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DEVELOPMENT OF GENERALIZED 2-D AND 3-D DISTINCT ELEMENT PROGRAMS FOR MODELING JOINTED ROCK

by

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The capabilities of the distinct element code, UDEC, have been improved to provide full generality of the program for modeling jointed rock. Complete features exist for simulating variable rock deformability, nonlinear behavior of distinct joints and intact rock, dynamic cracking, projectile impaction, and fluid flow and fluid pressure generation in joints and voids.

Further, the first stage in the development of a three-dimensional

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20. ABSTRACT (Continued).

distinct element program has been completed. A new data structure has been designed and a test-bed code produced for three-dimensional analysis.

PREFACE

This report presents the results of improvements and extension of the two-dimensional distinct element code, UDEC, and development of the data structure and skeleton code for a new three-dimensional distinct element program.

The work was performed for the U. S. Army Waterways Experiment Station under contract DACA39-82-C-0015. These improvements and extensions of the code supplement the original report "UDEC - A Generalized Distinct Element Program for Modeling Jointed Rock," written by Dr. P. A. Cundall in March 1980 for the U. S. Army European Research Office and Defense Nuclear Agency under contract DAJA 37-79-C-0543.

Mr. J. Drake of the Waterways Experiment Station initiated this project and the final report was prepared after consultation with Mr. Drake and Mr. B. Armstrong, also of the Waterways Experiment Station.

Commander and Director of the Waterways Experiment Station at the time of publication of this report was COL Robert C. Lee, CE. Technical Director was Mr. F. R. Brown.

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PART I: INTRODUCTION

Background

1. The Universal Distinct Element Code (UDEC)* is the latest and most advanced numerical program available for simulating the behavior of discontinuous geologic systems subjected to high and transient loads. UDEC provides in one package all of the capabilities that existed separately in previous distinct element codes. The program is built around a very powerful data structure and is able to handle simultaneously the interaction of a mixture of rock blocks that have different types of deformability.

2. During the initial development of UDEC several facilities were encompassed by the original design but were only implemented in skeleton form. Features such as joint constitutive behavior, dynamic cracking, fluid flow and fluid pressure effects were identified as requiring supplemental work in order to realize the full modeling potential of the code. Also, some utilitarian improvements were suggested: an improved capability for dealing with flying blocks for impact-type problems, automatic zoning for fully-deformable blocks, improved logic for handling special cases of splitting such as splitting through corners, and more general specifications for boundary conditions.

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* P. A. Cundall, "UDEC - A Generalized Distinct Element Program for Modeling Jointed Rock," Final Technical Report, European Research Office, U. S. Army, London, 1980.

3. In addition, it was recognized that the next logical extension of the distinct element method would be the development of a three-dimensional version. The first step in this formidable task would be the design and testing of a data structure and test-bed code which would be appropriate for three-dimensional analysis.

Scope of Present Study

4. The purpose of the present study was to address the considerations arising from the original development of UDEC. The first objective was to complete all the unfinished facilities identified above. This accomplished, the revised version of UDEC now has a general application to the following principal areas in jointed rock modeling:

a. Discontinuous systems can be modeled as assemblages of blocks or particles of differing deformability; either rigid, simply-deformable (with 3 degrees of freedom) or fully-deformable (internally decomposed automatically into finite difference zones).

b. Nonlinear constitutive models including dilatant and non-dilatant behavior can be prescribed for both the intact rock and the discrete joints.

c. Blocks can break, repeatedly, in accordance with a user-supplied cracking criterion.

d. Fluid flow and fluid pressure generation in joints and voids can occur with flow rate specified in terms of joint permeability and apparent aperture.

e. Directional loads can be applied to individual blocks and pressures can be prescribed to regions between blocks.

f. Blocks or groups of blocks can be explictly defined by the user as flying blocks for impact problems.

5. The second objective of this study was to begin the development of a new three-dimensional distinct element program. A data structure was developed which was well-suited for the extension of the method to 3-D. A test-bed code was then produced to evaluate various

aspects of the program such as the logic defining the characteristics of the block, the detection of contacts and the sequence for processing calculations. This effort has culminated in a workable but primitive distinct element program for three-dimensional analysis.

6. This report contains a description of the improvements made to UDEC and a discussion of the development of the three-dimensional program. In addition, a revised user's manual for UDEC and a new user's manual for the test-bed 3-D code are given as appendixes to this report.

PART II: IMPROVEMENT AND EXTENSION OF UDEC

Work Items

7. In the original report several areas were identified which required additional work to realize the full capacity of the two-dimensional distinct element code. Specifically, these work items are:

- a. complete edge-to-edge contact logic and install a simple constitutive model for rock joints;
- b. install fluid flow and fluid pressure generation logic;
- c. improve logic for dealing with flying blocks, i.e., blocks or groups of blocks not in contact with other blocks;
- d. install an automatic mesh generator for fully-deformable blocks;
- e. design logic to treat the case of splitting through a corner and allow re-entrant splits (one line crosses a single block twice);
- f. install dynamic cracking including the redistribution of forces, stresses and displacements on splitting, and create the framework for user specified criteria for crack development; and
- g. install more general boundary conditions.

Modifications have been made to UDEC to complete these facilities. In Appendix A a revised UDEC user's manual is given which contains a description of the improvements made to the code and a complete set of input commands and program guide. Sample problems are also given which demonstrate the improvements made to UDEC.

Data Structure

8. The program guide, given in Appendix A, contains the complete contents of all the groups in the data structure. Figures 1 through 5,

reproduced from the original report, show schematically the linkage of these various groups and should assist the user in following through the program guide. Figure 1 shows the "linked list" arrangement of the main data arrays. Figures 2, 3 and 4 illustrate the conventions for pointers and links in the block data, domain data and contact data arrays, respectively, and Figure 5 shows the structural arrangement of redundant memory groups. The program guide and the figures will assist the user in making any code modifications.

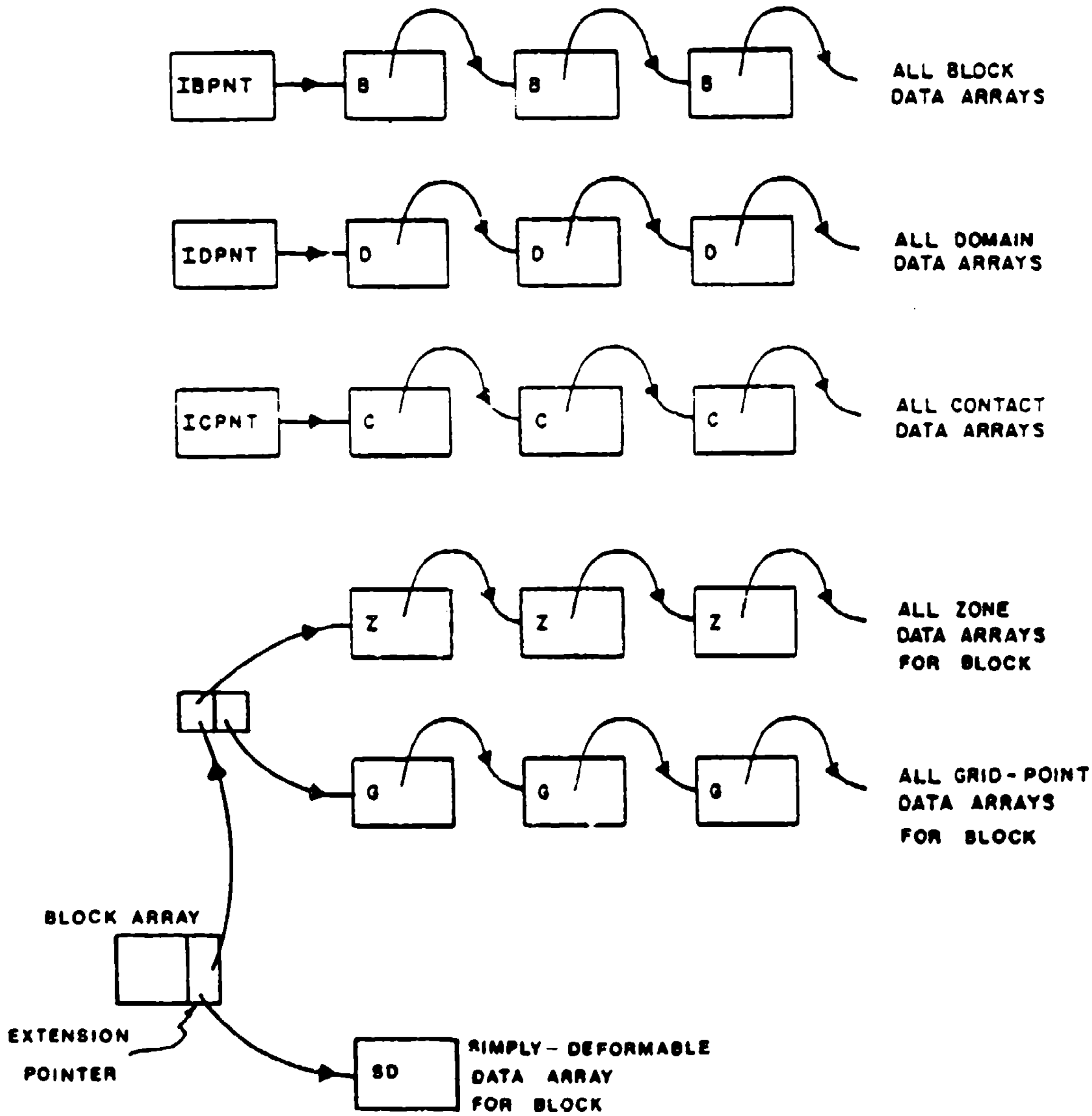


FIGURE 1: LINKED LISTS FOR MAIN DATA ARRAYS

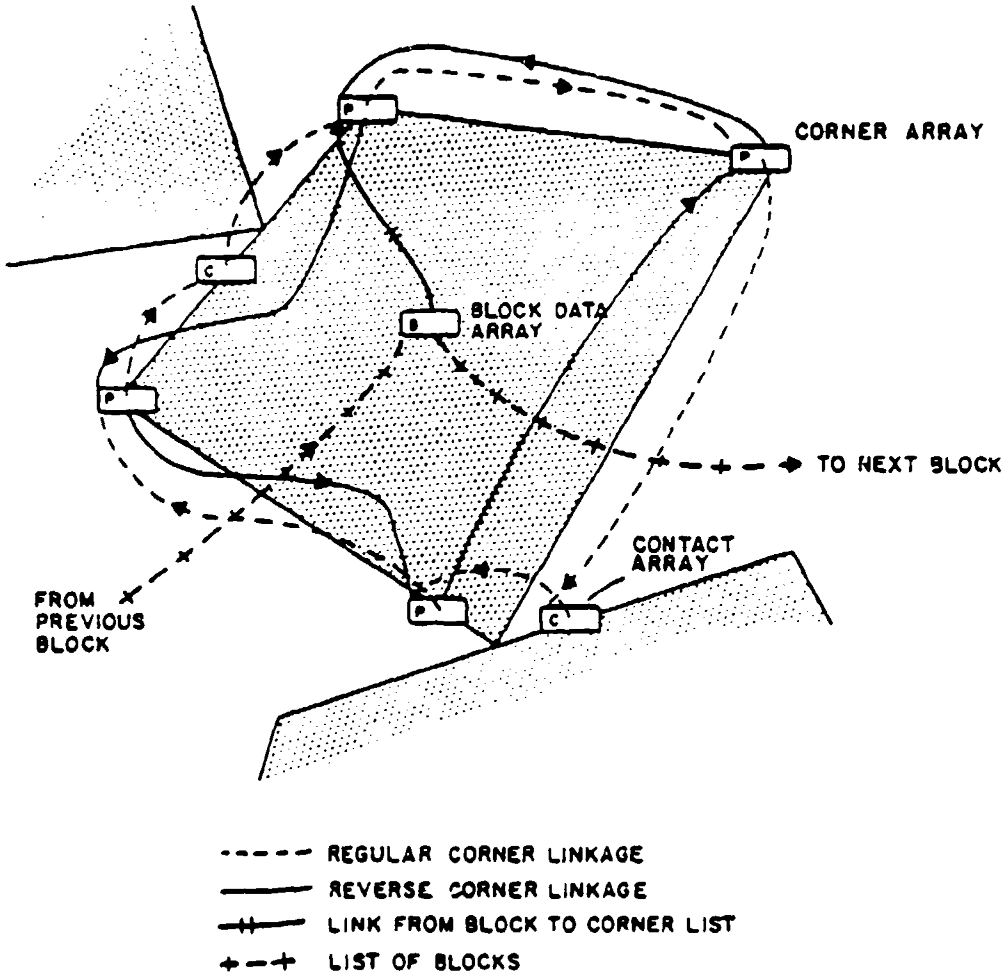


FIGURE 2: BLOCK POINTERS AND REVERSE CORNER LINKS

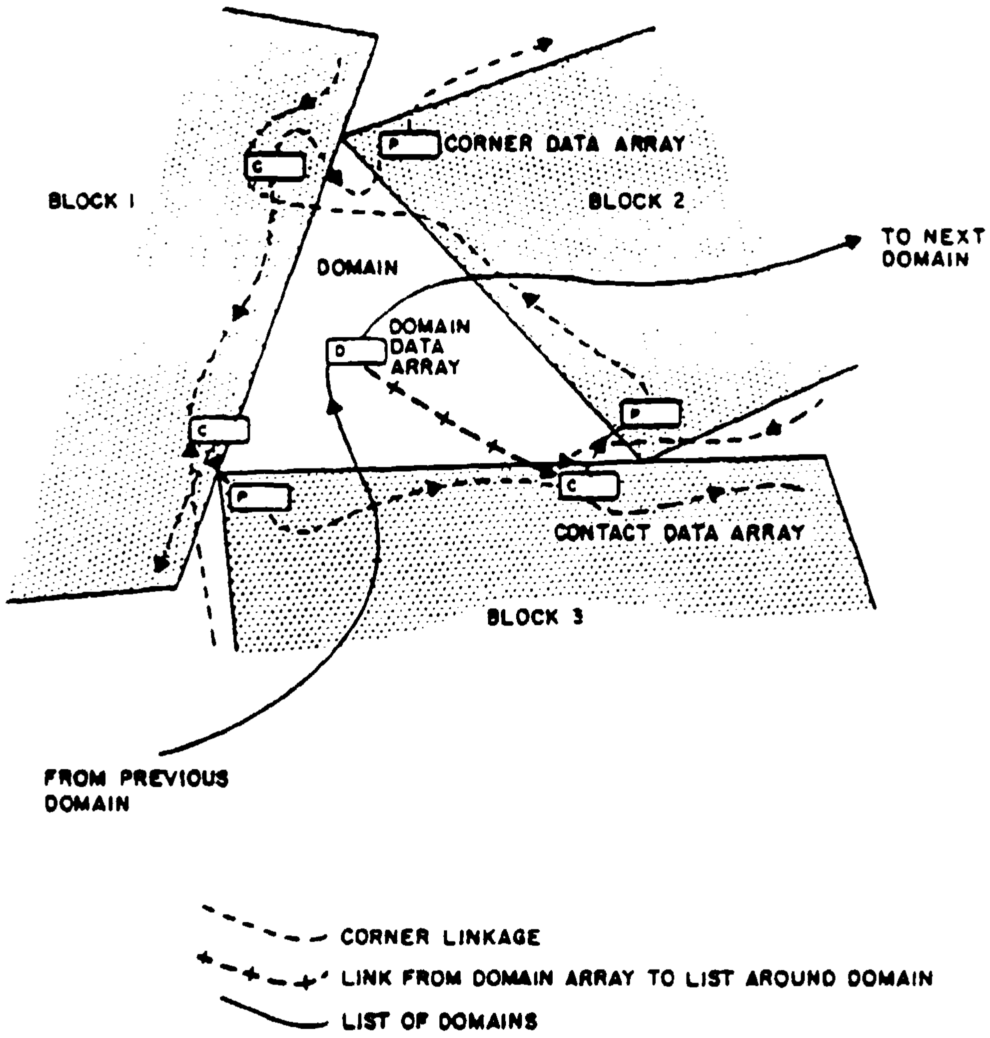
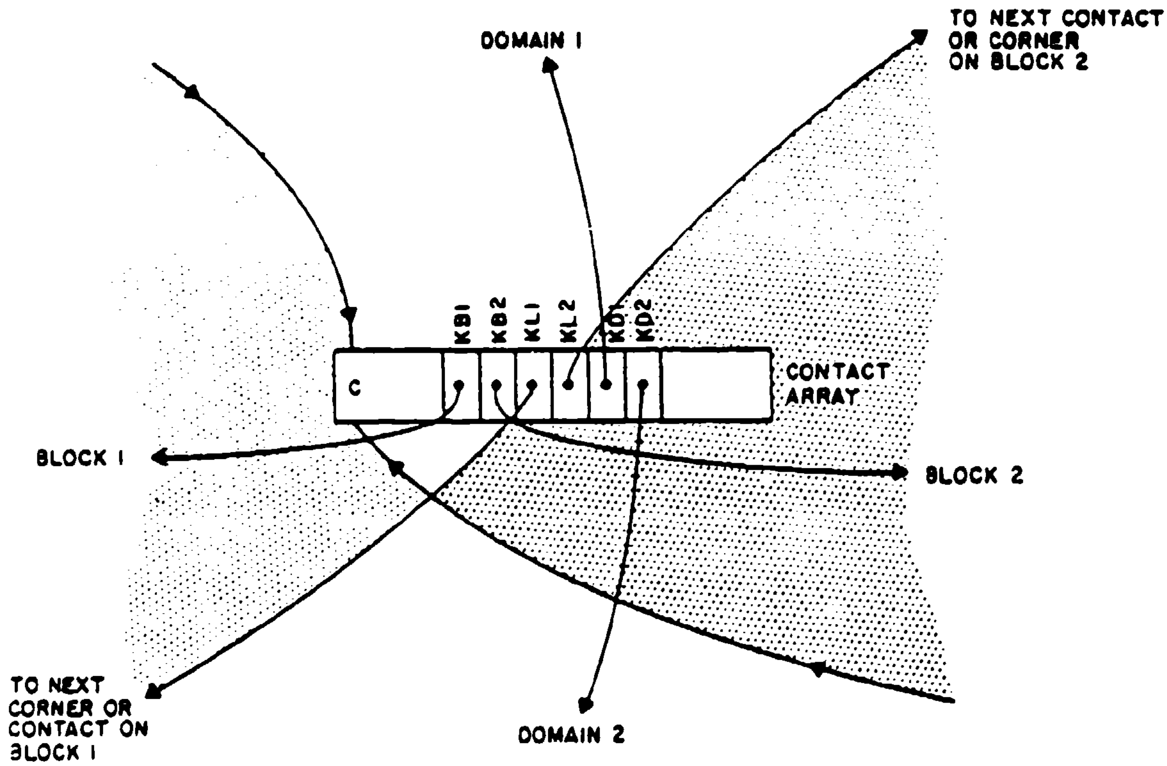


