(92) DEVELOPMENT OF SUBSTRUCTURE-BASED HYBRID LOADING SYSTEM OF EARTHQUAKE RESPONSE (SUB-HYLSER)

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Introduction Structures designed to survive intense earthquake ground motions should do so by sustaining large inelastic deformations at some critical locations without failing. Many analytical studies have been done to provide estimates of the ductility demands in structural systems subjected to severe earthquakes. Realistic assessment of such ductility demands using inelastic dynamic analysis programs can be obtained by incorporating hysteretic models that could closely reproduce actual behavior of each component elements.

Development of inelastic structural response analysis started with the simple bilinear elasto-plastic constitutive law, and then graduated into mathematically more involved models, such as the Ramberg-Osgood model that simulates the Bauschinger effect in steel. However, reinforced concrete (R/C) hysteretic behavior seems to defy any simplicity; nor does it observe much of mathematical sophistication. When subjected to substantial cyclic inelastic deformations, R/C members exhibit both stiffness and strength degradation. An interplay of various mechanisms involving flexural and shear deformations, bond slip, cracking and crushing of concrete, strain hardening of steel and the Bauschinger effect under load reversals, etc..., leads to a very complex behavior.

In recent years, vastly improved hysteretic models for R/C elements have evolved. The hysteretic relationship defined by these models traces the response paths through some prescribed mathematical rules. Laboratory testing serves to specify these rules, as well as to verify a model. Since a proposed model is calibrated and verified on the basis of a set of experimental results, predicted response to input loads outside the tested range should therefore be treated with discreetness.

In this paper, a substructure-based hybrid seismic testing system is proposed in view of some inherent limitations in presently available testing methods for calibration and verification of hysteretic models. Some observations taken from a series of still-unconcluded numerical simulation tests of a three-story single-bay frame model are briefly discussed.

Experimental Calibration and Verification of Hysteretic Models Among the available experimental testing methods, quasi-static cyclic loading tests provide model calibration and verification with the type of information needed, i.e., responses of a cyclically loaded specimen in terms of load and deformation characteristics directly observed throughout the duration of a prescribed loading history. Quasi-static cyclic loading tests are generally conducted on isolated-beam specimens or sub-assemblages by subjecting these to a slow sequence of arbitrarily prescribed loads or displacements involving full inelastic reversals in both directions. R/C parameters affected by scale influence (e.g., concrete cracks, bond slip) are irreproducible in reduced-scale prototypes tested on shaking tables. On the other hand, conducting cyclic loading tests on full-scale or near-scale isolated-beam specimens allows load-deformation characteristics to be closely observed and monitored.

The realism of test results depends on the degree to which the laboratory loading program represents actual earthquake conditions. For one, inertial and damping forces are absent in quasi-static tests. In spite of the voluminous data accumulated over years of testing isolated-beam specimens, interpretation and comparison have been made difficult by differences in defining realistic loading criteria among various research groups. Until now, there is still a lack of agreement on "realistic performance expectations" for conducting cyclic loading tests [Yorulmaz, 1981].

Hybrid Loading System of Earthquake Response   Earthquake response of single degree-of-freedom (SDOF) models have been realistically simulated by HYLSER (Hybrid Loading System of Earthquake Response) system [Iemura et al, 1980; 1984; 1986]. Detailed investigation of the hysteretic behavior of SDOF models by such hybrid analytical-experimental method gives better results than those possible under pure analytical studies or quasi-static cyclic loading tests. The HYLSER system was used to verify a stress-strain based model in which time-varying axial loads acted in combination with bending moment loads [Ristić, Yamada, and Iemura, 1986].

A far larger class of structures, however, cannot be modeled as SDOF systems. In cases of severe inelastic deformations limited to certain localized regions in a large structural system, considerable costs could be saved by testing only those portions where present state of development does not allow inelastic behavior to be modeled mathematically. Dermitzakis and Mahin [1985] have shown the feasibility of applying substructuring concepts in pseudo-dynamic testing method. This paper deals with a substructuring technique that could be used to extend the utility of the HYLSER system without entailing any additional hardware need.

Substructure-Based Hybrid Earthquake Loading System   It has been pointed out by a recent research [Sattary-Javid and Wight, 1986] that magnitude of tip displacements imposed during inelastic cyclic loading tests should be dependent not only on building drifts, but should also be some function of the location of the prototype beam in a complete structural system. Furthermore, results obtained by subjecting test specimens to arbitrarily-prescribed loading histories might not correlate well with members of a complete structure undergoing substantial inelastic deformations, in which extensive redistribution of stresses takes place among members.

Using the proposed substructure-based on-line hybrid loading system, seismic behavior of a member being studied is simulated by imposing on a cantilever model the local deformation level that a member sustains as part of a complete structural system under earthquake forces. These local deformations, transformed from generalized displacements corresponding to the test specimen, results from a step-by-step inelastic seismic structural analysis. Restoring forces developed on the loaded specimen are measured and transformed into generalized forces. These generalized experimental restoring forces are then assembled to those of the analytical members, whose properties are defined by mathematical constitutive laws.

At each time step, equations of motion are set up and reduced to a form similar to static force-displacement relationship.

$$\left[\mathbb{A}\right]\left\{\Delta\right\}^{t+\delta t}=\left\{\mathrm{B}\right\}$$

The **A**-coefficient matrix contains constants related to both mass and damping matrices; while the **B**-vector is updated incrementally for changes in applied earthquake loads, analytical stiffness matrix, and experimental restoring-force vector. Displacements at the next time step are explicitly determined based entirely on displacement vectors of the previous two steps. From there, step-by-step solution proceeds recursively to get the next displacement vector.

