ULTIMATE CAPACITY OF LOWRISE R/C BUILDINGS SUBJECTED TO INTENSE EARTHQUAKE MOTION

by

H. Takizawa[I] and P. C. Jennings[II]

SYNOPSIS

The ultimate capacity of lowrise R/C buildings to resist intense ground motions is examined extensively by use of planar structural models. The effects of cracking, yielding, crushing and spalling, and stiffness degradation are included in the analysis as well as the nonlinear geometrical effect associated with the overturning action of gravity. The study is intended to provide a realistic description of the process of ultimate failure in R/C flexural (flexural-shear) frames and to clarify their margin of safety when subjected to severe earthquake motion.

INTRODUCTION

The reliable description of the inelastic and hysteretic behavior of R/C structures is clearly a difficult problem. One approach is to use directly the empirical restoring force properties of structural components derived from a comprehensive review of laboratory tests. With the aid of some additional formulations, this leads to a generalized method of member-by-member analysis of the overall structure.[1] On the other hand, many of the essential features of inelastic structural response may be described by use of a much simpler model, if the gross mechanism of overall structural deformation is carefully reflected in the modeling. In practical terms this means that the mode of deformations must be prescribed, and if necessary to synthesize the restoring force characteristics of the model, according to the kinematic relationships in the yield-hinge mechanisms of the structural frame.[1,2] This generally results in an "equivalent" 1-DOF or multi-DOF idealization of the total structure, depending on the associated degrees of freedom. R/C frames of practical interest are often of a girder-collapse type or of a hybrid type of girder collapse and column collapse. For multi-story structures of these types, the conventional inelastic shear beam modeling can lead to a seriously unreliable evaluation of strong-motion response. The "equivalent" modeling may be satisfactorily used in such situations[1,2] (for short-period structures) and includes the shear beam modeling as a special case.

The equivalent structural system is formulated mathematically by specifying the mode of story-drifts and by incorporating the element properties. The governing equation of motion, including the gravity term, can be derived by use of a reasonable simplifying assumption concerning the mechanism of structural deformation.[2] This is done to avoid treating the full complexity of the nonlinear geometry in the deformed configuration. The geometrically nonlinear term accounts for the overturning action of gravity, which causes structural destabilization with increasingly large response. The equation of motion is more complicated than, but essentially similar to, the corresponding equation in the ordinary treatment of multi-DOF systems.

The equivalent 1-DOF model covers a broad class of R/C buildings of current interest because of their common property of strong columns and weak girders. Another case often encountered is failure localized at a relatively soft and vulnerable portion of the structure; the important features of this case can be described approximately by means of an equivalent 2-DOF system. In addition to the simplicity and efficiency of the equivalent

I Asst. Prof. of Struct. Eng., Hokkaido Univ., Sapporo, Hokkaido, Japan.
II Prof. of Appl. Mech., Calif. Inst. Tech., Pasadena, Calif., USA.

models, common R/C properties can be readily incorporated into the models, which facilitates the identification of the general characteristics of strong-motion response. By using this approach, the present study[2] examines the serious damage and ultimate failure of R/C frames under the action of intense earthquake ground motions.

CRITERIA OF FAILURE AND MEASURES OF SEVERITY OF GROUND SHAKING

The governing equation of the equivalent 1-DOF system is

$$\ddot{\Delta} + A_d - (g + \ddot{v}_0)\sin(\Delta/H) = -\ddot{u}_0\cos(\Delta/H)$$

in which Δ, A_d and H are the lateral drift, associated force (in terms of acceleration) and height, of the equivalent system. The notations $\ddot{u}_0$, $\ddot{v}_0$ and g stand for the horizontal and vertical ground accelerations and gravity, respectively. The restoring force A_d embodies the dynamic characteristics of the restoring forces of the overall structure and is specified by the history of the equivalent drift Δ and its time-derivative. The static restoring force relationships (A_s vs. Δ) of R/C frames are characterized by drastic softening (due to cracking) at relatively low stress levels, and by degrading stiffness; this latter property refers to the decrease in the effective modulus and the poor capacity for hysteretic energy consumption which occur during cyclic loading. Thus, a modeling of the restoring force which accounts for the prominent effects of cracking, yielding and stiffness degradation, is a requirement for idealization of R/C frames. The "degrading trilinear" hysteresis model[1] is among the simplest models meeting this need; the equivalent 1-DOF system characterized by this model (without the action of vertical excitation) is employed as the standard reference case in the current study. Fig.1-A shows the skeleton curve and the gravity-effect term, A_g.

