(113) ANALYTICAL AND SUBSTRUCTURED ON-LINE HYBRID ANALYSES OF INELASTIC R/C FRAMES

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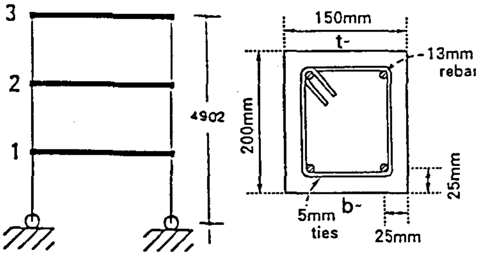
Summary Inelastic seismic response of a reinforced concrete frame using results from a substructured on-line hybrid experiment is first presented. Dispacement response and load-deformation response of the critical member are then compared with results computed by an inelastic dynamic analysis using hysteretic member models. Furthermore, moment-curvature reponse at the critical section is compared with analysis based on material stress-strain modeling.

Substructured Hybrid Experiment
In recent years, on-line hybrid experimental method has been developed in which large-scale specimens are subjected to realistic simulated earthquake motion by means of on-line computer control of loading actuators. Incorporating substructuring concepts, a substructured on-line hybrid test method is developed in which the critical regions are tested experimentally and the rest of the structure are modeled analytically. Iemura et al (Ref.1) used a substructured hybrid loading system for earthquake response (SS-HYLSER) to study extensively-nonlinear behavior of first-story columns in multistory R/C frames. Test results for a 3-story 1-bay frame (Fig.1) reported in Ref.1 is presented here for comparison with analytical solutions.



	Weights	Damping	Stiffness
1	3.5 t	5%	—
2	3.0 t	5%	.374 t/mm
3	2.0 t	5%	.374 t/mm

Fig.1 A 3-story frame model

Inelastic Dynamic Analysis Using Hysteretic Member Models In this comparative study, a flexural element is analytically separated into two cantilever elements at the point of inflection as suggested by Otani (Ref.2). Takeda hysteresis rule is used to characterize the nonlinear springs. Computed (indicated as IDA) first-story displacement response history is given in the same plot (Fig.2) as the response determined by substructured on-line hybrid experiment. Simulated moment-rotation response (Fig.3b) for 30 seconds is compared with that determined by SS-HYLSER (Fig.3a). Up to the first peak displacement, generally good agreement can be seen in these comparisons. However, dispacements during the strong excitation phase predicted by IDA are greater than those obtained by SS-HYLSER. Going from the maximum A to maximum B in the other direction, the unloading and loading stiffnesses simulated by IDA have deteriorated more than what had been measured.

