REQUIRED STRENGTH FOR PROBABILISTIC SEISMIC DESIGN AND
DAMAGE ASSESSMENT OF REINFORCED CONCRETE STRUCTURES

by

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SUMMARY

Nonlinear response analyses of single degree of freedom structural
systems were carried out in probabilistic terms by using a family of twenty
artificial earthquake accelerograms. In order to simulate wall-frame re-
inforced concrete buildings, the structural systems were composed of a
parallel combination of origin-oriented hysteretic models and degrading
trilinear hysteretic models which fail primarily in shear and flexure,
respectively. The stiffness properties of each model were varied in terms
of displacement and strength at cracking and yielding. Selected results
obtained in the overall investigation are presented and their application
are discussed compared with the independent results of each model.

INTRODUCTION

A criterion of seismic resistant design is to provide buildings with
strength and ductility so that response displacement does not exceed the
displacement capacity during an earthquake. Performance and damage assess-
ment of buildings is carried out by estimating their strength and ductility
capacities considering the intensity of earthquake ground motions. If the
characteristics of ground motions and hysteretic models are not changed,
and the peak acceleration level and the strength level alone are assumed
valiables, the peak acceleration, strength and ductility factor are con-
nected with each other so that one of them is obtained by determining the
others on nonlinear response analysis for the single degree of freedom
system. The strength level normalized by the product of the mass and peak
acceleration is called the required strength ratio of a ductility factor.

In general, reinforced concrete buildings are composed of various
types of framing system such as shear walls, short columns, and ductile
walls and frames. The purpose of the present paper is to discuss how
strength and ductility of each framing system have influence on the
seismic capacities of the overall system by computing nonlinear response
for idealized models, and to produce basic data to approach to more reliable
estimation of the earthquake resistant capacities of wall-frame reinforced
concrete buildings.

The required strength ratios had been independently obtained in probabil-
istic terms for an origin-oriented hysteretic model and four degrading trilinear
hysteretic models subjected to five types of artificial earthquake accelero-
grams, the former representing the behaviour of a structural wall and short
column failing in shear, and the latter simulating the flexural behaviour
of a frame structure [1]. In this investigation are adopted idealized
structural systems which are composed of a parallel combination of each of three
origin-oriented models containing the above-mentioned model and one of the
four degrading trilinear models to simulate wall-frame reinforced concrete

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buildings in the similar manner as the paper [2]. Since it was the intent of this investigation to concentrate on low-rise reinforced concrete buildings, nonlinear response analyses of single degree freedom structural systems were carried out in probabilistic terms by using a family of twenty artificial earthquake accelerograms equal to one of the five types. The stiffness properties of both models were varied in terms of displacement and strength at cracking and yielding. By using resulting response ductility factors were finally obtained the interaction curves between required strength levels of both models for various levels of ductility factors.

..RTIFICIAL EARTHQUAKE ACCELEROGRAMS

Since the required strength ratios of the four types (Types A, B, C, D) had been quite close each other, one of them was selected in this investigation, namely, Type B which represented that class of ground motion containing the N-S component of acceleration recorded during the 1940 El Centro, California, earthquake [1,3]. The characteristics of Type B are shown in Fig. 1 in terms of response acceleration ratios for linear model at four probabilisty distribution levels following the method of the paper [4]. The response acceleration spectra suggest that Type B has the characteristic period in the neighborhood of 0.4 sec. The required strength ratios of Type B for μ_{85} are shown in Figs. 2 and 3, where μ_{85} is a ductility factor at the 85% probabilisty distribution level. Note that required strength levels decrease, and the period corresponding to their peak levels becomes shorter, as ductility factor is larger as shown in Figs. 1 through 3, and that required strength levels decrease as period is longer as shown in Figs. 2 and 3.

STRUCTURAL MODELS

The single degree of freedom structural system shown in Fig. 4 is used in this investigation as the basic form for a parallel combination of two hysteretic models. The stiffness properties K_S and K_B are represented by three origin-oriented hysteretic models and a degrading trilinear hysteretic model, respectively. The overall hysteretic models are classified into three cases, namely, Case I, II and III depending on the characteristics of three origin-oriented models.