Using the notation defined in Fig.1 and introducing the normalized horizontal excitation $E(t) \triangleq \ddot{u}_0(t)/A_{max}$ [A_{max} : peak acceleration of $\ddot{u}_0(t)$], the normalized drift, or ductility factor, μ is seen to be a function of the following factors:

$$\mu = \mu(t;\ T_e,\ \zeta_e,\ a_c,\ \alpha_y,\ I,\ E(t),\ \alpha_g,\ A_y/g)$$

In this expression, $I\ (\triangleq A_{max}/A_y)$ and ζ_e represent, respectively, the relative strength of the excitation and the viscous damping factor. Consideration of gravity requires the last two factors; these can be reduced to the single parameter α_g if the first-order approximation is made to the nonlinear terms. The dimensionless parameter α_g which describes the relative influence of gravity provides also a measure of the deformability of the total structural system. For example, the yield translational angle R_y equals $(\alpha_g/\alpha_y)(A_y/g)$. Also, the elastic period is expressed in terms of this parameter by the relation $T_e = (2\pi\sqrt{h}/\sqrt{g})\sqrt{\alpha_g}\sqrt{n/\beta}$ where h and β are the average interstory height and the distribution factor of story-mass and story-height [$\beta \simeq 3n/(2n+1) = 1.0$ to 1.5], respectively. n is the total number of stories. Another useful parameter in identifying the effect of gravity is μ_g ($=\alpha_y/\alpha_g$, vide Fig.1) which is the static stability limit of the structure. The relative magnitude of the gravity force compared to the yield strength is shown to be $A_g/A_y = \mu/\mu_g$. For R/C frames of practical interest, $\alpha_g = (0.8$ to $8.0)\times10^{-3}$ depending on the degree of rigidity, $a_c = (1/3$ to $1/2)$ and $\alpha_y = (0.10$ to $0.30)$. In the subsequent analyses, typical values are taken for the system parameters: $a_c = 0.5$, $\alpha_y = 0.2$, $h = 3.75$m, $\zeta_e = 5\%$, and $\alpha_g = 6\times10^{-3}$ for soft frames ($\mu_g = 33.3$) and 1×10^{-3} for stiff frames ($\mu_g = 200$).

The difficulty in selecting a suitable measure of the severity of ground motion arises mostly from the fact that ground shaking can vary markedly in amplitude, frequency content and time-dependence. In particular, two ground motions having the same maximum amplitudes may have different damage potential because of different durations. Therefore, in addition to characterizing an individual motion by a measure such as the RMS, spectral intensity or total energy[4], at least one more parameter measuring the degree of duration is needed.[5] For purposes of the present study, three groups of excitations having significantly different properties have been chosen. These are Ensemble a of real accelerograms of engineering importance [a-1: strong motions with durations of 10 to 25 sec ($M \simeq 6$ to 7), and a-2: very short records of impulsive type motion ($M \simeq 4$ to 5, durations of 1 to 2 sec)] and Ensemble b of longer artificial motions ($M \simeq 8$) [see Table 1]. It is well-known that difficulties arise in defining the duration quantitatively in a generally satisfactory way. One approach is to utilize the time-accumulated energy function[5]; defining the duration as the interval during which 70% (15 to 85 %) of the total energy is transmitted provides a reasonable definition of duration for the accelerograms selected.[2] The durations, T, and RMS values over the duration, P', are used as two-parameter characterizations of the motions.

