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DYNAMICS OF WEAK-GIRDER REINFORCED CONCRETE FRAMES

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SUMMARY

With a view to obtaining reasonable bases for the ductility-dependent design of reinforced concrete buildings, studied is the kinematically failing behavior of strong-column and weak-girder frames under the action of intense earthquake shakings. Throughout the presentation, the associated mechanics is emphasized to tend to be featured by unexpected complexities. A modal decomposition method is first shown to aid their better understanding with respect to both deformation and force in story-level response. Then the examination focuses upon the peak stress produced at unyielding sections, for which an unsophisticated formulation to be used in practical design is reported toward its target of weak-girder failure.

INTRODUCTION

Manifestation of the principle of strong columns and weak girders is a recent worldwide trend in earthquake-resistant design of R/C structures. However the related mechanics from the viewpoints of frame analysis appears to be not yet clarified sufficiently with regard to local ductility and stress. Actually the effects of multi-dof dynamic loading influence significantly their yielding and hysteretic performance, and cannot be so simple as to permit the ordinary straightforward understanding by means of static analyses. This becomes particularly the case of peak stress produced at unyielding sections, the reliable identification of which poses an important pre-requisite for attaining the design target of girder-yielding failure. The current brief report is intended to review and summarize results of the authors' recent work (Refs. 1 to 5) with some additional extensions.

The model buildings in these studies consisted of three, six and nine-storied three-bay frames of purely moment-resisting type and, in addition, those with a continuous story-to-story row of shear walls at their midspan portion (henceforth referred to as F3, F6, F9, W3, W6 and W9, respectively). They have standard dimensions of geometry and static ultimate strength in accordance with the 1980 Japanese Building Regulations. Column-bottom critical sections at base story can yield besides all the critical sections of girders, while the remaining critical sections are rendered to remain unyielded. Their dynamic member-by-member analyses were performed by accounting for the significant softening due to cracking and the degradation of hysteresis loop as well as the effects of yielding sections. Only a set of examples by use of the Tohoku Univ. accelerogram (1F, NS comp., 1978 Miyagi-ken-oki EQ in Japan) is to be taken up in the following. Separately in the six frames, its amplitude was enlarged so as to realize a particular common situation of kinematic failure when the peak ductility factor of overall structure reaches 3.0.

Modal Decomposition Evaluation results of dynamic structural performance by means of a member-by-member analysis have a general tendency to exhibit somewhat involved microscopic features. Multiple interactions of yielding and hysteretic restoring force combined closely with the multi-dof action of inertial forces are mostly responsible for such notable singularities. A modal decomposition method, the mathe-

