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**A COMPUTER PROGRAM USING BEAM
ELEMENTS FOR THE NONLINEAR,
DYNAMIC ANALYSIS OF
LUMPED PARAMETER MODELS**

by

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**Kariotis
& Associates**

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LPM/II

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February, 1992

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PREFACE

This report presents the results of Category 2.0, Task 2.3 of the U.S. Coordinated Program for Masonry Building Research. The program constitutes the United States part of the United States-Japan coordinated masonry research program conducted under the auspices of The Panel on Wind and Seismic Effects of the U.S.-Japan Natural Resources Development Program (UJNR).

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FOREWORD

LPM/II is a general nonlinear dynamic analysis code developed for multi-degree-of-freedom (MDOF) structural systems. The principal use envisaged is the analysis of reinforced masonry or concrete walls. LPM/II is similar to and is based on elastic beam behavior but routines for incorporating the nonlinear properties of reinforced masonry or concrete represented as stiffness degradation is a feature of the analysis program.

The nonlinear code uses acceleration-time, velocity-time or force-time records as the dynamic loading. The stiffness/displacement relationship of each sub-element of the MDOF system is determined independently by a nonlinear analysis program such as FEM/1 (Ewing, 1987, 1990). The code updates the stiffness of the system, if needed, for each time step of the dynamic loading.

LPM/II is suitable for the analysis of the dynamic behavior of reinforced masonry and concrete shear walls. The sub-element behavioral model of LPM/II is a linear sub-element, with conventional types of damping, that has stiffness degradation implemented in the dynamic behavior. This beam element is capable of representing the response of all modes of vibration and can be used in combination with the nonlinear springs of LPM/I (Kariotis, 1992). These springs, translational and rotational, can have hysteretic damping as well as conventional damping.

LPM/II can be utilized to model a multi-story shear wall with masses at each story level representing the floor masses. The boundary conditions for the wall can vary from fixed to a spring type support that represents a flexible base. Multiple forcing functions and acceleration-time records can be applied to various DOFs simultaneously. LPM/II can also be used to represent a reinforced masonry or concrete wall excited normal to its plane by a ground motion at the base of the wall and by a diaphragm motion at the upper end. The out-of-plane wall model can be extended to walls in multistory structures excited at their ends normal to

their plane by linear or nonlinear diaphragm response.

LPM/II should be used in preference to LPM/I for the analysis of multistory shear wall buildings. The damping of LPM/II is assumed rather than hysteritic. Comparison of LPM/II and LPM/I used as a Q model (Saiidi, 1981), may quantify the appropriate damping for LPM/II. LPM/I uses hysteritic damping only and this hysteritic damping cannot be easily substituted for viscous damping. However, a probable effective viscous damping can be estimated for an LPM/I model and used for the and LPM/II model. The two models should have equal dynamic top displacements.

SECTION 1
GENERAL DESCRIPTION OF THE COMPUTER CODE

1.1 DESCRIPTION

LPM/II is a computer code for the nonlinear, dynamic analysis of lumped parameter models. The models can be one-, two-, or three-dimensional and are synthesized from a library of nonlinear elements using compatibility matrices. The code separates the nonlinear springs and nonlinear beams and treats them in a different manner, taking advantage of the computational efficiencies afforded by each portion. This version of the LPM/II code is operational on the COMPAQ 286, IBM PC/AT, and compatible personal computers.

The nonlinear element library includes a one-dimensional spring and a two-dimensional beam. The springs can develop axial forces or torsional moments. A three-dimensional beam element can be formed by the superposition of the nonlinear beams and springs. Three types of viscous damping are available for the model; namely, a damping matrix that is proportional to the global stiffness matrix (proportional damping), a damping matrix that is proportional to the global mass matrix (proportional damping), and a damping matrix that is assembled, element by element, based on a percentage of critical damping for each element (nonuniform damping). A combination of proportional and nonuniform damping can be used.

The nonlinear element library includes several one-dimensional springs that can develop axial forces or torsional moments. The springs can have several characteristics including non-linear elasticity, nonlinear inelasticity, hysteresis, two-way action, one-way action, and they can be gapped. Three basic types of damping are available; namely, viscous damping, viscous power damping, and Coulomb damping. The Coulomb damping can be constant or variable. The element library is modular, so that additional

elements can be added and thereby extend the useful life of the code.

The models can be subjected to excitations in the form of force or pressure time-histories and kinematic boundary conditions in the form of acceleration or velocity time-histories, together with initial displacements, velocities, and constant forces applied to the various degrees-of-freedom.

The code uses an explicit numerical integration algorithm for the solution of the system of coupled, second-order, ordinary differential equations of motion. The fourth-order Adams-Bashforth "2/3" predictor-corrector method (Ralston and Wilf, 1960) is used for the majority of the solution. However, this method is not self-starting, and the fourth-order Runge-Kutta method (Ralston and Wilf, 1960) is used to start the solution process. The solution of the equations of motion is obtained step-by-step, where the algorithm provides estimates of the displacements and velocities at each time step based on previous responses. The forces and accelerations are calculated using these estimates in the equations of equilibrium. In the predictor-corrector mode, the code uses a two-pass procedure for each time step. In the first pass, the displacements and velocities are predicted and the forces and accelerations are evaluated. In the second pass, the displacements and velocities are corrected based on the first-pass results, and the forces and accelerations are re-evaluated. In addition to the step-by-step solution of the nonlinear equations of motion, the code provides for the solution of the undamped natural frequencies and mode shapes of the linear portion of the model. The modal analysis is not used to obtain the system response, but is included to provide frequency and period information about the dynamic models. The highest frequency of a model is needed to assist in the determination of the integration time step for the dynamic response solution. Nonlinear models must be linearized to obtain these dynamic characteristics.

The output available from the code consists of selective printed, plot file, and formatted file output of all response quantities, including motions, internal forces, and internal deformations.

Every attempt has been made to make LPM/II a useful code by providing many user options, a great deal of modeling flexibility through model synthesis, and the capability to add new nonlinear elements. However, it is the user's responsibility to define meaningful dynamic models and forcing functions, and to properly interpret the results provided. Moreover, the code is not necessarily the proper tool for all classes of problems, but it can be quite useful in certain situations involving nonlinearities.

The formulation of the analysis methods is given in Section 2. The element library and damping are described in Section 3, along with a definition of the element sign conventions and procedure for forming the compatibility matrices that are used in the synthesis of dynamic models. Section 4 describes the various program options available and the data required for each option. A sample problem for program demonstration and verification is given in Section 5. Section 6 describes in engineering terms applications of LPM/II to analytical problems that are commonly encountered in dynamic analysis of structural systems.

1.2 BACKGROUND

This code is based on an earlier main frame computer program (Ewing, et al, 1982) that was extensively modified for the research on unreinforced masonry buildings conducted by ABK (1981) under a grant from the National Science Foundation (NSF). Also, under NSF Grant No. ECE-8517021, the User's Guide was extensively revised and expanded under the TCCMAR coordinated research program. The conversion of the code to be operational on the personal computer and the final revision and release of the User's Guide was conducted under the sponsorship of the NSF as noted in the preface.



SECTION 2
FORMULATION OF THE ANALYSIS METHOD

2.1 INTRODUCTION

LPM/II is a computer code for the linear or nonlinear, dynamic analysis of lumped parameter models subjected to external forcing functions and kinematic boundary conditions. The formulation of the analysis method for the code is based on the displacement method and provides for the dynamic, step-by-step, explicit solution of the equations of motion. The models can be one, two or three dimensional and are synthesized from a library of nonlinear elements using compatibility relations among the deformations of the stiffness and damping elements and the external degrees of freedom.

This section describes the formulation of the equations of motion and equilibrium, and the numerical solution method employed in the code.

2.2 EQUATIONS OF MOTION AND EQUILIBRIUM

The equations of motion of a nonlinear, multi-degree of freedom, discrete mass system may be written in matrix form as

$$[M] \{\ddot{x}\} + [C] \{\dot{x}\} + [K] \{x\} = \{R\} \quad (2-1)$$

where

- $\{\ddot{x}\}$ = Accelerations, external degrees of freedom
- $\{\dot{x}\}$ = Velocities, external degrees of freedom
- $\{x\}$ = Displacements, external degrees of freedom
- $[M]$ = Diagonal mass matrix
- $[C]$ = Nonlinear, proportional and/or nonuniform damping matrix
- $[K]$ = Nonlinear stiffness matrix
- $\{R\}$ = External applied forces

The terms that represent the nodal point resultants of the internal forces in the system, due to damping and stiffness, may be written as,

$$\{P\} = [K] \{x\} \quad (2-2)$$

$$\{D\} = [C] \{\dot{x}\} \quad (2-3)$$

where

$\{P\}$ = Nodal forces resulting from stiffness

$\{D\}$ = Nodal forces resulting from damping

The nodal forces due to system stiffness are evaluated from the internal forces and system geometry. The internal forces are determined from the internal deformations and element stiffnesses. The internal deformations are related to the external displacements by a compatibility transform, while the nodal forces are related to the internal forces by an equilibrium transform. In matrix form these relations are:

$$\{e\} = [A]^T \{x\} ; \text{Compatibility} \quad (2-4)$$

$$\{F\} = [S] \{e\} ; \text{Force-deformation} \quad (2-5)$$

$$\{P\} = [A] \{F\} ; \text{Equilibrium} \quad (2-6)$$

where

$\{e\}$ = Internal deformations

$\{F\}$ = Internal forces

$[A]$ = Equilibrium transformation matrix

$[A]^T$ = Compatibility transformation matrix

$[S]$ = Element stiffness matrix, uncoupled

It follows that the global stiffness matrix can be obtained from Equations (2-2), (2-4), (2-5), and (2-6) as:

$$[K] = [A] [S] [A]^T \quad (2-7)$$

If the system is subjected to kinematic motions and degrees of freedom (DOF) are to be eliminated¹, it is convenient to partition the equations of motion to separate the DOF with kinematic motion, DOF with unknown motion, and DOF to be eliminated. Accordingly, Equation 2-1 becomes:

$$\begin{aligned} [M_{11}] \{x_1\} &= \{R_1\} - \{P_1\} - \{D_1\} \\ [M_{22}] \{x_2\} &= \{R_2\} - \{P_2\} - \{D_2\} \\ [M_{33}] \{x_3\} &= \{R_3\} - \{P_3\} - \{D_3\} \end{aligned} \quad (2-8)$$

where the subscript 1 refers to the external DOF with kinematic motion, the subscript 2 refers to the external DOF with unknown motion, and the subscript 3 refers to the external DOF with unknown motion which are to be eliminated from the equations of motion. In addition, the DOF (x_1) that have kinematic motion and the DOF (x_3) that are to be eliminated cannot have an associated mass, damping, or external applied forces. Accordingly,

$$\begin{aligned} [M_{11}] &= 0 \\ [M_{33}] &= 0 \\ \{R_1\} &= 0 \\ \{R_3\} &= 0 \end{aligned}$$

Since the elements provided in this analysis method include:

- o Nonlinear beam elements
- o Nonlinear spring elements

it is convenient to partition these matrices to separate each element type, as given below:

¹ Frequently, it is necessary to assign internal and external DOF for some elements and nodes so that the element stiffness matrix is not overconstrained; and it is not desirable to retain these as dynamic DOF. This is particularly useful when modeling with nonlinear beam elements to account for joint rotations.

$$\{e\} = \begin{bmatrix} \{e_B\} \\ \{e_N\} \end{bmatrix} \quad (2-9)$$

$$\{F\} = \begin{bmatrix} \{F_B\} \\ \{F_N\} \end{bmatrix} \quad (2-10)$$

where

$\{e_B\}$ and $\{F_B\}$ are associated with the linear beams

$\{e_N\}$ and $\{F_N\}$ are associated with the nonlinear springs

Using the partitioning described above for external and internal DOF, the internal and external relations (Eq. 2-4 and 2-6) become,

$$\begin{bmatrix} \{e_B\} \\ \{e_N\} \end{bmatrix} = \begin{bmatrix} [A_{11}]^T & [A_{21}]^T & [A_{31}]^T \\ [A_{13}]^T & [A_{23}]^T & [A_{33}]^T \end{bmatrix} \begin{bmatrix} \{x_1\} \\ \{x_2\} \\ \{x_3\} \end{bmatrix} \quad (2-11)$$

$$\begin{bmatrix} \{P_1\} \\ \{P_3\} \end{bmatrix} = \begin{bmatrix} [A_{11}] & [A_{12}] & [A_{13}] \\ [A_{31}] & [A_{32}] & [A_{33}] \end{bmatrix} \begin{bmatrix} \{F_B\} \\ \{F_N\} \end{bmatrix} \quad (2-12)$$

Since elements with nonlinear characteristics cannot be associated with DOF that are to be eliminated, the submatrix (A_{33}) is null, or

$$[A_{33}] = [0]$$

The nonlinear terms can be calculated from the equations given previously using the uncoupled, nonlinear stiffness matrices of the individual nonlinear elements.

2.3 SOLUTION OF THE EQUATIONS OF MOTION

The code uses an explicit numerical integration algorithm for the solution of the system of coupled, second-order, ordinary differential equations of motion. The fourth-order Adams-Bashforth "2/3" predictor-corrector method (Ralston and Wilf, 1960) is used for the majority of the solution. However, this method is not self-starting, and the fourth-order Runge-Kutta method (Ralston and Wilf, 1960) is used to start the solution process. The solution of the equations of motion is obtained step-by-step, where the algorithm provides estimates of the displacements and velocities at each time step based on previous responses. The forces and accelerations are calculated using these estimates in the equations of equilibrium. Therefore, at each time step, the relationship between the response motion and the internal forces is satisfied. In the predictor-corrector mode, the code uses a two-pass procedure for each time step. In the first pass, the displacements and velocities are predicted and the forces and accelerations are evaluated. In the second pass, the displacements and velocities are corrected based on the first-pass results, and the forces and accelerations are re-evaluated. In the Runge-Kutta mode, the code uses a four-pass procedure for each time step, which operates in a manner similar to the predictor-corrector mode. The Runge-Kutta mode is used to start the solution and when the integration time step is changed.

In addition to the step-by-step solution of the nonlinear equations of motion, the code provides for the solution of the undamped natural frequencies and mode shapes of the linear portion of the system. The frequencies and modes are obtained by solving the eigenvalue problem using the sweeping technique (Hurty, et al., 1964). This technique uses a power method (i.e., an iterative method) and the orthogonality relationships among the normal modes. The modal analysis is not used to solve the equations of motion, but is included to provide frequency and period information about the dynamic models. The highest frequency of a model is needed to assist in the determination of the integration time step for the

dynamic solution. Nonlinear models must be linearized to obtain those dynamic characteristics.

Three guidelines have been established for determining the maximum allowable integration time step size that can be used in the code (Chuang, 1982). This time step is a function of the shortest period, T_{\min} , of the linearized system or the dynamic input, and the minimum rise time, T_r , of the input. These guidelines are:

- o For a nonlinear system, involving strain hardening,
 $\Delta t_{\max} = 0.2 * T_{\min}$
- o For any system,
 $\Delta t_{\max} = 0.1 * T_r$

The guidelines are based on a series of runs made with the code that produced not only stable solutions, but solutions that provided reasonable correlations with closed-form results.