FIGURE 3: DOMAIN LINKAGES



NOTE: KBI, KB2 —— KD2 REFER TO THE OFFSETS LISTED IN APPENDIX III

FIGURE 4: CONVENTION USED FOR POINTERS WITHIN A CONTACT ARRAY

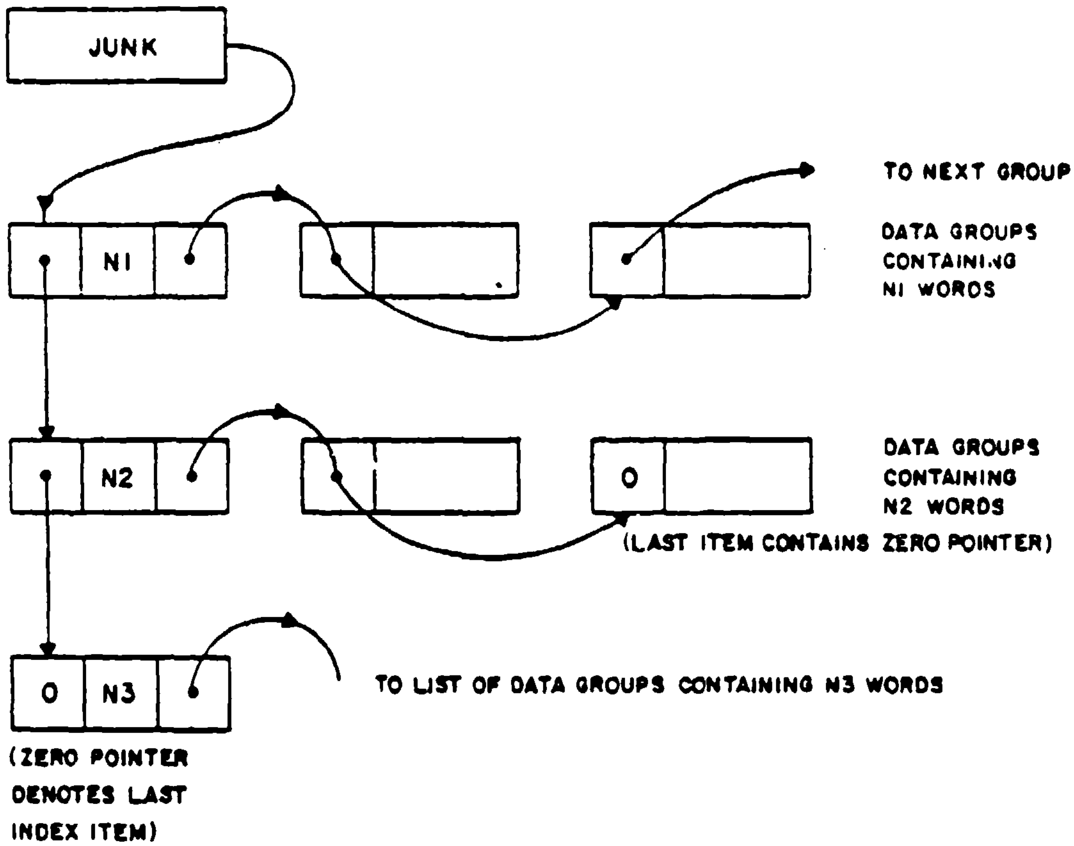


FIGURE 5: STRUCTURE OF 'JUNK LIST' HOLDING REDUNDANT GROUPS OF MEMORY.

PART III: APPROACH TO THREE-DIMENSIONAL MODELING

Introduction

9. This project is concerned mainly with the planning of a three-dimensional code based on the distinct element method. It is particularly important to design the data structure in a way that anticipates how the data will be used during a typical simulation of the behavior of a blocky assembly. Each physical quantity should be at hand when needed, with the minimum overhead of searching, or redundant calculations.

10. Even though the objective of the project was to arrive at a conceptual framework for future development, a working program, called D3, was written. The present deficiencies in D3 are in the areas of contact detection and updating and block creation. However, some aspects of the program are well-developed: for example, the data structure; the physical equations of motion and force-displacement law; and the determination of volumes and centroids for arbitrary blocks.

11. Throughout the program D3, functions or subroutines are used to perform common vector operations. This simplifies the coding considerably, at the expense of some increase in running time. All vector and tensor equations in this report are expressed in component form, where the subscripts i, j and k range from 1 to 3, and the Einstein summation convention applies for repeated subscripts.

Block Characteristics

Geometry

12. A three-dimensional block is defined by dividing its surface into triangular faces. Triangles are used instead of arbitrary polygons for the following two reasons.

a. A surface is determined uniquely by specifying three points in space. If four or more are given, the nature of the surface is undefined and ambiguous.

b. The data structure is simplified if exactly three vertices are associated with each face; three memory locations can be reserved in advance. Similarly, exactly three pointers can be provided to locate the three adjoining faces to a given face.

13. There is no loss of generality by adopting the requirement that the surface of a polyhedron be subdivided into triangles. Any arbitrary shape can be devised by using triangles as building blocks, including blocks with concave regions. At present, in D3, the vertices of each face must be given manually, but automatic surface zoning should be possible, using the zone generation logic of UDEC.

Volume

14. The calculation for block volume is based upon Gauss's divergence theorem, given by:

$$\frac{\partial p}{\partial x_i} = \frac{1}{v} \oint_a p n_i \, da \qquad (1)$$

where p is any scalar, vector or tensor variable

v is the enclosed volume, and

n_i is the outward unit normal to an element of surface, da.

If p is defined as any vertex vector x_i, equation (1) becomes:

$$\frac{\partial x_i}{\partial x_i} = \frac{1}{v} \oint_a x_i \, n_i \, da$$

or, solving for v using discrete areas,

$$v = \frac{1}{3} \sum x_i \, n_i \, a \qquad (2)$$

where Σ is the summation over all surface elements.

If area, a, is planar, $x_i\ n_i$ is constant over the area.
For a triangular area defined by the vectors $z_i^{(a)}$ and $z_i^{(b)}$ (see Figure 6) the area calculation is:

$$a = \frac{1}{2}\,|a_k| = \frac{1}{2}\sqrt{a_k \cdot a_k}$$

where $a_k = e_{ijk}\ z_i^{(a)}\ z_j^{(b)}$ (e_{ijk} is the permutation tensor) (3)

and the unit normal is

$$n_i = \frac{a_i}{2a} \qquad (4)$$

Substituting equations (3) and (4) in equation (2) produces

$$v = \frac{1}{6}\,\Sigma x_k\ e_{ijk}\ z_i^{(a)}\ z_j^{(b)} \qquad (5)$$

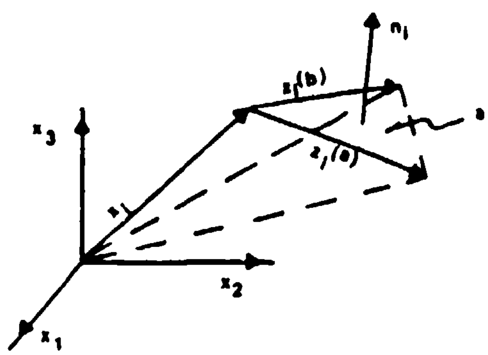


FIGURE 6: VECTORS DESCRIBING TRIANGULAR AREA a

The volume associated with each face, when defined by equation (5), represents the volume of a tetrahedron with a base of area, a, and apex at the coordinate axes origin. The block volume is then found from the sum of the tetrahedrons. To produce a positive tetrahedron volume the vertices defining a triangular face must be ordered counterclockwise when viewed from the axes origin.

Centroid

15. The centroid of the block is calculated by recognizing that the centroid and volume of each tetrahedron are related to the block centroid by:

$$r_i = \frac{r_i^{(N)} v^{(N)}}{v} \qquad (6)$$

where r_i is the centroid vector for the block

$r_i^{(N)}$ is the centroid vector for the Nth tetrahedron

v is the block volume

$v^{(N)}$ is the volume of the Nth tetrahedron

The centroid of each tetrahedron is calculated directly from the three vertex vectors ($x_i^{(1)}$, $x_i^{(2)}$ and $x_i^{(3)}$) that define a block face. The centroid lies along the same vector as the average of these three vectors. By simple integration techniques it can be shown that the magnitude of the centroid is 3/4 of the average vector, so that the tetrahedral centroid calculation becomes:

$$r_i^{(N)} = \frac{x_i^{(1)} + x_i^{(2)} + x_i^{(3)}}{4} \qquad (7)$$

The block centroid is then found by using this equation in equation (6) and summing over all tetrahedrons defining the block.

Radii of gyration

16. This calculation is incomplete in the present version of D3. Only dynamic behavior is affected by the moments of inertia, which are now taken to be equal, approximately, to:

$$\frac{1}{2}\bar{r}^{2}m \tag{8}$$

where $\bar{r}$ is the average distance from the centroid to vertices and m is the block mass.

Physical Calculations

Equation of motion

17. For each block, the following equations are integrated twice by central finite differences:

$$m\ddot{u}_i + \alpha m\dot{u}_i = \Sigma F_i \tag{9}$$

$$I_{(i)}\ddot{\theta}_i + \alpha I_{(i)}\dot{\theta}_i = \Sigma M_i \tag{10}$$

where $\ddot{u}_i$, $\dot{u}_i$ = components of acceleration and velocity

$\ddot{\theta}_i$, $\dot{\theta}_i$ = components of angular acceleration and velocity

ΣF_i = sum of forces acting on block

ΣM_i = sum of moments acting on block

m = mass of block

$I_{(i)}$ = moments of inertia about 1, 2, 3 axes.

α = damping coefficient

Knowing the centroid motion and the current locations of vertices and centroid, the velocities (and hence increments in displacement) of vertices are calculated as follows:

$$\dot{u}_i^{(p)} = \dot{u}_i^{(b)} + e_{ijk}\,\dot{\theta}_j^{(b)}\,(x_k^{(p)} - x_k^{(b)}) \tag{11}$$

where (p) refers to a vertex

(b) refers to the centroid of the block

e_{ijk} is the permutation tensor

The moment acting at the centroid owing to a force $F_i^{(p)}$ acting at a surface point p is given by:

$$M_i = e_{ijk}(x_j^{(p)} - x_j^{(b)})F_k^{(p)} \quad (12)$$

Contact forces

18. At each contact, the relative velocity of the two opposing points is calculated using equation (11) for both points and subtracting:

$$\dot{u}_i^{(c)} = \dot{u}_i^{(B)} - \dot{u}_i^{(A)} \quad (13)$$

where (A) and (B) denote the opposing points on blocks A and B. The relative contact velocity $\dot{u}_i^{(c)}$ is resolved into normal and shear partitions:

$$\dot{u}^{(n)} = \dot{u}_i^{(c)} n_i \quad (14)$$

$$\dot{u}_i^{(s)} = \dot{u}_i^{(c)} - \dot{u}^{(n)} n_i \quad (15)$$

where n_i is the contact normal.

Normal and shear force increments are then calculated as follows:

$$\Delta F^{(n)} = -\dot{u}^{(n)} k^{(n)} \Delta t \quad (16)$$

$$\Delta F_i^{(s)} = -\dot{u}_i^{(s)} k^{(s)} \Delta t - e_{ijk} e_{k\alpha\beta} F_j n_\alpha n'_\beta \quad (17)$$

where $k^{(n)}$ = normal contact stiffness
$k^{(s)}$ = shear contact stiffness
n_α = previous contact normal
n'_β = current contact normal

The second term on the right hand side of (17) corrects the current shear force for rotation of the contact normal during the previous time step. The expression is approximate only, and assumes that $\cos(\Delta\theta) \approx 1$. The contact normal may rotate because:

a. the two blocks concerned have rotated about a common axis; or

b. the contact location on one or both blocks has changed; hence the contact normal may have changed.

Contact forces may now be updated:

$$F^{(n)} := F^{(n)} + \Delta F^{(n)} \tag{18}$$

$$F_i^{(s)} := F_i^{(s)} + \Delta F_i^{(s)} \tag{19}$$

If $|F_i^{(s)}| > c + \mu F^{(n)}$ then

$$F_i^{(s)} := F_i^{(s)} \frac{(c + \mu F^{(n)})}{|F_i^{(s)}|} \tag{20}$$

where c = cohesion

μ = friction coefficient

:= means "replaced by"

Note that $F^{(n)}$ is stored in program D3 as a scalar, because the contact normal is stored independently. However, $F_i^{(s)}$ is stored as a vector with components referred to the global axes.

19. After calculation, the contact forces are applied immediately to the two blocks comprising the contact (in a positive sense to block B, and in a negative sense to block A). Equation (12) is used to compute the moment to be added, where $x_i^{(p)}$ is the contact coordinate.

Contact Characteristics and Detection

Prescription for contact normals

20. The blocks in UDEC have rounded corners in order to eliminate the singularities, force-jumps and "hang-ups" associated with sharp corners. In three dimensions the same idea is almost unworkable, since a single spherical cap cannot be fitted to a vertex because it will not be tangent to all adjoining faces. Some kind of variable-radius curve would have to be fitted to the vertex. It would have to be tangent not only to adjoining faces, but also somehow merge smoothly with adjoining edges, which would also be rounded. Although such a scheme may be feasible in principle, its use would add a large computing overhead, particularly in the case of simply-deformable blocks, where the angles at vertices are continuously changing.

21. A scheme has been devised that overcomes the problems with sharp corners, and even resolves the ambiguities present in UDEC for very large block overlays. A "prescription" or rule is proposed that furnishes a unique direction of contact normal to be associated with each point within a block. Because two blocks must overlap in order to establish contact, the contact point must lie within both blocks. The prescription is consulted to find the average contact normal for the blocks' internal point. Certain conditions must be fulfilled by the prescription:

- a. At the surface of a block, the prescribed normals must coincide with the real normals (with jumps at vertices and edges).
- b. There must be a smooth transition in normal direction from point-to-point within the block.
- c. The rate of change of normal direction with respect to coordinate should reduce as the depth of penetration increases.

In essence, the prescription provides a field of normal vectors for every internal point as illustrated in the figure below.

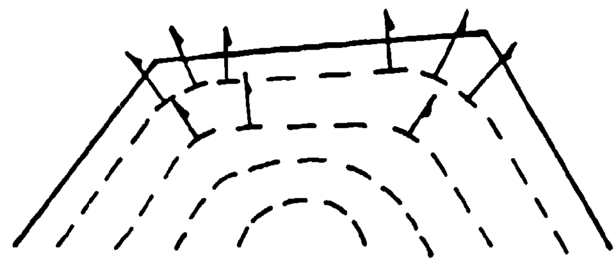


FIGURE 7: NORMAL VECTOR CONTOURS FOR 3-D CONTACT DETECTION

22. Much of the effect of UDEC's corner rounding is provided by the new scheme because there will be a smooth transition as a contact point moves around a corner. Furthermore, there is no need to know exactly which face is providing support close to a vertex; the known normal determines the direction of sliding and the direction in which the normal force increment is applied.

23. The following prescription for angles of contact normals is only tentative. More experience with its use in D3 is necessary before it can be accepted as being a reasonable analog of physical behavior.

- a. Select the vertex nearest the contact point.
- b. Determine the normal distance, $d^{(N)}$, of the contact point from each adjoining face, N.
- c. Compute the average normal face direction, weighted according to $1/d^{(N)}$. If the contact point lies exactly on one face N ($d^{(N)} = 0$), then the normal direction is that of face N.
- d. The required normal is the unit vector in the computed direction.

The prescription fulfills the conditions previously set out, except that there will be a slight change in normal angle for deep penetration when the "nearest vertex" changes.

Types of contact

24. Although six types of contact can be identified physically, only two are necessary for complete support between two blocks.