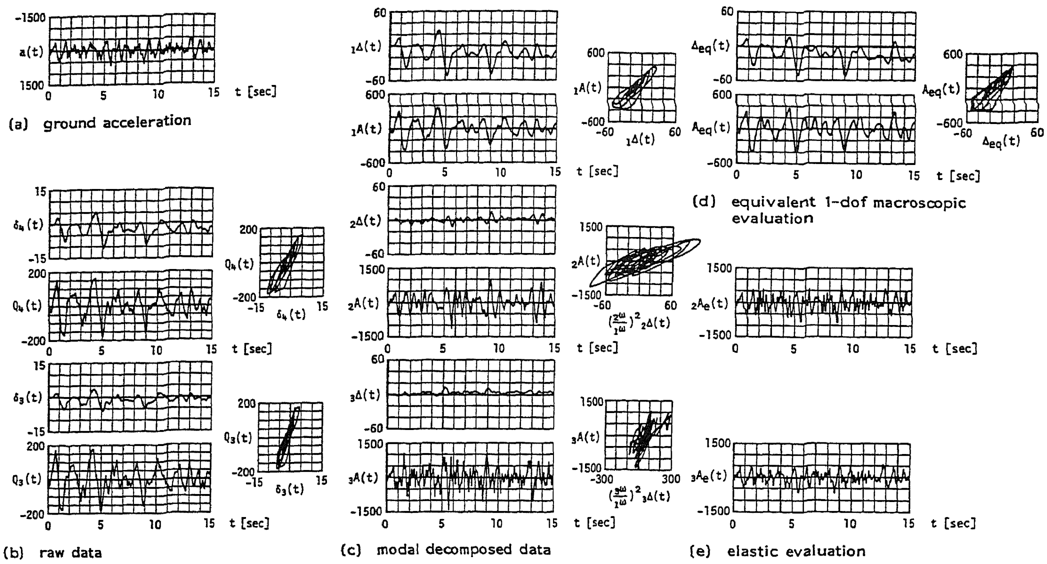


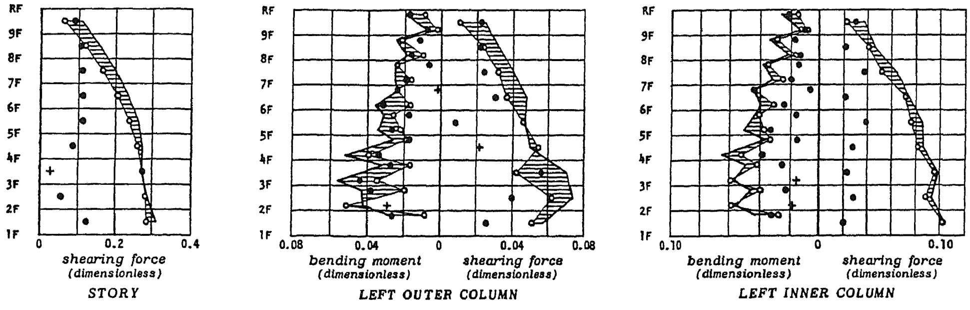
Figure 1

$a(t)$: *ground acceleration in gal*
$\delta_i(t)$: *interfloor drift at i-th story in cm*
$Q_i(t)$: *shearing force at i-th story in ton*
${}_s\Delta(t)$: *s-th order modal drift in cm*
${}_sA(t)$: *s-th order modal restoring force in gal*
[${}_s\omega$: *s-th order natural circular frequency at elastic stage*]
$\Delta_{eq}(t)$: *equivalent 1-dof drift in cm*
$A_{eq}(t)$: *equivalent 1-dof restoring force in gal*
${}_sA_e(t)$: *elastic version of* ${}_sA(t)$ *in gal*

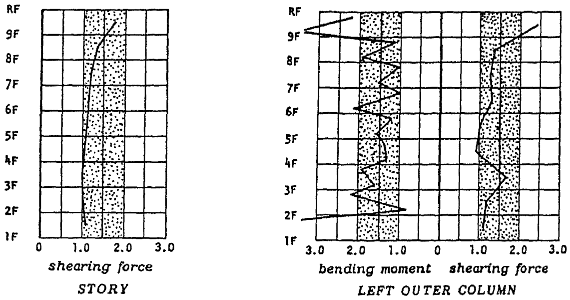
matical formulations of which are found in Ref. 2 together with its practical implications, can be advantageously used in these situations by permitting to extract relatively significant components. According to the method, choice of a certain suitable system of mutually orthogonal vectors allows to resolve the multi-dof pair of deformation and force into a corresponding pair of reference components and two rows of remaining redundant components, thus leading to identification of the dynamic effects as related to the contribution of higher-order oscillation modes. Featured by its completely formal nature, this is no more than a convenience to classify given data and differs essentially with the elementary modal decomposition as a solving tool for linear equations of motion. Note also that the term of higher order does not imply higher frequency. Even though its strict applicability is restricted to story-level data of response, the decomposition may also provide a reference framework for examining the dynamic effects contained in member-level data.

Application of the above method is best fitted to weak-girder frames, since a reference mode of oscillation can be determined rather uniquely throughout differing stages of yielding response. By selecting an example of F9, time-history appearence of the dynamic effects evidenced in story-level response is noted in Figure 1. Its part (b) illustrates time histories of interfloor drift and shearing force at two sampled stories and associated restoring force diagrams. They tend to contain singularities influenced by the mixture of higher-order oscillation modes. Then partial results of the modal decomposition truncated at the 3rd-order components are included in part (c). Rendered simple enough to describe the essential features, the drift-to-force pair of reference components is to be used for discriminating the dynamic effects. The simplicities are particularly noticeable in their restoring force diagram. Moreover this can be shown to be reproduced satisfactorily in a macroscopic analysis by means of the deflated "equivalent 1-dof" modeling of overall structure (Ref. 2). Actually a strikingly good correspondence in both drift and restoring force is seen in part (d). In addition, part (e) indicates that substitute use of elastic response for the higher-order components may become of a practical interest toward the restoring force only. The higher-order relations of restoring force are also shown therein to result in their totally erratic appearence.

