# DUCTILITY DEMANDS FOR R/C FRAMES IRREGULAR IN ELEVATION

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## SUMMARY

In this paper the ductility demands for R/C frames irregular in height are studied; inelastic behavior is taken into consideration by using, in the numerical model, Takeda's hysteresis rules. A method to define an equivalent duration of a seismic event for efficient inelastic analyses is proposed. In the records used the maximum recorded acceleration is scaled using the maximum acceleration likely to occur during the serviceable life of the structure. Responses of two R/C frames irregular in height, and their equivalent regular structure, are shown. The results here reported improve upon current methods.

## INTRODUCTION

Reinforced concrete buildings may experience inelastic behavior when subjected to strong motions. Field evidence shows that limit states of strength or service have been reached in several structures excited by strong earthquakes. The modern tendency for seismic design has been focussed on the definition of design criteria based on the energy dissipation of the structures due to inelastic effects. Unfortunately, inelastic behavior of R/C structures has not been sufficiently analyzed for seismic design purposes.

The inelastic models for seismic analysis involve parameters whose definition is complicated; simple structural models are useful to know the behavior of the structures only in a general context. A simplified model for inelastic systems must include relevant parameters such as the hysteretic behavior. Accurate models have been proposed by Aziz (Ref. 1) and Otani (Ref. 2) correlating the response of a multi-degree-of-freedom system to that of an equivalent shear beam model. The latter models use a trilinear moment-curvature relationship for the structural members (cracking, first yield in the tensile steel, and crushing of the most stressed fiber of concrete), and Takeda's hysteresis rules.

In this paper inelastic behavior is studied of R/C frames irregular in height when subjected to earthquake motions. The analyses are performed using the model proposed by Otani. In the design of the frames, parameters associated to the compressible soil of Mexico City were used (Ref. 3). The design was performed using the static method with different ductility factors. For the dynamic analyses two records were used, obtained at the same site in Mexico City the N00E component of the earthquake of 14 March 1979 and the N90W component of that of 24 October 1980.

The duration of the excitation for inelastic analysis was defined with basis on the Seismic Arias Intensity (Ref. 4). The relation between the max-

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imum acceleration in the soil, based on the maximum probable seismic response of soils in Mexico City (Ref. 5), and the maximum required for dynamic analyses was used to obtain a scale factor.

Two R/C frames were analyzed. The results pointed out the importance of the irregularities as a significant increase of the structural response.

## NUMERICAL MODEL

Some simplifying assumptions were adopted in the structural idealization of the frames: floors are considered diaphragms infinitely rigid in their planes; masses are lumped at floor levels, and represent the total mass of the structure; soil-structure interaction is not include and the dynamic excitation is applied at the supports. It is also assumed that viscous damping is a linear combination of the constant mass matrix and the variable stiffness matrix; the resulting viscous forces are assumed to act at floors levels.

For the dynamic analyses a version of the program SAKE (Ref. 6) implemented in a Burroughs 6700 computer was used to obtain the inelastic responses of the R/C frames. The program allows modeling structural members with four different elements: an Euler-Bernoulli elastic prismatic beam, an inelastic flexural spring, a spring to simulate the perfect bond between concrete and steel reinforcement, and a rigid element at each end.

The dynamic equilibrium equations are solved using Newmark's step-by-step integration method, with parameters corresponding to the linear acceleration scheme. Existing experience shows that a good approximation to the actual dynamic responses is attained only if the time step is chosen as a fraction of the smallest period of the system. In the linear variation scheme this step must satisfy the stability requirements. In structures with elastic behavior good results are obtained if a step is used equal to $T_n/10$, being $T_n$ the smallest period.

