Session 5.B: RESPONSE OF STRUCTURES TO GROUND SHAKING

Discussion of Paper No. 220

"EFFECT OF DEGRADING STIFFNESS ON THE RESPONSE OF MULTISTORY FRAMES SUBJECTED TO EARTHQUAKES"

by

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INTRODUCTION

The objectives of this discussion are: first to emphasize the significance of the results and conclusions offered in the paper; second to ask for clarification and/or elaboration regarding how some of the results presented were obtained; and finally to suggest an inelastic design procedure which attempts to satisfy the following two requirements put forth by the authors:

1. To avoid premature failure.
2. To rely upon the large potential of energy absorption capacity of the non-linear response.

SIGNIFICANCE OF AUTHORS' RESULTS AND CONCLUSIONS

The results presented by the authors points out clearly that when the efficiency of a proposed seismic design has to be judged by means of dynamic analyses it is of paramount importance to consider realistic mechanical model for the load-deformation relationship of reinforced concrete and to select very carefully the input ground motions and the response parameters that will be used as yardsticks to measure the degree of efficiency.

GROUND MOTION: The importance of the strong motion duration in the inelastic response of a structure is brought clearly in the results obtained for the Magnitude of Yielding i.e., increase in the girder ductility. By comparing the results obtained with earthquakes A-1 and B-1 it is evident that earthquakes with the same intensity (peak ground acceleration) can lead to considerably different ductility demands depending upon the duration of the strong motion. Similar results were obtained by Anderson and the writer(1). Recent studies in connection with the damage of the Olive View Medical Center during the san Fernando Earthquake(2) show that the structural inelastic response is not only sensitive to the strong motion duration but also to the area of the large acceleration pulses and their sequence. Therefore, in studying the reliability of any proposed seismic design one has to be careful in including analysis against

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earthquakes having the longest strong motion duration and largest acceleration pulses that could be expected during the service life of the structure.

NUMBER OF YIELD EXCURSIONS: Because of the degradation in stiffness which is included in the model DBL, the writer would have expected less number of yield excursions for this model than for the BL hysteretic model. However, the results presented in table 3 shows that this is not so. Therefore, it would be greatly appreciated if the authors can offer an explanation for the insensitiveness of this parameter to the different characteristics of the hysteretic models and also to clarify why the number of yield excursions are called "suggested" rather than "computed."

SYSTEMS OF FORCES: It is clear from the results presented that the ductility demands of an inelastic systems can not be obtained accurately by using the story shears, axial loads and/or the overturning moments. The writer has also found that in general the envelope of maximum lateral displacement (which is usually considered as an important parameter) is not a very sensitive parameter for judging ductility requirements at the critical regions(1,3). Thus, it would be of interest to know if the authors have obtained in their study the envelopes of maximum lateral story displacement for the two different models and can compare them.

MAGNITUDE OF DUCTILITY: It would be greatly appreciated if the authors can elaborate on the following:

1. What is the definition of the ductility factors that have been used in Fig. 3? Is it based on curvature or rotation ductility?
2. What mechanical model has been used in the dynamic analysis to determine such ductility factors? A two-component element model or just an one-component?
3. Did the computer program used in the dynamic analyses include the effects of the gravity forces, P-Δ and that of the axial forces in the yielding of the columns?

The above questions are raised because previous study(1) has shown that the computed ductility demands are very sensitive to most of the above parameters.

According to the results presented in Fig. 3(c) the ductility of the columns at the first story is smaller than 1. Is this because the frame analyzed had the columns hinged at the foundation?

The writer believes that in the cases of frames with short members for a proper evaluation of the ductility demands (inelastic rotations) it would be necessary to use a more realistic degrading system than the BDL suggested by the authors. The main reason for this belief is that in case of members with high shear there is an early significant degradation in stiffness which lead to a very significant reduction not only in energy absorption but specially in energy dissipation (4).

SUGGESTED SEISMIC DESIGN PROCEDURE

The discusser fully agrees with the authors remarks that "it is necessary to design for the system of forces associated with the yielding stage of the response in order; (1) to avoid premature failure; and (2) to rely upon the large potential of energy absorption capacity of the non-linear response."

As it has been expressed in a previous discussion(3) the writer believes that any structure in which safety requirements control the design and which is expected to be strained well into the inelastic range should be designed using inelastic models. In other words, it should be based on the limit state that actually controls the design and not on a fictitious state, as is usually the case using loading conditions prescribed in static-type seismic codes. In looking for an adequate seismic design procedure, the designer should recognize the non-deterministic nature of the earthquake-resistant design problem. Future extreme earthquakes cannot be predicted precisely, and great uncertainties are involved in defining the Design Earthquake. Even under any deterministically specified earthquake ground motion, the design problem cannot be reduced to one deterministic analysis because the structural parameters controlling the mechanical behavior of the building are not deterministic quantities. The designer should carry out several analyses considering possible bounds of the main parameters controlling the response of the building.