<u>Nature of Peak Stress</u> Indeed unfavorable for the weak-girder design is the practical difficulty in bounding the dynamic stress arising at critical sections, the yielding of which is to be rendered inadmissible. Actually this problem proves still less simple than expected from the static limit-state stress analysis of girder-yielding frames. The peak stress extends frequently far beyond an ordinary understanding, which reflects differing share of shearing force and position of

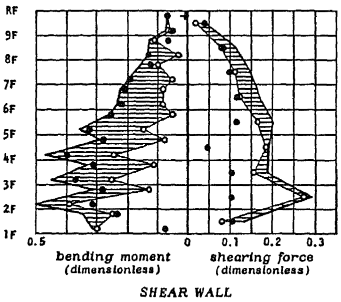


(a) F9

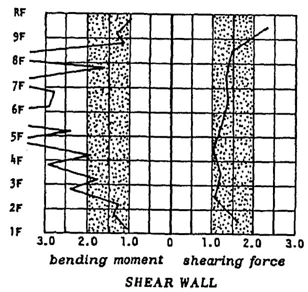


(b) dynamic increasing factors, F9

Figure 2



(a') W9



(b') dynamic increasing factors, W9

inflection point. According to the authors' study, this exhibits markedly erratic nature in the increasing order of story shearing forces, member shearing forces and bending moments. The associated dynamic effects become particularly significant at side columns of moment-resisting frames and at coupled shear walls.

A limited set of examples is given in Figure 2 by choosing the partial data of F9 and W9. A certain normalization for shearing force and bending moment is used there (for their complete presentation, vide Ref.5). Then introduce reference stress in order to examine quantitatively the associated dynamic effects. The latter is evaluated from a static version of the dynamic frame analysis, the loading mode in which follows the previous reference mode of oscillation. The dynamic and static analyses are designed to coincide one another in providing common "equivalent 1-dof drift" (Ref.2) along each of the positive and negative directions of loading. Parts (a) and (a') of Figure 2 include also the reference stress, its absolute difference with the dynamic peak stress being striped for clarity. Using notations of X and Y for the peak stress and the reference stress, respectively, the conventional measure for representing the dynamic effects is a multiplication factor defined by X/Y. The dynamic modification factors are shown in parts (b) and (b') of the same figure. This presentation highlights the increasingly erratic trends of peak stress in the above-noted order. Therefore the multiplication factor is concluded to be of little practical use due to its frequently excessive magnitude and the related irregularities.

Coupled bending action of girders upon columns or shear walls diminishes notably according to the yielding of girders. This causes serious time-dependent shift of the position of inflection point for columns and shear walls, together with the