SECTION 3
ELEMENT LIBRARY AND DAMPING

3.1 INTRODUCTION

The element library for the LPM/II code includes nonlinear beams and nonlinear springs. As noted in Section 2, the code uses an explicit integration algorithm and treats the beams and springs separately.

The nonlinear beam element is discussed in Section 3.2 with the special case of a linear beam element and expanding the theory into nonlinear element. The nonlinear spring element is introduced in Section 3.3, briefly discussing the possible applications of spring elements into LPM/II. A complete description of the nonlinear spring elements is presented in LPM/I.

3.2 NONLINEAR BEAM ELEMENTS

The nonlinear beam in its virgin state is a linear beam. In this section a description of the linear beam is presented and is followed by a discussion of the introduction of the nonlinear properties into the linear beam.

Three main components of the linear beams are discussed; the compatibility matrix formulation that relates internal deformations to external Degrees of Freedom, the stiffness matrix that relates forces to displacement, and the damping characteristics of the beam.

3.2.1 LINEAR BEAM COMPATIBILITY MATRIX

The linear beams are two-dimensional elements that have two internal degrees-of-freedom (deformations) and two moments per beam as shown in Figure 3-1a. The internal degrees of freedom, e , are the internal end rotations in the beam elements, and are defined as the angle in radians measured from a straight line joining the ends

of the beam to the tangent to the elastic curve at that end. For a fixed-fixed beam that is subjected to a unit lateral translation of end 2 in the vertical direction, the internal deformations are as shown in Figure 3-1b. If end 1 is given a unit lateral translation in the vertical direction, the internal deformations will have the same magnitude as shown in Figure 3-1b, but will be of opposite sign. For a beam that is fixed at one end and pinned at the other end and subjected to a unit clockwise rotation at the pinned end, the internal deformations are as shown in Figure 3-1c. In all cases the beam end moments have the same sign as the deformations.

The compatibility submatrices, A_{11}/A_{21} and A_{31} , (Eq. 2-11) are constructed using the sign convention defined above, and the relationship among the internal deformations, e , in the linear beams and the external degrees-of-freedom, x . Their construction can best be shown by considering an example. The beam element shown in Figure 3-2a has two internal degrees of freedom and four external degrees of freedom. The internal degrees of freedom are numbered e_1 and e_2 , and the external degrees of freedom are numbered 1 through 4 (i.e., x_1 , x_2 , x_3 , and x_4), none of which are to be eliminated. In this case, the A_{31} matrix is null. The positive directions for the e 's and x 's are defined by the arrows. The A_{11}/A_{21} matrix has four rows and two columns, where the rows correspond to the external degrees of freedom (x_1 through x_4) and the columns correspond to the deformations (i.e., internal degrees of freedom) in the linear beam (e_1 and e_2). The matrix is formed row by row. The first row of the matrix is obtained by holding x_2 , x_3 , and x_4 fixed, and deflecting x_1 one unit in its positive direction. When this is done, it can be seen from Figures 3-2a and 3-1b that rotations of $-1/L$ are induced in e_1 and e_2 . Accordingly, the first row of the A_{11}/A_{21} matrix becomes:

$$A(1,1) = -1/L$$

$$A(1,2) = -1/L$$

The second row is obtained by holding x_1 , x_3 , and x_4 fixed, and rotating x_2 one unit in its positive direction. From Figures 3-2a and 3-1c, it can be seen that e_1 is compressed one unit of rotation and e_2 is zero. The second row of the A_{11}/A_{21} matrix becomes:

$$A(2,1) = 1$$

$$A(2,2) = 0$$

Similarly, the third row is obtained by holding x_1 , x_2 , and x_4 fixed, and deflecting x_3 one unit in its positive direction. This induces rotations of $1/L$ in e_1 and e_2 (Figs. 3-2a and 3-1b), and the third row of the A_{11}/A_{21} matrix becomes:

$$A(3,1) = 1/L$$

$$A(3,2) = 1/L$$

The last row is obtained by holding x_1 , x_2 , and x_3 fixed, and rotating x_4 one unit in its positive direction. This results in e_2 being compressed one unit of rotation and e_1 is zero. The fourth and last row of the A_{11}/A_{21} matrix becomes:

$$A(4,1) = 0$$

$$A(4,2) = 1$$

The complete compatibility submatrix, A_{11}/A_{21} is shown in Figure 3-2b.

An identical procedure is used to form the compatibility submatrix, A_{31} , where the external degrees of freedom to be eliminated, N_3 , are numbered independently from those with known and unknown motion.

In summary, the i th row of the compatibility submatrices, A_{11}/A_{21} and A_{31} , is formed by deflecting the i th external degree of freedom one unit in its positive direction, while holding all other external degrees of freedom fixed, and determining the deformations induced

in all of the internal degrees of freedom in all linear beam elements.

3.2.2 LINEAR BEAMS STIFFNESS

The linear beams are two-dimensional elements that develop in-plane moments and shears, but not axial forces or torsional moments. Axial force and torsional moment capability can be included in the modeling by superposing linear spring elements onto top of the beam. Moreover, a three-dimensional beam can be modeled by the superposition of beams and springs. The linear beams have two internal degrees-of-freedom (deformations) and two moments per beam that are defined by e 's and M 's as shown in Figure 3-1a.

The linear beam elements can be prismatic or nonuniform (i.e., stepped section) as shown in Figure 3-3. In general, the uncoupled stiffness properties (Eq. 2-5) for each beam are defined by the values of SPAN, EI, and GAK in Card Group 10,

where

SPAN = beam length, L
EI = bending stiffness
GAK = shear stiffness

The uncoupled stiffness matrix relates the internal moments at each end of the beam to the internal rotations (deformations) at each end of the beam, as given by Equation 2-5. Referring to Figure 3-1a, this internal moment-rotation relation is:

$$\{M\} = [S] \{e\} \quad (3-2)$$

The uncoupled stiffness matrix, S , is given as

$$[S] = \begin{bmatrix} \frac{EI (4+\phi)}{L (1+\phi)} & \frac{EI (2-\phi)}{L (1+\phi)} \\ \frac{EI (2-\phi)}{L (1+\phi)} & \frac{EI (4+\phi)}{L (1+\phi)} \end{bmatrix} \quad (3-3)$$

where

- E = Modulus of elasticity
- I = principal moment of inertia of the beam
- L = beam length
- $\phi = \frac{12EI}{L^2GA} =$ shear deformation parameter
- G = shear modulus
- A = effective shear area

The global stiffness matrix, relating nodal point forces to nodal point deflections is given by Equation 2-7. Using the beam in Figures 3-2a and 3-3a and the compatibility matrix given in Figure 3-2b, the global stiffness matrix for the beam can be obtained from the triple matrix product.

$$[K] = [A] [S] [A]^T \quad (3-4)$$

Using the matrices defined by Equation 3-3 and Figure 3-2b, it can be shown that the global stiffness matrix in Equation 3-4 is defined by:

$$\begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} \frac{12EI}{L^3(1+\phi)} & \frac{-6EI}{L^2(1+\phi)} & \frac{-12EI}{L^3(1+\phi)} & \frac{-6EI}{L^2(1+\phi)} \\ \frac{-6EI}{L^2(1+\phi)} & \frac{EI(4+\phi)}{L(1+\phi)} & \frac{12EI}{L^2(1+\phi)} & \frac{EI(2-\phi)}{L(1+\phi)} \\ \frac{-12EI}{L^3(1+\phi)} & \frac{6EI}{L^2(1+\phi)} & \frac{12EI}{L^3(1+\phi)} & \frac{6EI}{L^2(1+\phi)} \\ \frac{-6EI}{L^2(1+\phi)} & \frac{EI(2-\phi)}{L(1+\phi)} & \frac{6EI}{L^2(1+\phi)} & \frac{EI(4+\phi)}{L(1+\phi)} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} \quad (3-5)$$

It can be seen that this is the standard stiffness matrix for a two-dimensional beam as given by Przemieniecki, (1968).

3.2.3 LINEAR BEAM DAMPING

Since the linear element properties do not change, the global stiffness and damping matrices for the linear portion of the synthesized system are formed once at the beginning of the solution. The nodal point forces due to stiffness and damping are then computed directly from these matrices.

The code has three viscous damping options for the linear portion of the system, that are controlled by the value of LDAMP in Card Group 4. The damping is defined by Equation 2-3 and for the linear portion of the system

$$\{D_L\} = [C_L] \{\dot{x}\} \quad (3-6)$$

where $\{D_L\}$ is the vector of nodal forces due to damping, $[C_L]$ is the linear damping matrix, and $\{\dot{x}\}$ is the vector of nodal velocities. Depending on the value of LDAMP, the linear damping matrix is defined in three ways.

If LDAMP = 0, no damping for the linear portion of the model is included in the system.

If LDAMP = 1, the linear damping matrix is defined to be proportional to the linear stiffness and mass matrices (proportional damping), and is described in Section 3.2.3.1.

If LDAMP = 2, the linear damping matrix is formed in a similar manner to the linear stiffness matrix, where the damping in each linear element is proportional to its individual uncoupled stiffness matrix (nonuniform damping). This formulation is described in Section 3.2.3.2.

If LDAMP = 3, the linear damping matrix is defined by proportional damping and nonuniform damping applied simultaneously.

3.2.3.1 PROPORTIONAL DAMPING

An assumption frequently used for elastic systems is that the global damping matrix is proportional to the linear stiffness matrix, as given below:

$$[C_L] = \alpha_k [K_L] \quad (3-7)$$

where $[K_L]$ is the linear stiffness matrix and α_k is the constant of proportionality. However, this formulation provides different amounts of the critical damping ratio in the various normal vibration modes of the system. It can be shown that the critical damping ratio, Y_i , in each normal vibration mode varies with the modal frequency as,

$$\alpha_k = 2 Y_i / \omega_i \quad (3-8)$$

where ω_i is the undamped circular frequency of the *i*th normal mode of vibration. The constant, α_k , is determined from Equation 3-8 by selecting a desired critical damping ratio, Y_i , in the *i*th mode

with circular frequency, ω_i . Once this constant is selected, the critical damping ratios in the other modes of vibration are fixed; where modes with higher frequencies will have a proportionately larger critical damping ratio and modes with lower frequencies will have a proportionately smaller critical damping ratio. So, this is essentially a high mode damper.

Another type of proportional damping is called mass damping where the global damping matrix is proportional to the mass matrix, as given below:

$$[C_L] = \alpha_m [M] \quad (3-9)$$

Where α_m is the constant of proportionality and $[M]$ is the diagonal mass matrix. This formulation again provides modal damping, such that the critical damping ratio γ_i for each normal mode of vibration varies with the modal frequency as:

$$\alpha_m = 2 \gamma_i \omega_i \quad (3-10)$$

This equation shows that for a fixed value of α_m , the critical damping ratio γ_i , varies inversely with ω_i , where modes with lower frequency have higher amount of damping. This is a primary low mode damper.

3.2.3.2 NONUNIFORM DAMPING

Nonuniform damping is a special form of proportional damping, where the global damping matrix for the linear part of the system is formed in the same manner as the linear stiffness matrix. Uncoupled damping matrices for the linear elements are defined to be proportional to their uncoupled stiffness matrices as given below:

$$[C]_k = \beta_k [S]_k \quad (3-11)$$

where

- $[C]_k$ = uncoupled damping matrix of the kth linear element
- β_k = constant of proportionality of the kth linear element
- $[S]_k$ = uncoupled stiffness matrix of the kth linear element

The constant of proportionality is defined by:

$$\beta_k = 2 Y_k / \omega_k \quad (3-12)$$

where

- Y_k = critical damping ratio of the kth linear element
- ω_k = undamped circular frequency associated with the kth linear element

In this manner, the global damping matrix is composed of the damping properties of each individual linear element, and is nonuniform.

For a linear, prismatic beam element, ω_k can be calculated from:

$$\omega_k^2 = n^4 EI / (L^4 m) \quad (3-13)$$

where

- E = modulus of elasticity
- I = principal moment of inertia of the beam
- L = beam length
- m = mass density per unit length of the beam

For a nonuniform beam, effective values of I, L, and m should be used in Equation 3-13, or ω_k must be determined by other methods. Nonuniform damping for the linear beams is defined by the values of PCTCR and FREQ in Card Group 10, where PCTCR = Y_k in Equation 3-12 and FREQ = ω_k from Equation 3-13. For this option, PCTCR must be ≥ 0.0 and FREQ must be > 0.0 .

3.2.4 NONLINEAR BEAM ELEMENT

The nonlinear beam is treated in the same manner as the linear beam element in many respects. The compatibility matrix is the same, the damping coefficients are based on the virgin state of the beam, and the stiffness matrix relating the forces and displacements has the same form. The main difference is that the nonlinear beam recognizes degradation in the stiffness of individual beams and updates the stiffness matrix accordingly.

Beam elements have an initial rigidity equivalent to EI , where E is Young's Modulus and I is the moment of inertia of the beam's gross cross section. Subjecting the beam to deflection and/or rotation of either end will produce little if any changes in the length, it will however, produce distortion across the cross section of the beam and induce stress in the beam. Increasing the stress on the beam will cause the tensile stress at the extreme edges of the beam to exceed the cracking stress of the material, thus causing cracks starting at the edge of the beam and propagating further as the stress increases. The reinforcement in a reinforced concrete or masonry structure will yield when the stress at the steel location exceeds the yield stress of the steel. Distortion of the cross section, cracking of the concrete or masonry and yielding of the reinforcement contribute towards degradation in the stiffness of the beam element. This degradation is represented by reducing the value of EI . Thus a relationship between the net internal rotation of the beam and EI will be adequate to describe the degradation in stiffness for a beam element that is primarily subjected to moment type loading.

The frequency and distribution of cracks vary along the beam length causing EI to vary, and it is actually expressed as $EI(x)$, where x is the distance from one end of the beam. An equivalent value of EI that is assumed uniform for the full length of the beam is determined and is referred to as the effective EI .

Each beam has two internal deformations e_1 and e_2 as shown in Figure 3-2a. These are expressed in terms of the external degrees of freedom at the ends of the beams using the compatibility coefficients as expressed in Figure 3-2b. An equivalent amount of degradation is represented by the total amount of deformation in the beam defined as the net internal deformation e_N as the summation of e_1 and e_2 . A relationship between EI and e_N can be evaluated for a beam by the use of a nonlinear Finite Element Analysis technique. This approach is discussed in Section 6.