Types of Physical Contact

face - face
face - edge
face - vertex } necessary for support
edge - edge }
edge - vertex
vertex - vertex

Each of the six physical categories can be constructed from one or more combinations of face-vertex and edge-edge. These two latter categories may be termed "logical contacts," which are recognized by the detection process and in the formation of the data structure. The physical behavior corresponding to the other categories can be duplicated by knowing the appropriate areas and lengths of contacts, in the same way that UDEC models the physical behavior of an edge-to-edge contact even though the logical contacts are of the corner-to-edge form. D3 does not contain this logic in its present state of development.

Contact detection

25. In any code that models interaction between arbitrary blocks or particles it is necessary to avoid exhaustive searches for those particles that are touching because the computer time for such searches increases as N^2, where N is the number of particles. Programs RBM and SDEM used a "box" classification scheme. Cundall (1980) discusses this scheme, and its limitations. UDEC uses a linked-list scheme whereby a block's contact candidates are found by local search of its surrounding domains. However, the two-dimensional data structure of UDEC has no convenient three-dimensional analog, as discussed in the next section.

26. D3 uses a scheme for which the search time is proportional to N, but which is less efficient than UDEC. D3 maintains links between blocks that are near each other. A given block can then interrogate this group of nearby blocks in order to detect potential contacts. The list of nearby blocks is updated in the following way. During an "update",

a block interrogates not only its local list of neighbors, but also the lists of its neighbors. Blocks that are further than a certain radius are not added to the list (or are deleted if they are on it already), and blocks within the radius are added. An "update" is only performed on a block after it has moved by some threshold distance since its previous update. In this way, updating of almost-stationary regions is avoided.

Data Structure

27. This section describes the form and use of the data structure in terms of the pointers and connecting links. The complete content of each data array is set out in Appendix B. Program D3 is modeled closely on UDEC as far as structure and operating logic are concerned.

General considerations

28. The program UDEC, which models two-dimensional block systems, maintains a data structure with the same topological form as the physical assembly. The notion of representing blocks by circulating lists that simultaneously encompass the void spaces seems infeasible in three dimensions. It is possible to have a stable assembly of three-dimensional blocks without having an associated collection of isolated void spaces, or "domains"; in some three-dimensional assemblies it is possible to journey from one portion of the void space to any other without needing to pass between two blocks in contact. In two dimensions, the voids can share the same linked lists that serve to describe blocks. (A void is traced by following a counterclockwise route, while blocks are delimited by the same list, but traced in a clockwise direction.) This convenient symmetry is not found in three dimensions.

29. Program D3 embodies, for three-dimensional systems, a data structure that ensures rapid access to data as it is needed during the calculation cycle, but the physical correspondence of UDEC's data structure is missing. This carries a penalty of more time-consuming searches for contacts and increased difficulty in representing fluid behavior in the

void spaces. Figure 8 shows the global lists that link blocks and contacts.

Block structure

30. For individual blocks, the data structure describes the block geometry and also permits the program to jump from one face to its neighbors directly, and from a face to its bounding vertices directly. Figures 9 and 10 illustrate this scheme. Triangular faces, apart from their physical advantages, noted earlier, lead to simplified data structures because exactly three pointers suffice to link faces to neighbors and faces to vertices. The connectivity of faces and vertices is specified completely by the pointers provided in the data array for faces, illustrated in Figure 10. A knowledge of face and vertex connectivity is necessary for an efficient scheme to detect and update contacts around a block. The data array for vertices contains only coordinate data, but each block has access to a list of its own vertices so that coordinates can be updated as the block moves. All coordinates are absolute, as components are referred to the global axes.

Contacts and links between blocks

31. Global connectivity of the block system is represented by a series of links between nearby blocks. When a block system is created initially, these links are established by exhaustive search. However, during operation, the program can determine potential contacts by interrogating just those blocks in its immediate neighborhood. In this way, the computer time needed for searching increases linearly with the number of blocks, N, and not as N^2. The scheme, however, is not nearly as efficient as that of UDEC because many more potential contacts need to be examined in D3 for each block.

32. Contacts come in three forms: one is a "degenerate" form, and the other two correspond to "real" contacts. A degenerate contact is a simple link between nearby blocks. The memory taken by such a contact is much less than that of a real contact, but the pointers have the same locations as those in real contacts. This permits both degenerate and real contacts to be included in the same scan. A code number identi-

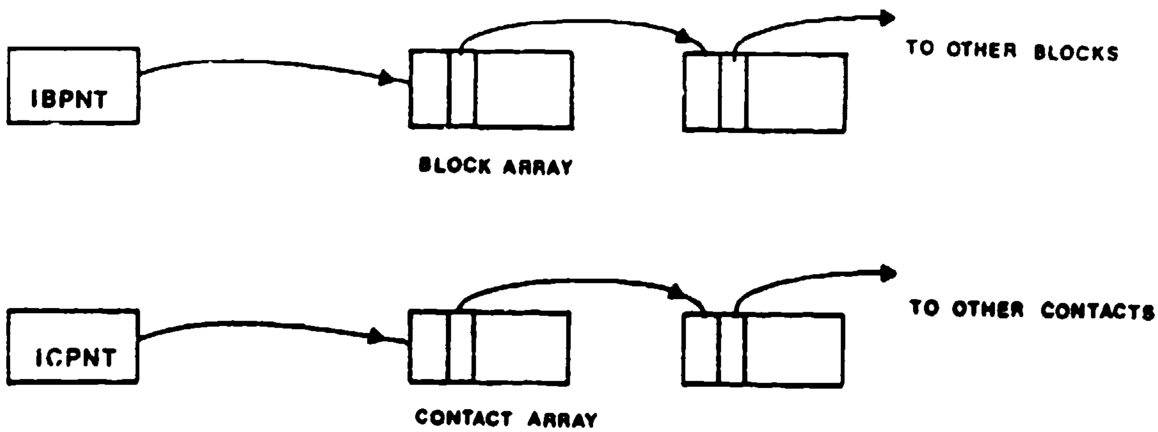


FIGURE 8 : GLOBAL BLOCK AND CONTACT LISTS

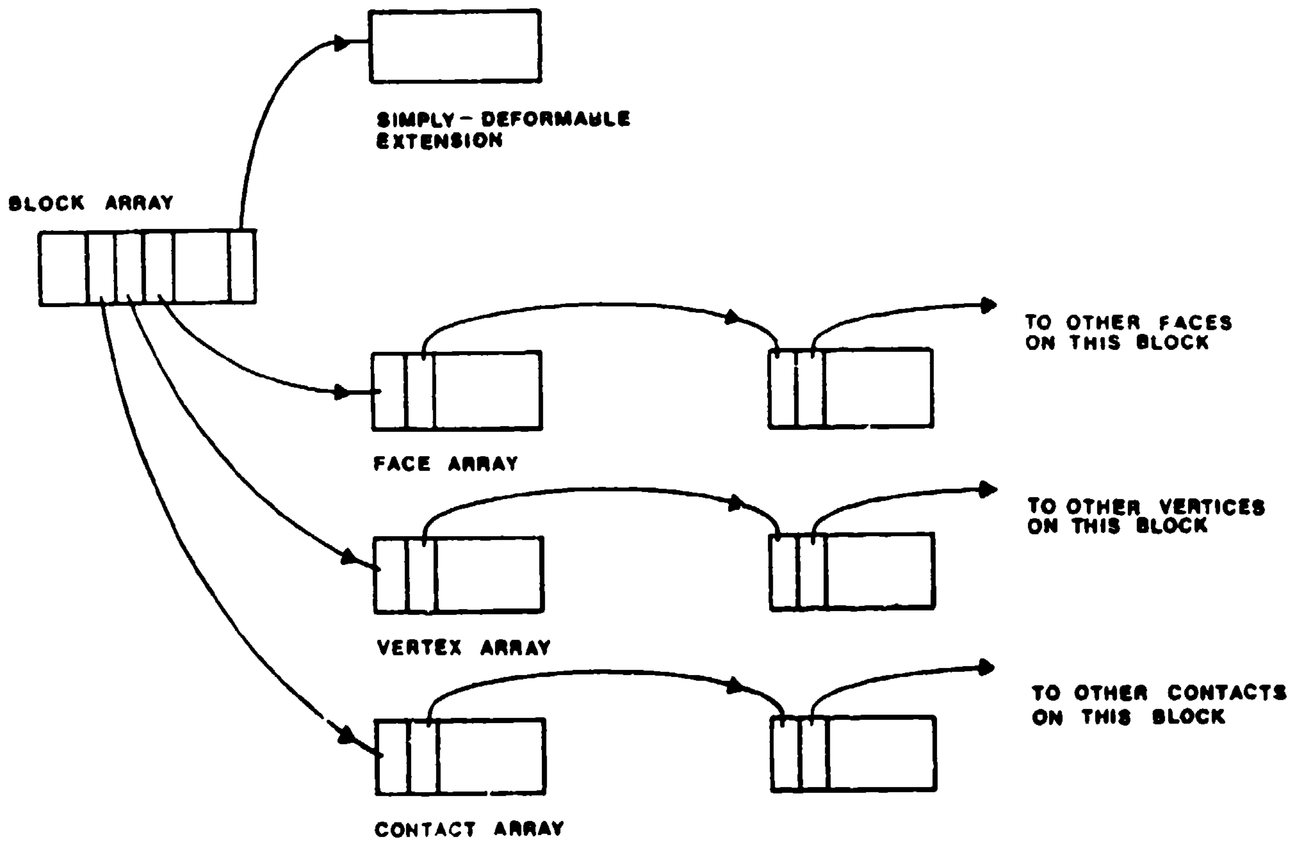


FIGURE 9 : LISTS ASSOCIATED WITH EACH BLOCK

F : NEIGHBORING FACE

V : VERTEX

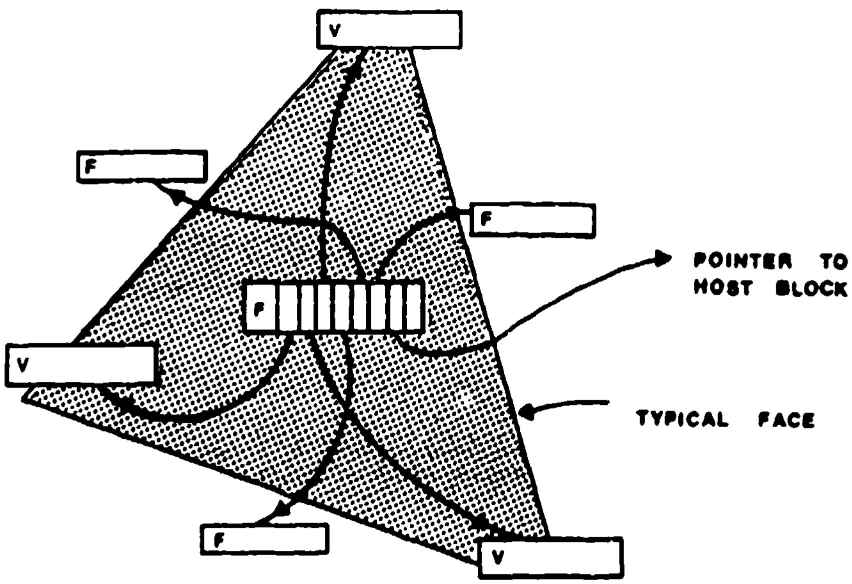


FIGURE 10 : POINTERS ASSOCIATED WITH EACH FACE

fies each type. Pointers and lists associated with each contact type are illustrated in Figure 11. The two forms of real contact are: vertex-to-face and edge-to-edge. These two categories are sufficient to capture all types of physical contact, as explained previously.

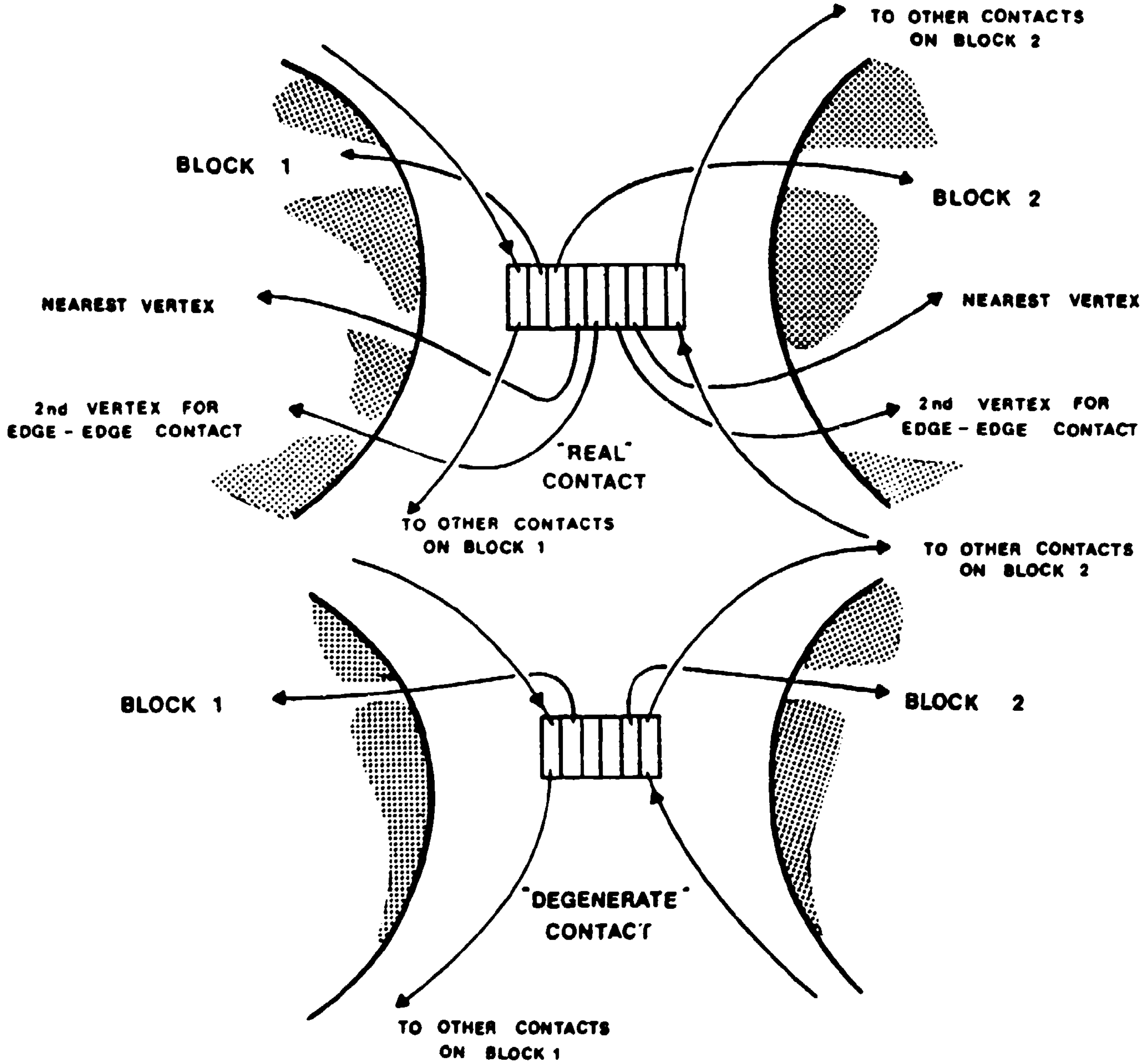


FIGURE 11 : POINTERS AND LISTS ASSOCIATED WITH EACH CONTACT

PART IV: CONCLUSIONS

Program UDEC

33. The two-dimensional program UDEC has been considerably enhanced: it can now be used to model a wide spectrum of problems ranging from continua to discontinua; from static to dynamic; and with or without pore fluid interaction. The utility of the canonical* data structure has been confirmed by the comparative ease with which the new features were installed.

Program D3

34. Considerable thought has been given to devising a good data structure and physical idealisation for representing three-dimensional block assemblies. The result is reported herein; much of the scheme has also been embodied in the test-bed program D3. In fact D3 contains a good deal more than that required by the contract: it includes the full equations of motion for blocks and surfaces, equations for interaction of contacts, primitive logic for contact detection and updating, and fixed/free boundary conditions.

35. It is possible to run very simple simulations with D3 as it stands, but the program is still only a skeleton code. The following developments are suggested, in order of priority.

a. Test thoroughly the prescription for contact normals, and, if necessary, propose modifications.

b. Generalize logic for contact detection and updating, and verify that it will work under extreme conditions.

c. Recognize, and treat correctly, all six categories of contact; install corresponding constitutive models.

d. Add simply-deformable logic.

---

*A "canonical" data structure is "a model of data which represents the inherent structure of that data." Martin, J. (1977), Computer Data-Base Organization, Prentice-Hall, Inc.

e. Install comprehensive boundary conditions:

   1. stress tensor

   2. arbitrary velocity prescription

f. Allow blocks to split, dynamically and statically; include point-to-point splitting law and Griffith's law for simply-deformable blocks.

g. Perform validation and simulation tests.

APPENDIX A: UNIVERSAL DISTINCT ELEMENT CODE (VERSION 1.2)
USER'S MANUAL

Introduction

1. This manual describes the latest improvements to the Universal Distinct Element Code (UDEC) and supplements the original report "UDEC - A Generalized Distinct Element Program for Modeling Jointed Rock" written by Dr. P. A. Cundall, March 1980, for the U. S. Army (European Research Office, and Defense Nuclear Agency under Contract DAJA 37-79-C-0548.

2. The improvements to UDEC were made in the following general areas:

a. joint logic

b. fluid flow

c. flying blocks

d. automatic mesh generator

e. general splitting logic

f. dynamic cracking of blocks

g. generalized boundary conditions

Descriptions of these improvements and their applications in UDEC are given in the next section.

