RESPONSE OF REINFORCED CONCRETE STRUCTURES CHARACTERIZED BY "SKELETON CURVE" AND "NORMALIZED CHARACTERISTIC LOOP" TO GROUND MOTIONS

by SUKENOBU TANI* and SETSURO NOMURA**

SYNOPSIS

NCL Model composed of "Skeleton Curve" and "Normalized Characteristic Loop" is treated as a model of load-displacement curves of reinforced concrete structures. The responses of this model to earthquake motions are presented and the influences of the following factors on the response are studied; figure and area of hysteresis loop, natural period, damping factor, ultimate strength, yield point level of a structure.

1. THE RESTOREING FORCE CHARACTERISTICS OF REINFORCED CONCRETE STRUCTURE

One of the important restoreing force characteristics of reinforced concrete structures is the decrease of overall stiffness of the hysteresis loop according to the deformation increase. The load-displacement curve to monotonic increasing loading is a soft spring type and generally called skeleton curve or backbone curve. A usual bilinear or trilinear model is based on the springs of this skeleton curve and these models are not suitable to include the above characterisic and the characteristics of loop figures. It is observed by many experiments that the skeleton curve nearly coincides with the envelope curve traced by connecting the peak points of each hysteresis loop under alternately repeated loadings increased gradually. The steady state hysteresis loop whose peak point is equal to the maximum point of skeleton curve experienced so far tends to converge to one loop, and normalizing this converged loop by its peak point we obtain a normalized steady state hysteresis loop. These normalized loops obtained at each loading level have a tendency to converge to almost one loop (named Normalized Characteristic Loop and shortened to NCL) up to 60% -70% of ultimate load whether the vertical load is acted on the top of the columns or not. Unsteady state hysteresis within NCL has a characteristic to proceed toward the latest reversal point.

The load displacement curve having the above characteristics can be well modelized by NCL Model which is composed of "Skeleton Curve" and "Normalized Characteristic Loop" including the arbitrary hysteresis within NCL, as shown in Fig-1.

2. NCL MODEL

The Skeleton Curves adopted herein are,

(1) $$F(X) = \frac{2}{\pi}*Qx*\tan^{-1}\left\{\frac{X}{(2/\pi)*Qx}\right\} \quad \text{------ SC-1}$$

(2) $$F(X) = \frac{Qx*X}{\sqrt{X^2 + Qx^2}} \quad \text{------ SC-2}$$

(3) $$F(X) = \frac{2}{\pi}*(Qx - Dy)*\tan^{-1}\left\{\frac{X - Dy}{(2/\pi)*(Qx - Dy)}\right\} + Dy \quad \text{------ SC-3}$$

* Prof. of Waseda Univ. ** Assoc. Prof. of Sience Univ. of Tokyo

$$(4) \quad F(X) = \frac{(Qx - Dy)*(X - Dy)}{\sqrt{(X - Dy)^2 + (Qx - Dy)^2}} + Dy \qquad \text{------ SC-4}$$

where Qx is a coefficient to decide the ultimate strength. Dy is a displacement at the yield point for SC-3 and SC-4 and as for SC-1 and SC-2, a yield point is temporary decided and under this point the skeleton curve is assumed to be elastic, though it is not linear.

The Normalized Characteristic Loop is,

$$f_{1,2}(X) = F(X)/F(\delta_0) = \mp A*(X/\delta_0)^4 + B*(X/\delta_0)^3 + (1 - B)*(X/\delta_0) \pm A$$

where the coefficient A and B coresponds to the area of NCL and the minimum value of the tangent modulus of NCL respectively.

The area of NCL = $\oint\{f_1(X) - f_2(X)\}*dX = (16/5)*A$ and the equivalent viscous damping factor h_e of hysteresis damping = (area of NCL)/2π = $1.6/\pi$.

The arbitrary hysteresis within a NCL is assummed to linear having the tangent modulus of the peak point of the NCL. Fig-2 shows the change of the figures and the areas of NCLs by the value of the coefficient A or B.

The equation of motion is $\ddot{X} + (c/m)*\dot{X} + P^2*F(X) = -\ddot{Z}$, where $p^2 = K/m$.

