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STRESS-STRAIN BASED MODELING OF INELASTIC EARTHQUAKE RESPONSE OF RC FRAME STRUCTURES WITH VARYING AXIAL FORCES

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SUMMARY

This paper introduces the concept of stress-strain based inelastic earthquake response analysis of RC frame structures considering the effects of actual dynamically varying axial forces. The material non-linearity of RC elements is evaluated by using a fiber model based on hysteretic stress-strain relations. The accuracy of concrete and steel constitutive laws are examined by the comparison of analytical and experimental inelastic moment-curvature relations. Non-linear earthquake structural response is computed by numerical step-by-step solution of the dynamic equation of motion. By the present analytical method, the inelastic seismic behavior of RC tower structures of cable-stayed PC girder bridges can be examined in detail and it was shown that dynamically varying axial forces are an important factor to evaluate the seismic safety of the structure.

INTRODUCTION

The structural limit state design concept is nowadays becoming reasonable and popular in which the material non-linearity of an RC element needs to be realistically considered. In the previous structural analysis of RC frame structures, element non-linearity was often assessed on the assumption of constant axial forces. However, in the cases of RC frame structures with high axial forces such as RC towers of cable-stayed bridges, high rice buildings and so on, the change of axial forces is an important factor in evaluating the safety of the integral system. It is extremely complex and difficult to take account the variational axial forces in the conventional modeling (1)(2) of RC beam elements.

To meet the demand for sophisticated analytical method in such cases, for practical design of earthquake resistant structure, the authors have developed stress-strain based concept for inelastic earthquake response analysis of RC frame structures taking into account dynamic variation of axial forces (3)(9). The stress-strain relations of concrete and steel used in this study were examined and approved in the experimental study (4) and the elementary study (5) of an RC beam under high axial Load(10).

The main futures of the presently developed analytical method are: (1) Non-linear earthquake response analysis of an arbitrary shaped 2-dimensional RC frame governed by an incremental-formed equation of motion, (2) Consideration in the analysis the real history of dynamically varying element axial forces, (3) Analytical simulation of material (concrete and steel) hysteretic stress-strain relations with improved accuracy, (4)Evaluation of non-linear element stiffness with desired refinement through enabled conditions for detailed discretization, (5)The evidence in induced spreading nonlinearity along the elements, (6) Simulation of structural damping employing Rayleigh-damping matrix, (7) Step-by-step solution of the dynamic equation of motion employing numerical integration scheme.

CONCEPT OF STRESS-STRAIN BASED INELASTIC BEHAVIOUR MODELING OF RC STRUCTURES

The basic concept of the present analytical model for non-linear dynamic analysis of RC structures consider evaluation of instenstaneous element stiffness matrix based on analytical representation of experimentally observed hysteretic stress-strain relations typical for concrete and steel material subjected to arbitrarily cyclic loads. The main considerations employed here are briefly summarized in the following.

Concrete and Steel Analyrical Models: Based on past experimental studies of stress-strain relations of structural materials under generalized cyclic loading, the stress-strain models for concrete and steel fibers are formulated including main parameters influencing these relations. The Muguruma-Watanabe's rule(6) is modified to represent stress-strain relations of confined and unconfined concrete fiber elements. In the model, concrete confinement levels(7), tension stresses, failure in tension, plastic strains, crush of concrete, compressive failure and stiffness degradation are described with nine different paths, five of which are previous path history dependent.

The Meneggoto-Pinto's rule(8) is adopted to represent stress-strain relation of steel fiber elements, which includes Baushinger effect, plastic strain and isotropic strain hardening for arbitrary strain history.

The adopted hysteretic rules of concrete and steel are schematically illustrated in Fig.1 and Fig.2. Details of the rules are presented in the reference(9).

Non-Linear Element Formulation: In formulation of non-linear stiffness matrix of an isolated RC member subjected to axial and bending loads the following three suppositions have been originally employed: (1) Plane cross-section remain plane after deformation, (2) Element stiffness is invariant in a time increment, and (3) No shear deformation is included. However, in global coordinate system, all three degrees of freedom per each element node have been considered assuming in addition arbitrary element spacing, so modeling of structures fith complex geometry have been provided. Non-linear stiffness matrix of each single RC element(Fig. 3) is computed in the following algorithm applying the beam theory:

1) Divide a beam element into some parts(Sub elements) along the axis line.
2) Compute axial strain ε_a and curvature ϕ at each deviding point from the current displacements at the ends of the element with the assumption that axial force is constant and bending moment varies linearly in the element.
3) Divide a sections(Interface elements) at each location point into some discrete areas (Fibers) considering existing total steel and concrete areas.
4) Compute strain ε_i at the location y_i of each Fiber using the assumption that a section remains flat.
5) Calculate tangential stiffness E_i corresponding to ε_i of each Fiber using the aforementioned hysteretic rules.
6) Compute sectional stiffness $[K_{ia}]$ by integrating E_i over the Interface element.
7) Compute stiffness of Sub-elements using the assumption of constant axial force and linearly varying bending moment in the element.
8) Compute stiffness of a beam element by integrating stiffness of Sub elements over the total length of the element.

