

2

MISCELLANEOUS PAPER SL-85-1



US Army Corps of Engineers

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

by

Peter A. Cundall, Roger D. Hart

Itasca Consulting Group, Inc.
PO Box 14806
Minneapolis, Minnesota 55414

AD-A153 927



DTIC ELECTE
MAY 17 1985
S B

January 1985

Final Report

Approved For Public Release Distribution Unlimited

DTIC FILE COPY

DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Contract No. DACA 39-82-C-0015

Structures Laboratory
US Army Engineer Waterways Experiment Station
PO Box 631, Vicksburg, Mississippi 39180-0631



**Destroy this report when no longer needed. Do not return
it to the originator.**

**The findings in this report are not to be construed as an official
Department of the Army position unless so designated
by other authorized documents.**

**The contents of this report are not to be used for
advertising, publication, or promotional purposes.
Citation of trade names does not constitute an
official endorsement or approval of the use of
such commercial products.**

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper SL-85-1	2. GOVT ACCESSION NO. AD-A153977	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEVELOPMENT OF GENERALIZED 2-D AND 3-D DISTINCT ELEMENT PROGRAMS FOR MODELING JOINTED ROCK		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Peter A. Cundall Roger D. Hart		8. CONTRACT OR GRANT NUMBER(s) Contract No. DACA 39-82-C-0015
9. PERFORMING ORGANIZATION NAME AND ADDRESS Itasca Consulting Group, Inc. PO Box 14806 Minneapolis, Minnesota 55414		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS DEPARTMENT OF THE ARMY US Army Corps of Engineers Washington, DC 20314-1000		12. REPORT DATE January 1985
		13. NUMBER OF PAGES 79
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) US Army Engineer Waterways Experiment Station Structures Laboratory PO Box 631, Vicksburg, Mississippi 39180-0631		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Rock deformation--Simulation methods (LC) Joints (Geology) (LC) Data structure (Computer science) (LC) Numerical calculations--Computer programs (LC) Block designs (LC) Universal Distinct Element Code (UDEC) (WES)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) 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 (Continued)		

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

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.

*1975-76 Key word: Implosion, rock mechanics,
1975-76 (Implosion Distinct Element Code);
1975-76 (Implosion Distinct Element Code);*

A

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

TABLE OF CONTENTS

	<u>Page</u>
PREFACE	i
PART I: INTRODUCTION	1
Background	1
Scope of Present Study	2
PART II: IMPROVEMENT AND EXTENSION OF UDEC	4
Work Items	4
Data Structure	4
PART III: APPROACH TO THREE-DIMENSIONAL MODELING	11
Introduction	11
Block Characteristics	11
Physical Calculations	15
Contact Characteristics and Detection	18
Data Structure	21
PART IV: CONCLUSIONS	28
Program UDEC	28
Program D3	28
APPENDIX A: UNIVERSAL DISTINCT ELEMENT CODE (VERSION 1.2) USER'S MANUAL	A1
Introduction	A1
Improvements to UDEC	A2
Input Commands	A8
Program Guide	A13
Sample Problems	A19
APPENDIX B: THREE-DIMENSIONAL DISTINCT ELEMENT TEST-BED CODE (VERSION 1.0) USER'S MANUAL	B1
Introduction	B1
Input Commands	B1
Program Guide	B4
Sample Problem	B8

LIST OF ILLUSTRATIONS

	<u>Page</u>
Figure 1. Linked Lists for Main Data Arrays	6
Figure 2. Block Pointers and Reverse Corner Links	7
Figure 3. Domain Linkages	8
Figure 4. Convention Used for Pointers Within a Contact Array	9
Figure 5. Structure of 'Junk List' Holding Redundant Groups of Memory	10
Figure 6. Vectors Describing Triangular Area, a	13
Figure 7. Normal Vector Contours for 3-D Contact Detection	19
Figure 8. Global Block and Contact Lists	23
Figure 9. Lists Associated with Each Block	24
Figure 10. Pointers Associated with Each Face	25
Figure 11. Pointers and Lists Associated with Each Contact	27
Figure A1. UDEC Sample Problem No. 1	A20
Figure A2. UDEC Sample Problem No. 2	A23
Figure A3. UDEC Sample Problem No. 3	A27
Figure A4. UDEC Sample Problem No. 4	A32
Figure B1. D3 Sample Problem	B8

DEVELOPMENT OF GENERALIZED 2-D AND 3-D

DISTINCT ELEMENT PROGRAMS FOR

MODELING JOINTED ROCK

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.

* 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 explicitly 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.