3. RESPONSE TO GROUND MOTIONS

Fig-3 - Fig-6 and Fig-7 show the force-displacement curves and displacement-time response curves respectively to El Centro 1940 NS 330 gal. These Figs well represent the difference of hysteresis with the change of the figure and area of NCL, though they have a same skeleton curve.

Fig-8 shows the relation between the maximum displacement Ymax and the coefficient A. In case of El Centro earthquake, Ymax decreases in accordance with the increase of the value A, i.e. the increase of the area of NCL: where the time YmaxT at Ymax is about 5.6sec when $A \leqq 0.4$, and YmaxT $\fallingdotseq$ 4.45sec when $A \geqq 0.5$. In case of Taft 1952 EW (expanded to 330 gal), when $A \leqq 0.3$ Ymax decrease in accordance with the increase of A where YmaxT $\fallingdotseq$ 8.0sec, but when $A \geqq 0.4$ it is reversed and where YmaxT $\fallingdotseq$ 6.9sec.

Generally speaking, the increase of the coefficient A means the increase of the hysteresis damping and then, Ymax is expected to decrease. It is true in case of steady state response, but in case of actual earthquake motions, it does not always true because of the influence of the randomness of ground motions as described above.

Fig-9 shows the relation between Ymax and the coefficient B. With the decrease of coefficient B which means the decrease of slip phenomena of NCL, Ymax decreases in El Centro and increases in Taft.

Fig-10 and Fig-11 are the response spectrums of acceleration, velocity and displacement to El Centro and Taft earthquake respectively with respect to the parameter Qx. It is said that Qx influences on Ymax, but small Qx does not always give a large Ymax in a certain period of structure by the nature of earthquake motion.

Fig 12 shows the displacement-time response with respect to the displacement of yield point Dy. The influence of Dy is small if Ymax is comparatively large, but the change of Dy influence on the Dyy (= Dy/Qx) and consequently on the skeleton curve after the yield point, which more or less influence on Ymax.

Fig-13 is the response spectrum with respect to damping factor h, which is included in the equation of motion as other dampings than the hysteresis damping. Fig-14 shows the force-displacement curve when this model is aplied to 3 storied structure with RC bracing in the 1st floor.