Selection of an excitation $E(t)$ from the three ensembles and use of the fixed values of system parameters as noted above permit the relation of the maximum normalized drift μ to a set of only three variables: T_e (or n), α_g and I; thus leading to the expression of relative intensity I as a function of T_e (or n) and α_g for a specified response level μ. Two specific intensities I_d and I_c are introduced by associating I with serious damage and with ultimate collapse of the equivalent structures. The damage intensity, I_d, is defined by $\mu_{max} = 3$ for specificity, while the collapse intensity I_c corresponds to the minimum intensity causing ultimate failure. The margin of safety against collapse, beyond motions that are damaging, is then identified quantitatively by the factor I_c/I_d. Fig.2 shows a few examples of the strong-motion responses, using this type of representation. A trend of continuity in the two curves for I_d derived for different values of α_g reflects the fact that the response at this level is not noticeably affected by the deformation-dependent effect of gravity. I_d is thus specified by a single factor T_e, and the correlation appears approximately bilinear on a logarithmic scale. On the other hand, a gross trend in I_c is that the two collapse zones appear to overlap together by employing n as the common abcissa. This feature suggests the relative unimportance of the factor T_e; more significant factors governing the nonlinear properties are A_y and the parameter describing the absolute magnitude of gravity effect, H [$\triangleq (n/\beta)h$]. Furthermore, the monotonically increasing dependence of I_c upon the single factor n/β is approximately linear on a logarithmic scale, which is consistent with an empirical formula derived for the collapse of bilinear systems under stationary excitation.[3] For all excitations examined, Fig.3 gives the relations I_c vs. n, I_d vs. T_e and I_c/I_d vs. (T_e or n, α_g). The figure is intended to display the characteristics of the three ensembles, under the same amplitude of peak acceleration. For example, a low destructive capability and a high margin of safety are obviously seen in the results for Ensemble a-2.

Reduction of the necessary parameters to a bare minimum leads to cruder correlation forms: $I_c \simeq \sqrt{n/\beta}/k_c$ and $I_d \simeq \mathrm{Max}[1/k_d,\ T_e/k_d']$, in which k_c, k_d and k_d' are correlation constants. Returning to the definition of I and eliminating the factor A_{max} by substitution of its recorded value, alternate expressions: $(A_y)_c \simeq {}^aA_y^c/\sqrt{n/\beta}$ and $(A_y)_d \simeq \mathrm{Min}[{}^sA_y^d,\ {}^\ell A_y^d/T_e]$ are derived, where $(A_y)_c$ and $(A_y)_d$ are interpreted as the minimum yielding capacity required for resisting the motion without sustaining ultimate collapse or serious damage, respectively. The collapse and damage accelerations ${}^aA_y^c$ ($\triangleq k_c A_{max}$), ${}^sA_y^d$ ($\triangleq k_d A_{max}$) and ${}^\ell A_y^d$ ($\triangleq k_d' A_{max}$) are rendered independent of structural parameters and can be used to represent the absolute severity of ground motions. For comparison, the intensity scales are summarized in Fig.4 which also includes

A_{max}, $(SI)_{20\%}$ and $\sqrt{E(\infty)}$ (square root of total energy). (${}^{1}A_y^c$ and ${}^{10}A_y^c$ are the collapse accelerations evaluated from $n=1$ and 10, without use of the simplified correlation.) The figure demonstrates the range of severities assigned from different points of view, and suggests any conventional single-parameter measure cannot adequately characterize the destructive potential of strong ground motion. A two-parameter characterization is examined by use of P' and T (Fig.5). Even though fluctuations are still notable there, the results shown indicate the significance of the duration of motion. (Peculiarities in the frequency content of the records are responsible for part of the deviations. For example, CHO has a relatively long predominant period.) Application of the regression $P'T^{\pi}$ results in $\pi=0.8$ (0.35), 0.35 (0.15), 0.6 (0.2) and 0.4 (0.15) for ${}^{a}A_y^c$, ${}^{s}A_y^d$, ${}^{\ell}A_y^d$ and $(SI)_{20\%}$, respectively. The numerals in parenthesis are those evaluated by excluding Ensemble a-2. This correlation was done because the parameter π can clarify the effect of duration with relation to the total energy ($\pi=1/2$) as well as to the RMS ($\pi=0$).

OTHER FACTORS INFLUENCING STRUCTURAL FAILURE

Vertical Shaking. The effective gravity undergoes time-dependent fluctuation due to the action of $\ddot{v}_0(t)$; this action might be expected to have an appreciable influence upon ultimate structural failure. However, the effect was found to be very minor in almost all cases of practical interest.[2,3]

Ductility Deterioration. Even in the case of flexural failure, R/C skeleton properties cannot be ideally ductile. The actual load-carrying capacity decreases gradually as deterioration progresses further (e.g., crushing and spalling of concrete), as schematically shown in Fig.1-b. The previous illustrations of I_c and I_d (Fig.2) also include the collapse zones I_c' in a model study including this deterioration ($a_u=1.05$, $\mu_u=3.0$ and $p=-0.010$). As anticipated from the drastic reduction of stability limits [$\mu_p=24.0$ and $\mu_g'=15.0$ (21.8) for $\alpha_g=6\times10^{-3}(1\times10^{-3})$], collapse is seen to be greatly accelerated, particularly in the stiffer frames, and the previously higher margin of safety for $\alpha_g=1\times10^{-3}$ turns out now to be comparable to that for $\alpha_g=6\times10^{-3}$. The degree of reduction (I_c'/I_c) is roughly consistent with $(a_u-p\mu_u/\alpha_y)/\sqrt{1-p/\alpha_g}$ [$=0.73$ (0.36) for $\alpha_g=6\times10^{-3}(1\times10^{-3})$].