As an investigative tool for studying general seismic behavior of frame structures, deformation (axial, lateral, rotational) histories need not be imposed in the exact manner outlined above. Great simplification is achieved by pinpointing the inflection on the frame member where a critical section is to be studied. Presumably, if the inflection point does not shift appreciably during dynamic motion, inelastic property of a frame member in focus could be modeled by forcing the tip displacements of an analytical cantilever sub-element and an experimental cantilever sub-element to deform so that these equal the lateral deformation of the simulated frame member at the inflection point. Based on this implementation,

$$\left[\mathbb{A}\right]=\frac{1}{(\delta t)^2}\mathbb{M}+\frac{1}{2\,\delta t}\mathbb{C}$$

$$\left\{\mathrm{B}\right\}=\mathbb{M}\,a_g{}^{t}-\left\{\Phi_\Delta^*\right\}^{t}-\left[\overline{\mathbb{K}}_\Delta^*-\frac{2}{(\delta t)^2}\mathbb{M}\right]\left\{\Delta\right\}^{t}-\left[\frac{1}{(\delta t)^2}\mathbb{M}-\frac{1}{2\,\delta t}\mathbb{C}\right]\left\{\Delta\right\}^{t-\delta t}$$

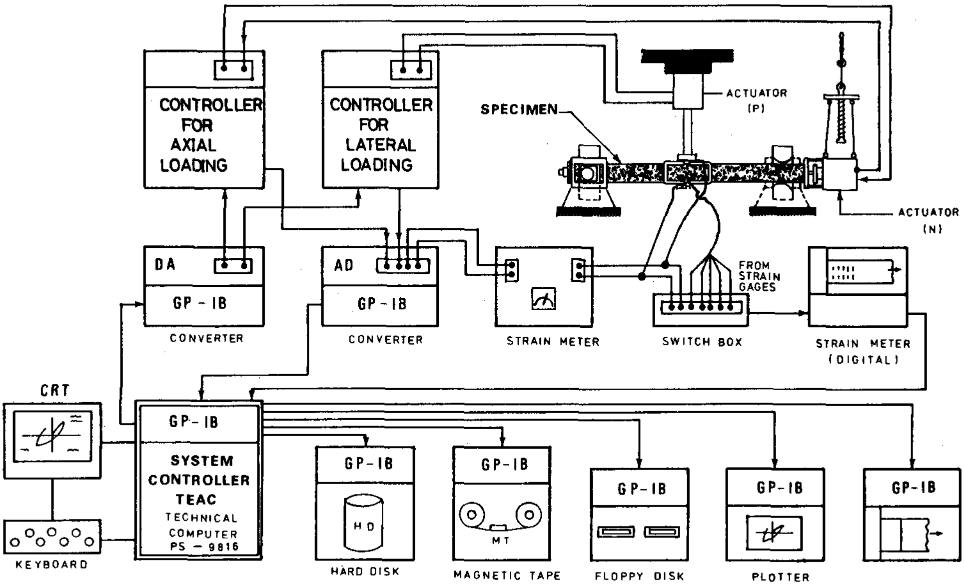
$$\left[\overline{\mathbb{K}}_\Delta^*\right]=\left[\overline{\mathbb{K}}_{\Delta\Delta}\right]-\left[\overline{\mathbb{K}}_{\Delta\theta}\right]\left[\overline{\mathbb{K}}_{\theta\theta}\right]^{-1}\left[\overline{\mathbb{K}}_{\theta\Delta}\right]$$

$$\left\{\Phi_\Delta^*\right\}=\left\{\Phi_\Delta\right\}-\left[\overline{\mathbb{K}}_{\Delta\theta}\right]\left[\overline{\mathbb{K}}_{\theta\theta}\right]^{-1}\left\{\Phi_\theta\right\}$$

Experimental setup of the proposed substructure-based on-line system (SUB-HYLSER) is shown on the next page. Flow diagrams charting the two main routines of SUB-HYLSER appeared in a previous paper [Yamada, Iemura, Izuno, and Tanzo, 1987].

Some Observations from Numerically Simulated Tests   A series of numerically simulated test runs on a three-story single-bay frame has been conducted to identify possible areas of difficulty in implementing the proposed SUB-HYLSER system. In the investigation, all analytical structural members are modeled by single-component models, in which each member is represented by an elastic beam element with inelastic point-hinges at the ends to capture the essential inelastic response of the whole member. The Takeda hysteretic model is employed to define properties of inelastic springs. Effects of finite joint sizes are accounted for by assuming that the portion of the frame common to both beam and column at their intersection is rigid. The 30-sec NS-component of the El Centro earthquake is used as the input record.

A range of structural properties were used to evaluate the stability criterion of the numerical integration scheme. Unlike in pure analytical studies where computation time could be compromised to achieve stability, a loaded specimen in a hybrid experiment should not be kept waiting too long. For instance, a 30-sec earthquake record digitized at 0.02 sec would require approximately 1 hour to complete one cycle of test on the three-story single-bay frame model. But if stability criterion necessitates a 0.001 time increment, then conducting a single test over 20 hours will no longer be feasible due to the strain rate effects on the hysteretic restoring-force characteristics [Wakabayashi et al, 1984]. While the central difference scheme offers computational ease, a suggested mixed implicit-explicit algorithm [Dermitzakis and Mahin, 1985] might proved advantageous in some cases to achieve a certain degree of unconditional stability.



Concluding Remarks The same SDOF-able HYLSER system is used to determine the earthquake response of a critical member as part of a MDOF structural frame, by implementing a so-called hybrid substructuring technique. The experimental program devised could test isolated-beam specimens under a better-defined realistic loading criteria (compared with quasi-static cyclic loading tests). Through a series of numerically simulated tests on a three-story single-bay frame model, possible areas of difficulty in implementing the proposed SUB-HYLSER system are pointed out.

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