Origin-Oriented Hysteretic Model

This model is shown in Fig. 5 where its original skeleton curve is a trilinear shape with stiffness changes at shear cracking point (Q_{sc}, δ_{sc}) and shear yielding point (Q_{sc}, δ_{sc}) [5]. Reduction of loads follows linear pass always directed through the origin, e.g. path A'O and A"O in Fig. 5 and reduces the stiffness K_1. The model pllotted in Fig. 5 is for Q_{sy}= 1.9 Q_{sc} and δ_{sy}= 10.0δ_{sc} corresponding to Case I and II, but the stiffness K_3 is negative in Case II. The model in Case I is all the same as that of the paper [1]. The model in Case III are characterized by Q_{sy}= 3.0 Q_{sc} and δ_{sy}= 6.0 δ_{sc} equal to those of the degrading trilinear model as stated later.

Degrading Trilinear Model

This model is shown in Fig. 6 where its original skeleton curve is

also a trilinear shape with stiffness changes at flexural cracking point
(Q_{bc}, δ_{bc}) and flexural yielding point (Q_{by}, δ_{by}) [5]. Up to yielding,
the model behaves exactly like the standard bilinear model having stiffnesses
K_1 and K_2. In a case where displacement exceeds the yielding displacement,
maximum displacement is treated as a new yielding point, e.g. point C in
Fig. 6, and the stiffnesses K_1 and K_2 are reduced to αK_1 and αK_2, respec-
tively. The Fig. 6 is for $Q_{by} = 3.0 \ddot{Q}_{bc}$ and $\delta_{by} = 6.0 \delta_{bc}$ and is used for
Case I, II and III. The model is one of four models in the paper [1] and
requires the largest strength levels among them.

Parallel Combination Model

The overall hysteretic model is characterized by changing the strength
and displacement levels corresponding to cracking and yielding point of two
hysteretic models connected in parallel. The models in Case I and II, and
Case III are illustrated in Fig. 7a and b, respectively, but the stiffness
K_3 in Case I is different from that in Case II and has no slope. The char-
acteristic parameters of all models are listed in Table 1. Note that each
characteristic displacement δ corresponds to the mean peak ground accelera-
tion equal to the acceleration of gravity and varies in proportion to the
acceleration. The values Q_{sc} and Q_{by} are assigned variables on dynamic re-
sponse analyses and are normalized by the product of the mass and mean peak
ground acceleration, changing into β_S and β_B, respectively. These parameters
can be considered as the ratio of base shear coefficient to coefficient of the
mean peak ground acceleration. Note that the natural period of each model
varies in inverse proportion to the square root of its strength level by
reason of constant displacement.

It should be recognized that response of a single degree freedom struc-
tural system can be applied to estimate response of corresponding multi-degree
freedom structural system based on engineering judgement in a case where the
latter system behaves in such a type as shown in Fig. 8a and b. Strong-
column and weak-girder frame structures are considered to be a typical type
shown in Fig. 8b.

DUCTILITY RESPONSE

The complete time history of dynamic response was generated for each
structural model subjected separately to the twenty artificial earthquake
accelerograms of Type B. The response quantity of primary interest is the
ductility factors μ_S and μ_B which are defined as $\delta(t)_{max}/\delta_{sc}$ and $\delta(t)_{max}/$
δ_{by}, respectively. Mean ductility factors and their corresponding co-
efficients of variation were generated for each model using the twenty
response time histories. Ductility factors μ_S and μ_B for various strength
ratios β_S and β_B of each model were computed in probabilistic terms by
using the above results. An example is shown in Fig. 9 for Case I-1 at
the 85% probabilisty distribution level following the Gumbel Type I
distribution of the paper [4].

REQUIRED STRENGTH LEVELS

Using data such as shown in Fig. 9 for each case, i.e. using curves
of μ_{85} vs. β_B, one can easily obtain the required strength ratios β_B of a
degrading trilinear model for the required strength ratios β_S of an origin-
oriented model.