Biaxial Shaking and Response. To be discussed in a separate presentation.[6]

Localized Structural Failure. The gravity-effect parameter α_g, identified at different sub-elements of an equivalent 2-DOF structural system, generally takes a larger value, being influenced by the local distribution of rigidity. Moreover, the dominance of inelastic drift at the softer and weaker portion leads to ultimate failure at lower intensities of motion.[2]

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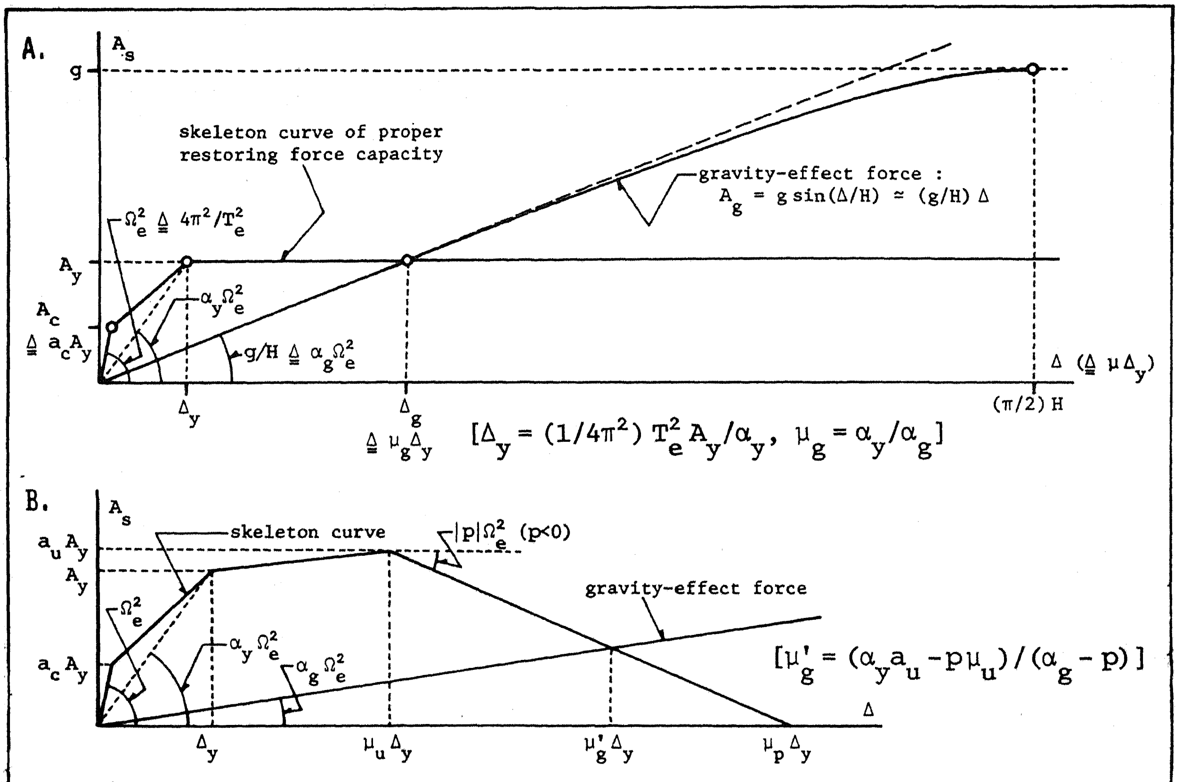


