BIAXIAL AND GRAVITY EFFECTS IN MODELING STRONG-MOTION RESPONSE OF R/C STRUCTURES

by

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SYNOPSIS

A mathematical formulation is presented for modeling the process of dynamic failure of R/C flexural (flexural-shear) columns subjected to lateral biaxial deformation. The model considered is a two-dimensional extension of the degrading quadrilinear hysteresis concept that accounts for the prominent effects of cracking, yielding, crushing and spalling, and stiffness degradation. By including another factor of gravity (P-Δ) effect responsible for their destabilization, example studies are made to clarify the role of particular factors in determining the capacity to resist intense seismic shakings in the horizontal plane, and significance of the combined effects of biaxial deterioration and gravity is emphasized.

INTRODUCTION

Sufficiently reliable description of the dynamic process of damage and ultimate failure of R/C buildings requires to model more precisely the behavior of structural elements subjected to highly inelastic deformation. One of the difficulties in this regard is the mathematical formulation which permits to adequately reflect the significant features in the two-dimensional interaction of restoring forces of columns acted upon by biaxial flexure and shear. This is caused by the two-directional seismic shaking in the horizontal plane, and may seriously expedite their deterioration as compared to the conventional prediction by one-dimensional analysis. Clearly, the identification of certain gross characteristics in this class of response behavior can be an important contribution to the better understanding of ultimate failure or collapse of R/C buildings.

Two different approaches have been taken in the limited literature on this important but difficult problem. One is the formulation of a conceptual nature, which applies a phenomenological analogy with the theory of plasticity. The elementary concept of elastoplastic yielding system was extensionally interpreted in two dimensions along this line, and the model has been used in studying the effects of biaxial shaking and response.[1,2] The other approach is intended to provide a more elaborate formulation of current concern, by modeling R/C column as an assemblage of longitudinal fiber elements that embody the uniaxial stress-strain properties of concrete and reinforcements.[3,4] This modeling comparatively sophisticated and cumbersome, however, may or may not be best fitted to describing the biaxial characteristics because of certain complexities pertinent to reinforced concrete.

In previous papers on this subject,[5,6] the author has formulated the behavior of R/C columns during the biaxial loading, and examined the validity by comparison with experimental data. The model developed falls within the former category mentioned above: a two-dimensional extension of the degrading trilinear hysteresis concept which is among the simpler idealizations of the uniaxial characteristics of flexural-failure-type R/C structures and can account for the significant effects of cracking, yielding and stiffness degradation. The papers also included discussion of the strong-motion response of R/C structures in two dimensions, employing observed components of ground shaking as the excitation for the system. Role of different system properties such as the stiffness degradation in the influence of biaxial motion was examined with a particular interest, and the results obtained have

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indicated the full significance of the current effect in the two-dimensional degrading trilinear system, the influences being relatively minor for non-degrading bilinear and trilinear cases. Furthermore, in order to relate the features of biaxial response to the nature of strong ground motions in the horizontal plane, an additional investigation was made with regards to the influences of the relative magnitude and the differing degree of cross-correlation between the two components of excitation, as well as the influence of its absolute magnitude.[7]

The study reported herein is along an extension of the foregoing investigations, the primary concern lying in the ultimate failure beyond sustaining serious damage.[8] In modeling this aspect of biaxial response, the reduction of load-carrying capacity can be a crucial factor in addition; the concurrent action of the two components of biaxial bending seriously expedites the deterioration of restoring force properties according to the crushing and spalling of concrete section and so on, thus leading to the loss of ductility at relatively lower level of intensity. The previous two-dimensional model is therefore modified to meet the need of taking this feature into account. By use of the biaxial structural system and by including the nonlinear geometrical effect associated with the overturning action of axial compression through sidesway drift, the capacity to resist intense seismic shakings is quantitatively examined in the presentation.