For the purpose of this code, a stair-step like relationship between EI and e_N is needed to execute the problem with nonlinearity implemented. The main features of this option is:

1. The user can describe the relationship between EI and e_N using pairs of values expressed as two vectors, one listing the rotation in an increasing order, the other listing the corresponding fraction of the initial EI with the appropriate units. At zero rotation the fraction of the initial EI is unity and it decreases as the net rotation increases. The current maximum number of pairs is 80, and it can be increased by a slight modification in the coding.
2. The user can define up to 25 different beam properties, and each individual property can have different numbers of pairs of points to describe the degradation rate.
3. The degradation relating EI and e_N is symmetric about the origin, but has an independent history in each direction. Positive deformation produces degradation in stiffness, and the degraded value is used for subsequent positive deformation only, while negative deformation has a stiffness that is dependent on the previous maximum negative internal deformation only, and is independent of the positive deformation history.

The logic of the coding follows the following steps:

1. After constructing the beam initial internal stiffness matrix, several transformation matrices are used to evaluate the global stiffness matrix of the whole system.
2. The external displacements representing the external DOF are evaluated after each time step.
3. The internal deformations of each beam are calculated from the external displacements using the compatibility matrices, and a net deformation for each beam is evaluated by simply summing the internal deformations at both ends of the beam.
4. EI is evaluated for each beam by using the values of e_N and then obtaining the corresponding EI from the beams property cards as determined by the nonlinear Finite Element Analysis or a similar technique.
5. Comparing current EI with the previous value of EI for the last time step for each beam. In the case that EI has changed for any beam, the local stiffness matrices are updated and the transformation matrices are used to evaluate the updated global stiffness matrix. If none of the beams suffered further degradation the previous global stiffness matrix is preserved and the solution is continued to the next time step.

The program recognizes only the last stiffness matrix at each time step, so, if the output needed involves the beam internal deformations or forces or the eliminated DOF's response, an actual evaluation of these quantities should be performed at this stage and stored. The user is required to specify a flag in card group 6 for this purpose.

An accurate and valid representation of the shear effects in the nonlinear beam elements is yet to be determined. The

linear beam has the shear area factor ϕ imbedded in the stiffness matrix as described in Section 3.3.2. Currently the user has the option to include this factor in the nonlinear beam element, and it is assumed as a constant and is only a function of the initial EI and it is not updated. It is important to recognize that the shear area effect should not depend on the individual beam subelement dimension, but rather on the overall dimension of beam or the wall, since this global dimension controls the type of behavior of the individual elements, whether it is flexure, shear or a combination of both.

Generally, for a tall wall, the primary mode of vibration is dominated by flexural deformation, thus, the shear effects can be ignored if the user is interested in primary mode response of the wall. This is usually true for evaluation of the top displacement of the wall. On the other hand, if the user is interested in quantities associated with higher modes, such as floor shears, a representation of the shear effects may become a necessity.

The damping discussed earlier for the linear beam is used for the nonlinear beam element with the exception of the proportional damping (i.e. stiffness damping) as shown in Equation 3-7. In this case, where the damping matrix is dependent on the updated stiffness matrix, the damping decreases with further degradation of the beam element. The nonuniform damping as defined in Equation 3-9 is a function of the elements initial stiffness and the damping matrix is constant throughout the calculation.

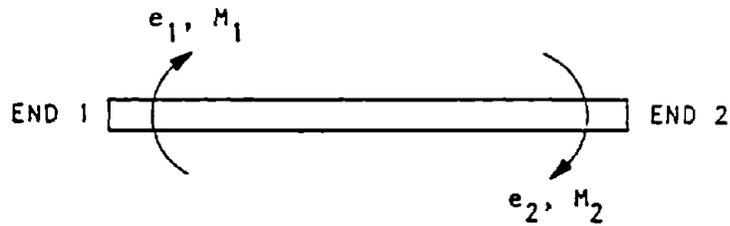
3.3 NONLINEAR SPRING ELEMENTS

The nonlinear element library for LPM/II contains 20 spring element types, 11 of which are currently used and 9 are available to add additional capabilities to the code. The nonlinear springs are one-dimensional elements that develop axial or shear forces or rotational moments. They have one internal degree of freedom

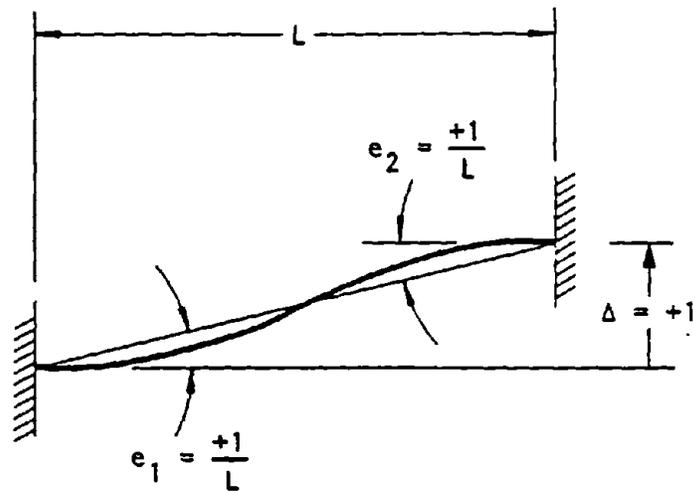
(deformation) and force per spring that are defined by e and F , respectively; where e can be an axial, shear, or rotational deformation and F can be an axial or shear force or rotational moment. The stiffnesses of the nonlinear springs are represented by force-deformation characteristics, where the spring force, F , is expressed as a function of its internal deformation, e .

The nonlinear springs are identified by a nonlinear spring type number (1 through 20) and their properties are defined in a set of material property tables. For each nonlinear spring included in a model, the user specifies the nonlinear spring type number, $NSTYPE$, and the appropriate set number, $NSMAT$, of its associated material property. These two values are defined in Card Group 12. The material properties for the nonlinear springs are defined in Card Group 13. The force-deformation characteristics are defined by the six material property values (i.e., $XK1$, $XK2$, $XK3$, $F1$, $F2$, and GAP) given on card 1 in Card Group 13. The damping characteristics are defined by the six material property values (i.e., $CVISC$, $EXPCV$, $COULMB$, $CFTHN$, $CNSFN$, and $VBAR$) given on card 2 in Card Group 13. A full description of the nonlinear springs and their characteristics is presented in LPM/I.

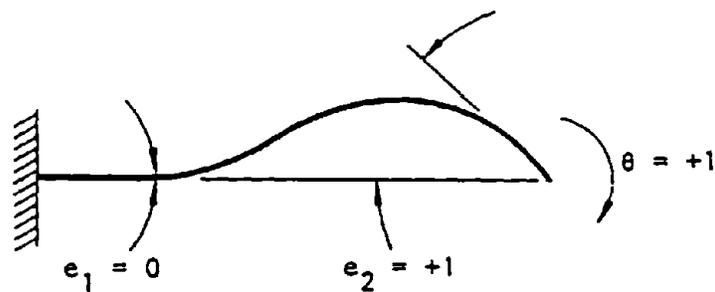
The nonlinear springs can be used in conjunction with the nonlinear beam elements. There are two main applications for springs in a multi-degree of Freedom system; a spring with zero stiffness can be connected between two degrees of freedom to monitor the relative displacement. This is useful in determining the relative story drifts or the relative response to the ground. On the other hand the user could easily obtain the absolute displacements of various degrees of freedom and perform a simple subtraction and processing after the run is completed. Another important application is to provide a spring support at any degree of freedom. The user is referred to LPM/I to choose an appropriate spring type to match the support type.



(a) Internal degrees-of-freedom and moments

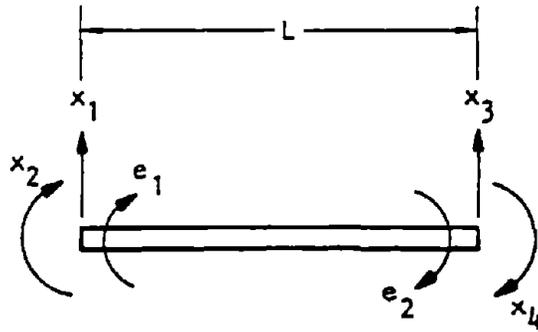


(b) Internal deformations for the lateral displacement of a fixed-fixed beam



(c) Internal deformations for the end rotation of a pinned-fixed beam

FIGURE 3- 1. SIGN CONVENTION FOR THE LINEAR BEAM ELEMENTS

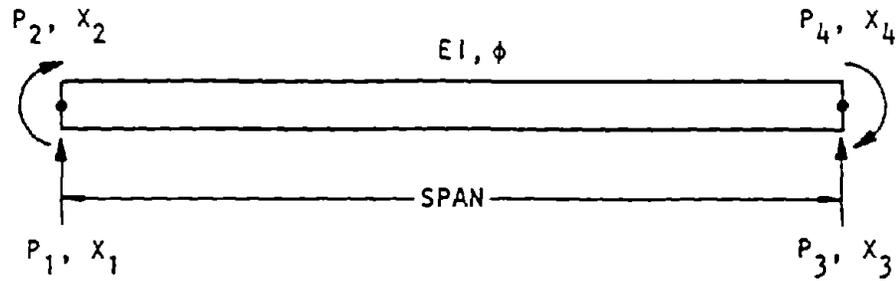


(a) Beam element, degree-of-freedom

$$\begin{bmatrix} A_{11} \\ \hline A_{21} \end{bmatrix} = \begin{array}{c|cc} & \mathbf{e} & \mathbf{1} & \mathbf{2} \\ \mathbf{x} & & & \\ \hline 1 & & -\frac{1}{L} & -\frac{1}{L} \\ 2 & & 1 & 0 \\ 3 & & \frac{1}{L} & \frac{1}{L} \\ 4 & & 0 & 1 \end{array}$$

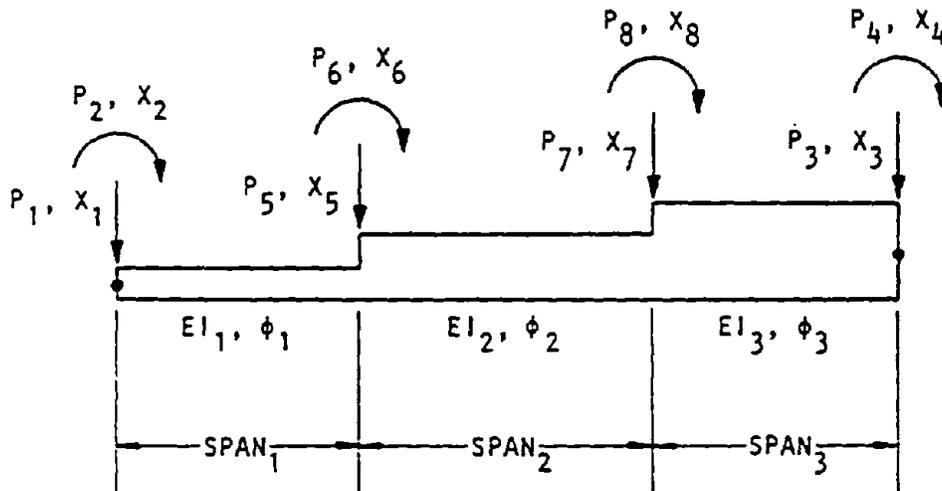
(b) Compatibility submatrix

FIGURE 3-2. CONSTRUCTION OF COMPATIBILITY SUBMATRIX, A_{11}/A_{21}



WHERE $\phi = 12EI/(GAK \cdot \text{SPAN}^2)$, A SHEAR DEFORMATION PARAMETER
 EI = BENDING STIFFNESS
 GAK = SHEAR STIFFNESS
 SPAN = BEAM LENGTH

(a) Prismatic beam



WHERE $\phi_i = 12EI_i/(GAK_i \cdot \text{SPAN}_i^2)$, A SHEAR-DEFORMATION PARAMETER
 FOR THE i th SUBELEMENT
 EI_i = BENDING STIFFNESS OF i th SUBELEMENT
 GAK_i = SHEAR STIFFNESS OF THE i th SUBELEMENT
 SPAN_i = LENGTH OF i th SUBELEMENT

(b) Nonuniform beam

FIGURE 3-3. LINEAR BEAM ELEMENTS

SECTION 4
DEFINITION OF INPUT DATA AND DECK SETUP

4.1 INTRODUCTION

The purpose of this section is to describe the input data required by the LPM/II computer program. It includes a description of the various execution or program options available, the input required for each option, and setup procedures for the input decks or files.

4.2 PROGRAM OPTIONS

The execution of the program is controlled and initiated by the use of program options. The input and calculations for a new problem are controlled by the Program Option "START". The termination of a jobstream which can include a sequence of program options and their input data is controlled by the Program Option "STOP".

The format for the program option cards is given in Section 4.4, Card Group 1, and the input data required for the various program options are given in Card Groups 2 through 27.

4.3 GENERAL DECK SETUP AND JOBSTREAMS

A jobstream consists of a series of program options, where each option is followed by its required data. The execution of the computer program and the sequence of operations performed are controlled by the order of appearance of the program options in the jobstream. The machine-dependent control cards that precede and follow the computer operating system are not given in this report.

Not all jobstreams and their sequence of operations are accepted by the computer program. A new problem execution is depicted in the following jobstream:

- a. START
- b. (data from Card Groups 2 through 26)
- c. STOP

The jobstream results in the following program operations:

- a-b Read the input for a new problem, perform calculations, and output the specified response quantities.

c. Terminate the jobstream.

4.4 DEFINITION OF INPUT DATA

The definition of the input data for the computer program is described in this section and consists of 26 card groups. Any system of units can be used, but, the input data must be in a consistent set of units. The following pages present the 26 card groups.

CARD GROUP 1:	PROGRAM EXECUTION OPTIONS
No. of Cards:	1
Format:	2A4

Columns	Variable	Entry	Notes
1-8	KTLCD(1) and KTLCD(2)	Program execution option = START ... (. denotes a blank) Read input for new problem; Go to Card Group 2.	
		= STOP Terminate program execution.	(1)

NOTES:

- (1) All jobstreams should end with this option to insure the proper wrap-up of any plot or formatted output files that have been generated in the run.

CARD GROUP 2: PROBLEM TITLE
No. of Cards 1
Format: 20A4

Columns	Variable	Entry	Notes
1-68	JOBHED(1) through JOBHED(17)	Problem Title, 68 characters maximum	(1)
69-80	JOBHED(18) through JOBHED(20)	Problem units description (e.g., IN-LB-SEC) 12 characters maximum	(1)

Go to Card Group 3.

NOTE:

- (1) This information is included in all forms of output provided by the program, and should be left justified in the fields provided.

CARD GROUP 3: MASTER CONTROL PARAMETERS-1
 No. of Cards: 1
 Format: 10I5

Columns	Variable	Entry	Notes
1-5	N1	Number of external DOF with kinematic motion.	(1)
6-10	N2	Number of external DOF with unknown motion (i.e., dynamic DOF).	(2)
11-15	N3	Number of external DOF to be eliminated.	(3)
16-20	NBEAMS	No. of nonlinear beam elements.	(3)
21-25	NUMBMAT	No. of properties for nonlinear beam elements.	(4)
26-30	NNS	No. of nonlinear spring elements.	(5)
31-35	NUMMAT	Number of properties for nonlinear spring elements.	(5)
36-40	NODWAF	Number of external DOF with applied forces.	(6)
41-45	NOFTH	Number of force-time histories.	(6)
46-50	NOMTH	Number of kinematic motion-time histories.	(1) (7)

Go to Card Group 4.