In inelastic structures restrictions in the step size are more stringent because the contributions of higher modes are normally of significance to the response; inherited errors due to round-off become important; and above all changes of branches in the evaluation of the inelastic parameters must be precisely defined. Saiidi and Hodson recommend use of a time step equal to $T_n/20$ (Ref. 1) and Otani equal $T_n/50$ (Ref. 2). In this paper we use $T_n/20$ because the predicted structural response was practically invariant with smaller time steps; however, more investigation on this topic is needed, since in the definition of the time step the relation between structural periods and the prevailing periods of the ground motion, i.e. those corresponding to the maximum energy content in the record are not considered.

P-Δ effects were included by using the second order actions for an equivalent lateral force acting at floor levels (Ref. 6). This effect is included by obtaining a 'geometric' stiffness matrix that is added directly to the structural stiffness matrix which is varying during the occurrence of the excitation.

## IRREGULAR BUILDINGS STUDIED

In Fig. 1 The R/C frames studied are whown; these structures were designed in accordance with the Mexico City Building Code (Ref. 3), with seismic design parameters associated to soft soil (zone III). Ductility factors Q of 1 and 4 were assigned in the static equivalent seismic forces; with these actions it was possible to design all structural members and to define the required data for the inelastic analyses with the computer program.

## SEISMIC EXCITATION

The Mexico City Building Code allows a step-by-step analysis with specific earthquakes as an alternative for seismic analysis of buildings; this may be performed using real or simulated records representative of the side where the building is located. In accordance with the code, and for the purposes of this paper, the N00E component of 14 March, 1979 eathquake and the N90W component of 24 October, 1980 were chosen (Fig. 2).

In Fig. 3 the Seismic Arias Intensity for these records is depicted; these plots show the time distribution of the energy of the earthquake at the recording site. From their analyses, representative durations for the excitations of use in inelastic analyses may be obtained by choosing time intervals in which the desired energy is contained. In this investigation it was considered that results would not be significantly affected if duration associated to an energy content of 90% of the total were used.

Since the registered maximum accelerations of the records used were smaller than those required to make inelastic effects significant, a scaling procedure was devised. In it the maximum acceleration is scaled assuming that for a single event the acceleration does not exceed a previously fixed value. This criterion is fundamented on results about the maximum probable seismic response of soils in Mexico City (Ref. 5). Thus, maximum accelerations of 1.5 m/sec$^2$ were found when a probability of approximately 100% of not being exceeded and a service life for the building of N=50 years were assigned (Fig. 4).

## ANALYSIS OF RESULTS

In Ref. 7 the structural design data for the structures under study are presented in detail; all members have approximately the same strength for positive and negative moment. The viscous damping matrix was obtained assuming two per cent of the critical damping for the first two modes.

Figures 5 to 8 show the ductility demands in columns and beams for both frames irregular and equivalent regular structures. It is found that for both models the demands in exterior beams are larger than in the interior ones. In columns of the irregular frame the demands in interior columns are greater than in the exterior ones; it is believed that this result is due to the P-$\Delta$ effect.

The irregular frames exhibit inelastic behavior even for the cases where a ductility factor equal one is used in the design.

In the irregular frames the maximum actual ductility demand is about twice the ductility factor, while in the equivalent regular ones is about one and a half times this factor. It was also observed that the demand increases in the neighborhood of the irregularity.

## CONCLUDING REMARKS

The importance of inelastic effects on the seismic analysis of R/C frames irregular in elevation was shown with the 'exact' step-by-step analyses of two typical cases. It was found that irregularities in elevation increase the ductility factor by a factor of approximately 2, thereby producing higher ductility demands. This effect was significant where there was a sudden change in the stiffness distribution of the building.

Due to the sensitivity of this type of analyses to the characteristics of the history of the record, it was important to define a procedure to use records of reduced duration to represent the overall inelastic behavior of the structure. Use of the Seismic Arias Intensity provided a realistic way for neglecting segments at the beginning and/or at the end of the record without significant changes in the structural responses. Scaling of real records to reach a desired maximum acceleration has received little attention from analysis. This paper suggests a procedure to scale maximum acceleration based on existent statistical information. Further research is being devoted to include in it the changes in frequency content due to increased acceleration.