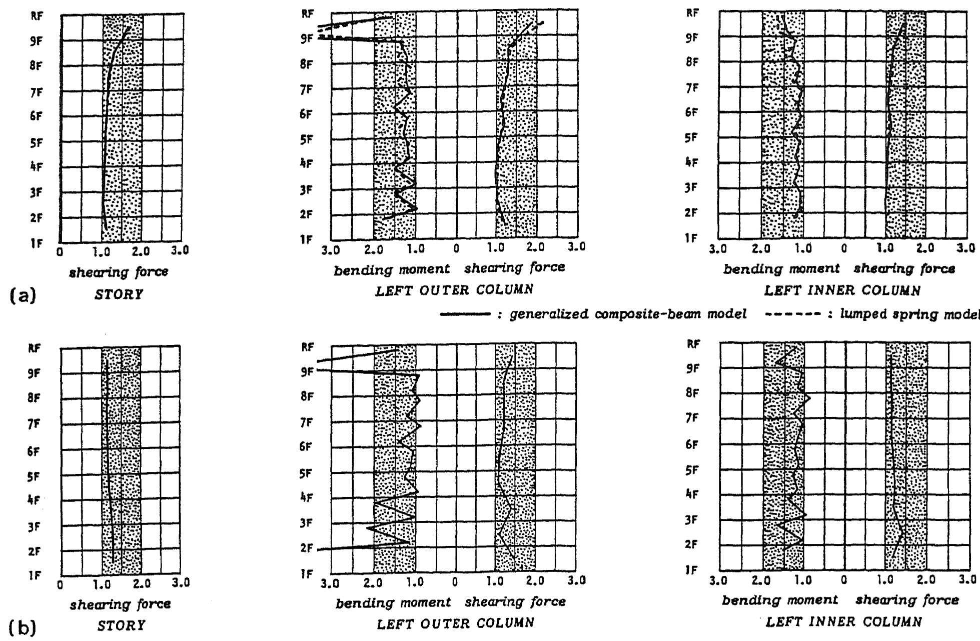


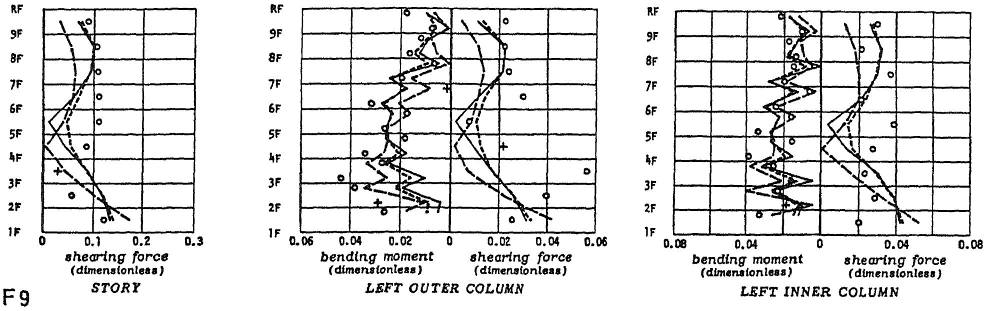
Figure 3 [*indicating the dynamic increasing factors in the same style as in part (b) of Figure 2*]

appreciable contribution of higher-order oscillation modes. Furthermore the hereditary pre-yield performance of columns, under their 2 x 2 interacted relations of restoring force as formulated by the so-called "beam modeling", appears to affect the remarkably singular characteristics observed at side columns. Overlapping of these effects results in an unexpected finding at side columns where stress is inclined to respond in a single direction (Ref. 3). The latter situation arises when repeated shifts of inflection point occur over the inside and outside of member by accompanying a non-vanishing tendency of unloaded stress.

These circumstances arouse caution in performing frame analyses for the current concern. Non-hysteretic modeling of unyielding columns and reduction to multi-storied single-column systems may become insufficient, while the hereditary effects in significant and cyclic shifts of inflection point should be realistically modeled. The beam model used in the authors' examinations is "parabola plus delta" formulation, discrepancies provided by different formulations of "generalized composite-beam model" and "lumped spring model" being indicated in part (a) of Figure 3 (for these beam models, vide Ref. 6). Since the latter two models prove improper when turned into nearly pure bending of member, the erratic tendencies are shown there to be considerably interrupted. Still the dynamic effects remain more pronounced at side columns. In addition, other caution should be used in the viscous damping assumption applied beyond elastic limit (Ref. 4). Unless dashpot factors are individually reduced according to the decrease of instantaneous tangent stiffness, entirely different features arise in the performance of unyielding members besides the unrealistic overestimation of damping forces. The dynamic modification factors evaluated under the alternative assumption of invariant dashpot factors (5% of critical damping) are shown in part (b) of Figure 3, which indicates notable disappearence of the dynamic effects.

<u>Simple Formulation of Peak Stress</u> The afore-mentioned nature suggests a better fitted use of SRSS summation rather than the multiplication for bounding the peak stress. Under the previous notations of X and Y, residual component of peak stress, Z, is thus defined by $Z = (X^2 - Y^2)^{1/2}$. In a direct comparison with X and Y, this is plotted within parts (a) and (a') of the foregoing Figure 2 [the symbol of + stands for $Z^* = (Y^2 - X^2)^{1/2}$ in the exceptional cases of $X < Y$]. Then it becomes advantageous to examine the residual stress by separating the problem into relative distribution over its ensemble and a single absolute factor expressed in acceleration. The detailed discussions can be found in Ref. 5.

Distribution mode of the residual stress is investigated with relation to the

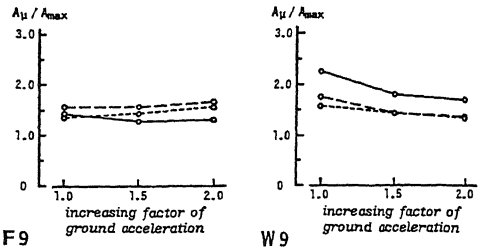


F9

Figure 4

o : "residual component"
(+ : vide its explanation in the text)

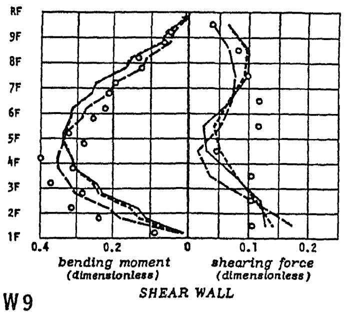
——— : substitute I
– – – : substitute II
------- : substitute III