NOTES:

- (1) If $N1 > 0$, $NOMTH$ must be > 0 .
- (2) $N2$ must be > 0 .
- (3) If $N3 > 0$, $NBEAMS + NLS$ must be > 0 .
- (4) If $NBEAMS > 0$, $NUMBMAT$ must be > 0 .
- (5) If $NNS > 0$, $NUMMAT$ must be > 0 .
- (6) If $NODWAF > 0$, $NOFTH$ must be > 0 . The force-time histories are defined in Card Groups 19 through 21.
- (7) The motion-time histories are defined in Card Groups 22 through 26.

CARD GROUP 4: MASTER CONTROL PARAMETERS-2
 No. of Cards: 1
 Format: 10I5

Columns	Variable	Entry	Notes
1-5	NSAVE	Data storage increment of calculated data.	(1)
6-10	NDAMP	Damping flag for nonlinear elements; ≤ 0 , no damping > 0 , damping included	(2)
11-15	LDAMP	Damping flag for nonlinear beam elements. ≤ 0 , no damping $= 1$, damping matrix = $D_p =$ $DAMPL1.[K_L] + DAMPL2.[M]$ (proportional damping) $= 2$, damping matrix = $[D_L]$ (nonuniform damping) ≥ 3 , damping matrix = $D_p + D_L$ (nonuniform plus proportional damping)	(3)
16-20	NMODES	Number of normal modes requested for the linear system.	(4)
21-25	MAXITR	Maximum number of iterations for calculating normal modes. Default = 100.	
26-30	MASSTD	Time-dependent mass flag $= 0$, no time-dependent mass > 0 , time-dependent mass; use force-time history number MASSTD to control mass as a function of time < 0 , time-dependent mass; use motion-time history number MASSTD to control mass as a function of time	(5)
31-35	KONFOR	Constant force flag; ≤ 0 , no constant forces applied at the nodes	(6)

36-40	KFCHEK	<p>> 0, constant forces applied at the nodes</p> <p>Nonlinear spring element number (7) to be monitored for the initiation of the applied forces;</p> <p>≤ 0, use control defined by TFSTAR (card 1 of Card Group 5)</p> <p>> 0, monitor force in nonlinear spring NFCHEK, when it reaches the value FCHECK (card 2 of Card Group 5) the forces are initiated</p>
41-45	KMTYPE	<p>Modal extraction flag</p> <p>≤ 0, sequentially extract NMODES starting with the lowest frequency</p> <p>= 1, sequentially extract NMODES starting with the highest frequency</p> <p>= 2, sequentially extract NMODES starting with the lowest frequency and then sequentially extract NMODE starting with the highest frequency</p>
46-50	KMASS	Reserved for future use.

Go to Card Group 5.

NOTES:

- (1) All output, except the maximum and minimum values of the absolute external DOF responses (N1 and N2) and nonlinear forces, are produced using the data saved. If NSAVE ≤ 0 , NSAVE is set to 1.
- (2) See Section 3.3.3 for a description of damping.
- (3) See Section 3.2.3 for a description of damping. DAMPL1 and DAMPL2 are defined on card 2 of Card Group 5. D_L is composed of the uncoupled damping matrices of individual elements.
- (4) NMODES must be $\leq N2$, if NMODES $> N2$, NMODES is set to N2.
- (5) The time dependent mass at each DOF is defined by VWT in Card Group 9. If MASSTD > 0 , NOFTH must be > 0 , and MASSTD \leq NOFTH. (The force-time histories are defined in Card Groups 19 through 21). If MASSTD < 0 , NOMTH must be

> 0 , and $MASSTD \leq NOMTH$. (The motion-time histories are defined in Card Groups 22 through 26).

- (6) The constant force at each DOF is defined by PCONS in Card Group 9.
- (7) If $NFCHEK > 0$, $NFCHEK$ must be $\leq NNS$ and $NOFTH$ must be ≥ 0 . (The force-time histories are defined in Card Groups 19 through 21).

CARD GROUP 5: MASTER CONTROL PARAMETERS-3
 No. of Cards: 2
 Format: 8F10.0/3F10.0

Card 1

Columns	Variable	Entry	Notes
1-10	DELTAT	Initial integration time step.	(1)
11-20	TSTART	Integration start time.	(2)
21-30	TSTOP	Integration stop time	(2)
31-40	TMSTAR	Time when kinematic motions are to be initiated.	(3)
41-50	TFSTAR	Time when applied forces are to be initiated.	(4)
51-60	TREST	Integration time for generation of a restart file or tape.	(5)
61-70	TCHGDT	Integration time to change the integration time step to DTCHG.	(6)
71-80	DTCHG	New integration time step.	(6)

Card 2

1-10	GRAVITY	Acceleration of gravity.	(7)
11-20	DAMPL1	Damping constant for the nonlinear system; $\alpha_k = \text{DAMPL1}$.	(8)
21-30	DAMPL2	Damping constant for the nonlinear system; $\alpha_m = \text{DAMPL2}$.	(8)
31-40	FCHECK	Force in nonlinear spring number NFCHEK to control the initiation of the applied forces, when the force in nonlinear spring NFCHEK reaches the value FCHECK the forces are initiated.	(9)

= 0` not used
 > 0, compression
 < 0, tension

Go to Card Group 6.

NOTES:

- (1) DELTAT must be ≥ 0.0 . If DELTAT = 0.0, no dynamic calculations will be performed
- (2) TSTOP must be \geq TSTART. If TSTOP = TSTART, no dynamic calculations will be performed.
- (3) Time intervals given in Card Group 26 are relative to this time. Can be thought of as a delay or arrival time for the kinematic motions.
- (4) Time intervals given in Card Group 21 are relative to this time. Can be thought of as a delay or arrival time for the applied forces. If this time is to be used to control the initiation of the applied forces, NFCHRK (Card Group 4) must be 0.
- (5) If TREST \leq TSTART, no restart tape or file will be created. If TREST > TSTART, a restart tape or file will be created.
- (6) If TCHGDT \leq TSTART, the time step will not be changed during the calculation. If TCHGDT > TSTART, the time step will be changed during the calculation and DTCHG must be > 0.0.
- (7) If GRAVITY ≤ 0.0 is set to 386.0. The values of CWT and VWT in Card Group 9 are divided by GRAVITY. If these values are input in force or weight units the value of GRAVITY must be in the correct units to convert the weights to mass units. However, if these values are input in mass units the value of GRAVITY should be equal to 1.0.
- (8) See Section 3.2.3 for a description of damping.
Damping matrix = $\alpha_k [K_L] + \alpha_m [M]$
- (9) FCHECK ignored if NFCHEK ≤ 0 .
See Card Groups 4 and 19 through 21.

CARD GROUP 6: OUTPUT CONTROL PARAMETERS
 No. of Cards: 2
 Format: 4I5/18I1

Card 1

Columns	Variable	Entry	Notes
1-5	NPRINT	Print increment of stored data, default =1.	
6-10	IPLLOT	Plot output option flag; ≤ 0 , no plot output > 0 , plot output	(1)
11-15	IPUNCH	Formatted output option flag; ≤ 0 , no formatted output > 0 , formatted output	(2)
16-20	IPRINT	Optional output flag; ≤ 0 , no optional output = 1, all allocations, transformation matrices, and stiffness and damping matrices are printed = 2, T_{β} is printed = 3, T_{α} is printed = 4, T_{F-x} is printed = 5, $[K_L]$, $[D_L]$ and nonlinear beams degraded stiffness is printed after each update. = 6, Final values of $[K_L]$, $[D_L]$ and nonlinear beams degraded stiffnesses are printed. ≥ 7 , no optional output	(3)

Card 2

Columns	Variable	Entry	Notes
1	IOTPR(1)	External DOF absolute displacement (N1N2); Print option flag. (Typical for all 18 values).	

CARD GROUP 6: OUTPUT CONTROL PARAMETERS (continued)

= 0, no print

= 1, print maximum and minimum values
only

= 2, print time-history decimated by
NPRINT and maximum and minimum
values

2	IOTPR(2)	Eliminated DOF absolute displacement (N3)
3	IOTPR(3)	External DOF absolute velocity (N1N2)
4	IOTPR(4)	Eliminated DOF absolute velocity (N3)
5	IOTPR(5)	External DOF absolute acceleration (N1N2)
6	IOTPR(6)	Eliminated DOF absolute acceleration (N3)
7	IOTPR(7)	Internal nonlinear spring force (NNS)
8	IOTPR(8)	Internal nonlinear spring deformation (NNS)
9	IOTPR(9)	Internal nonlinear spring velocity (NNS)
10	IOTPR(10)	Internal nonlinear spring acceleration (NNS)
11	IOTPR(11)	= 0.
12	IOTPR(12)	= 0.
13	IOTPR(13)	= 0.
14	IOTPR(14)	= 0.
15	IOTPR(15)	Internal nonlinear beam force (2 x NBEAMS)
16	IOTPR(16)	Internal nonlinear beam deformation (2 x NBEAMS)
17	IOTPR(17)	Internal nonlinear beam velocity (2 x NBEAMS)
18	IOTPR(18)	Internal nonlinear beam acceleration (2 x NBEAMS)

Go to Card Group 7.

CARD GROUP 6:
NOTES:

OUTPUT CONTROL PARAMETERS (concluded)

- (1) If $IPL\text{OT} \leq 0$, skip Card Group 7. If $IPL\text{OT} > 0$, Card Group 7 is required.
- (2) If $IPUNCH \leq 0$, skip Card Group 8. If $IPUNCH > 0$, Card Group 8 is required.
- (3) See Section 2 for description of optional output matrices T_{B} , T_{xx} , T_{Fx} , K_{L} , and D_{L} .
- (4) If the nonlinear beam internal deformation or internal forces, or the eliminated DOF responses are requested in the output, a flag > 0 should be used in this card for that particular response. This would assign a storage space at the onset of the solution procedure for the requested response.

CARD GROUP 7: PLOT CONTROL PARAMETERS
 No. of Cards: Variables*
 Format: I2,3X,15I5

Card 1

Columns	Variable	Entry	Notes
1-2	ITYPE	Output quantity defined by the numbers given in Card Group 6, card 2 (i.e., 1 to 18)	(1)
		For example, ITYPE=1 corresponds to the external DOF absolute displacements (N1N2)	
6-10	ITEMS (1)	DOF number to be plotted.	(2)
11-15	ITEMS (2)	DOF number to be plotted.	
76-80	ITEMS (15)	DOF number to be plotted.	
Next card(s)--if necessary.			
6-10	ITEMS (16)	DOF number to be plotted.	(2)
11-15	ITEMS (17)	DOF number to be plotted.	

Go to Card Group 8.

NOTES:

- (*) If $IPLOT \leq 0$ in Card Group 6, skip this card group.
- (1) ITYPE must be input in ascending order. This card group is terminated by $ITYPE \leq 0$.
- (2) Degree-of-freedom numbers must be in ascending order with up to 15 on a card. The list is terminated with a zero or negative DOF number. More than 1 card can be provided for each type if the list exceeds 15 quantities to be output. The format for additional cards is 5X,15I5.
- (3) If requested response include nonlinear beam responses or the eliminated DOF responses a flag > 0 should be set in card 6 for the particular response.

CARD GROUP 8: FORMATTED OUTPUT CONTROL PARAMETERS
 No. of Cards: Variable*
 Format: I2,3X,15I5

Card 1

Columns	Variable	Entry	Notes
1-2	ITYPE	Output quantity defined by the numbers given in Card Group 6, card 2 (i.e., 1 to 18). For example, ITYPE=1 corresponds to the external DOF absolute displacements (N1N2)	(1)
6-10	ITEMS(1)	DOF number to be output.	(1)
11-15	ITEMS(2)	DOF number to be output.	
	.		
	.		
	.		
76-80	ITEMS(15)	DOF number to be output.	

Next card(s)--if necessary.

6-10	ITEMS(16)	DOF number to be output.	(1)
11-15	ITEMS(17)	DOF number to be output.	

Go to Card Group 9.

NOTES:

- (*) IF IPUNCH \leq 0 in Card Group 6, skip this group.
- (1) See notes 1,2 and 3 in Card Group 7.

CARD GROUP 9: WEIGHTS, INITIAL CONDITIONS,
 AND CONSTANT FORCES
 No. of Cards: N2
 Format: I5,7F10.0

Columns	Variable	Entry	Notes
1-5	N	External DOF number.	(1)
6-15	CWT	Constant weight at DOF N.	(2)
16-25	VWT	Time-displacement at DOF N.	(2) (3)
26-35	DINIT	Initial displacement at DOF N.	
36-45	VINIT	Initial velocity at DOF N.	
46-55	PCONS	Constant force at DOF N.	(4)
56-65	DUM1	Reserved for future use.	
66-75	DUM2	Reserved for future use.	

Go to Card Group 10.

NOTES:

- (1) Data can be input in any order, but all N2 degrees of freedom must be specified, where $(N1 + 1) < N < (N1 + N2)$.
- (2) CWT and VWT are divided by the value of GRAVITY given on card 2 of Card Group 5.
- (3) If MASSTD = 0, ignore time-dependent weight. If MASSTD > 0, this weight varies according to input force-time history number MASSTD. If MASSTD < 0, this weight varies according to the kinematic motion time-history number |MASSTD|. See Card Group 4.
- (4) If KONFOR \leq 0, ignore constant force. See Card Group 4.

CARD GROUP 10: NONLINEAR BEAM ELEMENT PROPERTIES
 No. of Cards: NBEAMS*
 Format: A1,I4,5F10.0

Columns	Variable	Entry	Notes
1	FLAG	Alphanumeric character to specify the type of beam input, = ^, prismatic beam (^ denotes a blank) = K, stiffness matrix = S, stepped section = L, stepped section, last card	(1) (2) (2)
2-5	N	Beam element number (i.e., N = 1 to NBEAMS)	(3)
6-15	SPAN	Beam element length	
16-25	EI	Beam element bending stiffness	(4)
26-35	ϕ	Beam element shear factor	(5)
36-45	PCTCR	Percent critical damping for the beam element given as a fraction (e.g., 10% = 0.10)	(6)
46-55	FREQ	Angular frequency of the beam in rad/sec	(6)

Go to Card Group 11.

NOTES:

- (*) If NBEAMS \leq 0 from Card Group 3, skip this card group. Typically, the number of cards in this group will equal the number of beams. However, if stepped section properties are input, up to three cards will be required for each beam.
- (1) If FLAG = K, the member properties are known only in the form of a 2 x 2 uncoupled stiffness matrix (see Sec. 3.2.2.2). In this case, $S_{11} = \text{SPAN}$, $S_{12} = S_{21} = EI$, $S_{22} = GAK$, and the beam length is taken as unity.