611

The resulting required strength ratios β_B can then be plotted as functions of β_S as shown in Fig. 10. The other axes of abscissa and ordinate are expressed in terms of the initial natural periods depending on each of β_S and β_B, respectively. The resulting curves show the interaction effects between the required strength ratios β_S and β_B of both hysteretic models for various levels of ductility factors. The interaction curves obtained in the same manner are shown in Figs. 11 through 18.

The relationship shown in these figures will serve as basic one for wall-frame reinforced concrete buildings to estimate required strength level in seismic design, ductility factor in damage assessment and peak ground acceleration in seismic-capacity evaluation, where two of three parameters, namely, required strength level, ductility factor and peak ground acceleration are previously determined.

DISCUSSION OF REQUIRED STRENGTH LEVELS

Required strength ratios of each independent hysteretic model plotted on the axes of abscissa and ordinate can be evaluated by using the results in the paper [1]. For example, the values of β_B for μ_{BS} equal to 2, 4, 6 and 8 on the axis of ordinate in Fig. 10 are estimated as the intersecting point of four solid lines and two dotted lines shown in Fig. 3. The dotted line is determined in Eq. 1.

$$T_2 = \sqrt{2}\, T_1 = 0.2\sqrt{\delta_y/\beta_B} \tag{1}$$

where the value of δ_{by} equal to 2.25 or 6.75 cm corresponds to $\ddot{v}_g$ equal to the acceleration of gravity. It might be better to define the period of degrading trilinear models by the value of T_2 as stated in the paper [6] in a case where the models are characterized by the value of δ_{by}.

Required strength ratios β are independent of yielding displacement levels δ_y in a range of the constant value of β regardless of the periods T_1 as illustrated in Fig. 19. This trend is observed on the nearly constant values of β_S for μ_S and μ_B in Figs. 10 through 13 and on those of β_B for μ_B equal to 2 in Figs. 10, 13 and 14. In observing the Figs. 10 through 18, the values of β_S increase with increasing values of δ_{sc}, and the values of β_B decrease with increase values of δ_{by}. These trends are explained by the relationship between β, T_1, μ and δ shown in Figs. 2 and 3.

The interaction curves shown in Figs. 10 through 18 may be approximated by a straight line for all values of μ in Case I and Case III, and for the values of μ_S (smaller ductility factors) in Case II, giving solid line AB and dotted line CD illustrated in Fig. 20. The interaction curves for the value of μ_B in Case II may be approximated by an ellipse as illustrated by solid line CD in Fig. 20. One significant feature shown in Figs. 16, 17 and 18 is that the values of μ_S in Case II and III are very close each other in a range where the values of μ_B is relatively small. These trends result from the negative slope of the stiffness K_3 and from the different relationship between δ_{sy} and δ_{by}.

The interaction curves of required strength ratios for parallel combination models will be prepared by using the above-mentioned process. More required strength ratios β_B on the axis of ordinate can be obtained by using the results in the paper [1], where basic data had been prepared for three more degrading trilinear models subjected to five types of artificial earthquake accelerograms.

612

CONCLUSIVE STATEMENT

The interaction curves of required strength ratios for a parallel combination model idealizing wall-frame reinforced concrete buildings were prepared changing the characteristic parameters of the model and were related to independent required strength ratios of both hysteretic models composing the parallel combination model.

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[1] Murakami, M. and J. Penzien, "Nonlinear Response Spectra for Probabilistic Seismic Design and Damage Assessment of Reinforced Concrete Structures," Report No. EERC 75-38, University of California, Berkeley, Ca., U.S.A., November 1975.

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[5] Umemura, H., et al., "Earthquake Resistant Design of Reinforced Concrete Buildings, Accounting for the Dynamic Effects of Earthquake," Giho-do, Tokyo, Japan, 1973 (in Japanese).