3. The modifications to UDEC have led to the development of several types of constitutive models for the intact blocks and block contacts. Intact block behavior may be defined by separate deformation and fracture laws, while either point- or joint-contact constitutive models may be chosen. The different constitutive behaviors are discussed below and summarized in Table A1.

4. This manual also contains the revised user's input commands for UDEC and an updated program guide. Input and output files are presented for sample problems which illustrate the use of the improvements to UDEC.

Improvements to UDEC

Joint logic

5. UDEC recognizes edge-to-edge contacts between blocks as joints, and refers to a constitutive model that works in terms of stresses rather than forces. The joint logic is used for those blocks or joints that are given constitutive number 2 or 5 by the user (see Table A1). In addition, some or all of the following properties for joints should be defined:

sn_j .... normal stiffness (stress/displacement)
ss_j .... shear stiffness (stress/displacement)
c_j .... cohesion (stress/displacement)
f_j .... friction coefficient

Although the joint logic may be set for the whole block assembly, UDEC will still refer to contact parameters under some circumstances; therefore, these parameters should also be defined. A joint reverts back to being a contact if it no longer consists of planar block faces in opposition. The point-contact logic is also used if incremental normal deformation using the joint parameters would be greater than that using the contact parameters: i.e., if

$$sn_j l_j < sn$$

where l_j is the length of the joint and sn is the contact normal stiffness.

Fluid flow

6. Flow may occur between domains if a differential pressure exists between the domains. Two types of flow law are used, depending on whether a contact or a joint separates the domains. For a contact the flow-rate is

$$q = p_{diff} k_c$$

where p_{diff} is the pressure difference, and

k_c is a permeability constant, defined for contacts, for a particular material number.

For a joint the flow rule is:

$$q = p_{diff} k_j a_j^3 / l_j$$

where k_j is a permeability constant for joints,

l_j is the joint length,

a_j is the apparent aperture, defined as

$$a_j = \max(ares, a_o - strn'/sn_j)$$

where ares is the residual displacement (fully closed),

a_o is the aperture for an open joint,

strn' is the effective normal stress, and

sn_j is the joint normal stiffness.

The constants k_j, ares and a_o are defined by the user for a particular material number.

7. In one time-step, t_{del}, the adjustment to pressure, p_{del}, in a domain is as follows:

$$p_{del} = Q(bulkw)(t_{del})/A_d$$

where Q is the sum of flows into the domain,

bulkw is the bulk modulus of the fluid,

A_d is the area of the domain.

For a domain corresponding to a joint,

$$A_d = a_j l_j$$

(a_j and l_j defined previously). The quantities a_j and l_j are only defined for a joint. If constitutive numbers 2 or 5 are not set, the domain corresponding to an edge-to-edge contact will be assumed to have an area of A_d(min), which may be set by the user; otherwise it will default a small fraction of average block areas. For regular domains, A_d(min) is the limiting area for fluid calculations.

8. A printout of fluid flow in all joints and contacts may be requested by giving the PRINT FLOW command. Aperture and length are also printed for joints.

9. The influence of a fluid pressure gradient is included in UDEC for fully-saturated blocks subjected to gravity loading. This has been accomplished by adding a buoyancy force term to the law of motion for a block. The buoyancy force is defined by a fluid density parameter, rhow, in the FLUID input command.

Flying blocks

10. UDEC keeps track of "flying" blocks (i.e., blocks not in contact with other blocks) by retaining one link to the main data structure. This ensures that new contacts will be detected in the domain containing the flying block. The single link is of the same form as a regular contact, but it contributes no forces and is deleted immediately after the block comes into contact with other blocks. Groups of flying blocks are handled in an identical manner. The same logic ensures that the group is linked to the global data structure by one virtual contact. Blocks which are initially not in contact with other blocks must be linked to the main data structure using the LINK input command.

Automatic mesh generator

11. The automatic mesh generator is based upon that described in the report "Computer Modeling of Jointed Rock Masses" written by Dr. Cundall, et. al., (see Technical Report N-78-4 for the U. S. Army Engineers Waterways Experiment Station, August, 1978).

12. Automatic mesh generation for a fully-deformable block is accomplished in three stages. First, all corners of the boundary are linked so that the block is discretized as a triangular finite-difference mesh. Then, the triangles are split until all triangular sides are smaller than a maximum edge length specified by the user. Finally, all internal grid-points are adjusted until their coordinates coincide with the average of the coordinates of the surrounding grid-points. The generator appears to be sufficient for discretizing most

blocks provided the aspect ratio (longest to shortest dimensions) of the block is kept smaller than 2:1.

General splitting logic

13. The logic for splitting blocks has been overhauled so that a split may occur at any orientation. Splits through corners are allowed. If a given split-line passes too close to a corner, the line is diverted so that the corner is split. The criterion of "closeness" is based on the given rounding length; the line is diverted if a newly-created corner would interfere with the existing corner (i.e., their rounding arcs would overlap). After diverting a proposed split-line through corners (if necessary) a check is made to see if the line would coincide with an existing edge; if it would, the split is rejected for that block.

14. Block splitting is accomplished via subroutine XYSPL(MAT,ICONS). This routine only requires two coordinates ((x3,y3) and (x4,y4)) which define the split line through the block and MAT and ICONS which assign joint properties and constitutive behavior to the newly created joint.

Dynamic cracking of blocks

15. UDEC has been modified to allow dynamic cracking of rigid and simply-deformable blocks. The decision to check for cracking is made by introducing a tensile strength factor, tf, to the material property list. If a block has a specified tensile strength factor, it is searched once every cycle for conditions which would satisfy a user-supplied cracking criterion. If this criterion is met, the block is split into two. The joint created by splitting a block will take the material and constitutive numbers of the block.

16. Two cracking criteria are presently available in the code. A criterion based upon a relationship developed from "point-load" testing has been assigned to constitutive numbers 1 and 2. The tensile strength factor in this case is defined by:

$$tf = \frac{(f1 + f2)}{2d^2}$$

where f1 and f2 are two opposing contact forces applied to the block, and d is the distance between these forces. Splitting of the block occurs if the maximum value of the contact force-distance relationship equals or exceeds tf. Dynamic cracking is not permitted through corners or too close to corners (d < 1/2 smallest block edge) for this cracking criterion.

17. A criterion based on Griffith theory is assigned to constitutive numbers 4 and 5. This criterion evaluates conditions for cracking in terms of the internal stresses in SDEF blocks (tensile stresses are assumed positive). The relationships for block splitting are defined by:

$$tf = sp1 \qquad \text{if } 3sp1 + sp2 > 0$$

and

$$tf = \frac{-(sp1 - sp2)^2}{8(sp1 + sp2)} \qquad \text{if } 3sp1 + sp2 < 0$$

where sp1 is the maximum principal stress in the SDEF block,

sp2 is the minimum principal stress in the SDEF block,

tf corresponds to the uniaxial tensile strength of the intact material.

When stress conditions exceed the tensile strength, the block is split through its centroid in a direction parallel to sp2 and the block stresses are set to zero.

18. It should be noted that these two cracking models do not account for energy lost in the system when the fracture occurs. A more thorough approach should take into account the change of strain energy into kinetic energy at failure.

Generalized boundary conditions

19. Two types of boundary conditions can be used in UDEC. X and Y directional loads can be added to block centroids using the LOAD command. Domain pressure can be user-controlled using the PFIX and PFREE commands.

Summary of constitutive models

20. Each constitutive number gives the user a different combination of constitutive behavior for the intact block and the contact between blocks. Four combinations are presently defined (see table below). Other combinations are left to the discretion of the user.

Table A1

Constitutive Behavior Models

Constitutive Number	Intact Block: Deformation Law	Intact Block: Cracking Law	Contacts: Deformation Law
1	elastic-isotropic	point-load	point contact
2	elastic-isotropic	point-load	joint contact
3	elastic-isotropic	Griffith	point contact
4	elastic-isotropic	Griffith	joint contact

Input Commands

Notes: Upper-case letters in a command or parameter must be typed; the remaining letters are optional. Lower-case parameters stand for numeric values. Integers must be given for parameters starting with i, j, k, l, m, n. Real numbers may be given as integers, but not vice versa.

Input is free-format: parameters may be separated by any number of the following characters, in addition to spaces:

= ( ) , /

An END command is required at the end of the input file (after the STOP command). The first command must be START or RESTART.

* = comment line

\+ = continuation line

Block Material n Constitutive m x1 y1 x2 y2 ...

Create a rigid block of material number n and constitutive number m. Defaults are n=1, m=1, if m, n are omitted. Corner coordinates are: (x1,y1), (x2,y2) etc., in a clockwise direction. Continuation lines may be used, but a pair of numbers defining a corner must not be separated. Only one BLOCK command may be used per run at present. Further blocks may be created with a SPLIT command, and unwanted ones deleted with the DELETE command. Any blocks may be changed to simply- or fully-deformable with a CHANGE command.

CHange x1 x2 y1 y2 Sdef Material n Constitutive m
Fdef

All blocks with centroids lying within the range $x1<x<x2$, $y1<y<y2$ are changed to simply- or fully-deformable (Sdef or Fdef respectively). Material and constitutive numbers may also be changed.

Cycle n

Do n time-steps (cycle 0 is permitted as a check on data).

DAmping fcrit freq Mass
Stiffness
Internal

Viscous damping is applied in the form of Rayleigh damping. fcrit is the fraction of critical damping and freq is the center frequency. If a qualifier is not given as the third parameter, full damping is used. The word "Mass" eliminates the stiffness-proportional dashpots. The word "Internal" causes the specific damping to be applied to the 3 internal degrees of freedom of simply-deformable blocks.

DElete x1 x2 y1 y2

All blocks are deleted in the range x1<x<x2 , y1<y<y2

Dump n m

Dump memory to printer from the main array from address n to address m. Internal pointers MFREE, JUNK IBPNT, ICPNT and IDPNT are also printed. MFREE gives the highest memory location that is currently free.

End

Last input command.

Fix x1 x2 y1 y2

All blocks are fixed in the range x1<x<x2 , y1<y<y2.

FRAction f

f is taken as the fraction of critical time-step to be used.

FLuid rhow bulkw

Fluid properties are specified for an effective stress analysis. These are the density, rhow, and the bulk modulus, bulkw.

FRee x1 x2 y1 y2

All blocks are set free in the range x1<x<x2 , y1<y<y2.

Note: By default all blocks are free initially.

Generate x1 x2 y1 y2 Manual Gridpoints (glist) Zones (zlist)
Automatic (amax1)

All blocks encountered in the range x1<x<x2 , y1<y<y2 are discretized as fully-deformable. For automatic generation the parameter (amax1) must be given to define the maximum edge length of the triangular zones. For manual generation a list of grid-points, (glist), and zones, (zlist) must be given. The format for (glist) is:

x1 y1 x2 y2 x3 y3 .....,

where each x,y pair is a coordinate of a grid-point. The format for (zlist) is:

l1 m1 n1   l2 m2 n2 .....

Each triple corresponds to the three grid-points that define the zone, where the numbering of the grid-points refers to the order in (glist), starting with the last point (i.e., the last grid-point is number 1). The grid-points should be given in clockwise order around the zone. Both (glist) and (zlist) may extend over an arbitrary number of continuation lines, but doubles and triples should not be split over two lines. If a given coordinate lies within a certain tolerance of a block corner, the grid-point is placed on that corner. The tolerance is taken as 0.9 times the rounding length. Grid-point coordinates can be defined to coincide with block corners but should not be defined to lie along block edges, for manual generation.

Gravity   gx gy

Gravitational accelerations are set for the x- and y- directions.

Link   x1 y1 x2 y2

Links a flying block to the main data structure. (x1,y1) are the coordinates of any point inside the flying block and (x2,y2) are the coordinates of any point inside the block which will provide the link to the flying block. This block should be the one which is topologically closest to the flying block. (x1,y1) and (x2,y2) should be chosen close to the blocks' centroid locations to ensure correct linkage.

Load   x1 x2 y1 y2 xload yload

All blocks with centroids lying within the range x1<x<x2 , y1<y<y2

are prescribed static loads applied at the block centroid.

PFix ia p

The pressure is controlled in the domain with address ia. The real constant value for pressure, p, is inserted in the pore pressure offset of the domain list.

PFRee ia

The pressure is not controlled in the domain with address ia.

PLot Nofix Zones NC Vel

If no parameter follows the PLot command, all blocks and centroids are plotted. If "Nofix" is used, no fixed blocks are plotted. The keyword "Zones" is used to plot the zones in fully-deformable blocks. The word "NC" deletes corner rounding on all blocks and "Vel" plots block velocity vectors at block centroids.

Print Blocks Contacts CORners Domains List DList Flows

Data are printed on blocks, contacts, corners, domains and linked lists for blocks and domains. Fluid flows in joints and contacts are printed with the FLOWS keyword.

PROperty Material n keyword value

n

The first parameter must be the specification of the material number. Material properties are defined for material number n. Property keywords are:

Bulk(or K)	bulk modulus
G	shear modulus
Density	density
KN	contact normal stiffness
KS	contact shear stiffness
Cohesion	contact cohesion
Friction	contact friction coefficient
JKN	joint normal stiffness
JKS	joint shear stiffness
JCoh	joint cohesion
JFric	joint friction coefficient
Tf	tensile strength factor
JPerm	joint permeability constant

CPerm contact permeability constant

AZero aperture for zero normal stress

ARes residual aperture at high stress

(Units of joint normal and shear stiffness and joint cohesion are stress/displacement.)

Restart

The program is restarted using data from the restart file.

RSet v ia ioff

The real value v is inserted in the main array at address ia, with offset ioff.

ROund d

Each block corner is rounded with a circle that is tangential to the two corresponding edges at a distance d from the corner.

SAve

The current problem state is saved on the restart file.

SPlit x1 y1 x2 y2 Material n Constitutive m

All blocks in the path of a line extending from point (x1,y1) to (x2,y2) are split into two. The joint created by the split is assigned a joint material number n and a joint constitutive number m. If MAT or CONS are omitted, the joint or contact will take the material and constitutive numbers of one of the adjoining blocks (however no number will be printed when the PRINT CONTACTS command is given.)

STArt

The program does a cold start.

Stop

The run stops.

View ix1 ix2 iy1 iy2

The integer ranges ix1 to ix2 and iy1 to iy2 define the viewport region on the plotting device within which the plot will be made. Defaults are ix1=0, ix2=2000, iy1=0, iy2=1400.

Window x1 x 2 y1 y2

The coordinate ranges x1 to x2 and y1 to y2 define in real problem units the region of the model to be plotted. Defaults are x1=0, x2=10, y1=0, y2=7.

Parameters and Data Group

Offsets for block data array

Note: The first integer in each block array (offset 0) is the block type number, as follows:

1 rigid block
2 simply-deformable block
3 fully-deformable block

KB	Pointer to next block in block list.
KP	Pointer to one corner in block's corner list.
KMAT	Material number.
KCONS	Constitutive number.
KBCOD	Code number: 0 free block 1 fixed block
KX	x coordinate of centroid.
KY	y coordinate of centroid.
KXD	x velocity.
KYD	y velocity.
KTD	Angular velocity (counterclockwise positive).
KAREA	Block area.
KBM	Block mass.
KBI	Moment of inertia.
KBFX	x centroid force-sum.
KBFY	y centroid force-sum.
KBFT	Centroid moment sum.
KXL	x load applied to block centroid.
KYL	y load applied to block centroid.
KBEX	Extension pointer (to SDEF or FDEF data)

Offsets for corner data array

Note: The first integer (offset 0) contains the value MCOR to denote a corner.

KL	Pointer to next corner or contact on block, in clockwise direction.
KR	Pointer to next corner in counterclockwise direction.
KNB	Pointer to host block.
KXP	x coordinate of corner.
KYP	y coordinate of corner.
KXCP	x coordinate of local circle center.
KYCP	y coordinate of local circle center.
KRAD	Radius of local circle.

```
KXDP    x velocity of corner.
KYDP    y velocity of corner.
KGP     Pointer to corresponding grid-point if block
        is fully-deformable.

Offsets for contact data array
------------------------------
Note: The first integer (offset 0) contains
----  the value MCON to denote a contact.

KC      Pointer to next contact in contact list.
KB1     Address of first block involved in contact.
KB2     Address of second block involved in contact.
KL1     Pointer to next item in clockwise list
        of block corresponding to KB1.
KL2     Same as KL1, but for block KB2.
KD1     Address of domain to left of contact,
        going from block KB1 to KB2.
KD2     Address of domain to right of contact,
        going from block KB2 to KB1.
KCM     Material type number.
KCC     Constitutive number.
KXC     x contact coordinate.
KYC     y contact coordinate.
KXDC    Relative x velocity (of block KB2 relative
        to block KB1).
KYDC    Relative y velocity.
KCS     Relative shear displacement.
KCN     Relative normal displacement.
KCFS    Shear force.
KCFN    Normal force (compression positive).
KCCOD   Code number:
          1 corner/corner contact
          2 corner/edge contact (KB1...corner,
                                 KB2...edge)
          3 edge/corner contact (KB1...edge,
                                 KB2...corner)
KCAP    Mean aperture for joint
KCQ     Flow-rate in joint or contact
KCL     Length associated with joint

Offsets for domain data array
-----------------------------
Note: The first integer (offset 0) contains
----  the value MDOM to denote a domain.

KD      Pointer to next domain in domain list.
KDAR    Domain area.
KPP     Pore-pressure for domain.
KUMAX   Fictitious domain displacement.
KDLOOP  Pointer to one contact in counterclockwise
        list around domain.
KDCOD   Code number:
          0 domain pressure not controlled
          1 domain pressure controlled
```

Simply-deformable extension array

KED11)
KED12) Strain-rate
KED21) tensor
KED22)

KSI11)
KSI12) Internal stress
KSI21) tensor
KSI22)

KSA11) Applied stress
KSA12) tensor (multiplied
KSA21) by block area)
KSA22)

Offsets for grid-point data

KG Pointer to next grid-point in grid-point list.
KCOR Pointer to corresponding block corner.
KXG x coordinate.
KYG y coordinate.
KXDG x velocity.
KYDG y velocity.
KGFX x force-sum.
KGFY y force-sum.
KGPM grid-point mass.