MODIFIED FORMULATION OF R/C COLUMN BEHAVIOR IN TWO DIMENSIONS

Let the uniaxial skeleton curve for R/C flexural (flexural-shear) components up to the ultimate failure be represented by a quadrilinear function characterized by crack, yield and crush points, and the characteristics during a cyclic loading be modeled by associating the degrading hysteresis concept[6] with this curve. Fig.1 shows the skeleton properties along the principal axes X and Y, where an identical ratio of ultimate moment to yield moment is assumed for simplicity. A two-dimensional formulation of R/C column behavior on the basis of this uniaxial model can be developed[8] as summarized below, following the similar reasonings used in the previous modeling.[6]

In addition to the two criteria of crack and yield during an arbitrary history of biaxial loading, the same type of interaction formula, represented by another regular ellipse in the moment space, is now employed as the necessary condition of crushing. This leads to a four-part classification of plasticity range in the two dimensions: Range I (elastic), Range II (cracked), Range III (yielded) and Range IV (crushed). The crush ellipse in the case of Range IV contracts monotonically and translates in the moment space; otherwise, this keeps its current shape and position. The requirement of inscription between the current crush ellipse and the subsequent crush ellipse, which are similar to one another, specifies the law of contraction, while the shift of the center of crush ellipse follows the so-called Ziegler's hardening rule, however, directing its translation vector in the opposite direction. In this instance, the yield ellipse (which was previously assumed to expand and translate while inscribed with, and keeping its shape similar to, the current yield ellipse) is subjected to contraction in the same manner, instead of the expansion. Furthermore, accompanying the introduction of the new range of IV, a slight modification of the previous rules in Range III is needed for locating the yield ellipse within the crush ellipse at any instant. Namely, the inscription requirement of the mutually similar ellipses is alternatively used in case the application of the Ziegler's rule to specifying the shifting center of yield ellipse results in the intersection of the two ellipses. (This case is called Range III'.) The remaining rules of "hardening" for Ranges I, II, II', III, III' and IV can be identical with those in the previous formulation, and Fig.2 explains a set of hardening rules used in Range IV.

The location of biaxial moment {M} in the mutual configuration among the crack, yield and crush ellipses is illustrated in Fig.3 for Ranges III and IV. Case a shows an instant when the virginal crush is imminent to the yielded system (in Range III) with its current yield and crack ellipses under a translatory expansion. An example of the further progress of deterioration beyond the subsequent crush appears in Case b (Range IV) where the crush, yield and crack ellipses are contracting and translating. The system in Case c is subjected to reloading (in Range III passing Ranges I and II) after an unloading process from Case b, and the translating yield and crack ellipses are also expanding afresh within the reduced crush ellipse. Case d is again in Range IV, the yield ellipse being overlapped with the crush ellipse. The latter is corresponding to the uniaxial situation after the crush has occurred in both the positive and negative directions of loading.

The incremental flexibility relationship between the biaxial end-moment and associated end-rotation is expressed by resolving the latter into elastic and plastic components and by relating the respective components to the former. A "flow" rule specifies the increment of plastic component in terms of the normal vector at {M} of criterion ellipses and a stiffness matrix of diagonal form, while another diagonal matrix is relevant to the elastic component. The two stiffness matrices vary instantaneously according to the stiffness degradation in two dimensions as well as to the stiffness reduction. It is postulated that these are determined uniquely from the current plasticity range and the current values of the two parameters describing the degree of expansion or contraction of the yield and crush ellipses. This postulate permits to explicitly represent the two-dimensional stiffness, making use of the system parameters prescribed for uniaxial characteristics. In general, the resulting relationships of restoring forces are no longer piecewise linear. The successive discrimination of loading or unloading can be made by applying the requirement of positiveness for the rate of a certain plastic work in case of being subsequently loaded.

STRUCTURAL FAILURE UNDER BIAXIAL SHAKING AND GRAVITY LOADING

In order to gain some quantitative insights into the role of basic factors influencing the failure of R/C structures, a limited set of response evaluations[8] are made using a two-dimensional single-mass system with the biaxial restoring force characteristics. Even though being restricted to the most elementary model of overall structure, this will be sufficient for drawing significant trends of current interest. The conceptual structure is subjected to the excitations acting in the horizontal plane: the three typical accelerograms of El Centro-'40, Hachinohe Harbor-'68 and Hoshina-'66. Since the unimportance of vertical excitation (as fluctuating the effective gravity in its destabilizing action) is quite evident,[8] this component of excitation is not included in the gravity term. The uniaxial system parameters assumed up to yield point, identical for X(NS) and Y(EW) directions, are: elastic period = 0.30s, yield (crack) shear coefficient = 0.25 (0.125) and $\alpha_y = 0.20$, and the parameter describing the degree of gravity effect, α_g,[8] takes $6x10^{-3}$ (a representative value for soft frames). It should be noted that the absolute level of force need not be specified when interpreting this relatively to the earthquake strength. Two different cases of the uniaxial skeleton curve beyond yield point, ideally ductile or deteriorating, are taken up for comparisons. In the former case, the static stability limit μ_g (due to gravity) in terms of ductility factor is 40. On the other hand, the following values are used for the parameters relevant to the quadrilinear function in the case of deterioration: $a_u = 1.05$, $\mu_u = 3.0$ and $p = -0.010$, thus leading to the static stability limit in the restoring force capacity, μ_p, of 24 and this limit reduced by combining the gravity effect, μ_g', of 15.