Fig. 1

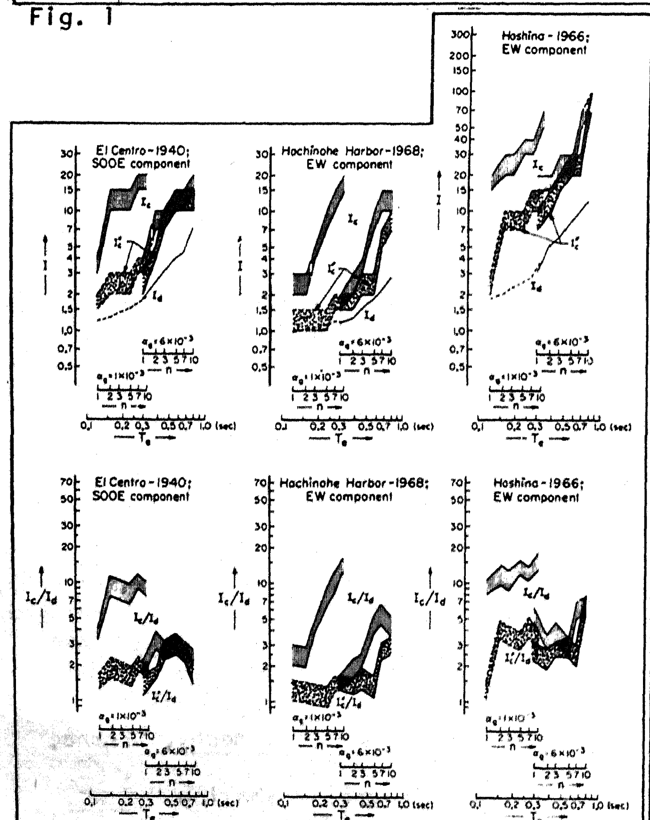


Fig. 2

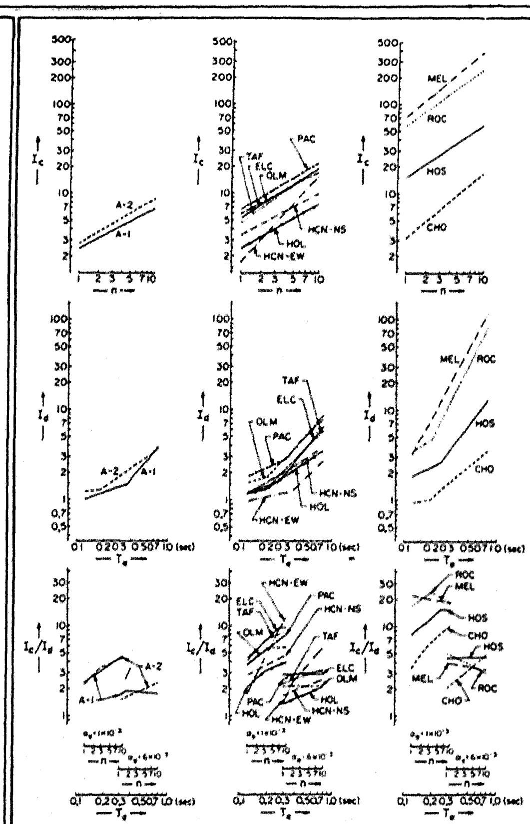


Fig. 3

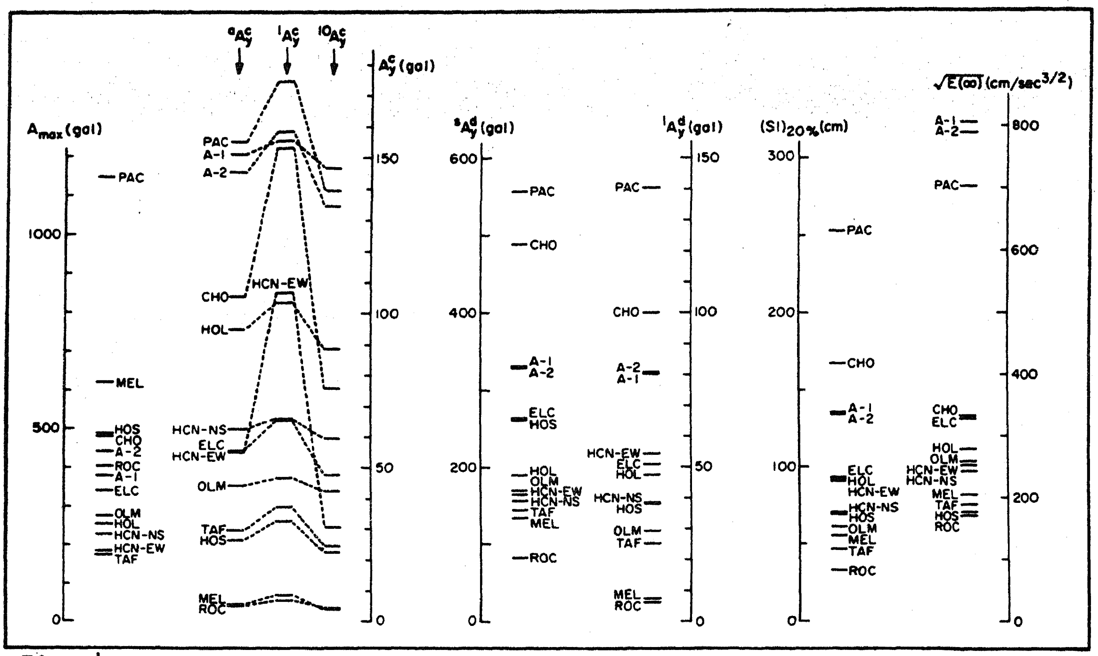


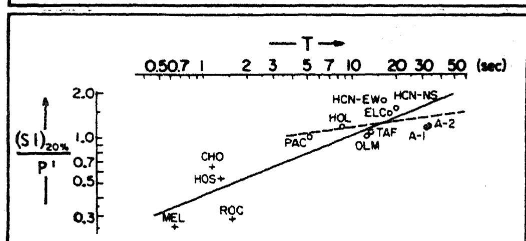
Fig. 4

Table 1

Ensemble a-1.	
El Centro-'40 (Imperial Valley EQ), S00E	ELC
Olympia-'49 (Western Washington EQ), S86W	OLM
Taft-'52 (Kern County EQ), S69E	TAF
Hachinohe-'68 (Tokachi-Oki EQ), NS	HCN-NS
ditto , EW	HCN-EW