Offsets for zone data

KZ Pointer to next zone in zone list.
KZG Start of triple pointer to 3 surrounding grid-points.
KZS11)
KZS12) Stress tensor
KZS22)
KZM Zone mass
KZLL Pointer to neighboring zone for mixed-discretization calculation.

Logical unit numbers

LUNIF Unit number for input file.
LUNOF Unit number for output file.
LUNG Unit number for general I/O (e.g. restart).
LUNP Unit number for plotted output.

Number of words in data arrays

NVCR Corner
NVBL Block
NVCN Contact
NVDO Domain
NVSD Simply-deformable extension
NVZO Zone
NVGP Grid-point

Array limits

MTOP Size of main array (IA).
NMAT Maximum number of materials.
NCONS Maximum constitutive numbers.
NTYP Number of block types (rigid, SDEF, etc.)

Head codes (contents of first integer in data groups)

MRIG = 1 Rigid block
MSDEF = 2 Simply-deformable block
MFDEF = 3 Fully-deformable block
MCOR Corner
MCON Contact
MDOM Domain

Main Common Block Variables

LINE(80)	Buffer for current input line in A1 format.
LINE1(80)	Buffer for next input line.
LPNT(I)	Pointer to start of parameter I in LINE( ) after removal of blanks, etc.
RAFLAG	
PPFLAG	.TRUE. if pore-pressure calculation requested.
ERFLAG	.TRUE. if an error has occured.
STFLAG	.TRUE. if the first input line has been processed.
DCFLAG	.TRUE. if the domain pressure is controlled.
COFLAG	.TRUE. if the current line is a continuation.
NCFLAG	.TRUE. if the next line is a continuation.
CRFLAG	.TRUE. if block splitting calculation is requested.
JMPSAV	Index of last computed GOTO in MON.
NERR	Error number.
JUNK	Pointer to list of spare memory groups.
MFREE	First unused memory address.
IBLOCK	Current block number.

IDOM	Current domain number.
ISTACK	Stack pointer.
NCYC	Currently requested number of cycles.
NCTOT	Total number of cycles.
TDEL	Time-step.
FRAC	Requested fraction of critical time-step.
IROUTE	Routing number, used in main routine.
NLINE	Output line count.
NPAGE	Output page count.
JMPGEN	Routing number for continuation line in GEN.
ALPHA	Mass damping coefficient.
BETA	Stiffness damping coefficient.
CON1	Damping factor (1.0-ALPHA*TDEL/2.0)
CON2	Damping factor (1.0/(1.0+ALPHA*TDEL/2.0))
BDT	BETA/TDEL
ALPB	Internal mass damping coefficient for simply-deformable blocks.
C1B	Damping factor (1.0-ALPB*TDEL/2.0)
C2B	Damping factor (1.0/(1.0+ALPB*TDEL/2.0))
DEGRAD	PI/180
PI	3.14159
DAMIN	Minimum domain area allowed.
ATOL	Distance between particles at which a contact is first formed.
BTOL	Distance between particles at which a contact is broken.
CTOL	Maximum (negative) overlap allowed when forming contacts.
DTOL	Rounding length.
DTOL2	DTOL/2.0 (maximum contact overlap)
ETOL	Limit on maximum domain displacement to trigger contact update.
FTOL	Total area of blocks for setting plotting scale factor.
GTOL	
HTOL	
IBPNT	Pointer to list of blocks.
ICPNT	Pointer to list of contacts.
IDPNT	Pointer to list of domains.
IODPNT	Pointer to outer domain.
AKN(I)	Normal contact stiffness, material I.
AKS(I)	Shear contact stiffness, material I.
AMU(I)	Contact friction coefficient, material I.
COH(I)	Contact cohesion, material I.
AKNJ(I)	Joint normal stiffness, material I.
AKSJ(I)	Joint shear stiffness, material I.
AMUJ(I)	Joint friiction coefficient, material I.
COHJ(I)	Joint cohesion, material I.
PERMJ(I)	Joint permeability constant, material I.
PERMC(I)	Contact permeability constant, material I.
AZERO(I)	Initial aperture, material I.
ARES(I)	Residual aperture, material I.

```
DAMIN        Minimum domain area for fluid calculations.
DENS(I)      Density, material I.
BULK(I)      Bulk modulus, material I.
SHEAR(I)     Shear modulus, material I.
TFAC(I)      Tensile strength factor, material I.
ALAM1(I)     Lame constant, material I.
ALAM2(I)     Lame constant, material I.
GRAVX        x component of gravitational acceleration.
GRAVY        y component of gravitational acceleration.
RHOW         Fluid density.
BULKW        Fluid bulk modulus.
IX1          Plotter viewport coordinate.
IX2          Plotter viewport coordinate.
IY1          Plotter viewport coordinate.
IY2          Plotter viewport coordinate.
RX1          Problem window coordinate.
RX2          Problem window coordinate.
RY1          Problem window coordinate.
RY2          Problem window coordinate.
IA( )        Main array.

Main Subroutine Calling Map
---------------------------

UDEC
     -SETUP
     -MON
     -HALT
     -PRINT
     -CREATE
     -SPLIT
     -APLOT
     -INI
     -CYCLE
             -PPSCAN
             -BLKSCN
             -PPCEN
             -PPDIS
             -CONSCN
             -CRKSCN
             -DOMSCN
     -CEN
```

Sample Problems

The following four sample problems illustrate the improvements made to UDEC.

No. 1 Single point-load cracking

No. 2 Pressurized cavity

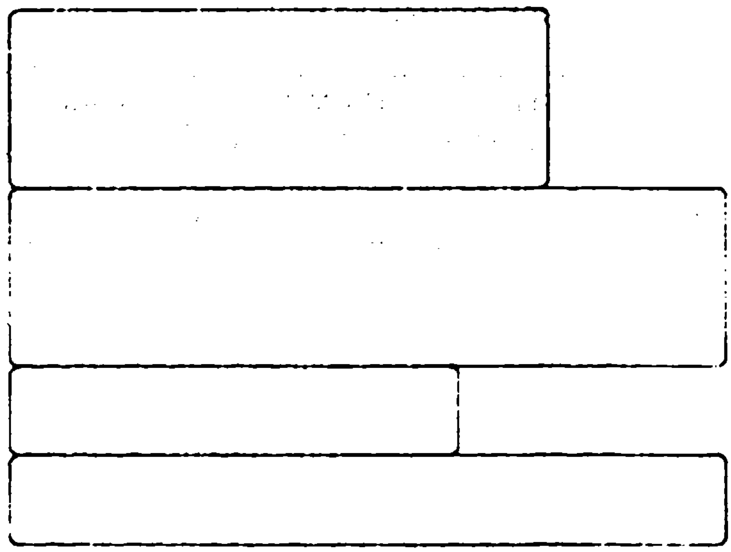
No. 3 Complex block deformation

No. 4 Projectile breaking beam

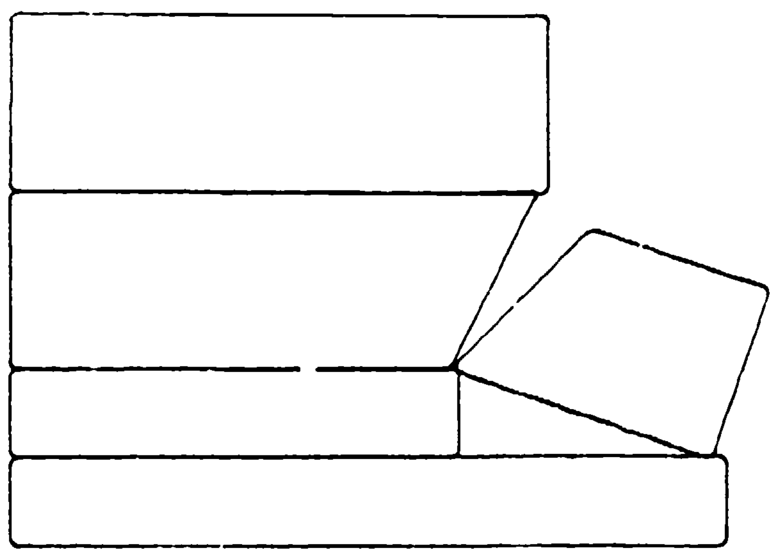
The printed output for each problem should be used to provide a check that the program is performing correctly.

Sample Problem No. 1

A single crack is induced by two opposing point contacts. Cracked block then falls and comes to rest on base.



a. Initial State



b. After 600 Cycles

Figure A1. UDEC Sample Problem No. 1

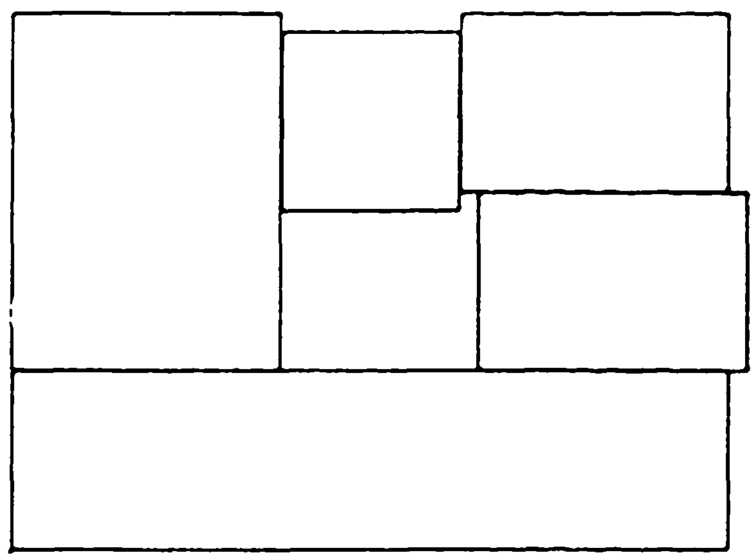
```
START
PROP MAT=1 DENS=2000 KN=1E8 KS=1E8 F=2 TF=2.5E4
GRAV 0 -10
DAMP .1 15 (MASS)
FRAC 0.1
BLOCK (0,0) (0,30) (40,30) (40,0)
SPLIT -1,10 41,10
SPLIT -1,20 41,20
SPLIT -1,5 41,5
SPLIT 25,2.5  25,12.5
DELETE 25,40 5,10
SPLIT 30,15  30,40
DELETE 30,40  20,30
WIND 0 50 0 50
FIX 0,40  0,5
PLOT
CYC 600
PRINT BLOCKS CONTACTS
PLOT
STOP
END
```

PROBLEM NO. 1 INPUT FILE

```
)START
                                               ............................................................
                                               PROGRAM UDEC: UNIVERSAL DISTINCT ELEMENT CODE (VERSION 1.2)
                                               ............................................................
THIS IS A START RUN
)PROP MAT=1 DENS=2000 KN=1E8 KS=1E8 F=2 TF=2.5E4
)GRAV 0 -10
)DAMP .1 15 (MASS)
  STIFFNESS-DAMPING TERM SET TO ZERO
)FRAC 0.1
)BLOCK (0,0) (0,30) (40,30) (40,0)
)SPLIT -1,10  41,10
)SPLIT -1,20  41,20
)SPLIT -1,5  41,5
)SPLIT 25,2.5  25,12.5
)DELETE 25,40  5,10
)SPLIT 30,15  30,40
)DELETE 30,40  20,30
)WIND 0 50 0 50
)FIX 0,40  0,5
)PLOT
)CYC 600
INITIAL TIMESTEP =  1.000E-02
CURRENT CYCLE COUNT =    600
)PRINT BLOCKS CONTACTS


BLOCK DATA

BLOCK MAT CONST    CENTROID COORDS.      MASS     POL. MOM.          X,Y,THETA VELOCITIES                X,Y,THETA FORCES
  195   1     1    3.446E+01  1.140E+01  2.596E+05  6.055E+06   -1.213E-04 -2.787E-04  1.984E-05 -4.002E+02  2.597E+06  2.644E+03
(RIGID)
    1   1     1    1.508E+01  2.473E+01  6.000E+05  5.000E+07    2.992E-05  5.592E-05  5.403E-07  7.786E+02  6.001E+06  1.216E+04
(RIGID)
  433   1     1    1.250E+01  7.427E+00  2.500E+05  1.354E+07    4.039E-05 -1.348E-04  6.709E-07 -4.573E+02  2.500E+06  2.752E+03
(RIGID)
  314   1     1    2.000E+01  2.500E+00  4.000E+05  5.417E+07    0.000E+00  0.000E+00  0.000E+00  8.787E+01 -1.649E+07  4.545E+07
(RIGID)
   76   1     1    1.355E+01  1.500E+01  5.391E+05  3.777E+07    3.317E-06 -1.002E-05  3.587E-06 -9.000E+00  5.389E+06 -7.680E+02
(RIGID)


CONTACT DATA

CONTACT MAT CONST      X,Y COORDS.               FORCE                 DISPLACEMENT
                                           NORMAL     SHEAR        NORMAL     SHEAR
   285    0     0  3.888E+01  4.995E+00  1.886E+06 -3.179E+05  -9.804E-03  3.179E-03
   166    0     0  2.904E+01  1.968E+01  3.061E+06 -4.290E+05  -1.753E-01  4.290E-03
   619    0     0  2.487E+01  9.759E+00  7.190E+05 -2.985E+05  -6.950E-05  1.126E-02
   552    0     0  2.401E+01  9.870E+00  6.715E+06 -1.817E+05  -7.174E-02  1.817E-03
   382    0     0  2.476E+01  1.017E+01  0.000E+00  0.000E+00   1.506E-01  0.000E+00
   588    0     0  2.450E+01  4.958E+00  8.486E+06  1.557E+05  -8.486E-02 -1.557E-03
   404    0     0  5.005E-01  4.969E+00  6.115E+06  1.560E+05  -6.115E-02 -1.560E-03
   263    0     0  5.432E-01  1.988E+01  2.939E+06  3.740E+05  -2.913E-02 -3.740E-03
   144    0     0  5.042E-01  9.916E+00  4.676E+06  1.621E+05  -4.624E-02 -1.621E-03
 )PLOT
 )STOP
```

Sample Problem No. 2

Upper block is forced into a cavity by an applied load. Pressure is thereby induced in the cavity, driving the righthand block outwards. The pressure also induces flows in the surrounding joints, and hence pressure-drops in the enclosed volumes between blocks. The outer domain is held to a fixed pressure of zero.



a. After 3,000 Cycles

Figure A2. UDEC Sample Problem No. 2

```
START
PROP MAT=1 DENS=2000 K=1.0E8 G=1.0E8 KN=1.E08 KS=1.E08 F=0.5
PROP MAT=1 CPERM=1E-9
FLUID 0.0 1.0E9
DAMP .5 16. MASS
FRAC 0.10
BLOCK 0.,0. 0.,30. 40.,30. 40.,0.
ROUND 0.2
SPLIT -1.,10. 41.,10. MAT=1 CONS=1
SPLIT 15.,9. 15.,31. MAT=1 CONS=1
SPLIT 25.,9. 25.,31. MAT=1 CONS=1
SPLIT 10,20 41,20 MAT=1, CONS=1
DELETE 15.,25. 10.,20.
FIX 0.,40. 0.,10.
FIX 0.,15. 0.,30.
FIX 25.,40. 20.,30.
PFIX 69 0.0
LOAD 15.,25. 20.,30 0.0 -1.0E6
WIND 0 50 0 40
CYCLE 3000
PRINT FLOWS, DOMAINS, BLOCKS
PLOT
STOP
END
```

PROBLEM NO. 2 INPUT FILE

```
)START

                                        -----------------------------------------------------------
                                        PROGRAM UDEC: UNIVERSAL DISTINCT ELEMENT CODE (VERSION 1.2)
                                        -----------------------------------------------------------

THIS IS A START RUN
)PROP MAT=1 DENS=2000 K=1.0E8 G=1.0E8 KN=1.E08 KS=1.E08  F=0.5
)PROP MAT=1 CPERM=1E-9
)FLUID 0.0 1.0E9
)DAMP .5 16. MASS
  STIFFNESS-DAMPING TERM SET TO ZERO
)FRAC 0.10
)BLOCK 0.,0. 0.,30. 40.,30. 40.,0.
)ROUND 0.2
)SPLIT -1.,10. 41.,10. MAT=1 CONS=1
)SPLIT 15.,9. 15.,31. MAT=1 CONS=1
)SPLIT 25.,9. 25.,31. MAT=1 CONS=1
)SPLIT 10,20  41,20  MAT=1, CONS=1
)DELETE 15.,25. 10.,20.
)FIX 0.,40. 0.,10.
)FIX 0.,15. 0.,30.
)FIX 25.,40. 20.,30.
)PFIX 69 0.0
)LOAD 15.,25. 20.,30 0.0 -1.0E6
)WIND 0 50 0 40
)CYCLE 3000
INITIAL TIMESTEP =  8.944E-03
CURRENT CYCLE COUNT =  3000
)PRINT FLOWS, DOMAINS, BLOCKS
```

FLOW ACROSS CONTACTS OR JOINTS ...