Based on computed non-linear stiffness matrices for all RC elements, in each computation step, the assembling of the local and global stiffness matrices of the integral structure generally follows the standard finite element comcept.

NON-LINEAR DYNAMIC RESPONSE ANALYSIS

Since the afore-mentioned non-linear stiffness is time-variant, using the assumption that stiffness is time-invariant in a short time step, the basic equation of motion of a system is given in the following incremental form(1).

$$[M]\ \{\Delta \ddot{u}\} + [C]\ \{\Delta \dot{u}\} + [K]^{t}\ \{\Delta u\} = \{\Delta R\} \qquad (1)$$

There are two numerical problems to solve non-linear equations, that is, a problem of iteration and a problem of an unbalanced force. While a problem of numerical iteration should be mainly discussed on computing time and numerical accuracy, a problem of an unbalanced force should be also discussed including methodology how to compute it. The varying stiffness method is popular to consider an unbalanced force, though it generally requires a great amount of computing time. The equivalent external force method (or the initial stiffness method) is also becoming popular because it requires less computing time than the former method, however there is another problem that an impulse due to an equivalent external force is often generated in response.

The varying stiffness method with iteration should be employed in this study because varying stiffness is computed at every time step according to the aforementioned. However, from the practical view point, no iteration is performed in the following numerical examples.

In a computer program developed in this study, the consistent mass matrix and the lumped mass matrix can be employed alternatively as the mass matrix. Rayleigh damping matrix is used as the damping matrix. Both Newmark's method and Wilson's method are available as a time integration schemes. The RC members can be alternatively processed as linear or non-linear elements.

TOWER MODELS OF CABLE-STAYED PC GIRDER BRIDGES AND COMPUTED RESULTS

Next, to study the seismic behavior of RC towers of PC girder bridges which must bear high varying axial forces, two types of an RC tower, A-shaped one and H-Shaped one, are analyzed and examined through each comparison. There RC towers are about 100m height and supposed to belong to 3-span cable-stayed PC girder bridges of which may cause high varying axial forces and the difference of seismic response due to configuration. The magnified El-Centro earthquake acceleration of which maximum value is 600(gal) is employed as an input ground motion. The duration is 6.0(sec). The time increment is 0.005(sec). Each analytical model is shown in Fig.4 and Fig.5. A-shaped model (call case-A in the following) has 26 elements and 26 nodes. H-shaped model (case-B) has 34 elements and 34 nodes. The material and damping constants used in this examples are given beside the figures, while the two constants of Newmark's integration cheme are assumed as $\delta = 1/2$ and $\alpha = 1/4$.

Fig.6 and Fig.7 show the displacement response at the top in case-A and case-B, respectively. Fig.10 and Fig.8 show the axial force(N) and the bending moment(M) response of the right-side bottom-end element (element AA in Fig.4) in case-A, respectively. Fig.11 and Fig.9 show the axial force and the bending moment response of the right-side bottom-end element (element HA in Fig.5) in case-B, respectively.

The stress-strain relation of concrete in case-A (element AB in Fig.4) and in case-B (element HB in Fig.5) are shown in Fig.12 and Fig.15. Further, the

M-N relation of these elements are shown in Fig.13 and Fig.16, while the M-ϕ relations of these elements (case A and case B)are also shown in Fig.14 and Fig.17, respectively.

These results show a typical inelastic behavior that acceleration becomes smaller (not included), displacement becomes bigger and bending moment becomes smaller than the results by linear analysis. It is shown that the lateral beam connecting section (element AB in Fig. 4) in case-A and the upper-lateral beam connected section (element HB in Fig.5) in case-B could fail first in each case. On the other hand, the static modified seismic analysis shows that the first failure member is the lateral beam connecting section in case-A and the lower-lateral beam connecting section (element HC in Fig.5) in case-B. These results are different from the present results. That may be because in case-B the static dominant mode of deformation is different from the dynamic dominant mode of deformation while they are similar in case-A. As to axial force in case-A, the change of it must have a great effect on the seismic safety of the structure because the varying range of N may be up to 10000.0(ton) in case-A(Fig.10) and there is a basic linear relation between N and M(Fig.13). Besides, the M-ϕ relation may be much affected by the varying axial force (Fig.14). While in case-B the varying range of axial force in the bottom member is not so big (Fig.16) and the M-ϕ relation of the member shows only slight stiffness degradation (Fig.17), but the first failure member shows a similar behavior as the bottom member in caseA.