[6] Murakami, M. and J. Penzien, "Nonlinear Response Spectra for Probabilistic Seismic Design of Reinforced Concrete Structures," Proceeding of 6th World Conference of Earthquake Engineering, India, January, 1977.

Table 1 Caracteristic Parameters of Each Model

	Origin-oriented Model				Degrading Trilinear Model		
	δsc(cm)	δsy(cm)	δsf(cm)	Qsy/Qsc	δbc(cm)	δby(cm)	Qby/Qbc
Case I-1	0.075	0.75	–	1.9	0.375	2.25	3.0
Case I-2	0.05	0.5	–	1.9	0.375	2.25	3.0
Case I-3	0.1125	1.125	–	1.9	0.375	2.25	3.0
Case I-4	0.05	0.5	–	1.9	0.25	1.5	3.0
Case I-5	0.1125	1.125	–	1.9	0.5625	3.375	3.0
Case I-6	0.225	2.25	–	1.9	1.125	6.75	3.0
Case II-1	0.075	0.75	2.25	1.9	0.375	2.25	3.0
Case II-2	0.225	2.25	6.75	1.9	1.125	6.75	3.0
Case III	0.375	2.25	6.75	3.0	0.375	2.25	3.0

Notes : relative displacement δ is for the mean peak ground acceleration equal to the acceleration of gravity, and varies in proportion to the acceleration.
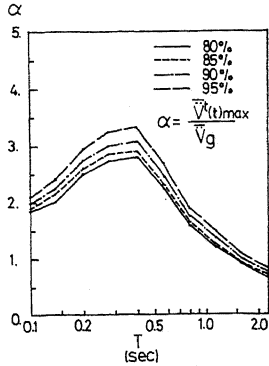
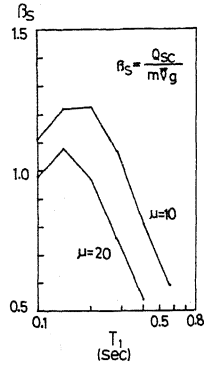Fig.1 Required Acceleration Ratios for Linear Model at Four Probability Distribution Levels

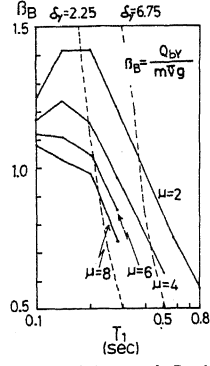Fig.2 Required Strength Ratios for Origin-oriented Model at the 85% Probability Distribution Level

Fig.3 Required Strength Ratios for Degrading Trilinear Model at the 85% Probabilisty Distribution Level
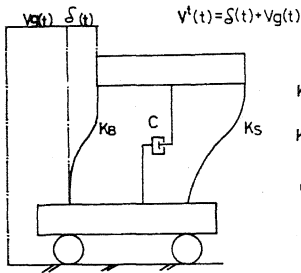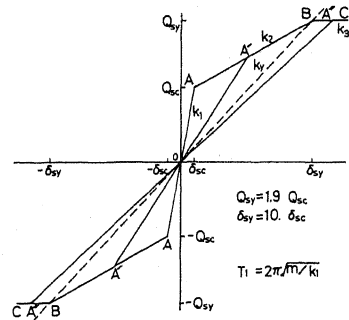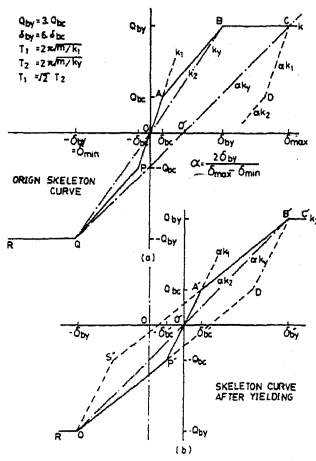
Fig.4 Single Degree of Freedom Model