CONTACT	X	Y	FLOW	LENGTH	APERTURE	DOM1	DOM2
883	1.500E+01	1.915E+01	2.944E-05	0.000E+00	0.000E+00	522	905
706	2.500E+01	2.020E+01	2.944E-05	0.000E+00	0.000E+00	522	728
648	3.980E+01	2.000E+01	-2.921E-05	0.000E+00	0.000E+00	69	670
626	2.625E+01	2.000E+01	2.944E-05	0.000E+00	0.000E+00	522	670
500	2.625E+01	1.000E+01	-2.944E-05	0.000E+00	0.000E+00	188	522
449	2.500E+01	2.875E+01	-2.921E-05	0.000E+00	0.000E+00	69	728
350	1.480E+01	1.000E+01	2.944E-05	0.000E+00	0.000E+00	522	372
285	1.500E+01	2.875E+01	-2.921E-05	0.000E+00	0.000E+00	69	905
166	3.980E+01	1.000E+01	-2.921E-05	0.000E+00	0.000E+00	69	188
144	2.000E-01	1.000E+01	-2.921E-05	0.000E+00	0.000E+00	69	372

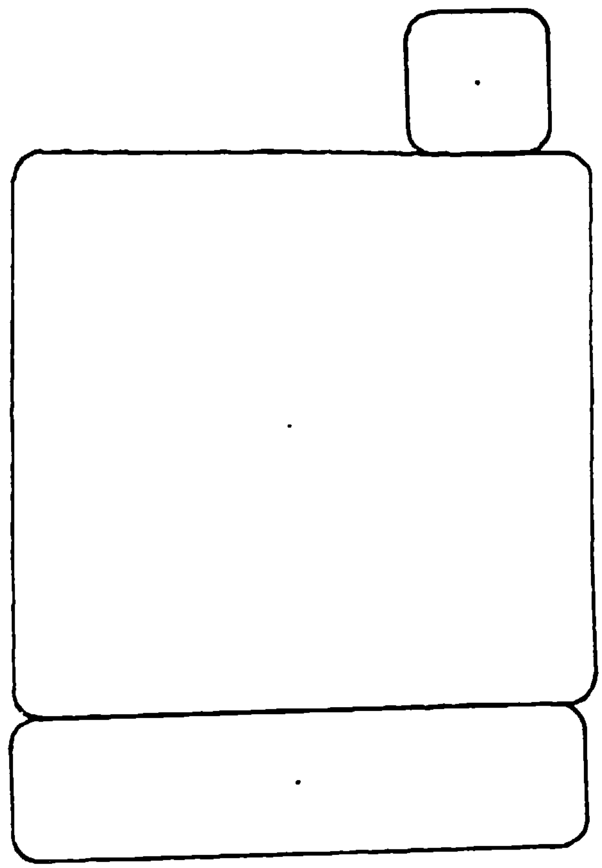
DOMAIN DATA

DOMAIN	PORE PRESSURE	VOLUME	MAXIMUM DISPLACEMENT
905	2.922E+04	4.800E-01	8.512E-04
728	2.922E+04	4.800E-01	5.951E-03
670	2.922E+04	4.800E-01	3.450E-04
522	5.864E+04	9.999E+01	1.196E-02
372	2.922E+04	4.800E-01	0.000E+00
188	2.922E+04	4.800E-01	3.450E-04
69 (OUTER BOUNDARY)	0.000E+00	4.800E-01	1.160E-02

```
BLOCK DATA

BLOCK MAT CONST    CENTROID COORDS.       MASS     POL. MOM.        X,Y,THETA VELOCITIES                    X,Y,THETA FORCES
  558   1    1    3.250E+01  2.500E+01  3.000E+05  8.125E+06   0.000E+00  0.000E+00  0.000E+00  6.508E+03 -3.254E+03  1.555E+03
(RIGID)
  381   1    1    3.355E+01  1.500E+01  3.000E+05  8.125E+06   3.857E-02 -2.511E-09 -7.426E-11 -1.171E-01 -2.284E-02 -5.432E-02
(RIGID)
  195   1    1    7.500E+00  2.000E+01  6.000E+05  3.125E+07   0.000E+00  0.000E+00  0.000E+00 -3.716E+04 -1.858E+04 -1.708E+05
(RIGID)
   76   1    1    2.000E+01  2.395E+01  2.000E+05  3.333E+06   3.218E-05 -3.945E-02  7.559E-06  3.065E+04  2.183E+04  1.312E+05
(RIGID)
    1   1    1    2.000E+01  5.000E+00  8.000E+05  1.133E+08   0.000E+00  0.000E+00  0.000E+00  5.286E-02 -1.057E-01 -1.820E+00
(RIGID)
 )PLOT
 )STOP
```

Sample Problem No. 3

A small heavy block sits on a large block that has low moduli and is fully deformable. After 1000 time-steps the plot shows the complex deformation pattern that develops, and the printout gives the internal stresses.



a. After 1,000 cycles

Figure A3. UDEC Sample Problem No. 3

```
START
PROP MAT=1  D=2000 KN=1E6 KS=1E8 FRIC=.1 G=1E6 BULK=2E6
PROP MAT=2 D=10000 KN=1E8 KS=1E8 FRIC=.1 G=1E8 BULK=1E8
ROUND = 0.2
BLOCK 2,2 2,8 6,8 6,2
SPLIT 0,7 7,7
SPLIT 4.5 6 4.5 9
DELETE 2 5 7 8
SPLIT 5.5 6 5.5 9
DELETE 5.5 6 7 8
SPLIT 0.3  8.3
CHANGE 4.5 5.5 7 8 MAT=2
CHANGE 2 6 3 7  FDEF
GEN  2 6  3 7 AUTO=1.1
FIX 2 6  2 3
GRAV 0 -10
DAMP .1 1 MASS
CYCLE 1000
WIND 0 8  0 10
PLOT
PRINT BLOCKS
STOP
END
```

<u>PROBLEM NO. 3   INPUT FILE</u>

```
)START

                              ---------------------------------------------------------
                              PROGRAM UDEC: UNIVERSAL DISTINCT ELEMENT CODE (VERSION 1.2)
                              ---------------------------------------------------------

THIS IS A START RUN
)PROP MAT=1  D=2000 KN=1E8 KS=1E8 FRIC=.1 G=1E6 BULK=2E6
)PROP MAT=2 D=10000 KN=1E8 KS=1E8 FRIC=.1 G=1E8 BULK=1E8
)ROUND = 0.2
)BLOCK 2,2  2,8  6,8  6,2
)SPLIT 0,7 7,7
)SPLIT 4.5 6  4.5 9
)DELETE 2 5  7 8
)SPLIT 5.5 6  5.5 9
)DELETE 5.5 6  7 8
)SPLIT 0,3  8,3
)CHANGE 4.5 5.5 7 8 MAT=2
)CHANGE 2 6  3 7   FDEF
)GEN  2 6  3 7 AUTO=1.1
)FIX 2 6  2 3
)GRAV 0 -10
)DAMP .1 1 MASS
  STIFFNESS-DAMPING TERM SET TO ZERO
)CYCLE 1000
INITIAL TIMESTEP =  1.789E-03
CURRENT CYCLE COUNT =  1000
)WIND 0 8  0 10
)PLOT
)PRINT BLOCKS
```

BLOCK DATA

BLOCK	MAT	CONST	CENTROID COORDS.		MASS	MOL. MOM.	X,Y,THETA VELOCITIES			X,Y,THETA FORCES		
195	1	1	4.000E+00	2.500E+00	3.?00E+03	1.133E+04	0.000E+00	0.000E+00	0.000E+00	1.626E+04	-3.772E+05	-2.102E+05
(RIGID)												
76	2	1	5.377E+00	7.374E+00	1.000E+04	1.667E+03	1.157E-01	6.630E-02	1.018E-01	-3.318E+03	3.307E+04	-1.156E+04
(RIGID)												
1	1	1	4.000E+00	5.000E+00	3.200E+04	8.533E+04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
(FDEF)												

ZONE	GRID-POINTS			SIGMA-11	SIGMA-12	SIGMA-22	MASS
1120	483	705	576	9.261E+03	2.736E+03	4.337E+03	5.000E+02
1129	429	576	705	1.298E+04	1.384E+03	-4.010E+03	5.000E+02
1138	483	642	705	2.307E+03	6.811E+03	-8.184E+03	5.000E+02
1147	429	705	642	5.938E+03	5.457E+03	-1.668E+04	5.000E+02
555	447	750	576	1.755E+04	3.954E+02	-4.475E+04	5.000E+02
1156	483	576	750	-5.399E+03	3.390E+03	-3.232E+04	5.000E+02
1165	447	615	750	1.504E+04	1.197E+03	-3.917E+04	5.000E+02
1174	483	750	615	-7.935E+03	4.196E+03	-2.677E+04	5.000E+02
723	429	771	576	1.459E+04	-7.903E+03	-2.758E+03	5.000E+02
1183	525	576	771	2.048E+04	-3.629E+03	-3.453E+04	5.000E+02
1192	429	633	771	1.096E+04	-1.499E+04	-2.986E+04	5.000E+02
1201	525	771	633	1.578E+04	-1.070E+04	-6.206E+04	5.000E+02
732	525	828	576	8.329E+03	-4.476E+03	-6.451E+04	5.000E+02
1210	447	576	828	2.155E+03	-2.497E+03	-5.085E+04	5.000E+02
1219	525	651	828	1.084E+04	-3.722E+03	-7.159E+04	5.000E+02
1228	447	828	651	4.527E+03	-1.724E+03	-5.805E+04	5.000E+02
741	483	897	642	7.773E+03	1.134E+03	-5.551E+03	5.000E+02

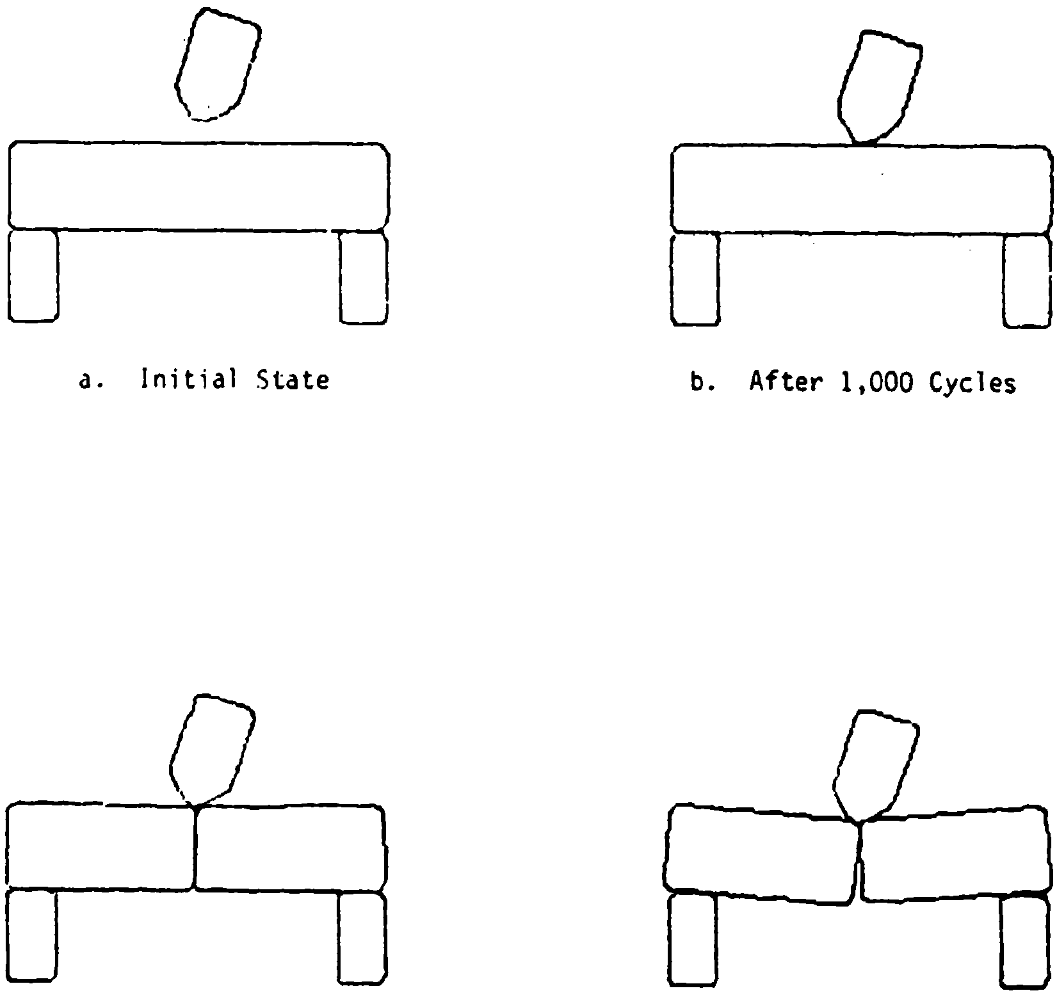
ZONE	GRID-POINTS			SIGMA-11	SIGMA-12	SIGMA-22	MASS
1237	411	642	897	1.738E+03	1.466E+02	7.710E+03	5.000E+02
1246	483	495	897	1.222E+04	3.225E+03	-3.302E+02	5.000E+02
1255	411	897	495	6.214E+03	2.237E+03	1.292E+04	5.000E+02
606	456	807	615	4.303E+03	-1.475E+03	-1.838E+04	5.000E+02
1264	483	615	807	1.927E+04	2.057E+03	-1.563E+04	5.000E+02
1273	456	495	807	-9.784E+03	2.280E+03	-2.066E+04	5.000E+02
1282	483	807	495	5.391E+03	5.808E+03	-1.779E+04	5.000E+02
780	447	624	615	1.545E+04	9.187E+03	-3.927E+04	5.000E+02
1291	546	615	624	2.065E+04	1.057E+04	-3.726E+04	5.000E+02
1300	447	669	624	4.390E+03	1.770E+04	-6.940E+04	5.000E+02
1309	546	624	669	9.348E+03	1.909E+04	-6.765E+04	5.000E+02
789	546	945	615	1.263E+04	6.276E+03	-4.003E+04	5.000E+02
1318	456	615	945	-1.209E+03	8.395E+03	-3.397E+04	5.000E+02
1327	546	696	945	4.723E+03	7.464E+03	-2.850E+04	5.000E+02
1336	456	945	696	-9.323E+03	9.582E+03	-2.263E+04	5.000E+02
798	402	924	633	5.768E+03	6.847E+03	-4.483E+04	5.000E+02
1345	525	633	924	1.291E+04	2.786E+03	-6.587E+04	5.000E+02
1354	402	438	924	5.751E+03	5.649E+03	-4.074E+04	5.000E+02
1363	525	924	438	1.300E+04	1.527E+03	-6.152E+04	5.000E+02
837	465	858	438	8.199E+03	-1.807E+03	-7.794E+04	5.000E+02
1372	525	438	858	1.103E+04	-4.621E+03	-6.726E+04	5.000E+02
1381	465	651	858	1.242E+04	-1.628E+03	-8.098E+04	5.000E+02
1390	525	858	651	1.574E+04	-4.408E+03	-6.978E+04	5.000E+02
867	465	888	651	1.357E+04	3.667E+03	-7.963E+04	5.000E+02
1399	585	651	888	7.384E+03	2.105E+03	-8.088E+04	5.000E+02
1408	465	687	888	8.461E+03	1.233E+04	-1.172E+05	5.000E+02
1417	585	888	687	1.606E+03	1.077E+04	-1.192E+05	5.000E+02
906	585	1031	651	-2.166E+04	1.078E+04	-9.285E+04	5.000E+02
1426	447	651	1031	1.129E+03	3.585E+02	-6.662E+04	5.000E+02
1435	585	669	1031	-3.658E+03	1.518E+04	-8.915E+04	5.000E+02
1444	447	1031	669	1.904E+04	4.754E+03	-6.289E+04	5.000E+02
915	546	963	696	5.523E+03	5.752E+03	-2.631E+04	5.000E+02
1453	420	696	963	-1.074E+04	2.403E+03	-2.694E+04	5.000E+02
1462	546	714	963	1.566E+04	8.839E+03	-5.301E+04	5.000E+02
1471	420	963	714	-1.453E+02	5.490E+03	-5.326E+04	5.000E+02
660	474	981	669	2.086E+03	1.157E+04	-7.534E+04	5.000E+02
1480	546	669	981	9.050E+03	8.270E+03	-6.746E+04	5.000E+02
1489	474	714	981	-1.342E+03	1.317E+04	-6.578E+04	5.000E+02
1498	546	981	714	6.482E+03	9.865E+03	-5.705E+04	5.000E+02
954	585	678	669	-3.674E+03	1.720E+03	-8.871E+04	5.000E+02
1507	474	669	678	5.960E+03	6.968E+03	-7.351E+04	5.000E+02
1516	585	516	678	-1.762E+03	6.091E+03	-1.120E+05	5.000E+02
1525	474	678	516	7.575E+03	1.133E+04	-9.716E+04	5.000E+02
972	393	1070	687	1.101E+04	1.112E+04	-1.291E+05	5.000E+02
1534	585	687	1070	7.505E+03	6.596E+03	-1.042E+05	5.000E+02
1543	393	516	1070	-4.683E+03	5.536E+03	-1.398E+05	5.000E+02
1552	585	1070	516	-7.650E+03	1.000E+03	-1.143E+05	5.000E+02