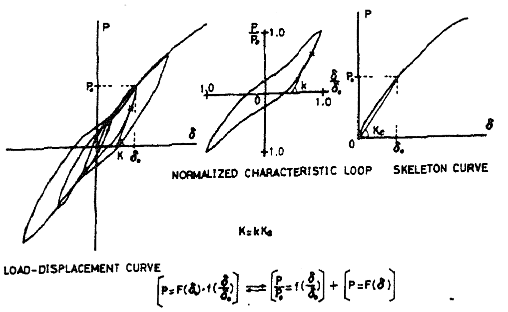

Fig-1

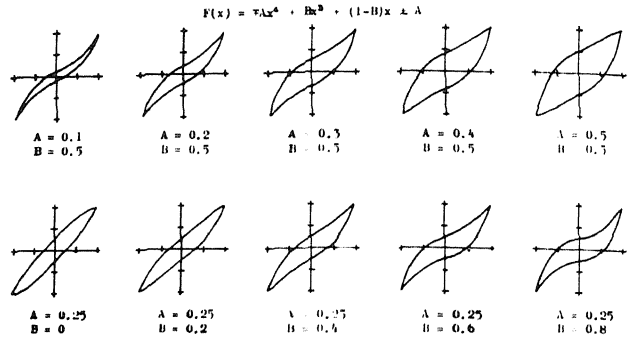

Fig-2

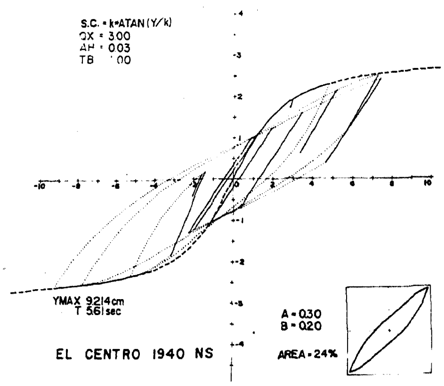

Fig-3

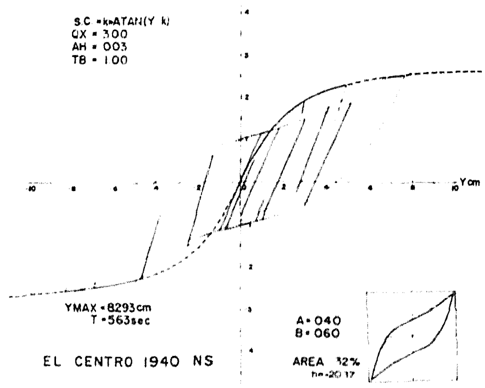

Fig-4

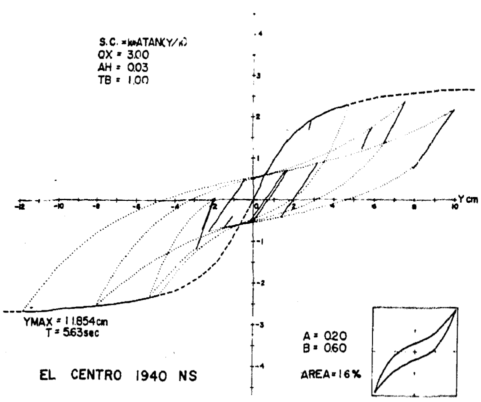

Fig-5

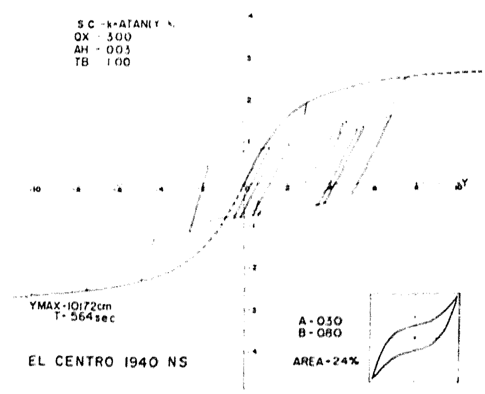

Fig-6

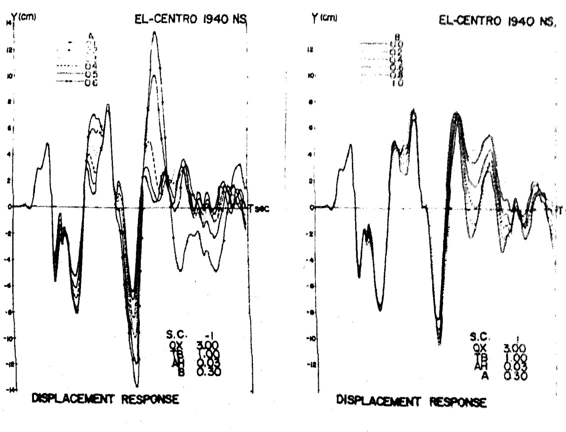

Fig-7