Fig.5 Origin-oriented Hysteretic Model

Fig.6 Degrading Trilinear Hysteretic Model
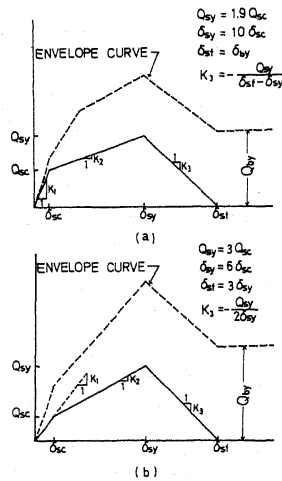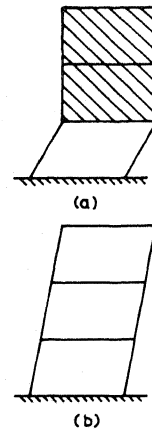
Fig.7 Skereton and Envelope Curves for Each Model

Fig.8 Idealized Model for Applicative Use

614
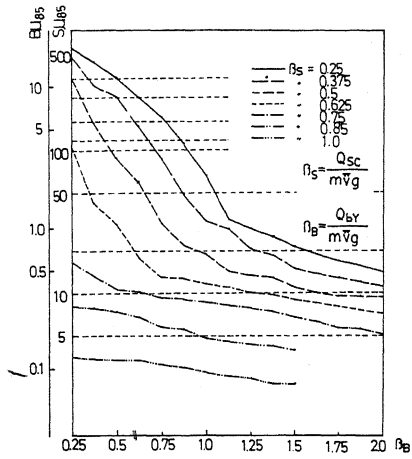
Fig. 9 Response Ductility Factors for
Parallel System at the 85% Pro-
bability Distribution Level
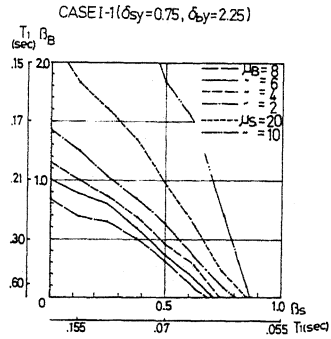
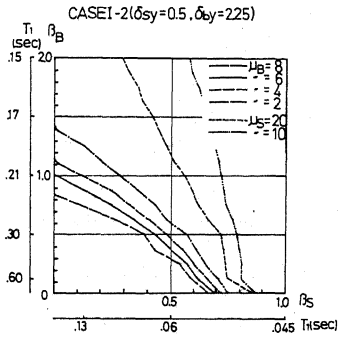Fig.10 Interaction Curves of Required Strength
Ratios for Case I-1

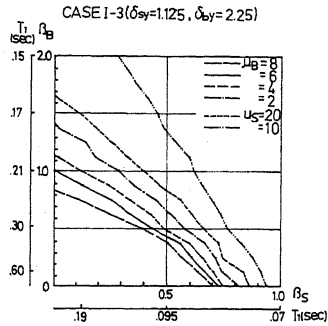Fig.11 Interaction Curves of Required Strength
Ratios for Case I-2

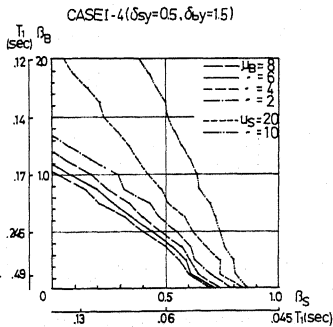Fig.12 Interaction Curves of Required Strength
Ratios for Case I-3

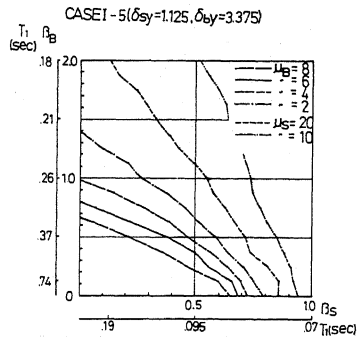Fig.13 Interaction Curves of Required Strength
Ratios for Case I-4