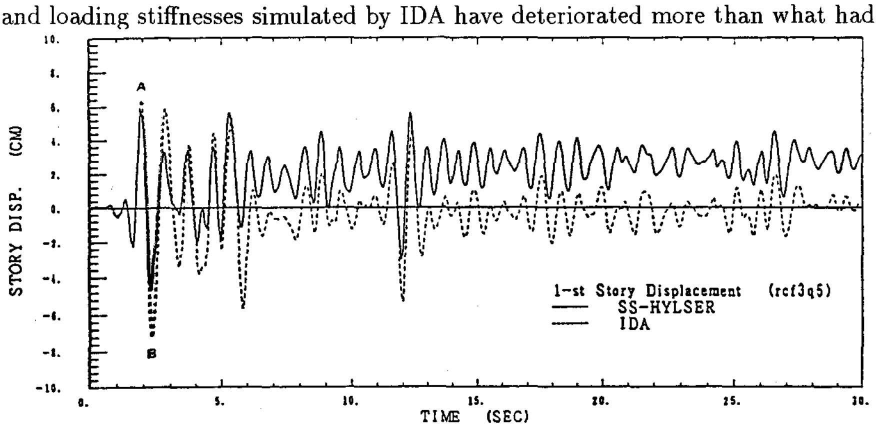


Fig.2 Displacement response of 1st-story column

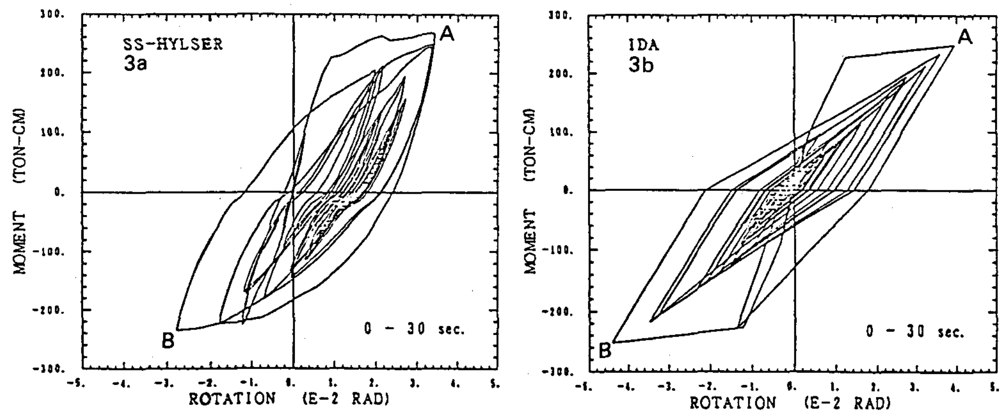


Fig.3 Moment-Rotation response of 1st-story column

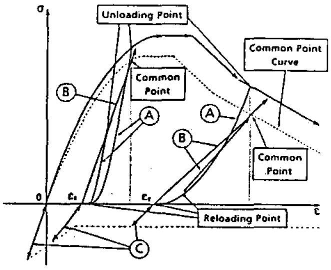


Fig.4 Concrete stress-strain model

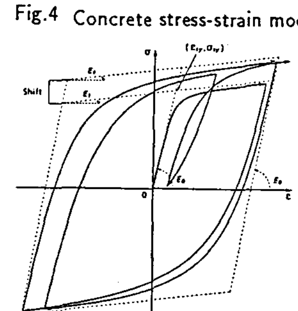


Fig.5 Steel stress-strain model

Inelastic Curvature Analysis Using Material Stress-Strain Models

A method of stress-strain based inelastic earthquake response analysis of R/C frame structures with varying axial loads has been developed by Ristić, et al (Ref.3). For the stress-strain model of concrete, concrete confinement levels, tension stresses, failure in tension, plastic strains, crushing of concrete, compressive failure and stress degradation are described with nine different rules, five of which are previous-path dependent (Fig.4). For the stress-strain model of steel fibers, Bauschinger effect, plastic strain and isotropic strain hardening are taken into account (Fig.5).

Using fiber analysis, moment-curvature response for the first 10 seconds of measured curvature history at the critical section is simulated, in which the cross section is discretized into 2 steel fibers and 74 concrete fibers. Analysis is computed at a time step of 0.001 sec. (1/10 of the experimental time steps).

Generally good agreement can be observed in the comparative plot (Fig.6a) of computed and measured (from restoring forces measured) moment histories. Computed peak moments are well predicted. For the ensuing smaller amplitude motion (e.g., between 6.s to 8.4s), however, simulated moments are larger than what were actually measured.

The stresses and strains at the extreme fibers are given: t- steel (#1); b- steel (#2); t- concrete (#35); b- concrete (#74). Crack openings of the concrete elements can be deduced from the stress and strain histories plots in Figs.8c–d when at large tensile strains (plotted negative) concrete stresses are zero. Maximum compressive stresses in the extreme concrete fibers (plotted positive in Figs.9c–d) are reached early, but maximum strains are less than 0.04 (no cover concrete spalling was observed during the test). Yield ($\epsilon_y \approx 0.002$) in both steel fibers were initiated early, with steel fiber #1 yielding at about 1.5s and steel fiber #2 follows at about 1.7s. This early yielding of both steel fibers precipitated large tensile strains in both directions. For most of the duration following this, cracks remain opened on both sides of the critical section with the steel couples providing the only resisting moments (e.g., at 2.4s). With a bigger curvature, crack on one side closes and concrete resumes to sustain compressive stresses (C in Fig.8d) resulting in sudden pickup of moment resistance and thus the abrupt change in stiffness in between A to B in Fig.7b. In the small-amplitude response following a sequence of large-amplitude response, for instance between 6.s to 8.4s, fiber model analysis indicated that cracks are opened at both sides and only the steel fibers (which have already yielded extensive) are providing the resisting couple (Fig.8a–d).