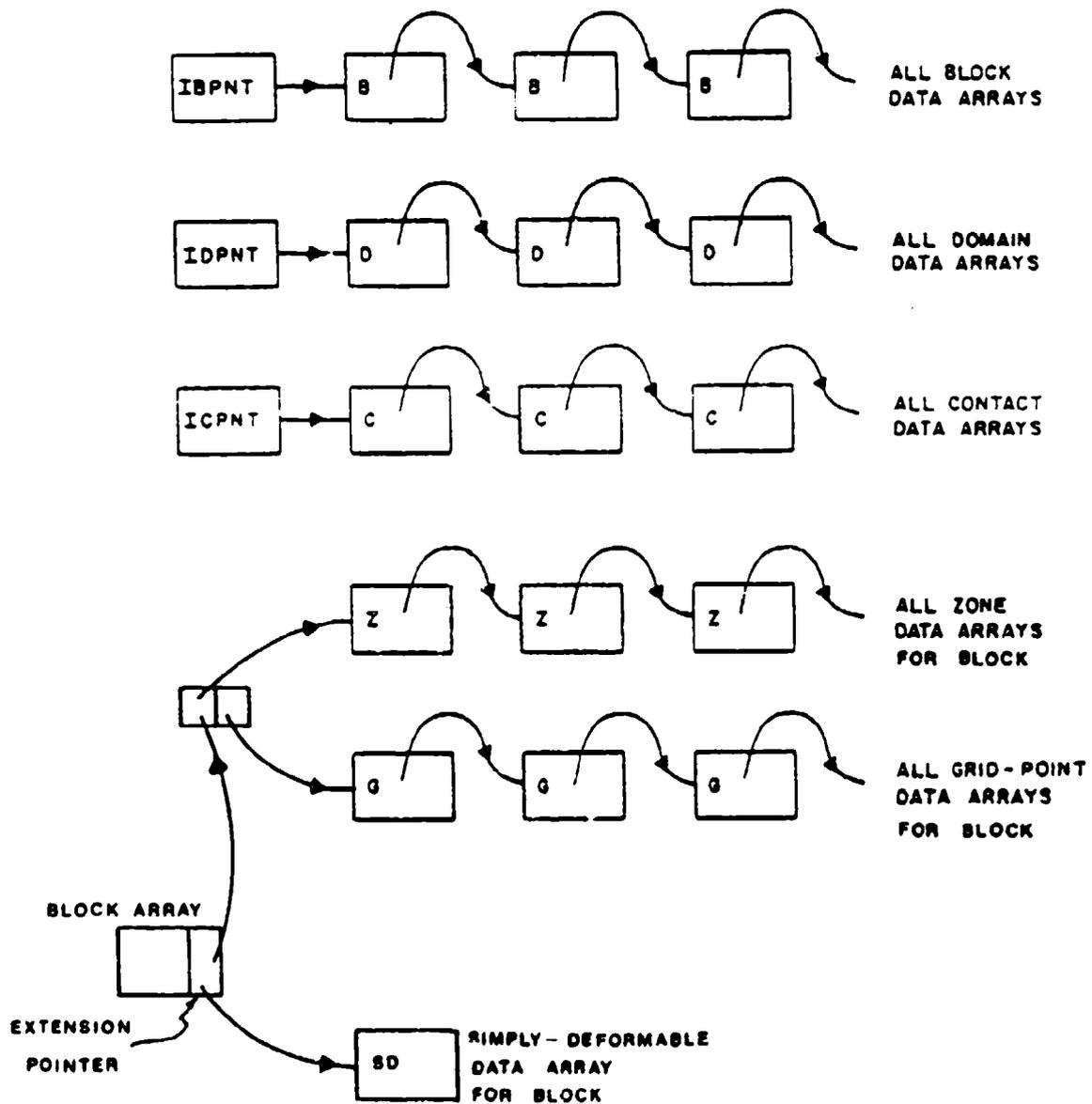


FIGURE 1: LINKED LISTS FOR MAIN DATA ARRAYS

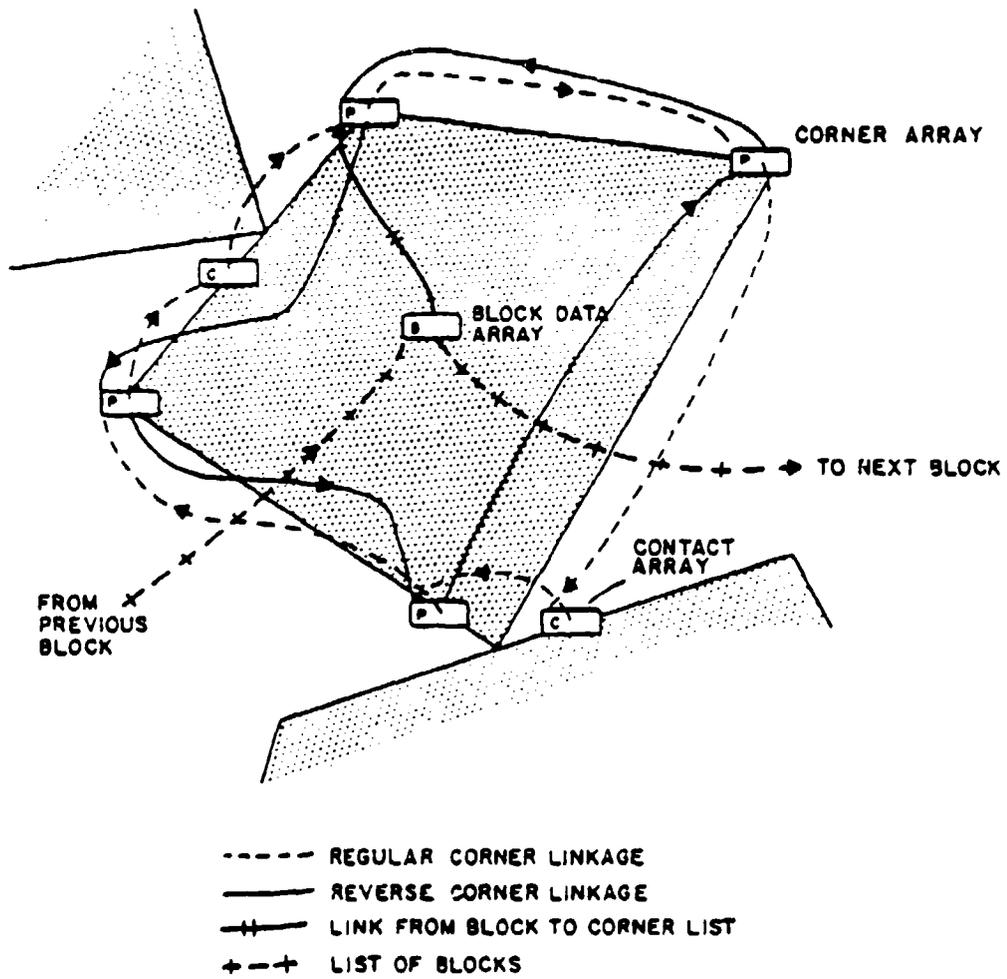