The maximum response in the biaxial evaluation is represented by the three components of ${}^{2}_{x}\mu_{max}$, ${}^{2}_{y}\mu_{max}$ and ${}^{2}_{r}\mu_{max}$ which are assigned from the normalization of X, Y and radial components of the two-dimensional drift with respect to uniaxial yield deformations. The maximum drifts ${}^{1}_{x}\mu_{max}$ and ${}^{1}_{y}\mu_{max}$, evaluated from the usual uniaxial calculations along X and Y directions, follow the conventional definition of ductility factor. Also, another maximum ${}^{1}_{r}\mu_{max}$ $[\triangleq \sqrt{({}^{1}_{x}\mu_{max})^2 + ({}^{1}_{y}\mu_{max})^2}]$ is used to represent the combined uniaxial responses, although this gives clearly an overestimated value as the vectorial synthesis. Along these lines of normalization, Figs. 4 and 5 show the results of strong-motion response calculations for the X and Y, and radial components, respectively. The magnification factor of intensity in the original accelerograms is taken as the abcissa; the biaxial and gravity effects in the ideally ductile or deteriorating system are examined under different input intensities. Arrows in the figures indicate the system fails at the next intensity level, and the influence of biaxial response can be quantitatively identified by ${}^{2}_{x}\mu_{max}/{}^{1}_{x}\mu_{max}$ and ${}^{2}_{y}\mu_{max}/{}^{1}_{y}\mu_{max}$, or by ${}^{2}_{r}\mu_{max}/{}^{1}_{r}\mu_{max}$.

As indicated in these figures, the input intensity causing ultimate failure is reduced, due to the biaxial effect, by a factor of 0.45(El Centro) or 0.65(Hachinohe) in the ductile case and by a factor of 0.85(El Centro) or 0.80(Hachinohe) in the deteriorating case. The results also show the same ranges of collapse intensity for the two cases of different skeleton properties, which suggests the more important effect of biaxial response than the effect of deterioration. The influence under the Hoshina excitation can be relatively insignificant because of its stronger trend of shaking confined in a single direction. On the other hand, the comparison of the collapse intensities derived under the gravity effect considered/neglected in the deteriorating case can lead to the identification of the relative degree of influence between the two effects of biaxial deterioration and gravity, which differs significantly among the three excitations in the case study. It should be also noted that the margin of safety against collapse of R/C structures is very small when the effects of biaxial response, deteriorating ductility and gravity are all combined.

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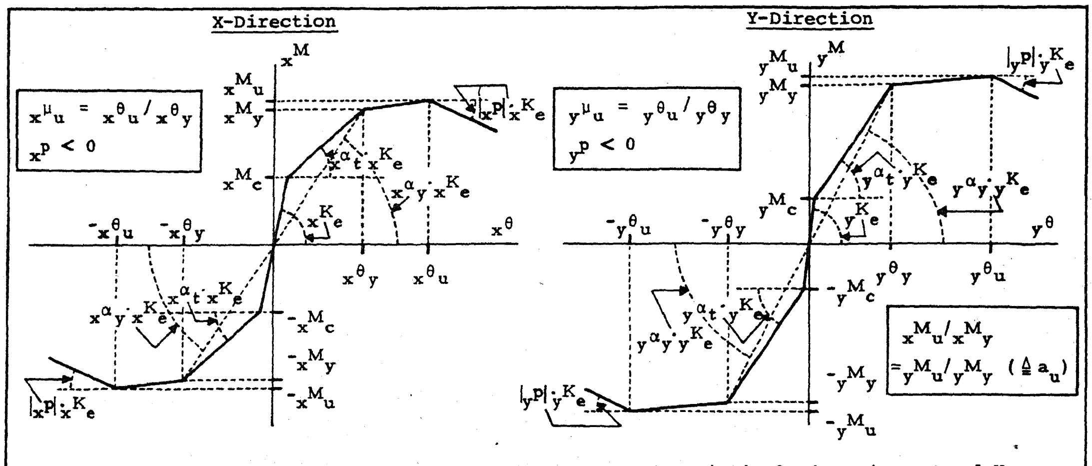