CARD GROUP 10: LINEAR BEAM ELEMENT PROPERTIES (concluded)

NOTES: (Concluded)

- (2) If FLAG = S or L, the member is a stepped section (see Section 3.2.2.2). Up to three stepped sections per beam are allowed. The last stepped section must have FLAG = S. The stepped section cards must be input in consecutive order and must be specified from the smaller internal deformation number to the larger. If nonuniform damping is used, it is based on PCTCR and FREQ of the first card (see Note 4).
- (3) Data can be input in any order except as noted above.
- (4) This represent the nonlinear initial stiffness EI. The degradation factors are to be multiplied by this value of EI for the actual degraded stiffness.
- (5) This factor is calculated by the user as defined in section 3.3.1 representing the shear effect of a beam in bending.
- (6) These parameters are required when the nonuniform damping option (see Section 3.2.3.2) is invoked (i.,e., LDAMP = 2 or 3 from Card Group 4); FREQ must be > 0.0 and PCTCR must be ≥ 0.0 .

CARD GROUP 11:
No. of Cards:
Format:

NONLINEAR BEAM ELEMENT PROPERTIES
NBEAMS*
3I5

Columns	Variable	Entry	Notes
1-5	N	Beam element number (i.e., N = 1 to NBEAMS)	
6-10	NBMAT	Beam property number (i.e., NBMAT = 1, to NUMBMAT)	
11-15	NBINC	Number of increment.	(1)

Go to Card Group 12.

NOTES:

- (*) If $NBEAMS \leq 0$ from Card Group 3, skip this card group. The number of cards in this group will equal the number of beams.
- (1) The number of increment can be different for each beam property cards. $NBINC < 80$.

CARD GROUP 12: NONLINEAR BEAM ELEMENT PROPERTIES
 No. of Cards: NUMBMAT*
 Format: 2I5,/,2F10.0

Card 1

Columns	Variable	Entry	Notes
1-5	NBMAT	Beam property number.	(1)
6-10	NBINC	Number of increment.	(1)

Card 2

1-10	THETA	Net rotation angle.	(2)
11-20	EIF	EI factor.	(3) (4)

Go to card group 13.

NOTES:

(*) If NBEAMS \leq 0 from Card Group 3, skip this card group. This group of cards is to be repeated NVMB MAT times.

(1) See card group 11.

(2) This represent the beam net internal deformation as a measure of the stiffness degradation. The units have to be consistent with the beam dimension.

(3) EI factor is a fraction of the initial stiffness of the beam as defined in card group 10. The effective EI for a particular beam at a particular net rotation is

$$EI \text{ (effective)} = EIF * EI \text{ (initial)}$$

There is no interpolation between values of the rotation, for a particular rotation, EI of the previous lower rotation is adopted. The step size should be fine in the critical region to achieve a higher degree of resolution to better represent the stiffness factor.

(4) Card 2 should be repeated NBINC times.

CARD GROUP 13:

NONLINEAR SPRING ELEMENT TYPE AND
MATERIAL PROPERTY NUMBER

No. of Cards:

NNS*

Format:

3I5,6F10.0

Columns	Variable	Entry	Notes
1-5	N	Nonlinear spring element number (i.e., N = 1 to NNS)	(1)
6-10	NSTYPE	Nonlinear spring type number	(2)
11-15	NSMAT	Nonlinear spring element material property number (i.e., NSMAT = 1 to NUMMAT)	
16-25	ELMS(1)	Spring pre-damage option flag ELMS(1) ≤ 0.0, spring is not pre-damaged ELMS(1) > 0.0, spring is pre-damaged	(3)
26-35	ELMS(2)	Spring permanent deformation, tension	(4)
36-45	ELMS(3)	Spring permanent deformation, compression	(4)
46-55	ELMS(4)	Spring maximum deformation, tension	(4)
56-65	ELMS(5)	Spring maximum deformation, compression	(4)
66-75	ELMS(6)	Reserved for future use	

Go to Card Group 14.

CARD GROUP 13:

NONLINEAR SPRING ELEMENT TYPE AND
MATERIAL PROPERTY NUMBER (concluded)

NOTES:

- (*) If $NNS \leq 0$ from Card Group 3, skip this card group.
- (1) Data can be input in any order.
- (2) See Section 3.3.2 for types available.
- (3) The nonlinear springs can be pre-damaged prior to the start of a run by setting $ELMS(1) > 0.0$ and setting the damage parameters in $ELMS(2)$ through $ELMS(5)$.
- (4) Ignored, if $ELMS(1) \leq 0.0$.

CARD GROUP 14: NONLINEAR SPRING ELEMENT MATERIAL
 PROPERTIES
 No. of cards: 2 x NUMMAT*
 Format: I5,7F10.0/5X,7F10.0

Card 1

Columns	Variable	Entry	Notes
1-5	N	Material property number (i.e. N = 1 to NUMMAT)	(1)
6-15	XK1	Spring constant 1	(2)
16-25	XK2	Spring constant 2	(2)
26-35	XK3	Spring constant 3	(3)
36-45	F1	Force of first transition point	(2)
46-55	F2	Force of second transition point	(2)
56-65	GAP	Spring gap at zero load	(2)
66-75	DUMMY	Reserved for future use	

Card 2

6-15	CVISC	Viscous damping constant	(3)(5)
16-25	EXPCV	Viscous damping velocity exponent	(3)(5)
26-35	COULMB	Coulomb damping constant	(4)(5)
36-45	CFTHN	Coulomb damping is a function of the input force-time history number CFTHN	(4)(5)
46-55	CNSFN	Coulomb damping is a function of the force in nonlinear spring number CNSFN	(4)(5)
56-65	VBAR	Velocity parameter for Coulomb damping	(4)(5)
66-75	DUMMY	Reserved for future use	

Go to Card Group 15.

CARD GROUP 14: NONLINEAR SPRING ELEMENT MATERIAL
 PROPERTIES (concluded)

NOTES:

(*) If $NNS \leq 0$ and/or $NUMMAT \leq 0$ from Card Group 3, skip this card group.

(1) Data can be input in any order.

(2) These parameters are material properties that are used to define the force-deformation characteristics of the various nonlinear spring types. See Section 3.3.2 for a detailed description of each spring type and definition of the various parameters used by each spring.

(3) Viscous damping force is

$$F_{CV} = CVISC * (e)^{EXPCV} * SIGN(e)$$

(See LPM/I Section 3.3.3.1 for a description of the nonlinear viscous damping.)

(4) The Coulomb damping force may take one of three forms:

Coulomb damping is a constant, except for spring velocities (e) between $\pm VBAR$, where the damping is proportioned based on the ratio of (e)/ $VBAR$.

$$F_{CC} = COULMB * SIGN(e); \text{ when } CFTHN = CNSFN = 0.0$$

Coulomb damping is a function of the input force-time history number $CFTHN$, evaluated at the current integration time.

$$F_{CC} = COULMB * F(CFTHN) * SIGN(e); \text{ when } CFTHN > 0.0$$

Coulomb damping is a function of the current force in nonlinear spring no. $CNSFN$. (Note: $CNSFN$ must be smaller than the current spring number).

$$F_{CC} = COULOMB * F_N(CNSFN) * SIGN(e); \text{ when } CNSFN > 0.0 \text{ and } CFTHN = 0.0$$

Only one form of Coulomb damping can be used.

(See LPM/I Section 3.3.3.2 for a description of the nonlinear Coulomb damping.)

(5) Viscous damping and one form of Coulomb damping can be used simultaneously.

CARD GROUP 15: COMPATIBILITY SUBMATRIX [A_{11}/A_{21}]
 (N1N2 x NLB)
 No. of Cards: Variable*
 Format: 2I5,F10.0,I5

Columns	Variable	Entry	Notes
1-5	I	Row number of a nonzero element in A_{11} the submatrix. A_{21}	(1)
6-10	J	Column number of the above nonzero A_{11} element in the submatrix. A_{21}	(2)
11-20	AIJ	Value of the above nonzero element, A_{11} $A(I,J)$, of the submatrix. A_{21}	
21-25	INXEL	Beam element number, if the value AIJ given above is to be divided by the beam length.	

Go to Card Group 15.

NOTES:

- (*) If NBEAMS \leq 0 from Card Group 3, skip this card group. One card is required for each nonzero element.
- (1) $0 < I \leq (N1 + N2)$. $I \leq 0$ signals the end of the input for the submatrix.
- (2) $0 < J \leq (2 \cdot NBEAMS)$.

CARD GROUP 16: COMPATIBILITY SUBMATRIX [A_{13}/A_{23}]
 (N1N2 x NNS)
 No. of Cards: Variable*
 Format: 2I5,F10.0,I5

Columns	Variable	Entry	Notes
1-5	I	Row number of a nonzero element in A_{13} the submatrix. A_{23}	(1)
6-10	J	Column number of the above nonzero A_{13} element in the submatrix	(2) (3)
11-20	AIJ	Value of the above nonzero element, A_{13} $A(I,J)$, of the submatrix A_{23}	
21-25	INXEL	Beam element number, if the value of AIJ given above is to be divided by the beam length.	

Go to Card Group 17.

NOTES:

- (*) If $NNS \leq 0$ from Card Group 3, skip this card group. One card is required for each nonzero element.
- (1) $0 < I \leq (N1 + N2)$. $I \leq 0$ signals the end of the input for the submatrix.
- (3) $0 < J \leq NNS$.

CARD GROUP 17: COMPATIBILITY SUBMATRIX $[A_{31}]$ ($N3 \times NLB$)
 No. of Cards: Variable*
 Format: 2I5,F10.0,I5

Columns	Variable	Entry	Notes
1-5	I	Row number of a nonzero element in the $[A_{31}]$ submatrix.	(1)
6-10	J	Column number of the above nonzero element in the $[A_{31}]$ submatrix.	(2)
11-20	AIJ	Value of the above nonzero element, $A(I,J)$, of the $[A_{31}]$ submatrix.	
21-25	INXEL	Beam element number, if the value AIJ given above is to be divided by the beam length.	

Go to Card Group 18.

NOTES:

- (*) If $Ns \leq 0$ and/or $NBEAMS \leq 0$ from Card Group 3, skip this card group. One card is required for each nonzero element. Input a blank card if matrix is null, when $N > 0$ and $NBEAMS > 0$.
- (1) $0 > I \leq N3$. $I \leq 0$ signals the end of the input for the submatrix.
- (2) $0 < J \leq (2 \text{ NBEAMS})$.

CARD GROUP 18: COMPATIBILITY SUBMATRIX $[A_{32}]$ ($N3 \times NLS$)
 No. of Cards: Variable*
 Format: 2I5,F10.0,I5

Columns	Variable	Entry	Notes
1-5	I	Row number of a nonzero element in the $[A_{32}]$ submatrix.	(1)
6-10	J	Column number of the above nonzero element in the $[A_{32}]$ submatrix.	(2)
11-20	AIJ	Value of the above nonzero element, $A(I,J)$, of the $[A_{32}]$ submatrix.	
21-25	INXEL	Beam element number, if the value AIJ given above is to be divided by the beam length.	

Go to Card Group 19.

(*) If $N3 \leq 0$ and/or $NLS \leq$ from Card Group 3, skip this card group. One card is required for each nonzero element. Input a blank card if matrix is null, when $N3 > 0$ and $NLS > 0$.

(1) $0 < J \leq NLS$.

CARD GROUP 19: EXTERNAL FORCING FUNCTION CONTROL
No. of Cards: 1*
Format: F110.0,I1

Columns	Variable	Entry	Notes
1-10	FACTR	Multiplicative scaling factor for all force-time histories. If FACTR = 0.0, a default value of 1.0 is assumed and no scaling is performed.	
11	IFPRT	Force-time history print flag; ≤ 0, print force-time histories before the scale factor is applied. = 1, print force-time histories after the scale factor is applied. ≥ 2, force-time histories are not printed.	

Go to Card Group 20.

(*) If NOFTH ≤ 0 from Card Group 3, skip Card Groups 19 through 21 and go to Card Group 22.

CARD GROUP 20: EXTERNAL FORCING FUNCTION PARAMETERS
No. of Cards: NODWAF*
Format: 2I5,F10.0

Columns	Variable	Entry	Notes
1-5	NDOF	External DOF number with applies force.	(1)
6-10	NFOR	Force-time history number to be applied at DOF number NDOF.	(2)
11-20	FFACT	Multiplicative scaling factor for force-time history NFOR, when applied at DOF number NDOF. No default value.	

Go to Card Group 21.

NOTES:

- (*) If $NODWAF \leq 0$ or $NOFTH \leq 0$ from Card Group 3, skip this card group.
- (1) $N1 < NDOF \leq (N1 + N2)$. Data can be input in any order, but all NODWAF cards must be input.
- (2) $0 < NFOR \leq NOFTH$.
- (3) FFACT is applied in addition to FACTR of Card Group 19.

CARD GROUP 21
No. of Cards:
Format:

EXTERNAL FORCING FUNCTION TIME HISTORIES
Variable*
8F10.0

Card 1

Columns	Variable	Entry	Notes
1-10	TIM	Time value, t_i	(1)
11-20	FORC(1)	Force value at t_i for time history 1.	(2)
21-30	FORC(2)	Force value at t_i for time history 2.	
		.	
		.	
71-80	FORC(7)	Force value at t_i for time history 7.	

Next card(s) -- if necessary

11-20	FORC(8)	Force value at t_i for time history 8.	(2)
		.	
		.	
		.	
---	FORC(NOFTH)	Force value at t_i for time history NOFTH.	

Go to Card Group 22.

NOTES:

- (*) If $\text{NOFTH} \leq 0$ from Card Group 3, skip this card group.
- (1) This card group is terminated when the time value is less than that given on the previous card. This data must be input in order of ascending time values and time values cannot be repeated. The force-time history must be specified to at least $\text{TIM} = \text{TSTOP} + 2.0 \cdot \text{DELTAT}$.
- (2) If $\text{NOFTH} \leq 7$, one card per time is input using the format 8F10.0. If $\text{NOFTH} > 7$, second and subsequent cards, if required, use the format 10X,7F10.0.

CARD GROUP 22: KINEMATIC MOTION CONTROL
 No. of Cards: 1*
 Format: F10.0,2I1

Columns	Variable	Entry	Notes
1-10	FACTK	Multiplicative scaling factor for all kinematic motion-time histories including their initial conditions. If FACTK = 0.0, a default value of 1.0 is assumed and no scaling is performed.	
11	MPRT	Motion time-history print flag; ≤ 0 , print motion-time histories before the scale factor is applied. $= 1$, print motion-time histories after the scale factor is applied. ≥ 2 , motion-time histories are not printed.	
12	MTYPE	Kinematic motion type flag; ≤ 0 , motion-time histories input in Card Group 26 are accelerations. ≥ 1 , motion-time histories input in Card Group 26 are velocities.	

Go to Card Group 23.

NOTES:

- (*) If NOMTH ≤ 0 from Card Group 3, skip Card Groups 22 through 26 and go to Card Group 1.