FIGURE 2: BLOCK POINTERS AND REVERSE CORNER LINKS

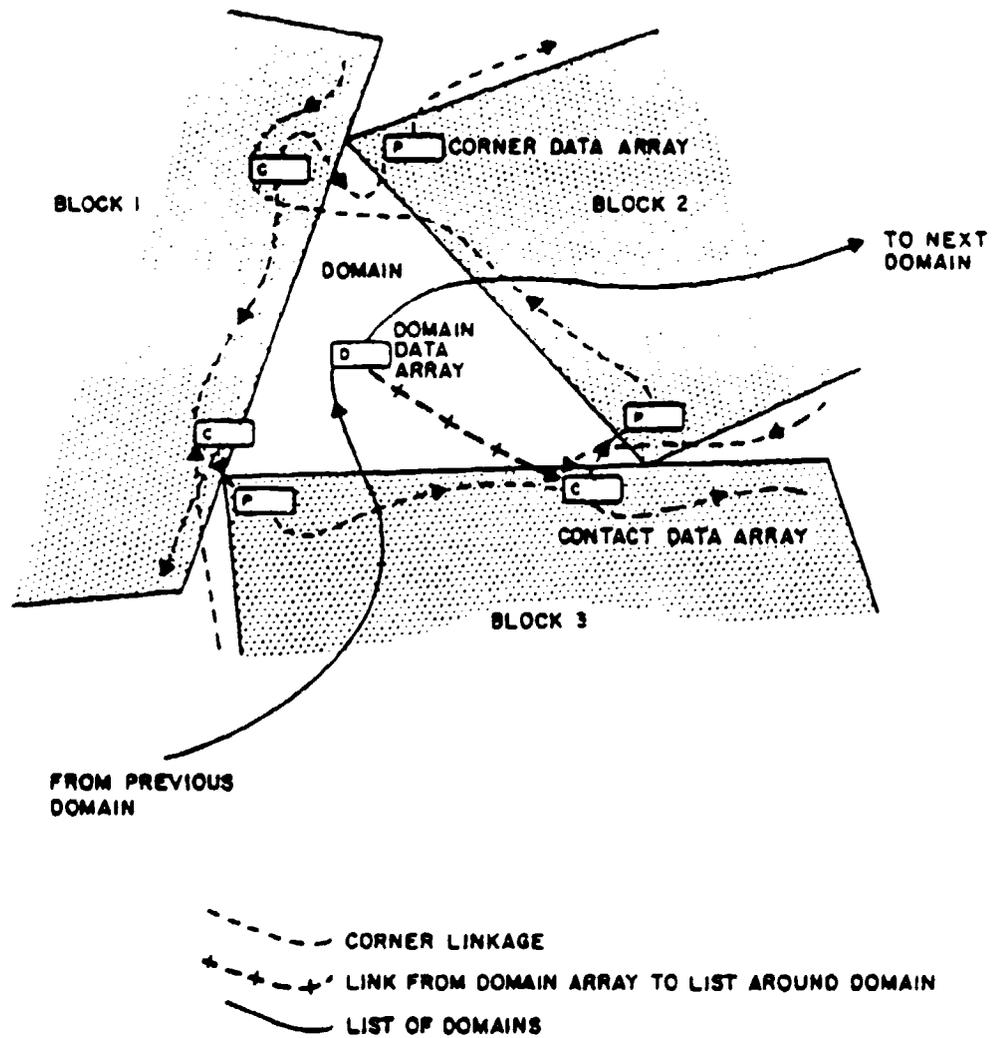
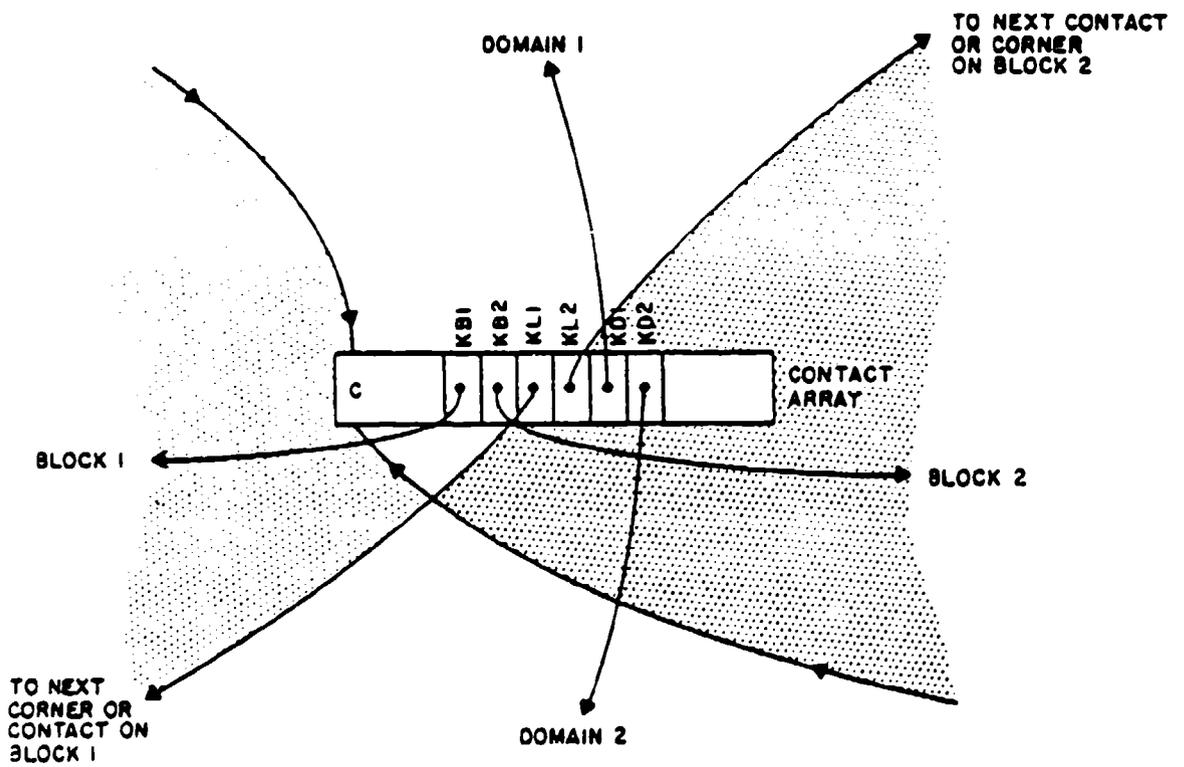