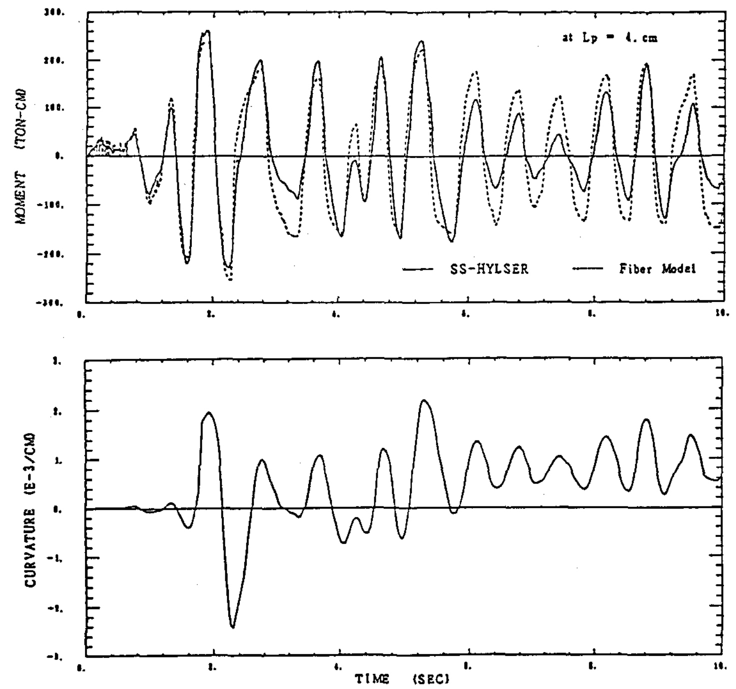


Fig.6 Moment and curvature histories

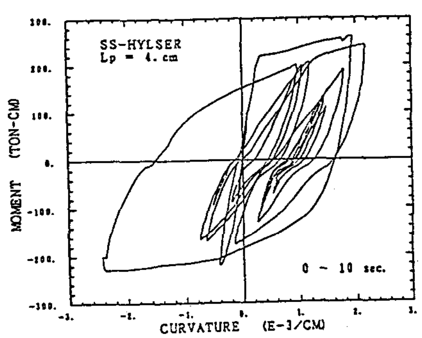


Fig.7a Measured moment-curvature curve

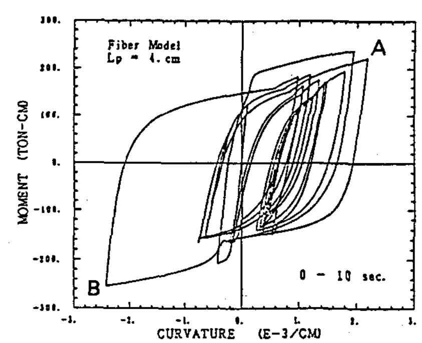


Fig.7b Simulated 10.s moment-curvature response

Concluding Remarks By substructured on-line hybrid method, critical sub-assemblages can be tested economically under realistic load histories and considering proper boundary conditions. Test can be done with simple set-up, testing only critical sub-assemblages that are likely to undergo extensive nonlinear behavior, while at the same time, inelastic response of the whole structure as affected by the complex behavior of the critical element(s) can be reliably predicted.

References [1] Iemura, Yamada, Tanzo (1988), "Testing R/C Specimens by a Substructure-based Hybrid Earthquake Loading System," *Proc., 9WCEE.* [2] Otani (1974), "Inelastic Analysis of R/C Frame Structures," *J. Struct. Div., ASCE,* 100(7). [3] Ristić, Yamada, Iemura, Petrovski (1988), "Nonlinear Behaviour and Stress-Strain Based Modeling of Reinforced Concrete Structures under Earthquake Induced Bending and Varying Axial Loads," *Research Report No.88-ST-01,* School of Civil Engineering, Kyoto University.