Quadrilinear Skeleton Curves for Uniaxial Flexure in Principal Directions X and Y

Fig.1

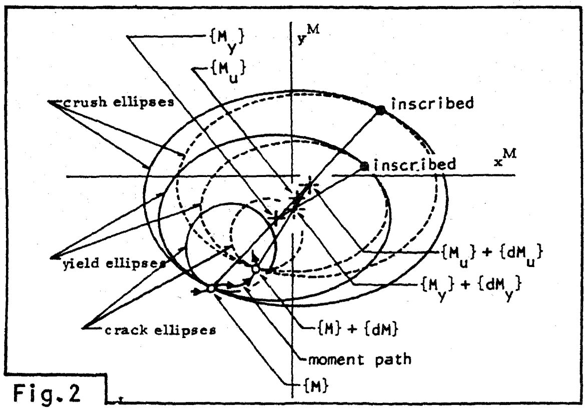

Fig.2

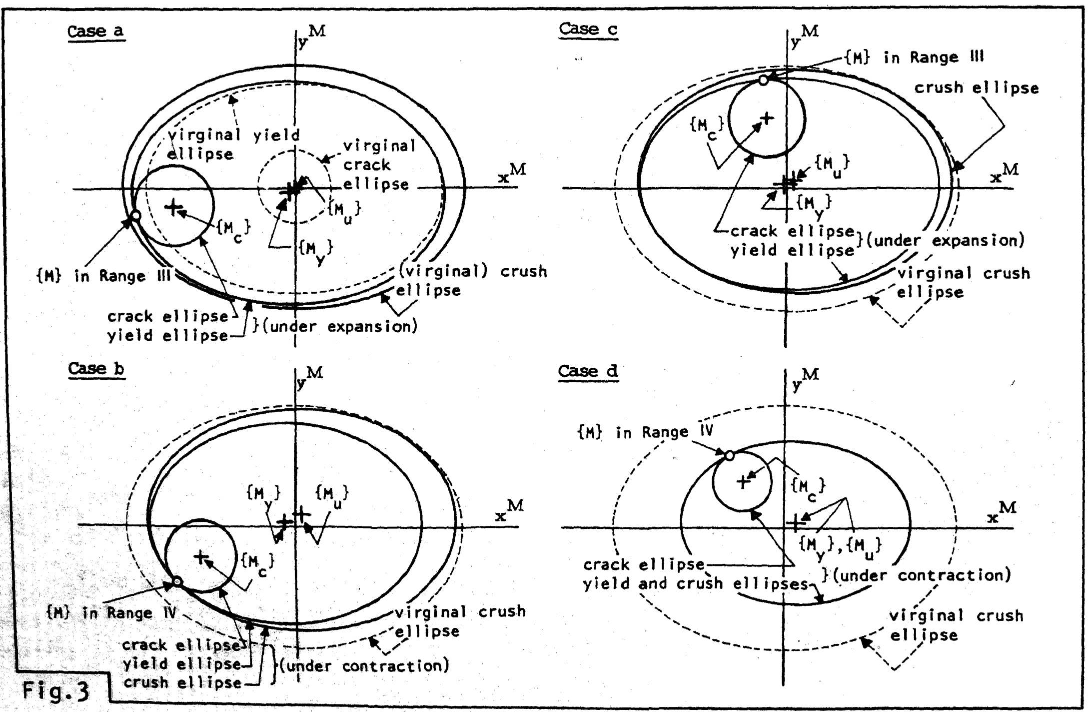

Fig.3

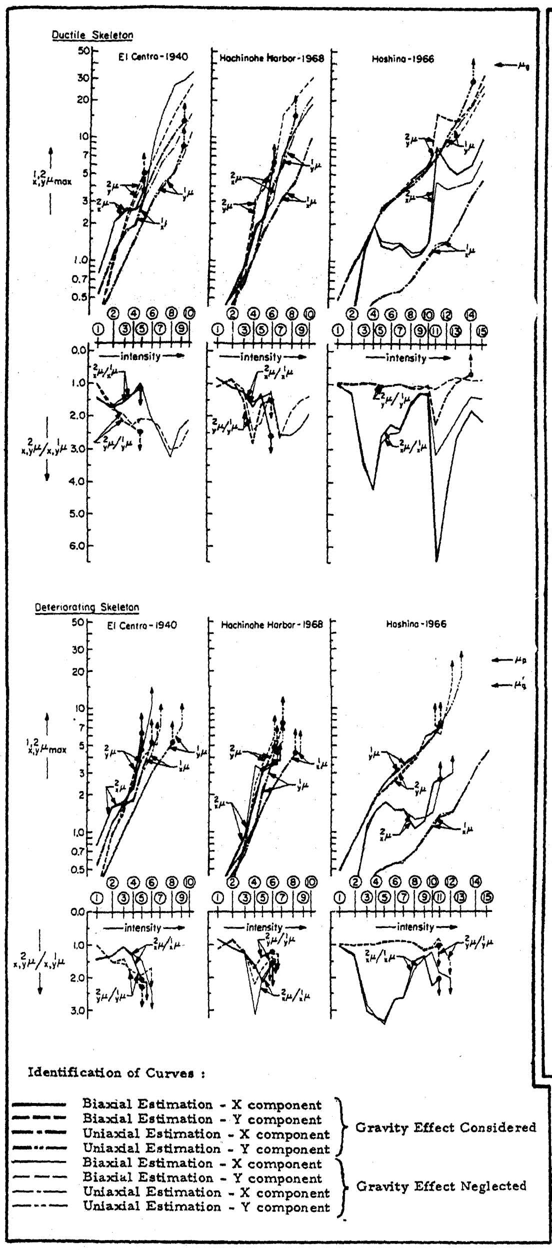

Fig.4

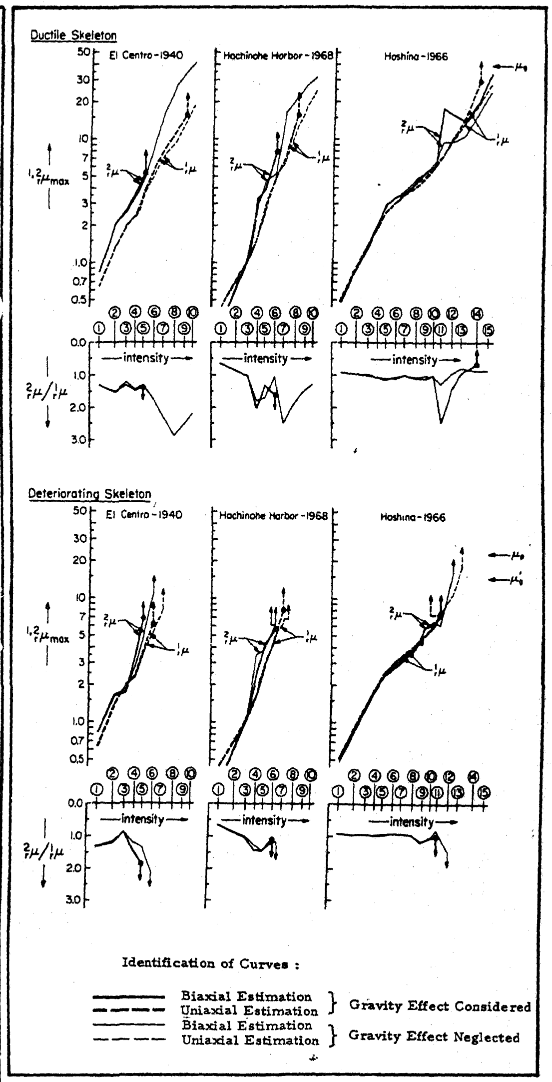

Fig.5

Indices of Abcissa (Intensity) :

indices	magnification factor	peak acceleration in gal					
		NS	EW	NS	EW	NS	EW
①	0.6	205	126	135	110	173	292
②	0.8	273	168	180	146	231	389
③	1.0	342	210	225	183	289	487
④	1.2	410	252	270	220	347	584
⑤	1.4	478	294	315	256	405	682
⑥	1.7	581	357	382	311	491	828
⑦	2.0	683	420	450	366	578	974
⑧	2.5	854	525	562	457	723	1217
⑨	3.0	1025	630	675	549	867	1461
⑩	3.5	1196	735	787	640	1012	1704
⑪	4.0	-		-		1156	1947
⑫	5.0	-		-		1445	2434
⑬	6.0	-		-		1734	2921
⑭	8.0	-		-		2312	3895
⑮	10.0	-		-		2890	4869
identification of excitation		El Centro -1940		Hachinohe Harbor -1968		Hoshina -1966	