Pacoima Dam-'71 (San Fernando EQ), S16E	PAC
Holiday Inn-'71 (San Fernando EQ), N00W	HOL

Ensemble a-2.	
Hoshina-'66 (Matsushiro EQ), EW	HOS
Cholame Shandon No.2-'66 (Parkfield EQ), N65E	CHO
Rocca-'72 (Ancona EQ), NS	ROC
Melendy Ranch-'72 (Stone Canyon EQ), N29W	MEL

Ensemble b.	
Jennings-Housner-Tsai, Type A -1	A-1
ditto -2	A-2
(vide Caltech EERL report, April '68)	



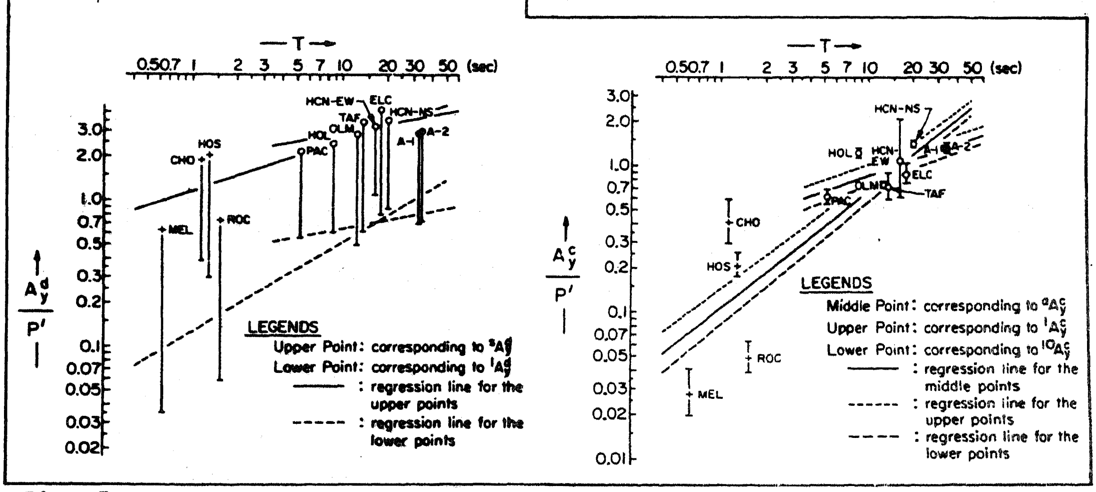


Fig. 5