## ACKNOWLEDGEMENT

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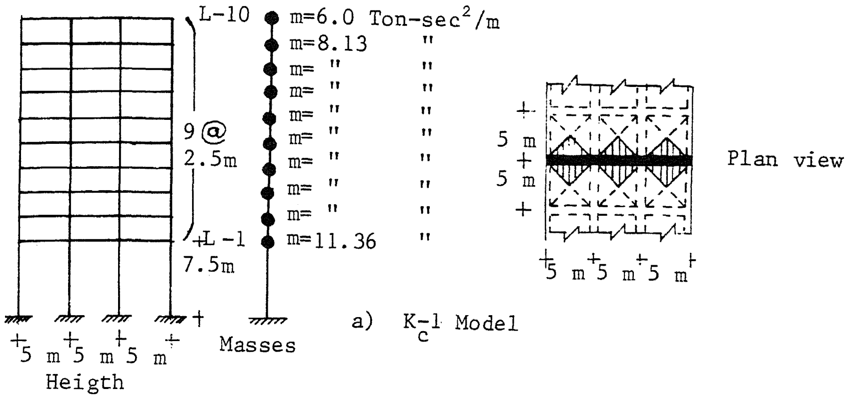
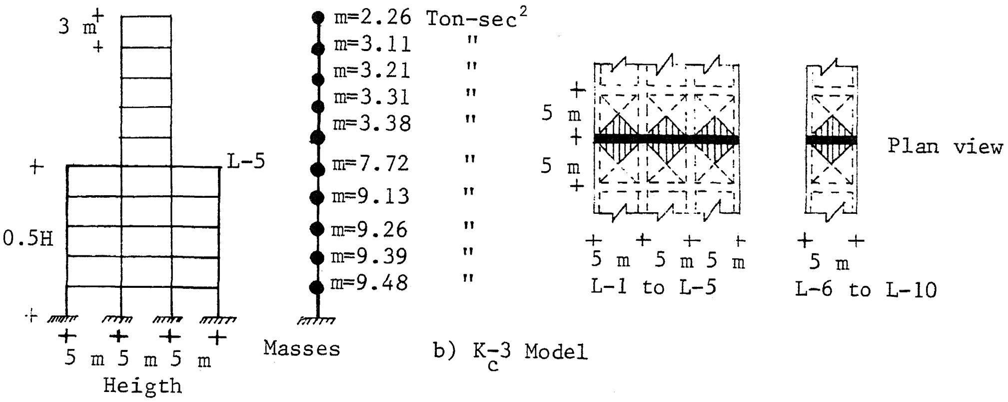