CARD GROUP 23: KINEMATIC MOTION PARAMETERS
 No. of Cards: N1*
 Format: 2I5,F10.0

Columns	Variable	Entry	Notes
1-5	NDOF	External DOF number with kinematic (i.e., known) motion	(1)
6-10	MTH	Kinematic motion-time history number to be applied at DOF number NDOF	(2)
11-20	FACTM	Multiplicative scaling factor for motion-time history MTH, when applied at DOF number NDOF. No default value.	(3)

Go to Card Group 24.

NOTES:

- (*) If $N1 \leq 0$ or $NOMTH \leq 0$ from Card Group 3, skip this card group.
- (1) $0 < NDOF \leq N1$. Data can be input in any order, but all N1 cards must be input.
- (2) $0 < MTH \leq NOMTH$.
- (3) FACTM is applied in addition to FACTK of Card Group 22.

CARD GROUP 24: KINEMATIC MOTION INITIAL CONDITIONS--
DISPLACEMENTS
No. of Cards: Variable*
Format: 10X,7F10.0

Card 10

Columns	Variable	Entry	Notes
11-20	DINIT(1)	Initial displacement for motion-time history 1.	
21-30	DINIT(2)	Initial displacement for motion-time history 2.	
	.		
	.		
	.		
71-80	DINIT(7)	Initial displacement for motion-time history 7.	

Next cards(s) if necessary

11-20	DINIT(8)	Initial displacement for motion-time history 8.
	.	
	.	
	.	
---	DINIT (NOMTH)	Initial displacement for motion-time history NOMTH

Go to Card Group 25.

NOTES:

(*) If NOMTH \leq 0 from Card Group 3, skip this card group.

CARD GROUP 25: KINEMATIC MOTION INITIAL CONDITIONS--
 VELOCITIES OR ACCELERATIONS
 No. of Cards: Variable*
 Format: 10X,7F10.0

Card 1

Columns	Variable	Entry	Notes
11-20	VAINT(1)	If MTYPE \leq 0, initial velocity for motion-time history 1. If MTYPE \geq 1, initial acceleration for motion-time history 1.	
21-30	VAINT(2)	If MTYPE \leq 0, initial velocity for motion-time history 2. If MTYPE \geq 1, initial acceleration for motion-time history 2.	
	.		
	.		
	.		
71-80	VAINT(7)	If MTYPE \leq 0, initial velocity for motion-time history 7. If MTYPE \geq 1, initial acceleration for motion-time history 7.	

Next card(s) -- if necessary

11-20	VAINT(8)	If MTYPE \leq 0, initial velocity for motion-time history 8. If MTYPE \geq 1, initial acceleration for motion-time history 8.	
	.		
	.		
	.		
---	VAINT (NOMTH)	If MTYPE \leq 0, initial velocity for motion-time history NOMTH. If MTYPE \geq 1, initial acceleration for motion-time history NOMTH.	

Go to Card Group 26.

NOTES:

(* If NOMTH \leq 0 from Card Group 3, skip this card group.

CARD GROUP 26: KINEMATIC MOTION TIME HISTORIES
 No. of Cards: Variable*
 Format: 8F10.0

Card 1

Columns	Variable	Entry	Notes
1-10	TIM	Time value, t_i .	(1)
11-20	AMOT(1)	Motion value at t_i for motion-time history 1.	(2) (3)
21-30	AMOT(2)	Motion value at t_i for motion-time history 2.	
	.		
	.		
	.		
71-80	AMOT(7)	Motion value at t_i for motion-time history 7.	

Next card(s) -- if necessary

11-20	AMOT(8)	Motion value at t_i for motion-time history 8.	
	.		
	.		
	.		
---	AMOT	Motion value at t_i for motion-time history NOMTH.	

Go to Card Group 1.

NOTES:

- (*) If $nomth \leq 0$ from card group 3, skip this card group.
- (1) This card group is terminated when the time value is less than that given on the previous card. The data must be input in order of ascending time values and the time values cannot be repeated. The motion-time history must be specified to at least $TIM = TSTOP + 2.0 \cdot DELTAT$.
- (2) Motion values are in acceleration or velocity units depending on the value set for MTYPE in Card Group 22. If $NOMTH \leq 7$, one card per time is input using the format 8F10.0. If $NOMTH > 7$, the second and subsequent cards, if required, use the format 10X,7F10.0

CARD GROUP 26: KINEMATIC MOTION TIME HISTORIES (concluded)

NOTES: (concluded)

- (3) If acceleration values are input, linear interpolation is used to obtain accelerations at any time t ; velocity and displacement are obtained using a linear acceleration assumption (i.e., quadratic velocity variation and cubic displacement variation).

If velocity values are input, accelerations are calculated at the input time values using a linear acceleration assumption, and all kinematic quantities are obtained as described above.

See Appendix D of Kariotis, (1992), for a more detailed description of the linear interpolation algorithms utilized in the code.

SECTION 5
SAMPLE PROBLEM

Sample Problem

The problem represents a five-story shear wall with lumped masses representing floor weights at each story height. The model is represented by five beams and five masses as shown in Figure 5-1. Each beam element represents a floor level.

Beam Properties:

Beam length = story height = 12 ft. = 144 inches.

Beam width = 20 ft. = 240 inches.

Beam thickness = 7.6 inches.

E = 3000 ksi.

$$EI = 3000 \times \frac{7.6 \times (240)^3}{12} = 2.628 \times 10^{10} \text{ k} - \text{in.}^2$$

$$\text{Mass} = \frac{30}{386.4} = 0.0776 \quad \text{k} - \text{sec}^2/\text{in.}$$

Dynamic Model:

The active DOF as shown in Figure 5-2 are subdivided into known and unknown DOF. The ground motion is the known and the translational DOF of all five masses are the unknowns. There are two DOF associated with each mass at the end of the beam. Since only the translational DOF are to be considered, the rotational DOF are to

be eliminated. These DOF are shown in Figure 5-2. Also, the internal deformation of all beams are shown in Figure 5-2.

Compatibility Matrices:

The only non-zero matrices are; $[A_{11}]$, $[A_{21}]$ and $[A_{31}]$. $[A_{11}]$, $[A_{21}]$ relate the active DOF to the beams internal deformations. $[A_{31}]$ relates the eliminated DOF to the beams internal deformation.

Results:

A sample input file and a part of the output is presented in the following section.

The relationship of the degrading EI value of the beam with the rotation angle is shown in Figure 5-3. The EI ratio is the degraded EI value as a percentage of the initial EI. Figure 5-4 represents the ground motion used for the analysis. The displacement of the top mass relative to the ground is shown in Figure 5-5. This is for linear beam elements with no degradation allowed.

Comparisons of the top displacement as evaluated by LPM/II and SAP90 are presented in Figures 5-6 and 5-7. The stiffness used in the SAP90 model is the fully degraded stiffness of the beam elements as obtained from the LPM/II prism. There is no damping

for the response in Figure 5-6 while the response as shown in Figure 5-7 has a mass damping ratio of 0.75. Tables 3 and 4 show the ratio of EI compared to the initial EI for both damping conditions.

Conclusions:

The displacement for the linear beam with no degradation as shown in Figure 5 indicated a smaller amplitude and higher frequency contents than the response of an identical system with degraded elements. Figure 5-6 show the response of LPM/II with no damping compared to the SAP90 response of a linear beam that has properties equal to the final degraded stiffness as obtained from LPM/II. It is clear that SAP90 response is greater than LPM/II, since it starts with the final stiffness of LPM/II. Adding damping for similar runs forces the displacements to converge at about six seconds into the record as shown in Figure 5-7.

Tables 3 and 4 indicated that damping controls the maximum rotation and thus controls the degradation of the beams.

TABLE 1
BEAMS INITIAL PROPERTIES

BEAM NO.	LENGTH	INITIAL EI
1	144.0	2.6E+10
2	144.0	2.6E+10
3	144.0	2.6E+10
4	144.0	2.6E+10
5	144.0	2.6E+10

TABLE 2
MATERIAL STIFFNESS DEGRADATION RATE

INCREMENT NO.	ROTATION (rad.)	EI RATIO
1	0.000000	1.0
2	0.000005	0.9
3	0.000030	0.8
4	0.000070	0.7
5	0.000110	0.6
6	0.000160	0.5
7	0.000250	0.4
8	0.000350	0.3
9	0.000400	0.2
10	0.000600	0.1
11	0.000800	0.05
12	0.100000	0.05

TABLE 3

BEAMS FINAL DEGRADED STATE, AND
THE TIME OF OCCURRENCE FOR THE
CASE WITH MASS DAMPING = 0.75

BEAM NO.	ROTATION (rad.)	FINAL EI RATIO
1	0.002736	0.05
2	0.000262	0.40
3	0.000110	0.60
4	0.000042	0.80
5	0.000003	0.90

TIME = 5.47 (sec.)

TABLE 4

BEAMS FINAL DEGRADED STATE, AND
THE TIME OF OCCURRENCE FOR
THE CASE WITH NO DAMPING

BEAM NO.	ROTATION (rad.)	FINAL EI RATIO
1	-0.002439	0.05
2	-0.002299	0.05
3	-0.000805	0.05
4	0.000056	0.40
5	0.000060	0.60

TIME = 13.44 (sec.)

SAMPLE PROBLEM, TEST FIVE STORY MODEL, ELCENTRO N-S

```

1 5 5 5 1 0 0 0 0 1
100 0 0 5 0 0 0 0 0
0.0001 0.0 20.0 0.0 0.0 0.0 0.0
1.0 0.00 0.75 0.0
1 1 0 5
00000000000000000000
1 1 6 0
0
2 0.0776 0.0 0.0 0.0 0.0
3 0.0776 0.0 0.0 0.0 0.0
4 0.0776 0.0 0.0 0.0 0.0
5 0.0776 0.0 0.0 0.0 0.0
6 0.0776 0.0 0.0 0.0 0.0
1 144.0 2.628E10 0.0 0.0 0.0
2 144.0 2.628E10 0.0 0.0 0.0
3 144.0 2.628E10 0.0 0.0 0.0
4 144.0 2.628E10 0.0 0.0 0.0
5 144.0 2.628E10 0.0 0.0 0.0
1 1 12
2 1 12
3 1 12
4 1 12
5 1 12
1 12
0 1.0
0.000005 0.9
0.000030 0.8
0.000070 0.7
0.000110 0.6
0.000160 0.5
0.000250 0.4
0.000350 0.3
0.000400 0.2
0.000600 0.1
0.000800 0.05
1.1 0.05
1 1 1.0 1
1 2 1.0 1
2 1 -1.0 1
2 2 -1.0 1
2 3 1.0 2
2 4 1.0 2
3 3 -1.0 2
3 4 -1.0 2
3 5 1.0 3
3 6 1.0 3
4 5 -1.0 3
4 6 -1.0 3
4 7 1.0 4
4 8 1.0 4
5 7 -1.0 4
5 8 -1.0 4
5 9 1.0 5
5 10 1.0 5
6 9 -1.0 5
6 10 -1.0 5
0
1 2 1.0
1 3 1.0

```

SAMPLE INPUT DATA FILE

2	4	1.0	
2	5	1.0	
3	6	1.0	
3	7	1.0	
4	8	1.0	
4	9	1.0	
5	10	1.0	
0			
1.000	20		
1	1	1.0	
		0.0	
		0.0	
	0.0000	-0.5512	
	0.0200	-4.2520	
	0.0400	-3.9764	
	0.0600	-3.4646	
	0.0800	-3.7401	
	.	.	
	.	.	
	.	.	
	53.1400	-1.1024	
	53.1600	-0.2756	
	53.1800	-0.9055	
0.0			
STOP			

SAMPLE INPUT DATA FILE

SAMPLE PROBLEM, TEST FIVE STOREY MODEL, ELCENTRO N-S

MASTER CONTROL PARAMETERS

NO. OF EXTERNAL D-O-F WITH KINEMATIC MOTION	=	1
NO. OF EXTERNAL D-O-F WITH UNKNOWN MOTION	=	5
NO. OF EXTERNAL D-O-F TO BE ELIMINATED	=	5
NO. OF NONLINEAR BEAM ELEMS	=	5
NO. OF PROPERTIES FOR NONLINEAR BEAM ELEMENTS	=	1
NO. OF NONLINEAR SPRING ELEMENTS	=	0
NO. OF PROPERTIES FOR NONLINEAR SPRING ELEMENTS	=	0
NO. OF EXTERNAL D-O-F WITH APPLIED FORCES	=	0
NO. OF FORCE TIME HISTORIES	=	0
NO. OF MOTION TIME HISTORIES	=	1
DATA STORAGE INCREMENT	=	100
DAMPING FLAG FOR NONLINEAR SPRING ELEMENTS	=	0
DAMPING FLAG FOR LINEAR ELEMENTS	=	0
NO. OF NORMAL MODES REQUESTED FOR THE LINEAR SYSTEM	=	5
MAX. NO. OF ITERATIONS FOR CALCULATING NORMAL MODES	=	100
TIME DEPENDENT MASS FLAG	=	0
SPECIAL FULL MASS MATRIX FLAG	=	0
CONSTANT FORCE FLAG	=	0
BLANK COMMON BLOCK SIZE	=	65000
INITIAL INTEGRATION TIME STEP	=	1.0000E-04
INTEGRATION START TIME	=	0.0000E-01
INTEGRATION STOP TIME	=	2.0000E+01
NO. OF INTEGRATION STEPS AT INITIAL TIME STEP	=	2.0000E+05
TIME WHEN KINEMATIC MOTIONS ARE TO BE INITIATED	=	0.0000E-01
TIME WHEN APPLIED FORCES ARE TO BE INITIATED	=	0.0000E-01
INTEGRATION TIME FOR GENERATION OF RESTART	=	4.0000E+01
INTEGRATION TIME TO CHANGE TIME STEP	=	4.0000E+01
NEW INTEGRATION TIME STEP	=	0.0000E-01
ACCELERATION OF GRAVITY	=	1.0000E+00
DAMPING CONSTANT STIFF LINEAR SYSTEM	=	0.0000E-01
MAX. ACCELERATION ALLOWED BEFORE PROGRAM TERMINATION	=	1.0000E+15
ITERATION TOLERANCE FOR CALCULATING NORMAL MODES	=	1.0000E-06
NONLINEAR SPRING ELEMENT NO. TO BE MONITORED FOR THE INITIATION OF THE APPLIED FORCES	=	0
FORCE IN NONLINEAR SPRING ELEMENT TO CONTROL THE INITIATION OF THE APPLIED FORCES	=	0.0000E-01

SAMPLE OUTPUT DATA FILE

COMPATIBILITY SUBMATRIX A11/A21

ROW(I) (MAX. OF 6)	COL(J) (MAX. OF 10)	A(I,J)	BEAM ELEMENT NO. (MAX. OF 5)
1	1	1.00000E+00	1
1	2	1.00000E+00	1
2	1	-1.00000E+00	1
2	2	-1.00000E+00	1
2	3	1.00000E+00	2
2	4	1.00000E+00	2
3	3	-1.00000E+00	2
3	4	-1.00000E+00	2
3	5	1.00000E+00	3
3	6	1.00000E+00	3
4	5	-1.00000E+00	3
4	6	-1.00000E+00	3
4	7	1.00000E+00	4
4	8	1.00000E+00	4
5	7	-1.00000E+00	4
5	8	-1.00000E+00	4
5	9	1.00000E+00	5
5	10	1.00000E+00	5
6	9	-1.00000E+00	5
6	10	-1.00000E+00	5

