-girder columns (Fig. 1(a)), and high-damping rubber seismic isolators (Fig. 1(b)).

The control computer used in these sets of experiments is a TEAC PS-9000 series 300 technical computer 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.

Control Algorithms   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 main procedure of the basic control algorithm is outlined as follows:
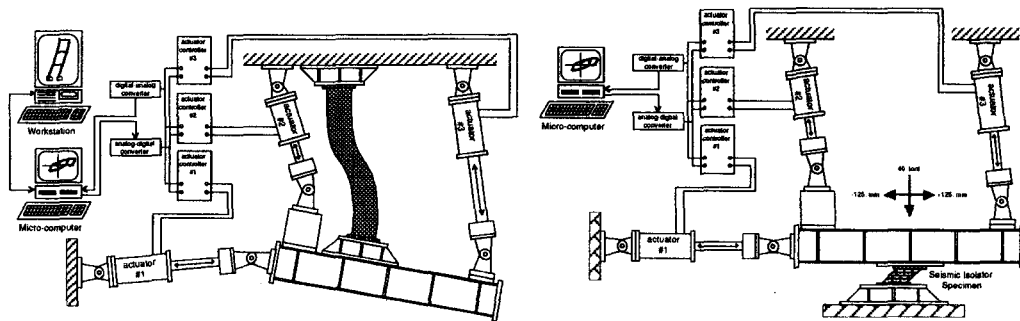
(a) Column Specimen   (b) Seismic Isolator Specimen
Fig. 1   Specimens Tested by the 3-DOF Loading System

(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.

   For most practical purposes, control by the basic algorithm is difficult to achieve. Especially for column specimens, the axial displacement degree of freedom is much smaller than the sensivities of loading actuators. For this reason, a modified control algorithm is used in which a feedback control is used until the target axial load is achieved within certain accuracy.

Applications   Using the 3-DOF general in-plane loading system, seismic isolators and columns had been tested under quasi-static loading and substructured hybrid loading tests. Test results on seismic isolators are presented in Ref. [1], while recent test results conducted on steel box-shaped beam columns will be presented in the two related papers by Yamada, Iemura, Yasuda, and Oka in this convention.

Summary and Conclusions   Using the 3-DOF general in-plane loading system, inelastic behavior of structural elements can be tested under combined axial, shear, and bending loads. 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.

Reference   [1]. Y. Yamada, H. Iemura, W. Tanzo, Y. Uno, and S. Nakamura [1991]: "Hybrid Loading Test of the High Damping Rubber Bearings Subjected to Sinusoidal and Random Earthquake Ground Motion," to appear in Proc. of the Structural Engineering, Japan Society of Civil Engineers.