a) $K_c$-1 Model



b) $K_c$-3 Model

Fig. 1 Irregular in heigth R/C frames

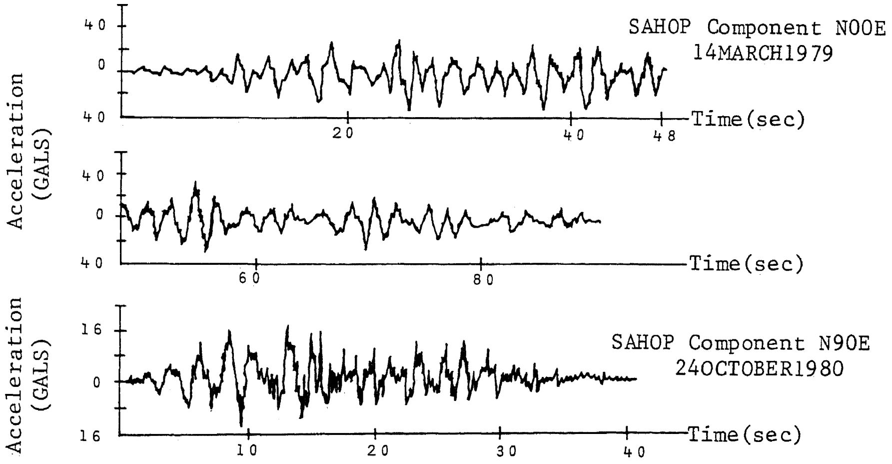


Fig. 2 Mexico City earthquakes

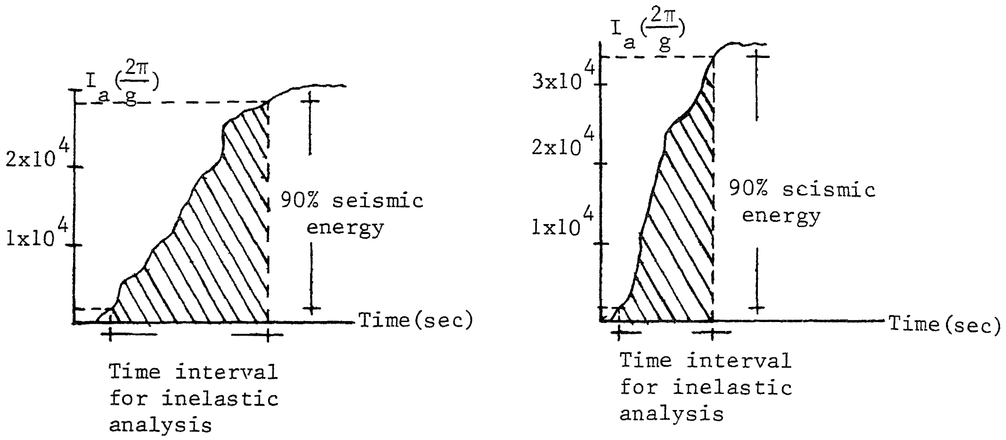


Fig. 3 Seismic Arias Intensity

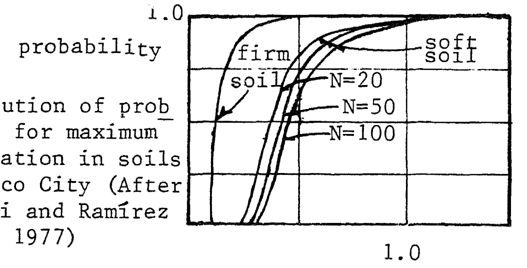


Fig. 4 Distribution of probability for maximum acceleration in soils of Mexico City (After Faccioli and Ramírez Flores, 1977)