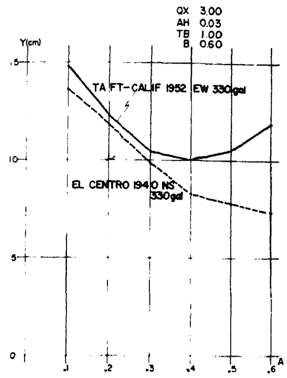

Fig-8

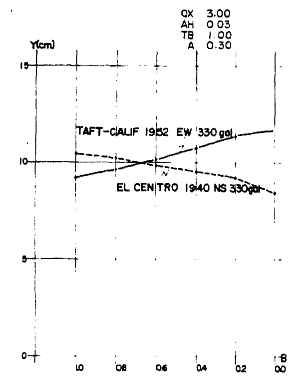

Fig-9

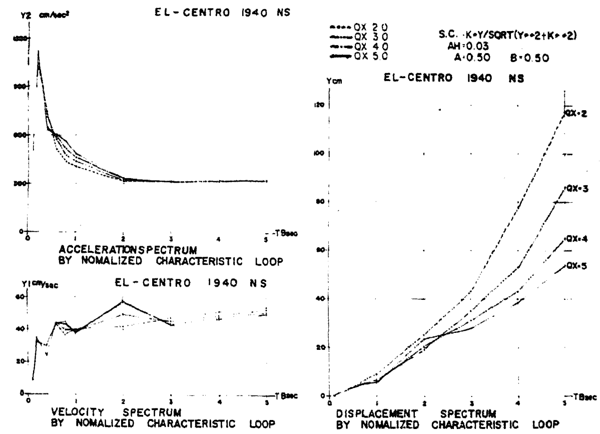

Fig-10

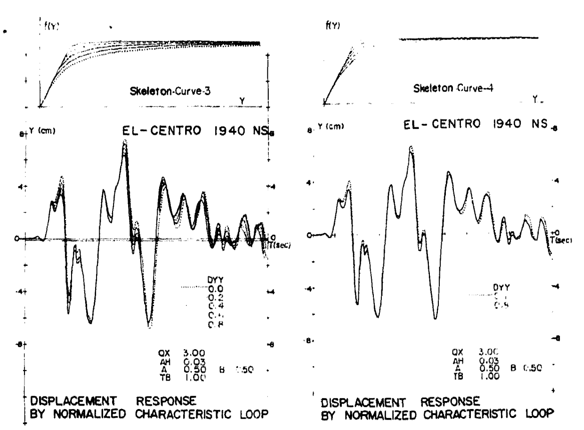

Fig-12

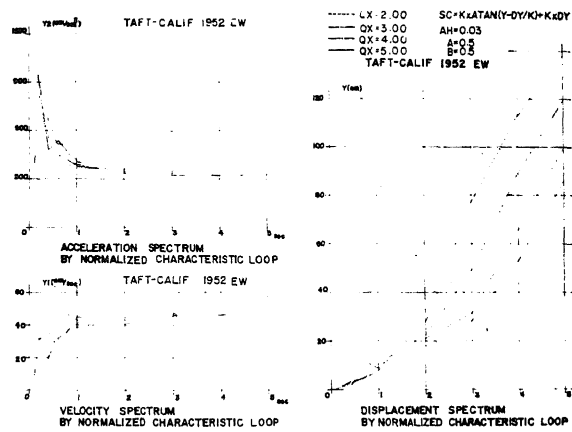

Fig-11

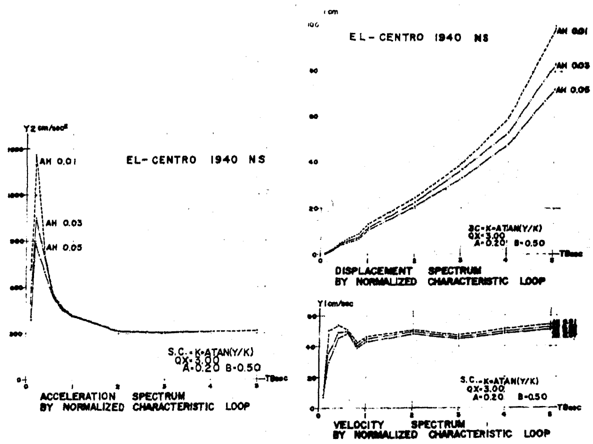

Fig-13

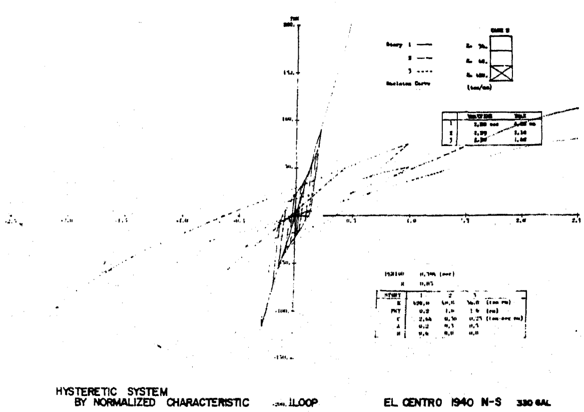

Fig-14