FIGURE 3: DOMAIN LINKAGES



NOTE: KB1, KB2 — KD2 REFER TO THE OFFSETS LISTED IN APPENDIX III

FIGURE 4: CONVENTION USED FOR POINTERS WITHIN A CONTACT ARRAY

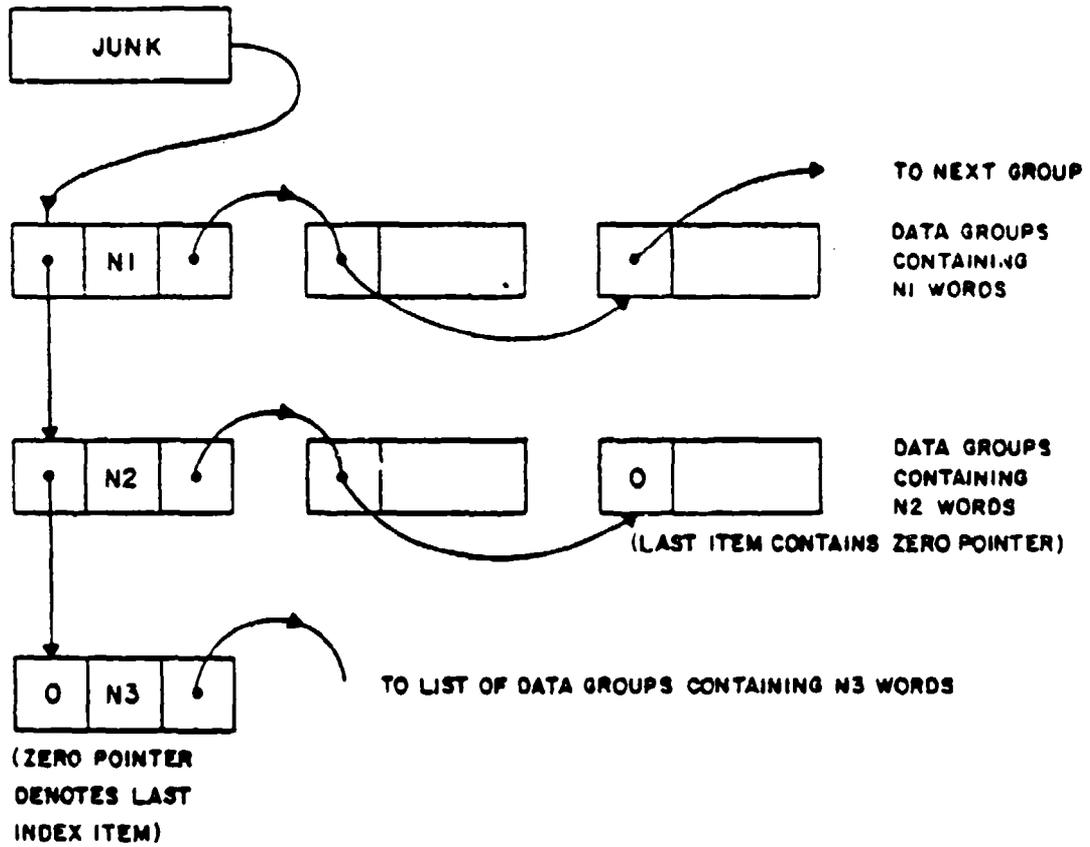


FIGURE 5: STRUCTURE OF 'JUNK LIST' HOLDING REDUNDANT GROUPS OF MEMORY.