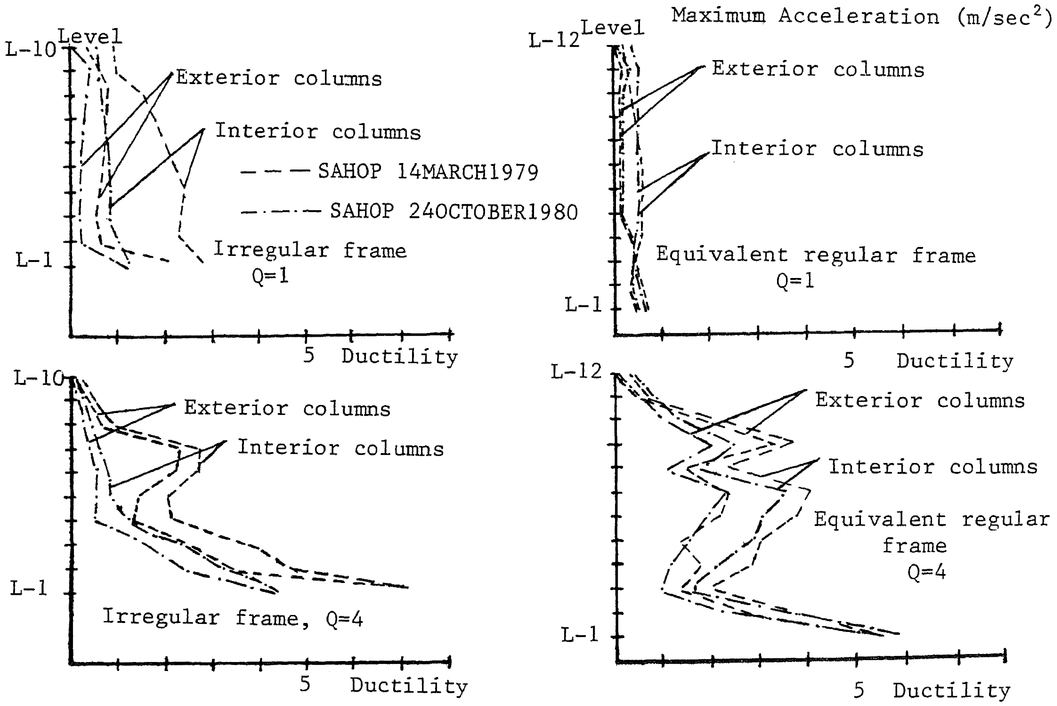


Fig. 5 Ductility demands in columns for the $K_c$-1 model

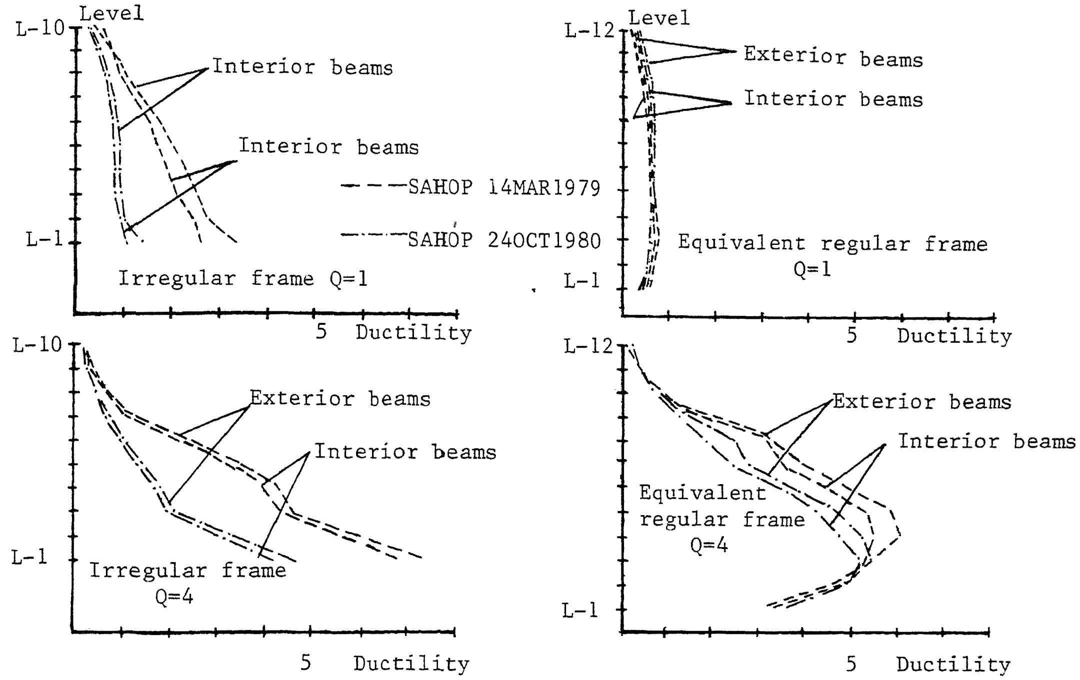


Fig. 6 Ductility demands in beams for the $K_c$-1 model