COMPATIBILITY SUBMATRIX A31

ROW(I) (MAX. OF 5)	COL(J) (MAX. OF 10)	A(I,J)	BEAM ELEMENT NO. (MAX. OF 5)
1	2	1.00000E+00	0
1	3	1.00000E+00	0
2	4	1.00000E+00	0
2	5	1.00000E+00	0
3	6	1.00000E+00	0
3	7	1.00000E+00	0
4	8	1.00000E+00	0
4	9	1.00000E+00	0
5	10	1.00000E+00	0

COMPATIBILITY SUBMATRICES

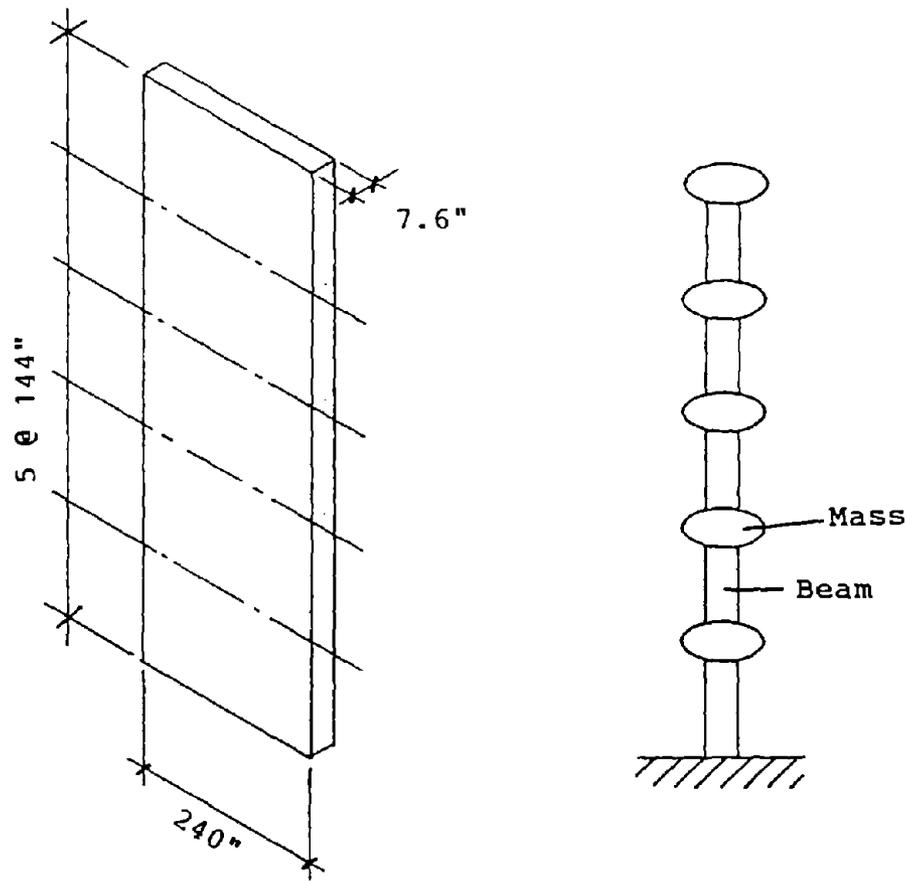


FIGURE 5-1 MODEL DIMENSIONS

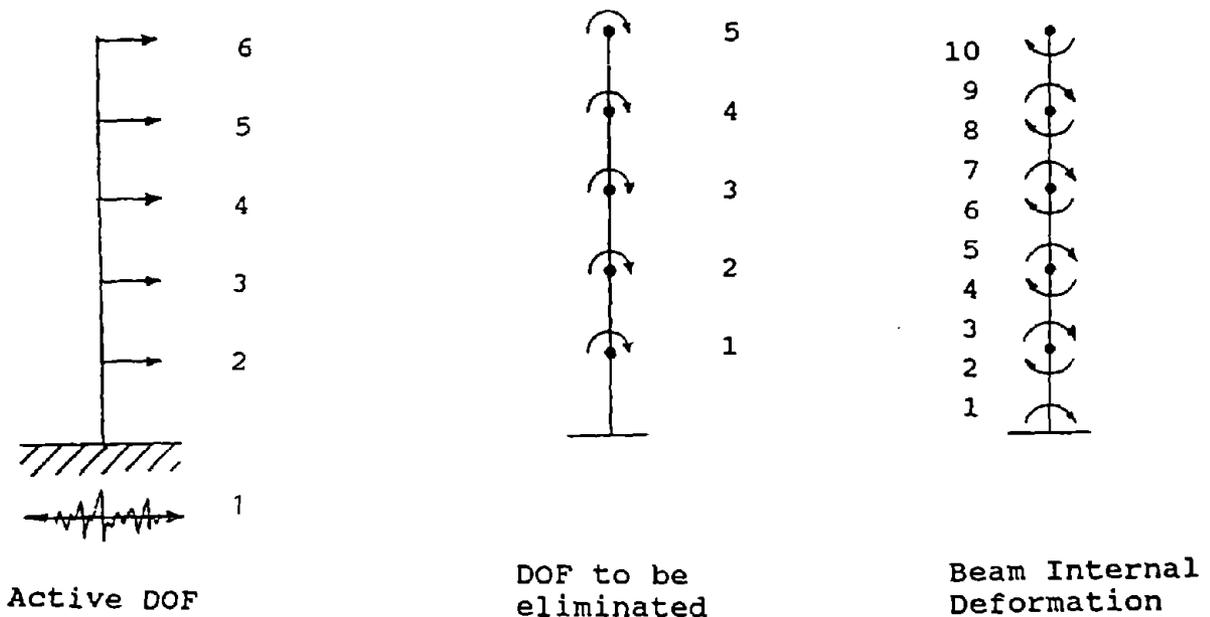


FIGURE 5-2 DYNAMIC MODEL DOF

EI RATIO

NORMALIZED TO INITIAL EI

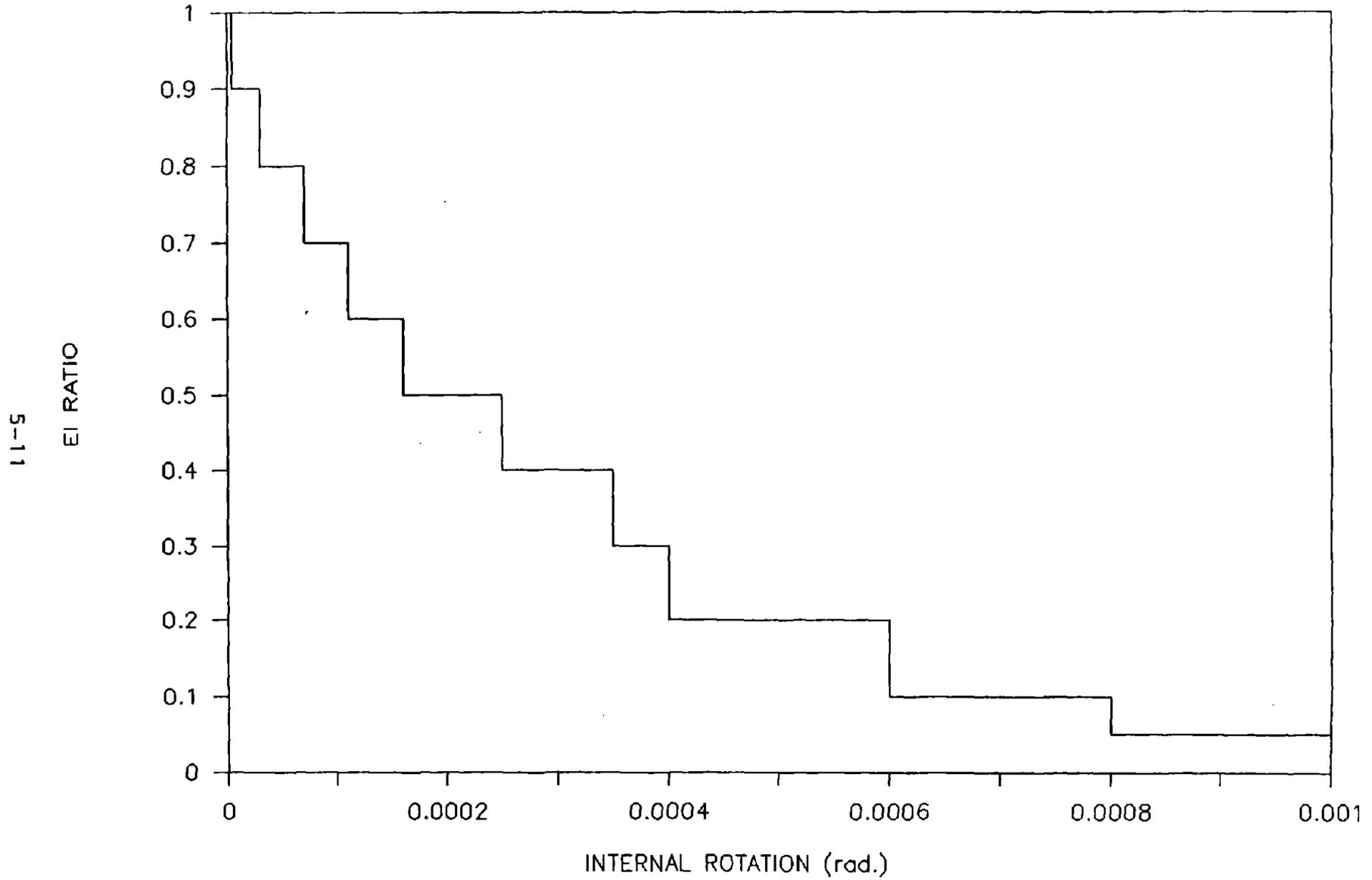
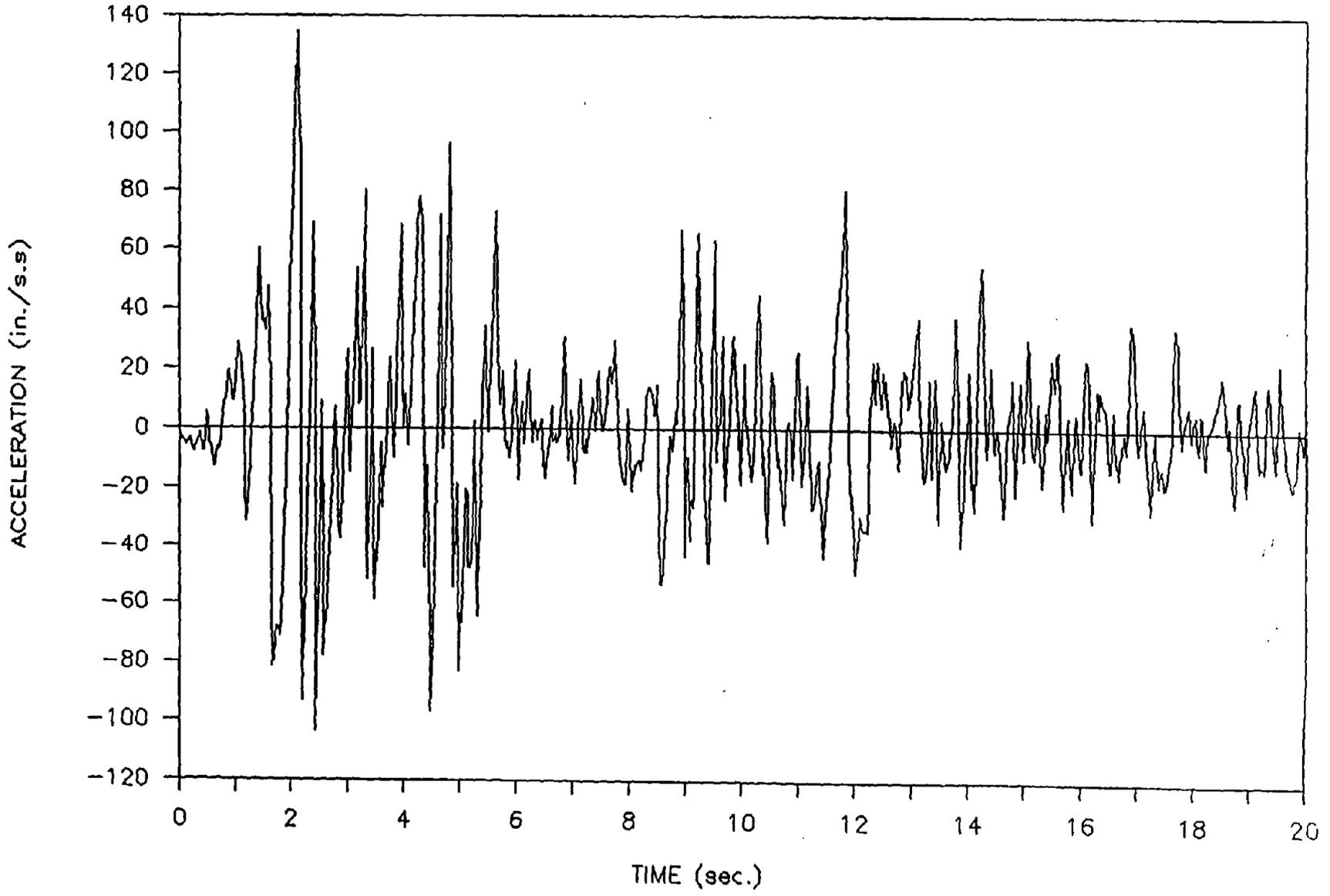