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:

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

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,

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

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

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

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

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

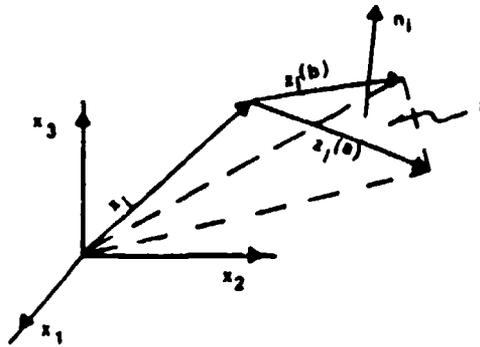


FIGURE 6: VECTORS DESCRIBING TRIANGULAR AREA •

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:

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

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:

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

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:

$$\frac{1}{2} \bar{r}^2 m \quad (8)$$

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:

$$m\ddot{u}_i + \alpha m\dot{u}_i = \Sigma F_i \quad (9)$$

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

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:

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

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:

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

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

where n_i is the contact normal.

Normal and shear force increments are then calculated as follows:

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

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

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:

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

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

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

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

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.

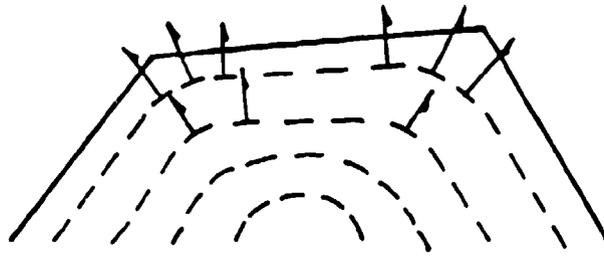


FIGURE 7: NORMAL VECTOR CONTOURS FOR 3-D CONTACT DETECTION

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-

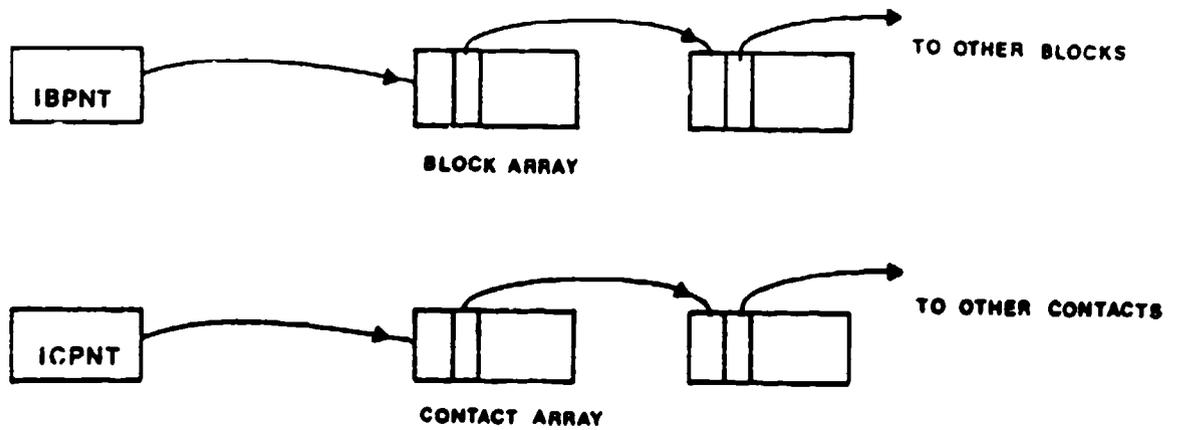


FIGURE 8 : GLOBAL BLOCK AND CONTACT LISTS

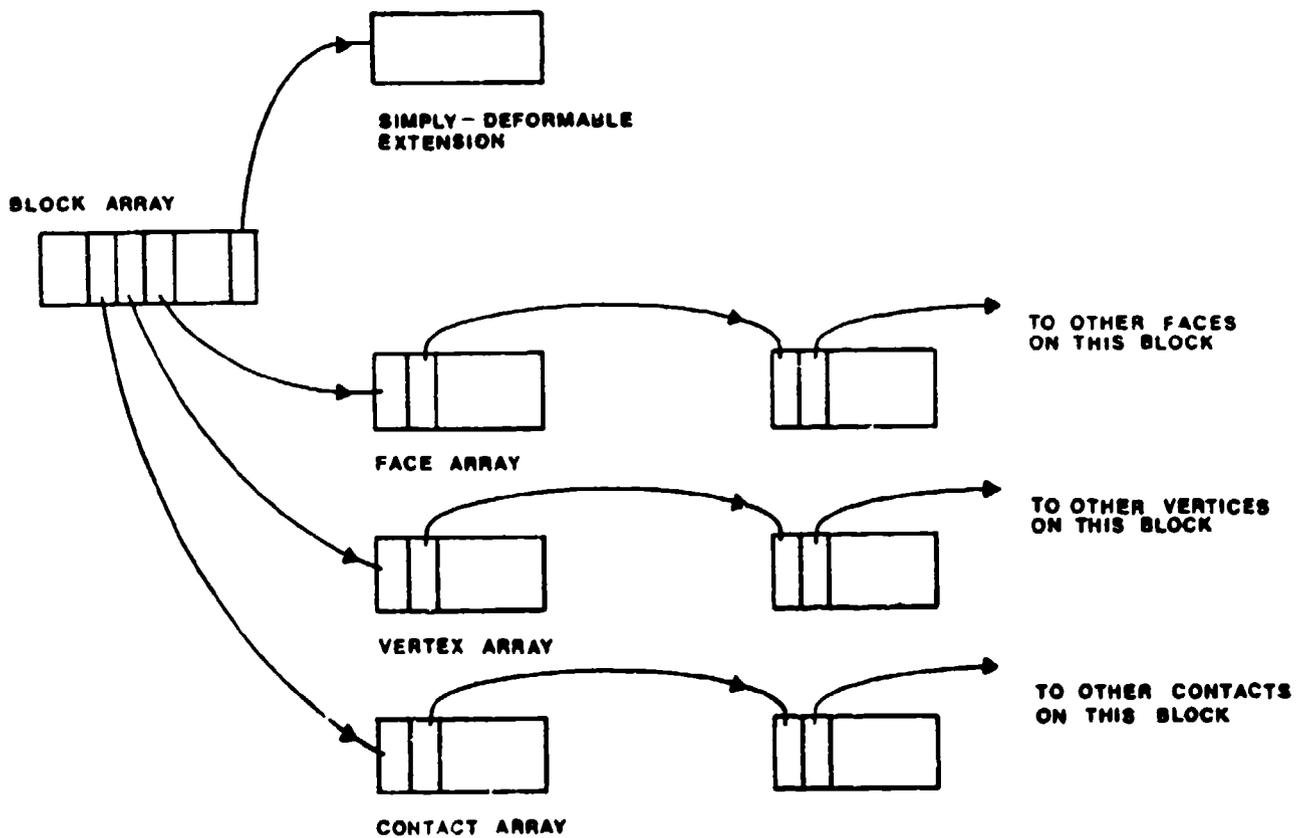


FIGURE 9 : LISTS ASSOCIATED WITH EACH BLOCK

F : NEIGHBORING FACE

V : VERTEX

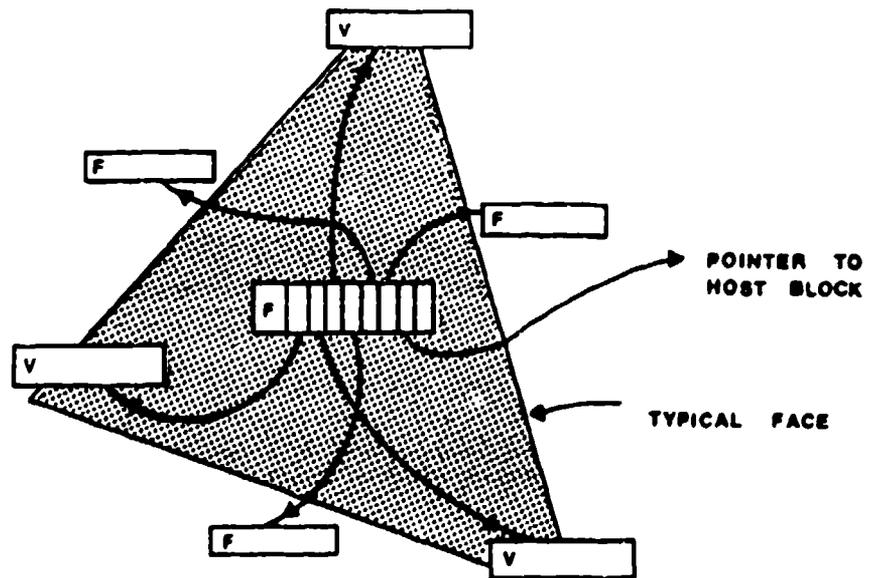


FIGURE 10 : POINTERS ASSOCIATED WITH EACH FACE

files 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.