The initial sectional force due to own weight, cable tension of the initial maladjustment of structure is another important factor to the seismic safety of structure because it determines the starting point of stress-strain relation (Fig.12, Fig.15). Among them, the initial sectional force due to the initial maladjustment has a serious effect on the change of N because it is uncertain in nature and causes big initial sectional forces.

CONCLUDING REMARKS

In this study, a method of stress-strain based inelastic earthquake response analysis of RC frame structures with varying axial forces is introduced, and the following concluding remarks are obtained from numerical study.

(1) A varying axial force has a nonnegligible effect on M- relation of a section and the seismic response of an RC frame structures.
(2) The varying range of axial force may become more than the degree of the initial axial force, depending on configuration of an RC frame structures.
(3) The initial sectional force due to the initial maladjustment has a great effect on the seismic response of an RC frame structures.
(4) The seismic behavior of RC towers of cable-stayed PC girder bridges and their limit seismic bearing capacity are affected by many kinds of parameters and the structures need to be examined in detail by the non-linear analytical method which can consider the effect of varying axial forces.

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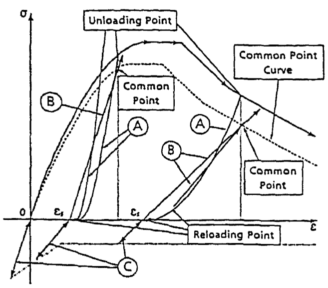


Fig.1 A hysteretic rule of concrete

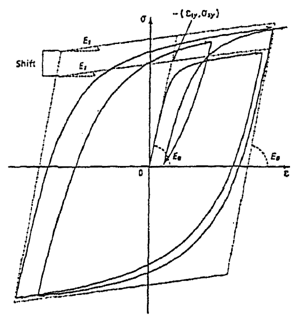


FIg.2 A hysteretic rule of steel

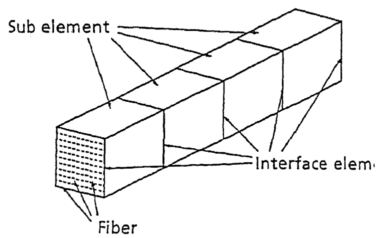


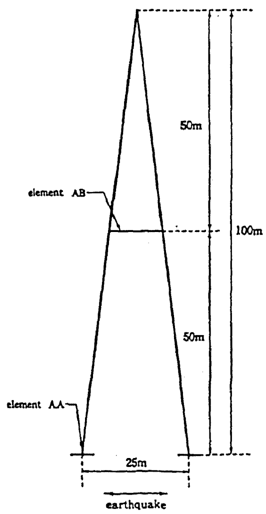
Fig.3 Division of a beam element

- Material constant

$\sigma_{ck} = 3400.0 t/m^2$
$\sigma_{sy} = 30000.0 t/m^2$
$\varepsilon_{cu} = 0.0100$
$\gamma_c = 2.35 t/m^3$
$\sigma_{cu} = 1700.0 t/m^2$
$\varepsilon_{cy} = 0.0020$
$\varepsilon_{cl} = 0.0210$
$\sigma_{tk} = 340.0 t/m^2$
$\varepsilon_{cr} = 0.0024$
$\varepsilon_{sy} = 0.0015$