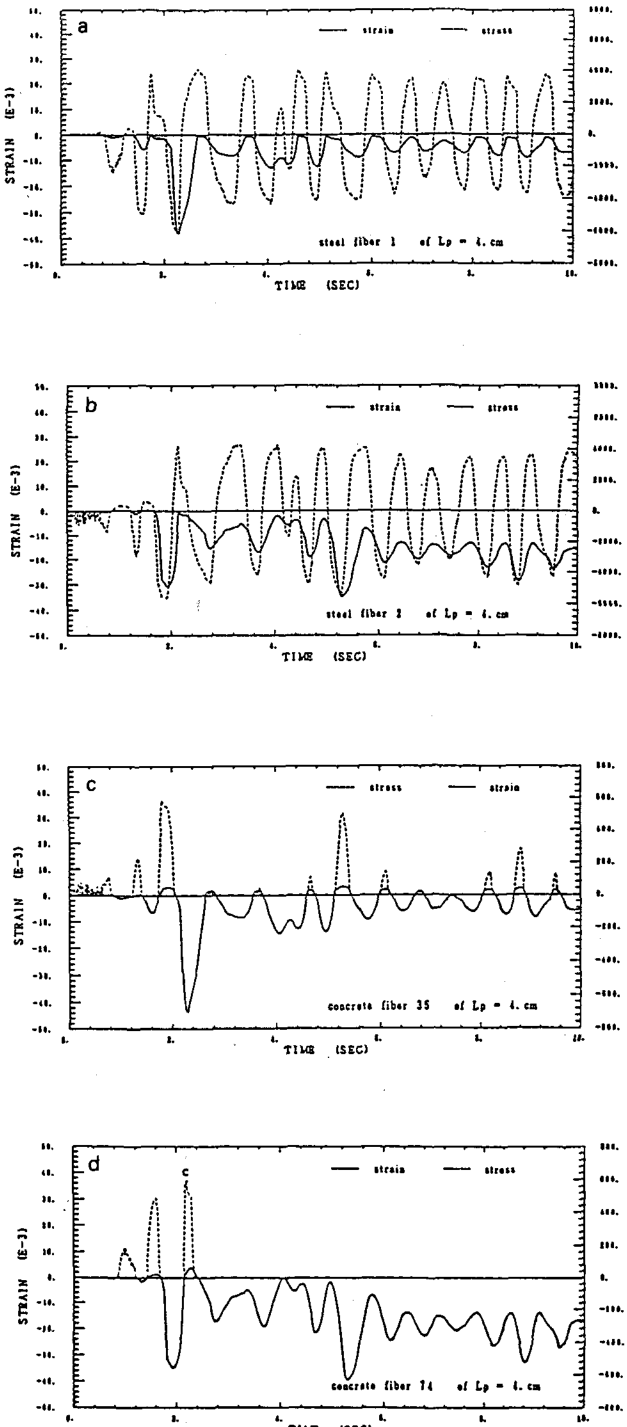


Fig.8 Stress and strain histories of concrete and steel fibers

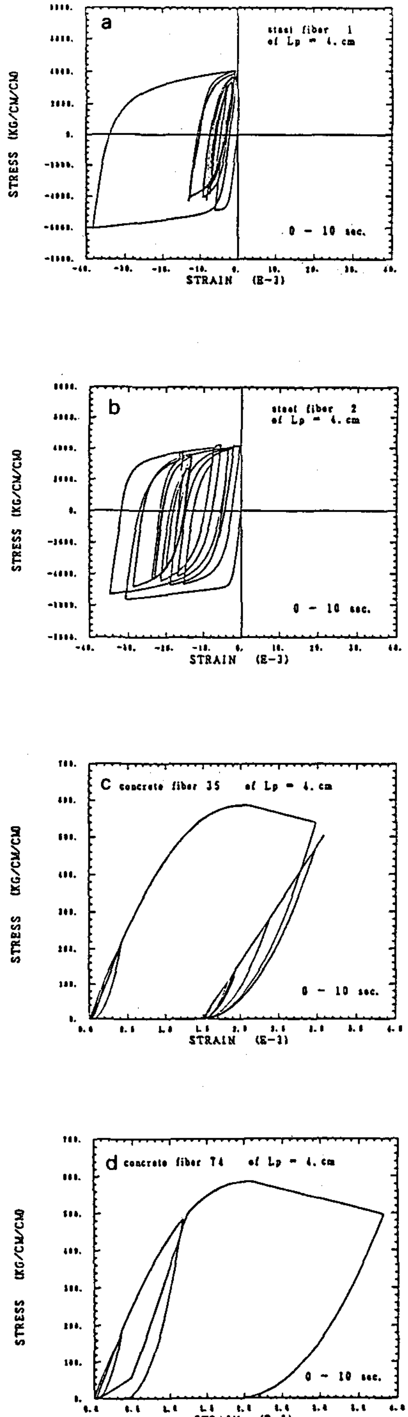


Fig.9 Stress-strain curves
of concrete and steel fibers