GRID-POINT	CORNER-LINK	X	Y	X,Y VELOCITIES		X,Y FORCES		MASS
420	108	2.031E+00	3.000E+00	-7.926E-02	4.314E-04	5.391E+02	-4.995E+03	3.333E+02
411	96	2.132E+00	6.982E+00	-1.894E-01	1.646E-01	1.317E+03	-4.744E+03	3.333E+02
402	120	6.152E+00	6.868E+00	2.362E-01	2.911E-01	-5.960E+03	1.803E+04	3.333E+02
393	227	6.083E+00	2.999E+00	5.754E-03	4.124E-02	2.342E+02	9.801E+02	3.333E+02
447	0	4.087E+00	4.948E+00	3.222E-01	8.775E-02	-1.492E+04	4.838E+03	1.333E+03
429	504	4.135E+00	6.926E+00	-2.463E-02	1.389E-01	5.517E+03	6.349E+03	6.667E+02
456	534	2.072E+00	4.985E+00	1.007E-01	-1.053E-01	-8.405E+03	9.637E+03	6.667E+02
465	564	6.113E+00	4.911E+00	1.839E-02	3.367E-02	-1.518E+04	4.863E+03	6.667E+02
474	594	4.047E+00	2.979E+00	1.472E-01	4.260E-02	5.811E+03	1.748E+03	6.667E+02
483	0	3.103E+00	5.954E+00	5.316E-02	-2.257E-01	-1.181E+04	2.212E+04	1.333E+03
525	0	5.117E+00	5.904E+00	1.350E-01	2.089E-01	8.919E+02	1.699E+04	1.333E+03
546	0	3.050E+00	3.978E+00	2.160E-01	-3.205E-02	4.386E+03	1.287E+04	1.333E+03
585	0	5.075E+00	3.960E+00	3.623E-01	4.209E-02	1.564E+04	6.366E+03	1.333E+03
576	0	4.105E+00	5.929E+00	1.917E-02	6.850E-02	2.137E+03	3.300E+04	1.333E+03
642	759	3.131E+00	6.950E+00	-2.439E-01	2.264E-02	-3.914E+03	8.564E+03	6.667E+02
615	0	3.076E+00	4.962E+00	1.097E-01	-1.158E-01	-5.304E+03	1.524E+04	1.333E+03
495	816	2.099E+00	5.979E+00	-1.985E-01	-1.806E-01	2.903E+03	1.631E+04	6.667E+02
633	846	5.143E+00	6.879E+00	5.093E-02	2.085E-01	4.551E+03	2.712E+04	6.667E+02
438	876	6.131E+00	5.882E+00	-6.894E-02	6.179E-02	-5.830E+03	9.543E+03	6.667E+02
651	0	5.097E+00	4.931E+00	1.661E-01	2.523E-02	6.198E+03	8.508E+03	1.333E+03
696	933	2.045E+00	3.992E+00	1.104E-01	-9.888E-02	-3.748E+02	7.345E+03	6.667E+02
669	0	4.063E+00	3.973E+00	1.043E-01	-7.978E-02	5.552E+03	-2.553E+03	1.333E+03
714	990	3.038E+00	2.999E+00	1.138E-01	1.451E-02	-7.430E+02	2.059E+04	6.667E+02
687	1049	6.092E+00	3.953E+00	3.827E-01	-1.255E-01	-5.301E+03	-1.230E+04	6.667E+02
516	1079	5.064E+00	2.999E+00	-1.107E-02	-3.507E-02	2.562E+03	1.135E+04	6.667E+02
705	0	3.618E+00	6.441E+00	-4.517E-03	-7.032E-02	6.721E+03	-1.327E+04	6.667E+02
750	0	3.590E+00	5.447E+00	1.190E-01	2.087E-01	1.352E+04	1.794E+03	6.667E+02
771	0	4.623E+00	6.409E+00	-1.665E-01	-4.274E-02	-4.787E+03	1.590E+03	6.667E+02
828	0	4.600E+00	5.429E+00	4.420E-02	1.521E-01	2.907E+03	-3.691E+03	6.667E+02
897	0	2.615E+00	6.465E+00	1.595E-01	1.291E-02	-8.959E+02	3.712E+03	6.667E+02
807	0	2.585E+00	5.470E+00	-1.319E-02	2.526E-01	1.809E+04	2.077E+02	6.667E+02
624	0	3.570E+00	4.463E+00	1.749E-01	-1.399E-02	-1.304E+04	1.820E+04	6.667E+02
945	0	2.558E+00	4.480E+00	2.162E-01	-6.608E-02	1.131E+04	-4.137E+03	6.667E+02
924	0	5.637E+00	6.381E+00	2.528E-02	-2.027E-01	-9.123E+02	9.597E+03	6.667E+02
858	0	5.615E+00	5.405E+00	1.357E-01	6.610E-02	-5.226E+03	8.272E+03	6.667E+02
888	0	5.593E+00	4.436E+00	1.348E-01	3.767E-01	-3.125E+03	2.541E+04	6.667E+02
1031	0	4.583E+00	4.451E+00	-3.233E-02	1.588E-01	-2.732E+04	1.456E+04	6.667E+02
963	0	2.538E+00	3.490E+00	1.458E-01	1.104E-01	1.312E+04	1.691E+04	6.667E+02
981	0	3.550E+00	3.488E+00	1.379E-01	5.038E-01	-4.618E+03	1.021E+02	6.667E+02
678	0	4.562E+00	3.482E+00	9.105E-02	1.550E-01	-8.637E+03	4.083E+03	6.667E+02
1070	0	5.576E+00	3.475E+00	-5.486E-02	1.040E-01	9.440E+03	2.305E+04	6.667E+02

)STOP

Sample Problem No. 4

A projectile hits a beam and breaks it into two (fracture based on Griffith theory).



a. Initial State

b. After 1,000 Cycles

c. After 1,200 Cycles

d. After 2,000 Cycles

Figure A4. UDEC Sample Problem No. 4

```
START
PROP MAT=1 DENS=2000 K=1.0E8 G=1.0E8 KN=1.E08 KS=1.E08 F=0.1
PROP MAT=1 TF=3240.
GRAVITY 0. -10.
ROUND 0.1
DAMP .5 16. MASS
DAMP .5 16. INTERNAL
FRAC 0.10
BLOCK MAT=1 CONS=4 1.,0. 1.,3.35 5.,3.35 5.,0.
SPLIT 0,1  6,1
SPLIT 0,1.9  6,1.9
SPLIT 1.5,-0.5 1.5,1.5
SPLIT 4.5,-0.5 4.5,1.5
DELETE 1.5,4.5  0.1
SPLIT 2.5,1.7  3.25,4
SPLIT 3.25,1.8  4,4.1
SPLIT 2.65,1.87  3.75,2.48
SPLIT 3.15,1.8  2.55,2.05
SPLIT 2.6,3.5  4,3.05
DELETE 1,2.5  1.9,3.3
DELETE 3.75,5  1.9,3.3
DELETE 2.6,3.4  1.9,2.4
DELETE 3,3.75  3.15,3.35
CHANGE 1,5 1,2 SDEF
LINK 3,3  4.1.5
FIX 1,5  0,1
LOAD 1,5 2,3.35 -0.3E4 -0.95E4
VIEW 0 700 700 1400
WIND 0 6 0 7
PLOT
CYCLE 1000
VIEW 700 1400 700 1400
PLOT
CYCLE 200
VIEW 0 700 0 700
PLOT
CYCLE 800
VIEW 700 1400 0 700
PLOT
P B C CON DL L
STOP
END
```


PROBLEM NO. 4 INPUT FILE

```
)START
                                  ------------------------------------------------------------
                                  PROGRAM UDEC: UNIVERSAL DISTINCT ELEMENT CODE (VERSION 1.2)
                                  ------------------------------------------------------------
THIS IS A START RUN
)PROP MAT=1 DENS=2000 K=1.0E8 G=1.0E8 KN=1.E08 KS=1.E08 F=0.1
)PROP MAT=1 TF=3240.
)GRAVITY 0. -10.
)ROUND 0.1
)DAMP .5 16. MASS
 STIFFNESS-DAMPING TERM SET TO ZERO
)DAMP .5 16. INTERNAL
 NOTE - ONLY MASS-DAMPING USED
)FRAC 0.10
)BLOCK MAT=1 CONS=4 1.,0. 1.,3.35 5.,3.35 5.,0.
)SPLIT 0,1  6,1
)SPLIT 0,1.9  6,1.9
)SPLIT 1.5,-0.5 1.5,1.5
)SPLIT 4.5,-0.5 4.5,1.5
)DELETE 1.5,4.5  0,1
)SPLIT 2.5,1.7  3.25,4
)SPLIT 3.25,1.8  4,4.1
)SPLIT 2.65,1.87  3.75,2.48
)SPLIT 3.15,1.8  2.55,2.85
)SPLIT 2.6,3.5  4,3.05
)DELETE 1,2.5   1.9,3.3
)DELETE 3.75,5  1.9,3.3
)DELETE 2.6,3.4  1.9,2.4
)DELETE 3,3.75  3.15,3.35
)CHANGE 1,5 1,2 SDEF
)LINK 3,3  4,1.5
)FIX 1,5  0,1
)* SET FORCE OF PROJECTILE
)LOAD 1,5 2,3.35 -0.3E4 -0.95E4
)VIEW 0 700 700 1400
)WIND 0 6 0 7
)PLOT
)CYCLE 1000
INITIAL TIMESTEP =  6.325E-04
CURRENT CYCLE COUNT =  1000
)VIEW 700 1400 700 1400
)PLOT
)CYCLE 200
INITIAL TIMESTEP =  6.325E-04
CURRENT CYCLE COUNT =  1200
)VIEW 0 700 0 700
)PLOT
)CYCLE 800
INITIAL TIMESTEP =  6.325E-04
CURRENT CYCLE COUNT =  2000
)VIEW 700 1400 0 700
)PLOT
)P B C COR DL L
```

```
BLOCK DATA

BLOCK MAT CONST     CENTROID COORDS.        MASS     MOL. MOM.         X,Y,THETA VELOCITIES                  X,Y,THETA FORCES
 1373   1     4    4.023E+00  1.407E+00  3.600E+03  1.443E+03    4.066E-02 -8.201E-02  1.565E-01  7.292E+03  2.126E+04  1.135E+04
(SDEF)
      ED11       ED12       ED21       ED22       SI11       SI12       SI21       SI22       SA11       SA12       SA21       SA22
 1.264E-03 1.996E-03-1.783E-03 3.673E-03-8.399E+03-2.915E+02-2.915E+02-6.093E+03-3.025E+04-8.582E+02-1.777E+03-2.231E+04

  500   1     4    4.750E+00  5.000E-01  1.000E+03  1.042E+02    0.000E+00  0.000E+00  0.000E+00  4.203E+03 -2.397E+04  1.672E+03
(RIGID)
  195   1     4    3.160E+00  2.373E+00  1.448E+03  1.937E+02   -1.664E-02 -2.353E-01 -9.981E-03  1.761E+03  6.843E+03 -1.094E+02
(RIGID)
   76   1     4    1.973E+00  1.403E+00  3.600E+03  1.443E+03   -4.776E-02 -8.438E-02 -1.687E-01 -8.535E+03  2.078E+04 -1.227E+04
(SDEF)
      ED11       ED12       ED21       ED22       SI11       SI12       SI21       SI22       SA11       SA12       SA21       SA22
 1.264E-03 1.996E-03-1.783E-03 3.673E-03-8.399E+03-2.915E+02-2.915E+02-6.093E+03-3.025E+04-8.582E+02-1.777E+03-2.231E+04

    1   1     4    1.250E+00  5.000E-01  1.000E+03  1.042E+02    0.000E+00  0.000E+00  0.000E+00 -4.721E+03 -2.492E+04 -1.598E+03
(RIGID)


CONTACT DATA

CONTACT MAT CONST       X,Y COORDS.              FORCE                 DISPLACEMENT
                                             NORMAL     SHEAR       NORMAL     SHEAR
  1167    1     4 3.066E+00  1.780E+00   2.336E+03  2.336E+02  -5.317E-05 -6.424E-04
   619    1     4 3.007E+00  1.680E+00   1.067E+04  1.067E+03   5.096E-05 -1.821E-02
  1429    0     0 2.948E+00  1.765E+00   5.255E+03  5.255E+02   1.602E-04 -7.676E-03
   648    0     0 4.593E+00  9.996E-01   2.419E+04 -2.419E+03  -2.376E-04  5.412E-02
   433    0     0 1.409E+00  9.995E-01   2.522E+04  2.522E+03  -2.623E-04 -6.533E-02
   166    0     0 4.892E+00  1.011E+00   0.000E+00  0.000E+00   2.195E-02  0.000E+00
   144    0     0 1.110E+00  1.013E+00   0.000E+00  0.000E+00   2.600E-02  0.000E+00


CORNER COORDINATES (IN X,Y ORDER)

BLOCK  1373
   3.002E+00   1.782E+00      4.966E+00   1.929E+00      5.053E+00   1.034E+00      3.050E+00   8.851E-01
BLOCK   500
   4.500E+00   1.000E+00      5.000E+00   1.000E+00      5.000E+00   0.000E+00      4.500E+00   0.000E+00
BLOCK   195
   3.652E+00   2.781E+00      3.373E+00   1.923E+00      2.946E+00   1.724E+00      2.720E+00   2.118E+00      3.000E+00   2.981E+00
BLOCK    76
   2.921E+00,  8.665E-01      9.362E-01   1.041E+00      1.015E+00   1.929E+00      3.018E+00   1.763E+00
BLOCK     1
   1.500E+00   0.000E+00      1.000E+00   0.000E+00      1.000E+00   1.000E+00      1.500E+00   1.000E+00
```

DOMAIN LINKED LISTS

```
DOMAIN  1189
  CONTACT 1167, BLOCK1  1373, BLOCK2   195  CORNER/EDGE
  CORNER   544, BLOCK   1373, R-LINK  1393
  CORNER   239, BLOCK   1373, R-LINK   544
  CORNER   108, BLOCK   1373, R-LINK   239
  CONTACT  166, BLOCK1  1373, BLOCK2   500  EDGE/CORNER
  CORNER   120, BLOCK    500, R-LINK   556
  CORNER    57, BLOCK    500, R-LINK   120
  CORNER   532, BLOCK    500, R-LINK    57
  CONTACT  648, BLOCK1   500, BLOCK2  1373  CORNER/EDGE
  CORNER  1393, BLOCK   1373, R-LINK   108
  CONTACT  619, BLOCK1    76, BLOCK2  1373  CORNER/EDGE
  CORNER   709, BLOCK     76, R-LINK   215
  CORNER  1034, BLOCK     76, R-LINK   709
  CONTACT  433, BLOCK1     1, BLOCK2    76  CORNER/EDGE
  CORNER   334, BLOCK      1, R-LINK    96
  CORNER   358, BLOCK      1, R-LINK   334
  CORNER    21, BLOCK      1, R-LINK   358
  CONTACT  144, BLOCK1     1, BLOCK2    76  CORNER/EDGE
  CORNER   132, BLOCK     76, R-LINK  1034
  CORNER   215, BLOCK     76, R-LINK   132
  CONTACT 1429, BLOCK1   195, BLOCK2    76  CORNER/CORNER
  CORNER  1216, BLOCK    195, R-LINK   828
  CORNER  1240, BLOCK    195, R-LINK  1216
  CORNER   370, BLOCK    195, R-LINK  1240
  CORNER  1405, BLOCK    195, R-LINK   370
  CORNER   828, BLOCK    195, R-LINK  1405
DOMAIN   937(OUTER BOUNDARY)
  CONTACT 1167, BLOCK1  1373, BLOCK2   195  CORNER/EDGE
  CONTACT 1429, BLOCK1   195, BLOCK2    76  CORNER/CORNER
  CONTACT  619, BLOCK1    76, BLOCK2  1373  CORNER/EDGE
DOMAIN   670
  CONTACT  648, BLOCK1   500, BLOCK2  1373  CORNER/EDGE
  CORNER   556, BLOCK    500, R-LINK   532
  CONTACT  166, BLOCK1  1373, BLOCK2   500  EDGE/CORNER
DOMAIN   188
  CONTACT  433, BLOCK1     1, BLOCK2    76  CORNER/EDGE
  CONTACT  144, BLOCK1     1, BLOCK2    76  CORNER/EDGE
  CORNER    96, BLOCK      1, R-LINK    21
```

BLOCK LINKED LISTS

```
BLOCK  1373
 CORNER   1393, BLOCK   1373, R-LINK   108
 CONTACT   619, BLOCK1    76, BLOCK2  1373  CORNER/EDGE
 CONTACT  1167, BLOCK1  1373, BLOCK2   195  CORNER/EDGE
 CORNER    544, BLOCK   1373, R-LINK  1393
 CORNER    239, BLOCK   1373, R-LINK   544
 CORNER    108, BLOCK   1373, R-LINK   239
 CONTACT   166, BLOCK1  1373, BLOCK2   500  EDGE/CORNER
 CONTACT   648, BLOCK1   500, BLOCK2  1373  CORNER/EDGE
BLOCK   500
 CORNER    532, BLOCK    500, R-LINK    57
 CONTACT   648, BLOCK1   500, BLOCK2  1373  CORNER/EDGE
 CORNER    556, BLOCK    500, R-LINK   532
 CONTACT   166, BLOCK1  1373, BLOCK2   500  EDGE/CORNER
 CORNER    120, BLOCK    500, R-LINK   556
 CORNER     57, BLOCK    500, R-LINK   120
BLOCK   195
 CORNER    370, BLOCK    195, R-LINK  1240
 CORNER   1405, BLOCK    195, R-LINK   370
 CORNER    828, BLOCK    195, R-LINK  1405
 CONTACT  1167, BLOCK1  1373, BLOCK2   195  CORNER/EDGE
 CONTACT  1429, BLOCK1   195, BLOCK2    76  CORNER/CORNER
 CORNER   1216, BLOCK    195, R-LINK   828
 CORNER   1240, BLOCK    195, R-LINK  1216
BLOCK    76
 CORNER    709, BLOCK     76, R-LINK   215
 CORNER   1034, BLOCK     76, R-LINK   709
 CONTACT   433, BLOCK1     1, BLOCK2    76  CORNER/EDGE
 CONTACT   144, BLOCK1     1, BLOCK2    76  CORNER/EDGE
 CORNER    132, BLOCK     76, R-LINK  1034
 CORNER    215, BLOCK     76, R-LINK   132
 CONTACT  1429, BLOCK1   195, BLOCK2    76  CORNER/CORNER
 CONTACT   619, BLOCK1    76, BLOCK2  1373  CORNER/EDGE
BLOCK     1
 CORNER    334, BLOCK      1, R-LINK    96
 CORNER    358, BLOCK      1, R-LINK   334
 CORNER     21, BLOCK      1, R-LINK   358
 CONTACT   144, BLOCK1     1, BLOCK2    76  CORNER/EDGE
 CORNER     96, BLOCK      1, R-LINK    21
 CONTACT   433, BLOCK1     1, BLOCK2    76  CORNER/EDGE
)STOP
```

APPENDIX B: THREE-DIMENSIONAL DISTINCT ELEMENT TEST-BED CODE (VERSION 1.0) USER'S MANUAL

Introduction

1. This manual describes the test-bed code, D3, written to evaluate features developed in the design of a new three-dimensional distinct element program. D3 is in skeleton form with several facilities provided for in the code but not completed at present. The input commands and program operation follow closely those given for UDEC.