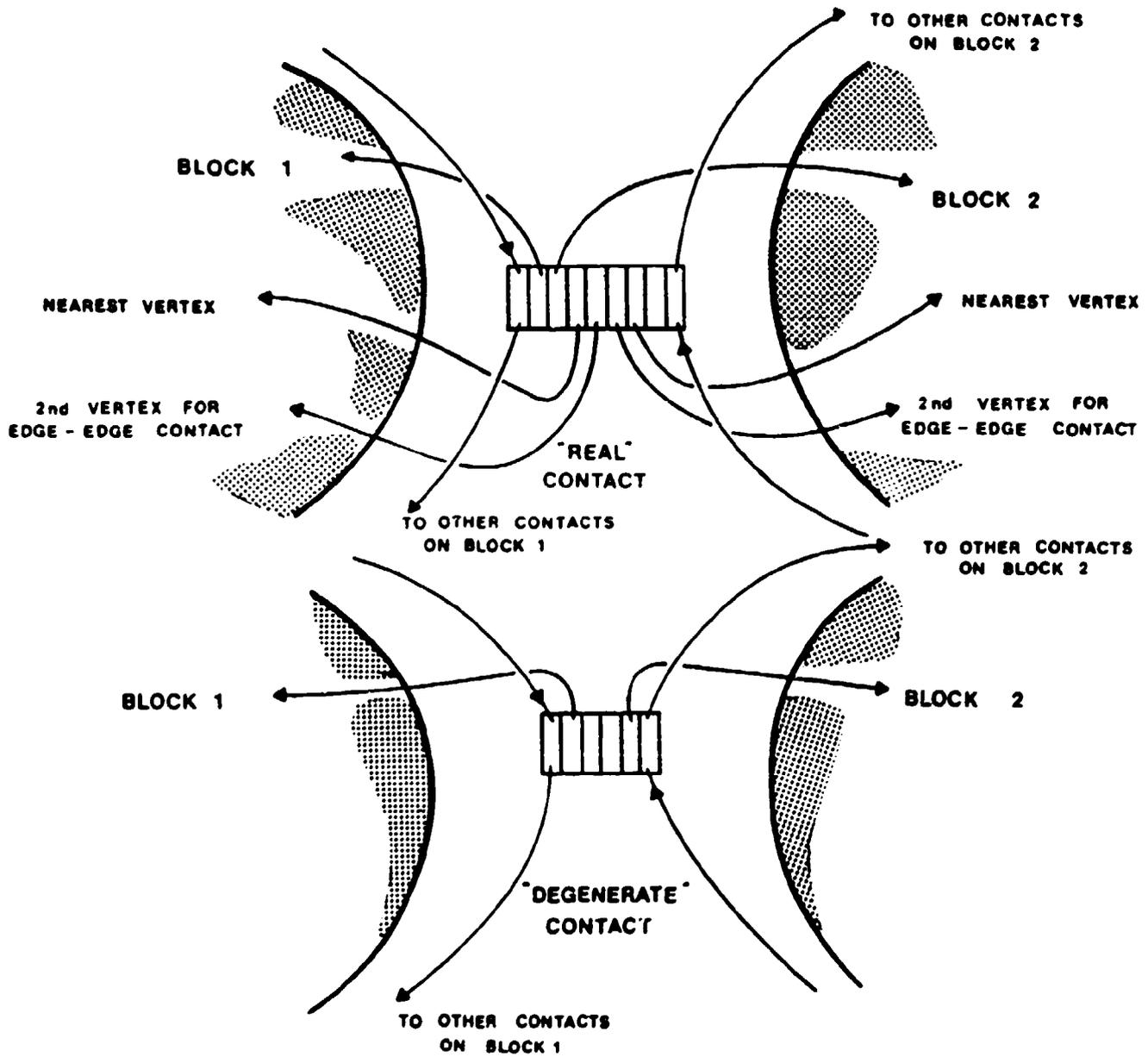


FIGURE 11 : POINTERS AND LISTS ASSOCIATED WITH EACH CONTACT

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 (UDEEC) and supplements the original report "UDEEC - 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 UDEEC 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 UDEEC are given in the next section.

3. The modifications to UDEEC 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 UDEEC and an updated program guide. Input and output files are presented for sample problems which illustrate the use of the improvements to UDEEC.

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

$$a_j = \max(a_{res}, a_0 - \text{strn}' / \text{sn}_j)$$

where a_{res} is the residual displacement (fully closed),
 a_0 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 , a_{res} and a_0 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:

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

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 $A_d(\text{min})$, which may be set by the user; otherwise it will default a small fraction of average block areas. For regular domains, $A_d(\text{min})$ 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, ρ_{flow} , 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, t_f , 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:

$$t_f = \frac{(f_1 + f_2)}{2d^2}$$

where f_1 and f_2 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 t_f . 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:

$$t_f = s_{p1} \quad \text{if } 3s_{p1} + s_{p2} > 0$$

and

$$t_f = \frac{-(s_{p1} - s_{p2})^2}{8(s_{p1} + s_{p2})} \quad \text{if } 3s_{p1} + s_{p2} < 0$$

where s_{p1} is the maximum principal stress in the SDEF block,

s_{p2} is the minimum principal stress in the SDEF block,

t_f 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 s_{p2} 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		Contacts
	Deformation Law	Cracking Law	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 $x_1 < x < x_2$, $y_1 < y < y_2$

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 $x_1 < x < x_2$, $y_1 < y < y_2$.

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 $x_1 < x < x_2$, $y_1 < y < y_2$.
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 $x_1 < x < x_2$, $y_1 < y < y_2$ 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:

$x_1 y_1 x_2 y_2 x_3 y_3 \dots$,

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

$l_1 m_1 n_1 l_2 m_2 n_2 \dots$

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 $g_x g_y$

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

Link $x_1 y_1 x_2 y_2$

Links a flying block to the main data structure. (x_1, y_1) are the coordinates of any point inside the flying block and (x_2, y_2) 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.

(x_1, y_1) and (x_2, y_2) should be chosen close to the blocks' centroid locations to ensure correct linkage.

Load $x_1 x_2 y_1 y_2 x_{load} y_{load}$

All blocks with centroids lying within the range $x_1 < x < x_2$, $y_1 < y < y_2$

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 x2 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.

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
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.

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

KC Pointer to next grid-point in grid-point list.
KCOR Pointer to corresponding block corner.
KXG x coordinate.
KYG y coordinate.
KXDC x velocity.
KYDC y velocity.
KCFX x force-sum.
KCFY y force-sum.
KCPM grid-point mass.

