GENERAL PURPOSE COMPUTER PROGRAM FOR INELASTIC DYNAMIC RESPONSE OF PLANE STRUCTURES

by

G. H. Powell[I] and A. Kanaan[II]

SYNOPSIS

A brief description is presented of the concepts and procedures used in the development of a general purpose computer program for the dynamic response analysis of plane inelastic structures under earthquake loadings.

INTRODUCTION

It is generally agreed that inelastic behavior is inevitable in many structures subjected to strong earthquakes. Rational design procedures should therefore attempt to estimate the amount of inelastic bahavior to be expected. Methods of dynamic response analysis based on linear elastic assumptions can be carried out conveniently and economically, and can greatly assist in the production of safe designs. Such methods can not, however, provide direct information on the inelastic behavior of the structure. There is therefore a need for practical and efficient computer programs which can account directly for inelastic behavior.

Early analyses of the dynamic response of simple inelastic structures established basic computational procedures and confirmed that ductile structures should be able to withstand strong earthquakes. Computer programs suitable for the inelastic dynamic response of tall buildings have been described by several workers. Space does not permit a listing of references herein.

These programs are mostly restricted to plane frames, with rather elementary yield criteria and yield mechanisms. Some studies have taken into account diagonal bracing, panel zone deformations, the "PΔ" effect, and the interaction between axial force and bending in columns. A few studies of three-dimensional frames have been reported, with more sophisticated multidimensional yield criteria. However, most available programs are too limited in scope, capacity or efficiency to be suitable for use in design.

The computer program described here is intended as a practical tool for use in design studies. The program is limited to two dimensional structures, largely because of the great simplifications in scale and complexity that result, but the basic principles are also applicable to three dimensional structures. The program is not, however, limited

[I] Associate Professor of Civil Engineering, University of California, Berkeley, California.

[II] Senior Engineer, EDS Nuclear, San Francisco, California. Formerly graduate student, University of California, Berkeley.

to building frames or to structures with particular geometric configurations, but can be applied to the analysis of virtually any structure which can be idealized two-dimensionally. Further, the program is designed so that its capabilities can be extended by the addition of subroutines for new types of structural elements, without modifying the original program. The following sections describe the idealization procedure and program structure.

STRUCTURE IDEALIZATION

The structure must be idealized as a planar assemblage of discrete elements. Analysis is by the Direct Stiffness Method, with the nodal displacements as unknowns. Each node possesses up to three displacement degrees of freedom, as in a typical plane frame analysis. However, provision is made for degrees of freedom to be deleted or combined, so that the total number of unknowns may be much less than three times the number of nodes. Any degree of freedom may be specified to be completely restrained (i.e. to have a zero displacement relative to the ground), in which case no degree of freedom number is assigned. Further, the translational or rotational displacements of any group of nodes may be specified to have identical values, in which case the same degree of freedom number is assigned to all of these displacements. This provision provides the analyst with substantial freedom in the idealization of the structure, and may permit the size of the problem to be greatly reduced. For example, if the floors of a tall building frame may be assumed to be inextensible, as is often the case, the horizontal displacements may be specified to be equal at all nodes on each floor. If, however, this is not a reasonable assumption at some floors, as when occassional heavy truss bracing is provided or the building consists of two towers connected only at certain levels, different horizontal displace ments may be permitted. Tube buildings can be analyzed by unfolding them into a single plane, with identical vertical displacements but different horizontal and rotational displacements specified along the "folds". Semi-rigid connections and joint panel zones can be idealized by creating two adjacent nodes which are specified to have identical translational displacements but independent rotations, and introducing an element connecting these rotations to represent the deformable joint.

The structure mass is assumed to be lumped at the nodes only, so that the mass matrix is diagonal. Program modifications could be made to consider coupled mass matrices if desired. The earthquake excitation is defined by time histories of ground acceleration, which may be different in the horizontal and vertical directions. All support points are assumed to move in phase. However, a special purpose modification of the program has been made for the analysis of pipelines on nonlinear supports, in which the ground motion is assumed to propagate past the structure as a wave, so that the effects of relative support displacement are taken into account. Static loads may be applied prior to the dynamic loading, but in the current version no yielding is permitted under these loads.

The structural elements may be of virtually any type. At the time of writing subroutines for the following elements have been developed.

(1) Truss bar, which may yield in tension and yield or buckle elastically in compression.

(2) Beam-column element, which may be of variable cross section and strength, and which yields through the formation of concentrated plastic hinges at its ends. Interaction between axial force and moment may be taken into account for cross sections of steel or reinforced concrete type. Fixed end moment values may be specified, and the PΔ effect may be taken into account by including a geometric stiffness based on the axial force under static loads.

(3) Semi-rigid connection element, with a bilinear moment-rotation relationship.

(4) Shear panel element, to represent infill panels. The panel has shear stiffness only, and may yield and/or fail in a brittle fashion.

DYNAMIC RESPONSE ANALYSIS

The response is determined by step-by-step integration, with a constant acceleration assumption within any step. The tangent stiffness of the structure is used for each step, and linear structural behavior is assumed during the step. If an element yields or unloads, information must be returned from the element subroutine. Changes are then made to the tangent stiffness matrix and the triangularization operation of Gauss elimination is repeated. Any unbalanced loads resulting from errors in the assumed linear behavior within the step must also be returned from the element subroutine. These are then eliminated by applying corrective loads in the subsequent time step. Viscous damping of mass-dependent and/or stiffness-dependent type may be specified. Viscous damping elements could be developed and incorporated into the program.

PROGRAM STRUCTURE

The program consists of a number of "base" subroutines which read and print the structure and loading data, carry out a variety of bookkeeping operations, assemble the structure stiffness and loading, and determine the displacement response of the structure. The base program is then combined with element subroutines to produce a complete program. All data reading and printing operations and all stiffness and state calculations associated with elements must be carried out within the element subroutines, and information returned to the base program. The procedures for return of information have been simplified to a minimum number of operations, with the base program performing as much of the computation as possible. Hence, subroutines for new elements can be developed and added to the program with relative ease.

The available core storage is allocated dynamically at execution time. The structure stiffness matrix must first be held in core (a limitation which will be removed in future versions). The remaining core is then available for storage of the element data necessary for keeping track of the element behavior. This data is compacted into the available storage as a one-dimensional array. If the data for all elements can be accomodated in core, then it remains there and no input/output operations to scratch storage are required. If, however, the storage is insufficient, then the data is stored on scratch files in blocks, each block containing as many elements as can be held in core at one time. The blocking and input/output operations are carried out automatically within the base program.

The program incorporates a very efficient equation solver. Hence, although the structure stiffness is triangularized many times, the computer execution times have been found to be reasonable. For example, a 10 story, 3 bay frame has been analyzed for 7 seconds of earthquake (700 time steps) in an effective time of 500 seconds on a CDC 6400, with a core storage requirement of 75000 (octal). If special purpose beam and column elements were developed to replace the complex beam-column element currently used, this time could be reduced substantially.

VERIFICATION AND DOCUMENTATION

The program has been compared with those of Kamil et al (2) Workman (4) and Anderson and Bertero (1). Excellent agreement has been obtained with Kamil and Anderson, and fairly close agreement with Workman. Examples considering panel zone and infill panel effects in building frames have been analyzed. In the infill panel case, complete collapse was predicted. A special purpose modification has been used extensively for the analysis of pipelines on nonlinear supports. The program is described in detail in Reference 3. Copies of the program are available through the National Information Service for Earthquake Engineering, University of California, Berkeley.

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