Input Commands

Notes: Upper-case letters in a command or parameter must be typed; the remaining letters are optional. Lower-case parameters stand for numeric values. Integers must be given for parameters starting with i, j, k, l, m, n. Real numbers may be given as integers, but not vice versa.

Input is free-format: parameters may be separated by any number of the following characters, in addition to spaces:

= ( ) , /

An END command is required at the end of the input file (after the STOP command). The first command must be START or RESTART.

* = comment line

\+ = continuation line

Block Material n Constitutive m x1 y1 z1 x2 y2 z2 ...

Create a rigid block of material number n and constitutive number m. Defaults are n=1, m=1, if m, n are omitted. The block's surface is divided into triangular faces. Vertex coordinates. (x1, y1, z1), (x2, y2, z2), etc., are entered three at a time for each triangular face. Continuation lines may be used but a set of three vertices defining a face must not be separated. Vertices must be ordered counterclockwise looking along the outward normal.

CHange x1 x2 y1 y2 z1 z2 Sdef Material n Constitutive m

All blocks with centroids lying within the range $x1<x<x2$, $y1<y<y2$ and $z1<z<z2$ are changed to simply-deformable (Sdef) or may have material and constitutive numbers changed.

Cycle n

Do n time-steps (cycle 0 is permitted as a check on data).

DAmping fcrit freq Mass
Stiffness
Internal

Viscous damping is applied in the form of Rayleigh damping. fcrit is the fraction of critical damping and freq is the center frequency. If a qualifier is not given as the third parameter, full damping is used. The word "Mass" eliminates the stiffness-proportional dashpots, and "Stiffness" eliminates the mass-proportional dashpots. The word "Internal" causes the specific damping to be applied to the 3 internal degrees of freedom of simply-deformable blocks.

Dump n m

Dump memory to printer from the main array from address n to address m. Internal pointers MFREE, JUNK, IBPNT and ICPNT are also printed. MFREE gives the highest memory location that is currently free.

End

Last input command.

FRAction f

f is taken as the fraction of critical time-step to be used.

Gravity gx gy gz

Gravitational accelerations are set for the x-, y- and z-directions.

Print Blocks Faces Velocities VERtices Contacts

Data are printed on blocks, faces, block velocities, vertices and contacts, respectively.

PROperty Material n keyword value

n

The first parameter must be the specification of the material number. Material properties are defined for material number n.

Property keywords are:

Bulk(orK)	bulk modulus
G	shear modulus
Density	density
KN	contact normal stiffness
KS	contact shear stiffness
Cohesion	contact cohesion
Friction	contact friction coefficient
JKN	joint normal stiffness
JKS	joint shear stiffness
Jcoh	joint cohesion
JFric	joint friction coefficient

Restart

The program is restarted using data from the restart file.

RSet v ia ioff

The real value v is inserted in the main array at address ia, with offset ioff.

SAve

The current problem state is saved on the restart file.

STArt

The program does a cold start.

Stop

The run stops.

Program Guide

Parameters and Data Group

Offsets for block data array

Note: The first integer in each block array (offset 0) is the block type number, as follows:

1 rigid block
2 simply-deformable block

KB	Pointer to next block in block list.
KF	Pointer to one face in block's face list.
KMAT	Material number.
KCONS	Constitutive number.
KRCOD	Code number: 0 free block 1 fixed block
KCEN	Start of triple pointer to x,y,z coordinates of block centroid.
KXD	Start of triple pointer to x,y,z components of velocity.
KTD	Start of triple pointer to x,y,z components of angular velocity (counterclockwise positive).
KVOL	Block volume.
KBM	Block mass.
KBI	Start of triple pointer to moment of inertia about x,y and z axes.
KBFX	Start of triple pointer to x,y,z components of block centroid force sum.
KBFT	Start of triple pointer to x,y,z components of block centroid moment sum.
KXL	Start of triple pointer to x,y,z components of load applied to block centroid.
KBEX	Extension pointer (to SDEF data)
KV	Pointer to one vertex in block's vertex list
KC	Pointer to block's contact list

Offsets for face data array

Note: The first integer (offset 0) contains the value MFAC to denote a face.

KNF	Pointer to next face on this block.
KNB	Pointer to host block.
KF1	Pointer to first connecting face.
KF2	Pointer to second connecting face.

```
KF3    Pointer to third connecting face.
KV1    Pointer to first vertex of this face.
KV2    Pointer to second vertex of this face.
KV3    Pointer to third vertex of this face.

Offsets for vertex data array
-----------------------------
Note: The first integer (offset 0) contains
----  the value NVER to denote a vertex.

KNV    Pointer to next vertex on this block
KVX    Start of triple pointer to x,y,z coordinates
       of vertex.

Offsets for contact data arrays
-------------------------------

Note: The first integer (offset 0) contains
----  the value NCON to denote a contact

KNC    Pointer to next contact in global list
KCB1   Block 1 of block pair
KCB2   Block 2 of block pair
KCN1   Pointer to next contact in block-1's list
KCN2   Pointer to next contact in block-2's list
KCCOD  Code number
             (above offsets shared by degenerate contact)
KCV1   Nearest vertex on block-1
KCVEE1 2nd. vertex, block-1, for edge-edge contact
KCV2   Nearest vertex on block-2
KCVEE2 2nd. vertex, block-2, for edge-edge contact
KCX    coordinate vector (triple)
KCNORM unit normal vector (triple)
KCFN   normal force (scalar)
KCFS   shear force vector (triple)

Logical unit numbers
--------------------

LUNIF  Unit number for input file.
LUNOF  Unit number for output file.
LUNC   Unit number for general I/O (e.g. restart).
LUNP   Unit number for plotted output.
```

Number of words in data arrays

NWBL Block
NWFR Face
NWVR Vertex
NWCN Contact
NWDC Degenerate contact

Array limits

MTOP Size of main array (IA).
NMAT Maximum number of materials.
NCONS Maximum constitutive numbers.
NTYP Number of block types (rigid, SDEF, etc.)

Head codes (contents of first integer in data groups)

MRIG = 1 Rigid block
MSDEF = 2 Simply-deformable block
MFAC Face
MVER Vertex
MCON Contact

Contact codes

MCEE edege-to-edge
MCVF vertex-to-face
MCDC degenerate

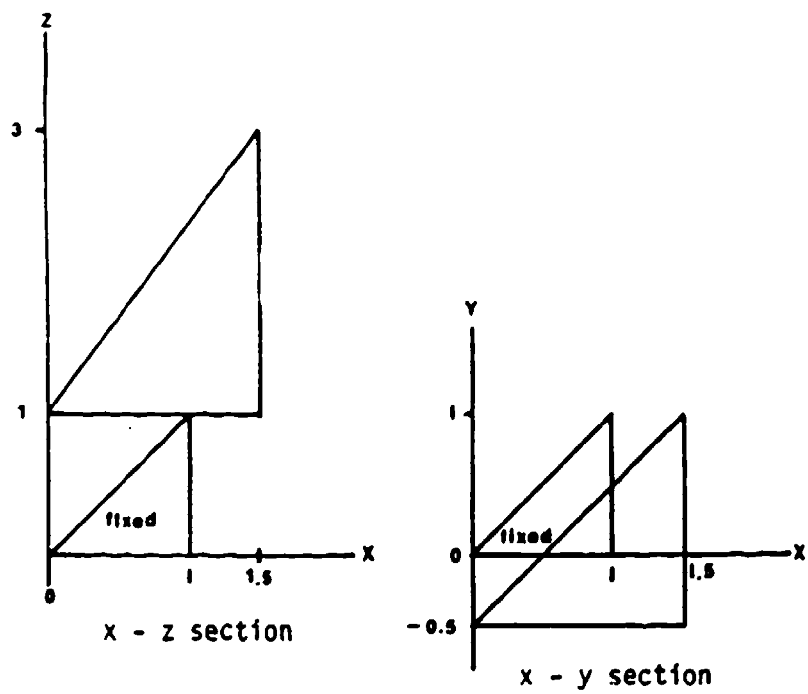
Main Common Block Variables

LINE(80)	Buffer for current input line in A1 format.
LINE1(80)	Buffer for next input line.
LPNT(I)	Pointer to start of parameter I in LINE( ) after removal of blanks, etc.
VNULL(3)	vector of zero length
ERFLAG	.TRUE. if an error has occured.
STFLAG	.TRUE. if the first input line has been processed.
COFLAG	.TRUE. if the current line is a continuation.
NCFLAG	.TRUE. if the next line is a continuation.
JMPSAV	Index of last computed GOTO in MON.
NERR	Error number.
JUNK	Pointer to list of spare memory groups.
MFREE	First unused memory address.
IBLOCK	Current block number.
ISTACK	Stack pointer.

NCYC	Currently requested number of cycles.
NCTOT	Total number of cycles.
TDEL	Time-step.
FRAC	Requested fraction of critical time-step.
IROUTE	Routing number, used in main routine.
NLINE	Output line count.
NPAGE	Output page count.
JMPGEN	Routing number for continuation line in GEN.
ALPHA	Mass damping coefficient.
BETA	Stiffness damping coefficient.
CON1	Damping factor (1.0-ALPHA*TDEL/2.0)
CON2	Damping factor (1.0/(1.0+ALPHA*TDEL/2.0))
BDT	BETA/TDEL
ALPB	Internal mass damping coefficient for simply-deformable blocks.
C1B	Damping factor (1.0-ALPB*TDEL/2.0)
C2B	Damping factor (1.0/(1.0+ALPB*TDEL/2.0))
DEGRAD	PI/180
PI	3.14159
ATOL	Distance between particles at which a real contact is formed.
CTOL	
DTOL	Distance between particles at which a degenerate contact is formed
ETOL	
FTOL	
IBPNT	Pointer to list of blocks.
ICPNT	Pointer to list of contacts.
AKN(I)	Normal contact stiffness, material I.
AKS(I)	Shear contact stiffness, material I.
AMU(I)	Contact friction coefficient, material I.
COH(I)	Contact cohesion, material I.
AKNJ(I)	Joint normal stiffness, material I.
AKSJ(I)	Joint shear stiffness, material I.
AMUJ(I)	Joint friiction coefficient, material I.
COHJ(I)	Joint cohesion, material I.
DENS(I)	Density, material I.
BULK(I)	Bulk modulus, material I.
SHEAR(I)	Shear modulus, material I.
ALAM1(I)	Lame constant, material I.
ALAM2(I)	Lame constant, material I.
GRAV(3)	vector of gravitational acceleration.
A( )	Main array.

Sample Problem

Two tetrahedral blocks are created. The lower block is fixed, and the upper block allowed to come into contact with the upper vertex of the fixed block. Gravity acts in the -z direction. Since the centroid of the upper block is not directly above the fixed vertex, the block translates and rotates, and develops shear forces at the contact as well as a normal force.



a. Initial State

Figure B1. D3 Sample Problem

```
START
PROP MAT=1 D=2000 KN=1E8 KS=.5E8 F=1.0
BLOCK MAT=1 (0,0,0) (1,0,0) (1,1,0)
+ (1,0,0) (1,0,1) (1,1,0)
+ (0,0,0) (1,1,0) (1,0,1)
+ (1,0,0) (0,0,0) (1,0,1)
BLOCK MAT=1 (0,-0.5,1) (1.5,-0.5,1) (1.5,1,1)
+ (1.5,-0.5,1) (1.5,-0.5,3) (1.5,1,1)
+ (0,-0.5,1) (1.5,1,1) (1.5,-0.5,3)
+ (0,-0.5,1) (1.5,-0.5,3) (1.5,-0.5,1)
FIX 0 1 0 1 0 1
GRAV 0 0 -10
CYC 1
PRINT CON VEL
CYC 5
PRINT CON VEL
CYC 10
PRINT CON VEL
STOP
END
```

INPUT FILE

```
>START
                                        --------------------------------------------
                                        PROGRAM 3D: TEST-BED 3-D DISTINCT ELEMENT CODE
                                        --------------------------------------------
THIS IS A START RUN
>PROP MAT=1 D=2000 KN=1E8 KS=.5E8 F=1.0
>BLOCK MAT=1 (0,0,0) (1,0,0) (1,1,0)
>+ (1,0,0) (1,0,1) (1,1,0)
>+ (0,0,0) (1,1,0) (1,0,1)
>+ (1,0,0) (0,0,0) (1,0,1)
>BLOCK MAT=1 (0,-0.5,1) (1.5,-0.5,1) (1.5,1,1)
>+ (1.5,-0.5,1) (1.5,-0.5,3) (1.5,1,1)
>+ (0,-0.5,1) (1.5,1,1) (1.5,-0.5,3)
>+ (0,-0.5,1) (1.5,-0.5,3) (1.5,-0.5,1)
>FIX 0 1 0 1 0 1
>GRAV 0 0 -10
>CYC 1
        TIMESTEP =  2.582E-04
        CURRENT CYCLE COUNT =      1
>PRINT CON VEL
CONTACT     TYPE       BLOCK-1 BLOCK-2      X(1)       X(2)       X(3)      FS(1)      FS(2)      FS(3)         FN
   184 (VERTEX-EDGE)       1      89  1.000E+00  0.000E+00  1.000E+00  0.000E+00  0.000E+00  0.000E+00  6.667E+01
   177 (DEGENERATE)       89       1
 BLOCK  CODE     UXDOT      UYDOT      UZDOT      TXDOT      TYDOT      TZDOT
    89     0  0.000E+00  0.000E+00 -2.582E-03  0.000E+00  0.000E+00  0.000E+00
     1     1  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
>CYC 5
        TIMESTEP =  2.582E-04
        CURRENT CYCLE COUNT =      6
>PRINT CON VEL
CONTACT     TYPE       BLOCK-1 BLOCK-2      X(1)       X(2)       X(3)      FS(1)      FS(2)      FS(3)         FN
   184 (VERTEX-EDGE)       1      89  1.000E+00  0.000E+00  1.000E+00  6.424E-01 -6.424E-01  0.000E+00  1.379E+03
   177 (DEGENERATE)       89       1
 BLOCK  CODE     UXDOT      UYDOT      UZDOT      TXDOT      TYDOT      TZDOT
    89     0  8.883E-08 -8.883E-08 -1.509E-02  4.979E-05  4.979E-05  0.000E+00
     1     1  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
>CYC 10
        TIMESTEP =  2.582E-04
        CURRENT CYCLE COUNT =     16
>PRINT CON VEL
CONTACT     TYPE       BLOCK-1 BLOCK-2      X(1)       X(2)       X(3)      FS(1)      FS(2)      FS(3)         FN
   184 (VERTEX-EDGE)       1      89  1.000E+00  0.000E+00  1.000E+00  2.653E+01 -2.653E+01  0.000E+00  8.169E+03
   177 (DEGENERATE)       89       1
 BLOCK  CODE     UXDOT      UYDOT      UZDOT      TXDOT      TYDOT      TZDOT
    89     0  1.307E-05 -1.307E-05 -3.295E-02  9.141E-04  9.141E-04  0.000E+00
     1     1  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
>STOP
```