- Damping constants

$\alpha = 0 \qquad \beta = 0.0318$



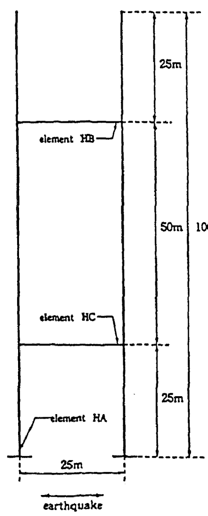


Fig.4 A－shaped RC tower model FIg.5 H－shaped RC tower model

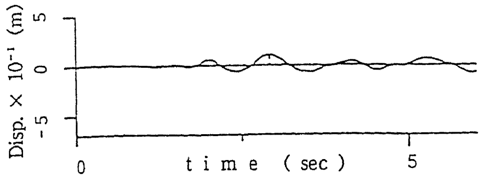


Fig.6 Displacement response at the top in case − A

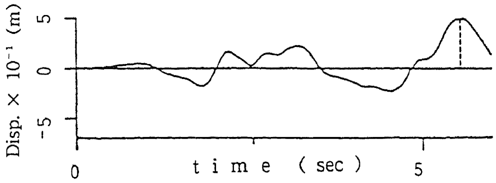


Fig.7 Displacement response at the top in case − B

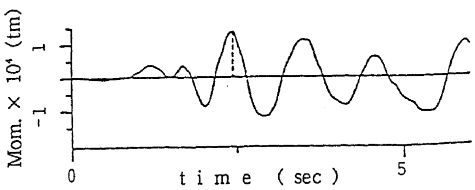


Fig.8 Bending moment response at A in case − A

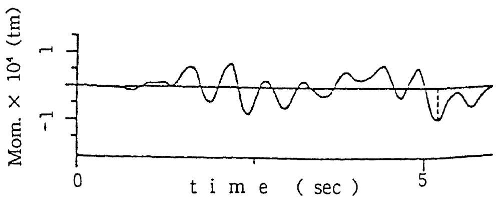


Fig.9 Bending moment response at A in case − B

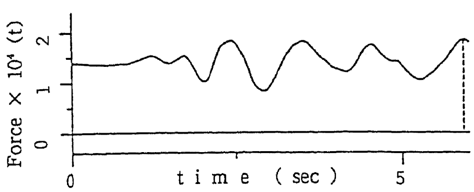


Fig.10 Axial force response at A in case − A

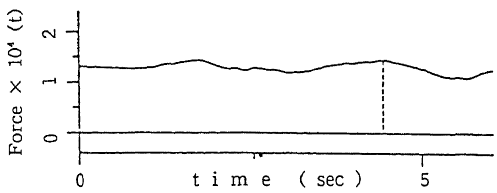


FIg.11 Axial force response at A in case − B

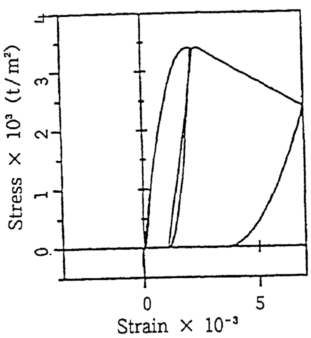


Fig.12 Stress − strain of con-
crete fiber − A

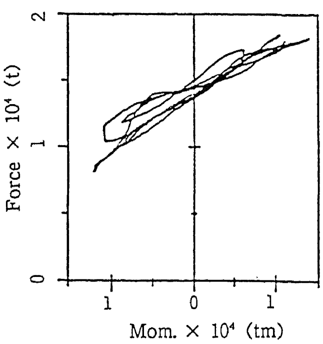


FIg.13 M − N relation : case − A

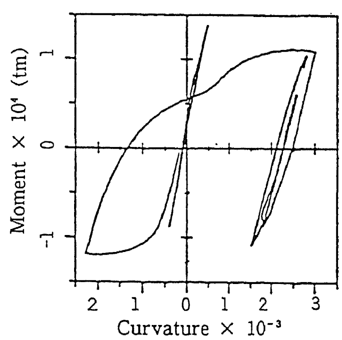


FIg.14 M − ϕ relation : case − A

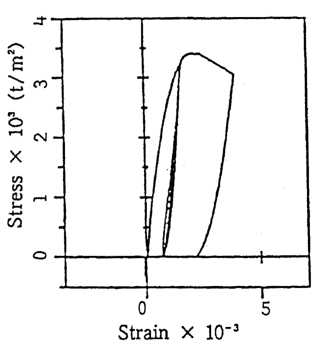


FIg.15 Stress − strain of con-
crete fiber − B

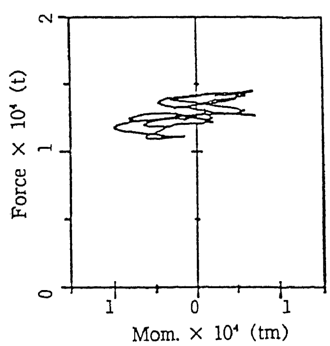


FIg.16 M − N relation : case − B

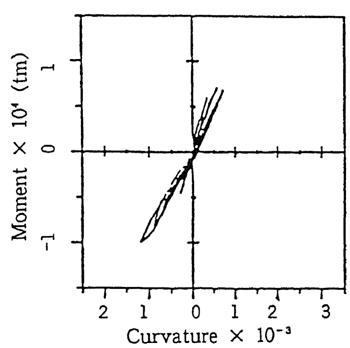


FIg.17 M − ϕ relation : case − B