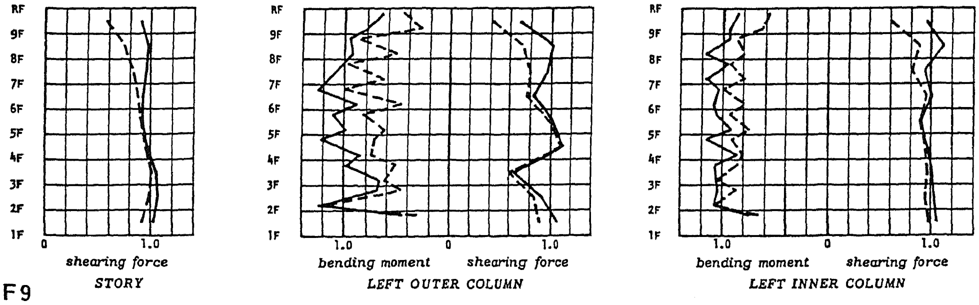
F9 W9

Figure 5

——— : story shearing force
– – – : member shearing force
------- : bending moment



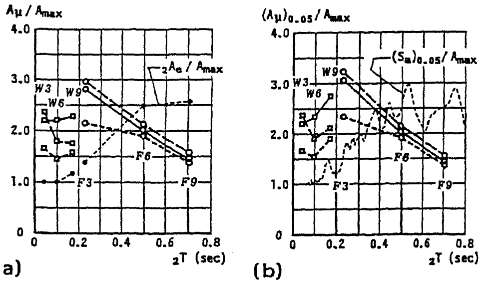
W9



F9

Figure 6

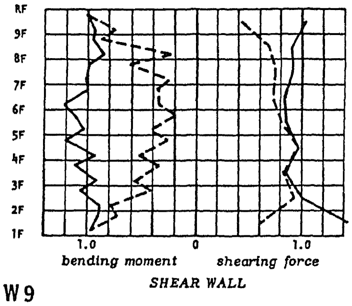
——— : X_μ / X – – – : Y / X



(a) (b)

Figure 7

——— : story shearing force
– – – : member shearing force
------- : bending moment



W9

contribution of higher-order oscillation in two linear systems. One is the ideally elastic frame, while partially differing reduction of secant stiffness is taken into account in another system. Without getting involved in trivial details during the latter linearization (henceforth referred to as pseudo-elastic), reduction factors relative to elastic stiffness equal to 0.5 and 0.05 at unyielding and yielding critical sections, respectively. Also let all the higher-order modes be condensed into a single one. Three different ways of the condensation are used under certain approximations, the simplest among them accounting for the 2nd-order oscillation only. Results of a close examination have concluded that any of the 2 by 3 combination of different modes leads to a similar trend in interpreting the relative distribution of residual stress. The pseudo-elastic formulation can be, if anything, more advantageous, examples of which are shown in Figure 4 under the three condensations and in a direct correspondence to the previous Figure 2. The degree of coincidence obtained therein may not be so satisfactory; however it will become evident that considerable portion of the distribution can be understood by the unsophisticated formulations. In particular, their usefulness is appealingly seen in bending moment at coupled shear walls.

Application of least-square fit in the present correlation provides a factor of magnitude, A_μ, for the residual stress. This corresponds to the absolute acceleration response of an elementary pendulum, and is to be determined separately in the three ensembles of story shearing forces, member shearing forces and bending moments. Contrary to an ordinary understanding, the factor proves unbounded even after the complete formation of kinematic sway mechanism. Rather this tends to increase in proportion to ground acceleration as evidenced in Figure 5. Data for 1.5 and 2.0 times the standard intensity are recruited therein, and A_{max} represents peak amplitude of ground acceleration. An additional illustration of Figure 6 is then intended to highlight the reproducibility of peak stress. This follows the definition of $X_\mu = (Y^2 + Z_\mu^2)^{1/2}$ where Z_μ is a substitute for Z by one of the three least-square fits in the preceding Figure 4. The presentation demonstrates clearly advantages and limitations in the current formulations.

According to the above finding, identification of an amplification ratio of A_μ/A_{max} suffices for characterizing the absolute magnitude of residual stress. Part (a) of Figure 7 summarizes its values assigned to the six frames of F3, F6, F9, W3, W6 and W9. The abscissa is 2nd-order natural period of the individual pseudo-elastic systems. For comparisons, the figure includes an elementary measure of ${}_2A_e/A_{max}$ where ${}_2A_e$ is a pseudo-elastic version of A_μ. The spectral expression proves incomplete when recognizing the fact that the damping factor for 2nd-order oscillation differs each other among the six frames. The latter correction leads to part (b) of Figure 7 where A_μ and ${}_2A_e$ are being modified into $(A_\mu)_{0.05}$ and $(S_a)_{0.05}$, respectively, under a common damping factor of 5%. The continuous curve of $(S_a)_{0.05}$ coincides with the conventional spectrum of acceleration response, no consistencies with A_μ being immediately evidenced in the comparisons. The ratio of A_μ/A_{max} extends over the broad band of 2.0 ± 1.0, and reflects seemingly the specific properties of frames.

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