Our inadequate knowledge of real mechanical behavior (excitation and mechanical model) should be supplemented by providing the building with high ductility. This can be accomplished with a more careful detailing of the critical regions which control the inelastic response and a more thorough inspection of their execution (construction) than has been done in the past or than is used in standard (non-earthquake-resistant) structures. Therefore, one of the designer's main problems is to recognize the critical regions and to obtain guide values that control their detailing. While the location of critical regions is not a very difficult problem, determination of the parameters controlling their possible behavior and therefore their detailing is more complex. At present it is accepted that one of the most important factors in this detailing is the so-called required rotation ductility. The writer would like to go a little further than this and state that more important than ductility requirements is obtaining a good idea of the complete moment-rotation and shear force-shear distortion hysteretical behavior of these regions during probable extreme earthquakes (extreme in intensity of acceleration pulses, frequency content and duration).

While for the very simple case of standard structures and a specified standard earthquake ground motion, it might be possible to get an idea of the "ductility" requirements from assumed "elastic" dynamic responses and by applying experience and good judgment, it has been shown that in general results obtained from dynamic linear elastic analyses cannot lead to reliable estimates of actual rotation ductility requirements(1).

Furthermore, the use of a "constant displacement ductility factor" -- usually 2 to 6 -- as the only yardstick in deciding whether to accept a seismic design is not adequate. In case of real mechanical behavior in which the load-deformation relationship is far from being linear elastic-perfectly plastic, it is not clear how to define the critical displacement ductility ratio. This is especially true in case of reinforced concrete structures in which considerable degradation in stiffness and therefore in energy dissipation capacity usually occur.

To assure safety against structural failure and to achieve an economic design, it is necessary that the variation of the maximum ductility requirements throughout the structure follow a properly selected pattern. Selection of proper ductility patterns should be done considering not only the possible state of stress at the critical regions but also the tolerable degree of damage and the repair cost. Present design methods usually based on prediction of the linear elastic mechanical behavior of structures cannot in general guarantee a desirable distribution of ductility. Thus, attempting to achieve the most economical and practical design which is both serviceable and able to resist severe earthquakes safely, an inelastic design method has been developed for the design of multistory unbraced frames(5). This method of design is based on the dissipation of the earthquake input energies through inelastic deformations occurring at predetermined regions, and according to a preselected pattern of variation of ductility requirements. It consists of a step-by-step computer-aided design procedure which basically is carried out in 5 steps: (1) Preliminary Analysis; (2) Preliminary Design; (3) Analysis of Preliminary Design; (4) Optimum Designs; (5) Analysis of the Reliability of the Optimum Design.

In the first step, serviceability and safety requirements are established and the corresponding "Design Earthquakes" are selected. This selection takes the form of smoothed or average linear elastic response spectra for selected damping coefficients. The smoothed linear elastic response spectra for extreme earthquakes is then reduced to take into account inelastic behavior corresponding to a properly selected pattern of values of ductility. Based on values of periods and modal shapes selected from tabulated values obtained from experiment and analytical investigations already carried out on similar frames, preliminary story shear forces are obtained from mode superposition analysis. A step-by-step iterative procedure is used to achieve a proper combination of the values for the fundamental period, drift, damping, ductility and seismic coefficient. The values so obtained for the story shear forces are the ones considered for the subsequent preliminary design of the structural members.

The preliminary design consists of a story-wise strong column-weak girder design using an optimization technique to obtain first the sizes of the girders and then the sections for the columns. A computer program developed for this purpose is based on rigid plastic analysis using a single story subassemblage where the P-Δ effect is taken into account. Working load drift limitations can also be imposed(6).

The static response of the preliminary designed subassemblages and dynamic response of the whole structure are analyzed using two nonlinear computer programs (5,6) based on elasto-plastic with linear strain hardending moment-curvature relationship. The plastic hinge rotations, which are assumed to take place at localized plastic hinges, are computed to provide a measure of the inelastic rotation demand on the critical regions of the structure. The P-Δ effect and the influence of axial force on the column yielding strength and flexural stiffness are also taken into account. Application of the nonlinear dynamic program permits the evaluation of the response of the preliminary design structure to different earthquake motions.

From the outputs of the above two programs, values and time histories of the rotation and displacement ductilities are obtained. If these ductility values and their variation agree closely with those preselected, and if the pattern of maximum shear forces obtained from the dynamic analysis, as well as that corresponding to the maximum story shear capacity obtained from the static analysis, is close enough to the one used in the preliminary design, then the shear forces obtained from the analysis are used for the final optimum design of the frame. If the agreement of one or more of the above parameters is poor, the results obtained in the preliminary analysis and design must be reviewed and modified until satisfactory agreement is achieved.

The optimum design is carried out by a procedure similar to the one used for the preliminary design, but it uses more sophisticated subassemblages and a linear programming technique.

Finally the reliability of the optimum design is evaluated by analyzing its behavior under service and ultimate loading conditions. Analyses of the response to several different time-history earthquakes can be carried out using the nonlinear dynamic computer program already described or even more refined computer programs. One of these programs includes the simultaneous effect of one horizontal and the vertical component of the ground motion (7). Another computer program includes the effect of inelastic shear distortion at the panel zone of teh joints (8).

All the above computer programs consider only bilinear type stable hysteresis loops, neglecting the degradations in stiffness and in strength that have been observed experimentally when reinforced concrete structures are subjected to cycles of reversal deformation beyond yielding. Therefore, Imbeault and Nielsen should be commended for developing the proposed DBL hysteretic system. This degrading model has been simple enough to permit the authors to incorporate it into practical computer programs for analysis of tall buildings and appears to be close enough to reality to permit the depiction of the essential features of the actual degradation effects.

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