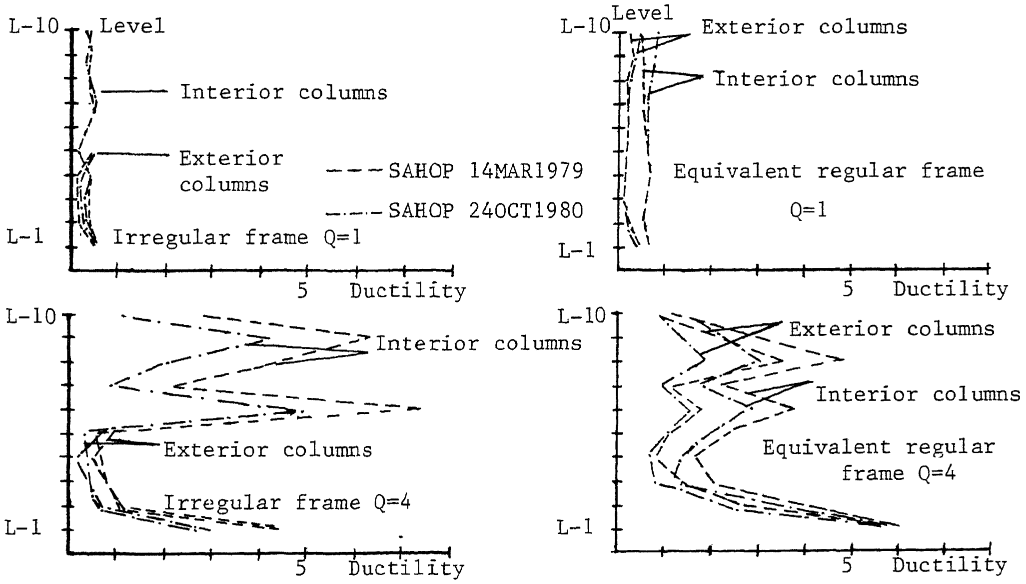


Fig. 7 Ductility demands in columns for the $K_c$-3 model

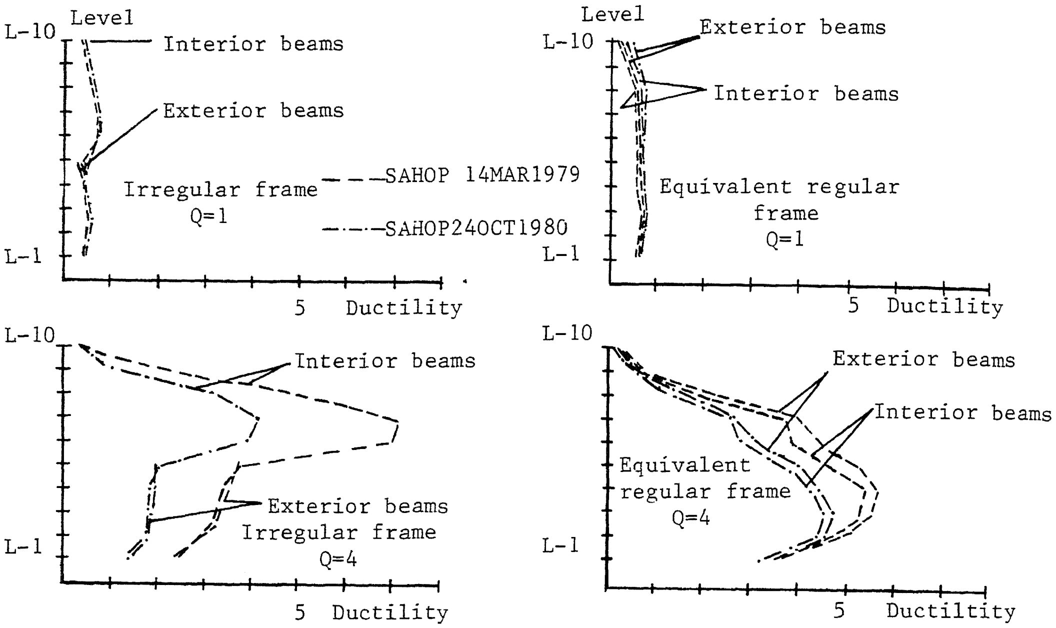


Fig. 8 Ductility demands in beams for the $K_c$-3 model