FIGURE 5-3 DEGRADATION RATIO

ELCENTRO N-S

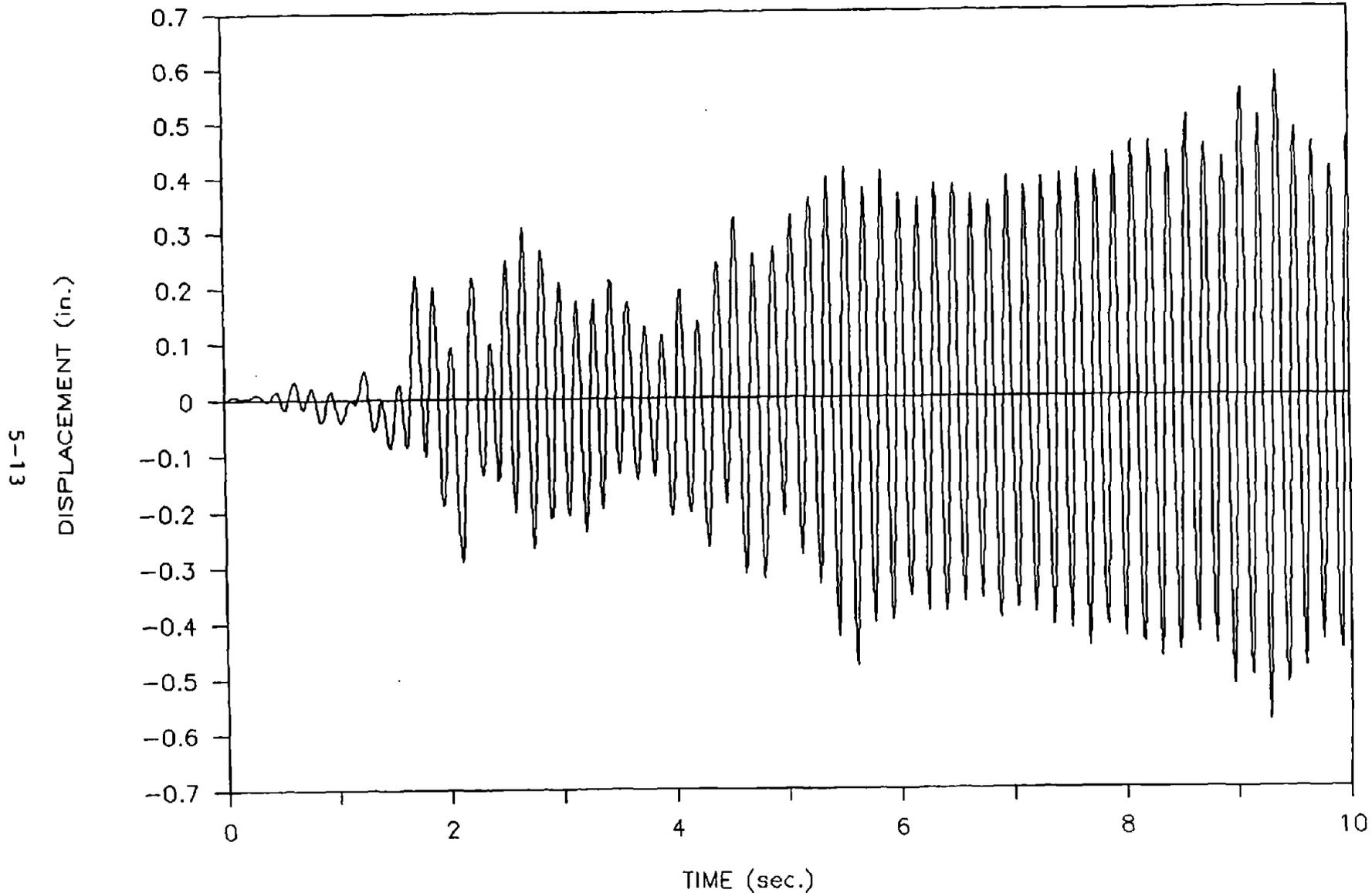


5-12

FIGURE 5-4 INPUT GROUND EXCITATIONS

START

LINEAR BEAM ELEMENT.



5-13

FIGURE 5-5 TOP DISPLACEMENT OF UNDEGRADED LINEAR SYSTEM

TOP DISPLACEMENT

ELCENTRO N-S, NO DAMPING

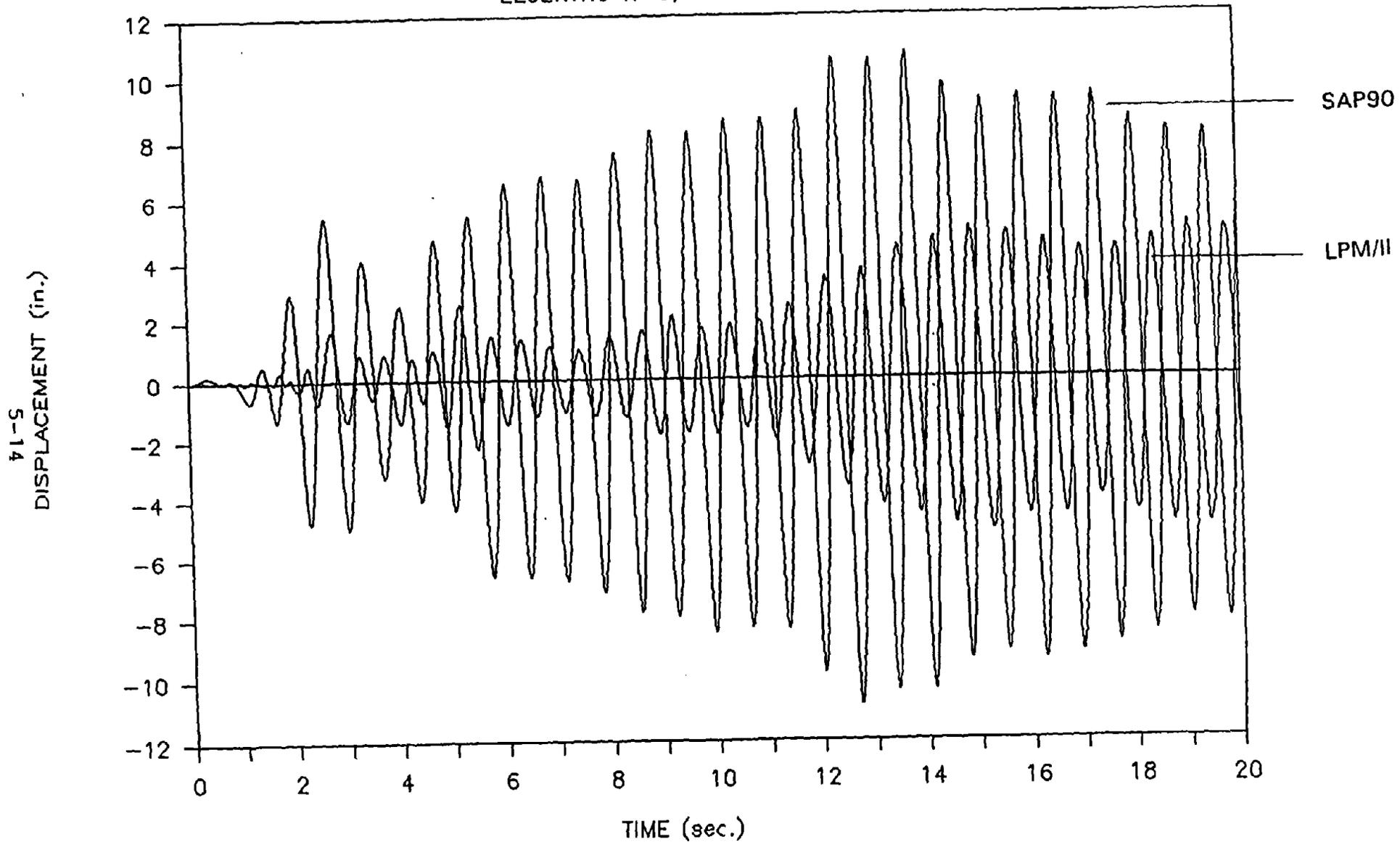


FIGURE 5-6 UNDAMPED LPM/II AND FULLY DEGRADED SAP90 RESPONSE COMPARISONS

TOP DISPLACEMENT

ELCENTRO N-S, MASS DAMPING = 0.75

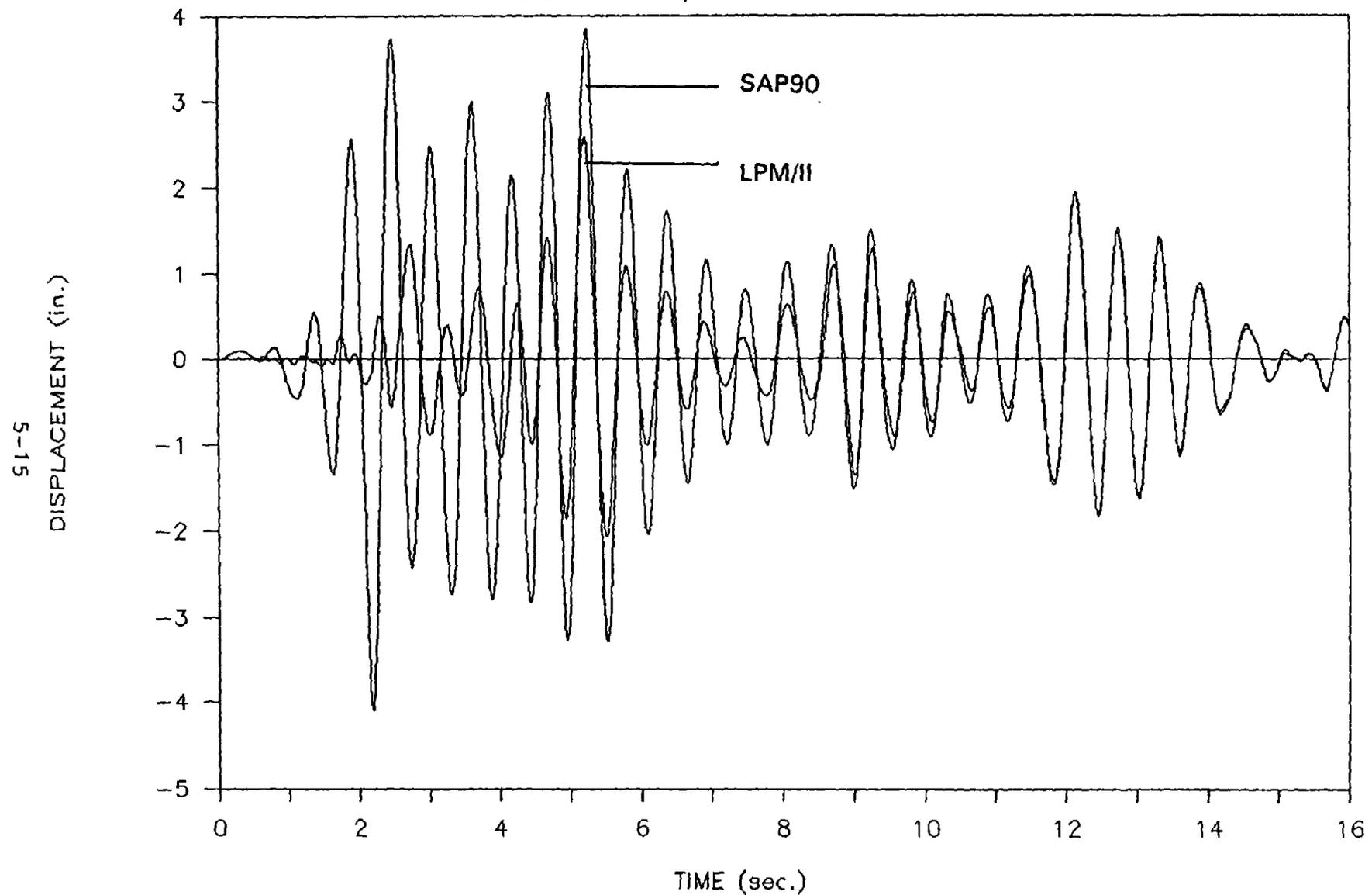


FIGURE 5-7 DAMPED LPM/II AND SAP90 RESPONSE COMPARISONS

SECTION 6
APPLICATIONS

6.1 INTRODUCTION

LPM/II is a general purpose dynamic computer code that is explicit in that the materials or element behavior is determined by one of several separate methods. The behavior of the elements is then coupled with the LPM/II code to determine dynamic displacements of the system. The dynamic model is excited by acceleration/time or velocity/time sequences. These sequences may be scaled recorded ground motions or artificially generated records. Selection of the input data used for excitation of the dynamic model is generally made by comparing the spectra of a large number of available records or generated records with a spectrum that is appropriate for the analysis. As a general rule several records, five to ten, are used to develop a data base for interpretation of the dynamic behavior of the structural element or system. These five to ten records are amplitude scaled within a selected range of frequency, to an intensity equal to the appropriate spectra. Selection of the frequency range and methods of scaling are discussed in the following references, (Kariotis, 1989), (Kariotis, 1992).

LPM/II is restricted to dynamic analysis in time domain. The dynamic behavior of the structural system is best presented as plot of displacement versus time. These dynamic displacements are related to materials stress and nonlinear strains by reference to

the materials model that was used to define the stiffness and strength degradation/displacement relationship.

The following example is a description of an application of LPM/II to a specific problem. Assume the problem is to analyze the nonlinear behavior of a multistory reinforced masonry shear wall. This shear wall provides the lateral resistance to earthquake caused inertial forces at floor levels and a partial support of the vertical floor loads. The reinforcement of the masonry shear wall and its dimensions have been determined by a design procedure. The weight of each floor level are known and these floor diaphragms are very stiff for loading in their plane and can be considered as rigid in the plane of the diaphragm.

The stiffness degradation of the shear wall is determined by FEM analysis of each story height of the wall. This analysis imposes a constant value of moment on the story height of the wall section and the stiffness degradation in the story height section is related to that moment. The moment value used in LPM/II for determination of stiffness is the maximum value that may occur at either end of the wall section. This procedure tends to favor replication of primary mode displacements and may over estimate higher mode displacements.

The building model is a series of cantilever shear walls, either fixed at their base or with a rotational spring at the base, that are slaved to a common displacement and mass at each diaphragm level. Each story height of every shear wall is described as a

beam element. The curvature/effective EI relationship is given for each element. The base of each shear wall is considered fixed and the ground motions are applied to the system at the fixed base.

The LPM/II model provides output in curvature at each story level. Internal stresses and strains in the beam element are found by reviewing the FEM analysis. The stresses and strains caused by ground motions scaled to a 475 year average return period earthquake are not limited to "code" stresses and strains. The 475 year average return period spectrum represents a ground motion where nonlinear behavior of structural elements is implicitly accepted. The nonlinear dynamic analysis is to determine if drift limitations are exceeded. If conformance with stress limitations are the criteria, it is common practice to scale their time-histories of ground motions to a Lower Level Earthquake (LLE). The LLE is commonly defined as that spectrum that has a 50 percent probability of being exceed in a 50 year time period. The average return period of the LLE, defined in this manner, is 72 years.

LPM/II is efficient for the dynamic analysis of reinforced concrete or masonry walls shaken normal to the plane of the wall. The length (height) of the wall is subdivided into beam elements. Engineering judgement is used to select the length of the element. Obviously two elements will be a poor representation of a wall that is free to rotate at both ends. Ten elements may cause a lengthy run time and not produce better data than an eight element subdivision.

The curvature/effective EI relationship of the reinforced wall is determined by a static analysis of the segment by FEM/I. The curvature is imposed incrementally and a plot of moment curvature is obtained. The stiffness degradation of the wall element is programmed with the FEM data. The input motion to the ends of the wall, its top and bottom, is either a dynamic motion scaled to a deterministic spectrum or to a motion that is the result of the dynamic motion of the wall support, generally a diaphragm.

Reference (Kariotis, 1992) describes the analysis of two single story buildings using LPM/II and LPM/I. The out-of-plane walls use LPM/II beam elements. The inplane shear wall and the diaphragm was modeled by LPM/I springs. A multistory masonry bearing wall building is also analyzed in the same reference by LPM/II. The cantilever shear walls were modeled by LPM/II beam elements. The out-of-plane walls in each story height were also modeled by LPM/II beam elements.

SECTION 7

REFERENCES

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