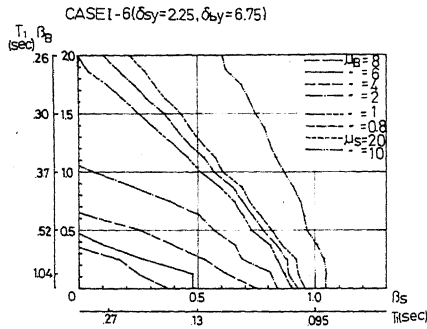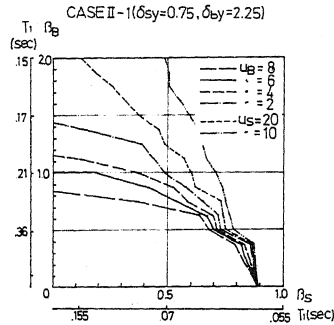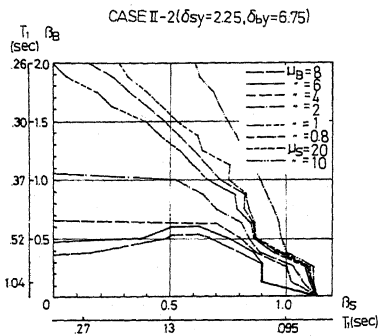Fig.14 Interaction Curves of Required Strength
Ratios for Case I-5
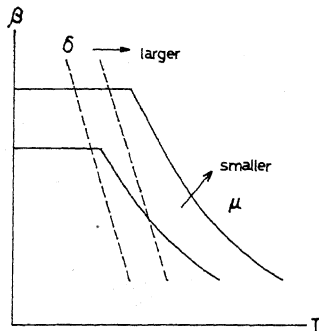
615

CASE I-6(δsy=2.25,$\delta$by=6.75)

T_1 β_B
(sec)

$u_B = 8$
" = 6
" = 4
" = 2
" = 1
" = 0.8
$\mu_S = 20$
" = 10

β_S
T_1(sec)

Fig.15 Interaction Curves of Required Strength
Ratios for Case I-6

CASE II-1(δsy=0.75,$\delta$by=2.25)

T_1 β_B
(sec)

$u_B = 8$
" = 6
" = 4
" = 2
$u_S = 20$
" = 10

β_S
T_1(sec)

Fig.16 Interaction Curves of Required Strength
Ratios for Case II-1

CASE II-2(δsy=2.25,$\delta$by=6.75)

T_1 β_B
(sec)

$u_B = 8$
" = 6
" = 4
" = 2
" = 1
" = 0.8
$\mu_S = 20$
" = 10

β_S
T_1(sec)

Fig.17 Interaction Curves of Required Strength
Ratios for Case II-2

CASE III (δsy=$\delta$by=2.25)

T_1 β_B
(sec)

$u = 8$
" = 6
" = 4
" = 2
" = 1
" = 0.8

β_S
T_1(sec)
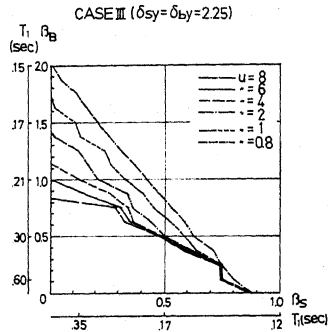
Fig.18 Interaction Curves of Required Strength
Ratios for Case III

β

δ — larger

smaller

μ

T

Fig.19 Relationship between Required Strength
Levels, Natural Periods, Ductility Fac-
tors and Yielding Displacement Levels

β_B

$\beta_S = \dfrac{Q_{SC}}{m\bar{v}g}$
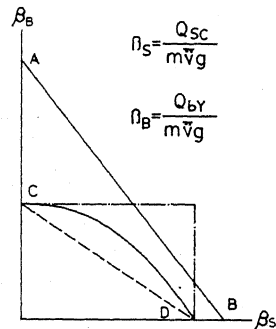
$\beta_B = \dfrac{Q_{bY}}{m\bar{v}g}$

A
C
D
B
β_S

Fig.20 Idealized Interaction Curves of
Required Strength Ratios

616