Offsets for zone data

KZ Pointer to next zone in zone list.
KZC 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.
LUNC 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.
NTIP 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 occurred.
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.
JMPCEN	Routing number for continuation line in GEN.
ALPHA	Mass damping coefficient.
BETA	Stiffness damping coefficient.
CON1	Damping factor $(1.0 - \text{ALPHA} * \text{TDEL} / 2.0)$
CON2	Damping factor $(1.0 / (1.0 + \text{ALPHA} * \text{TDEL} / 2.0))$
BDT	BETA/TDEL
ALPB	Internal mass damping coefficient for simply-deformable blocks.
C1B	Damping factor $(1.0 - \text{ALPB} * \text{TDEL} / 2.0)$
C2B	Damping factor $(1.0 / (1.0 + \text{ALPB} * \text{TDEL} / 2.0))$
DECRAD	$\text{PI} / 180$
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	$\text{DTOL} / 2.0$ (maximum contact overlap)
ETOL	Limit on maximum domain displacement to trigger contact update.
FTOL	Total area of blocks for setting plotting scale factor.
CTOL	
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 friction 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.
CRAVX	x component of gravitational acceleration.
CRAVY	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
- PPGEN
- PPDIS
- CONSCN
- CRKSCN
- DOMSCN
- CEN

Sample Problems

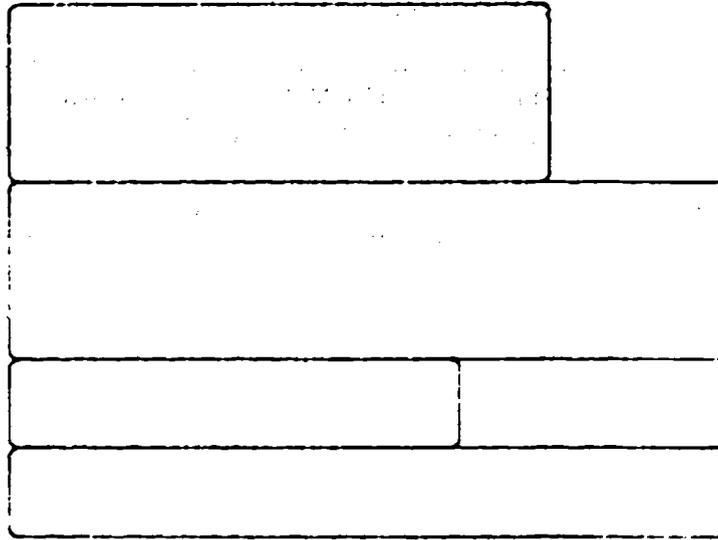
The following four sample problems illustrate the improvements made to UDEC.

- No. 1 Single point-load cracking
- No. 2 Pressurized cavity
- No. 3 Complex block deformation
- No. 4 Projectile breaking beam

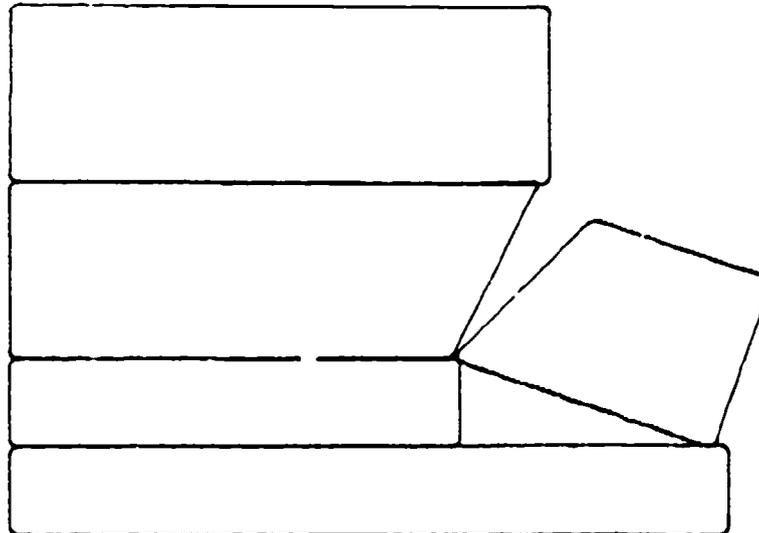
The printed output for each problem should be used to provide a check that the program is performing correctly.

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 RAT=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
*IND 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 KH=1E8 KS=1E8 P=2 TF=2.5E4
)ORIG 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)												

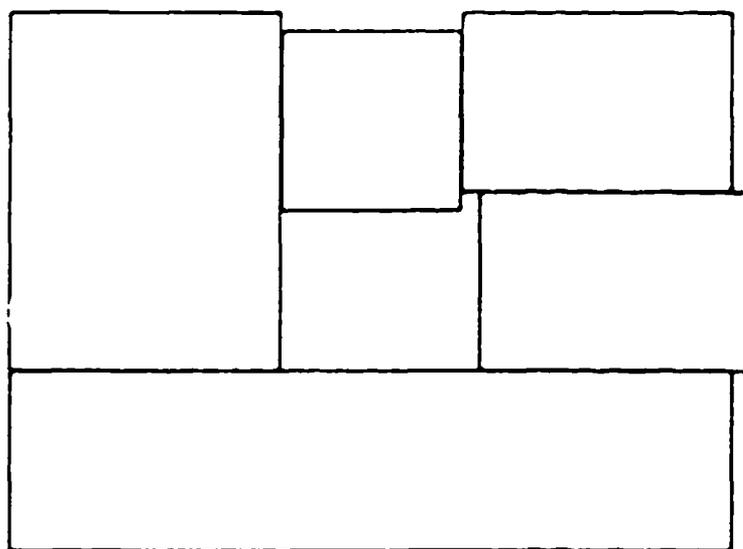
CONTACT DATA

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=1.0E8 KS=1.0E8 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 CONG=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.
PFX 69 0.0
LGAD 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 ID=1.E08 KS=1.E08 F=0.5

)PROP MAT=1 CPERM=1E-9

)FLUID 0.0 1.0E9

)DAMP .5 16. MAGE

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.

)PFX 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	0.000E+00	4.800E-01	1.160E-02

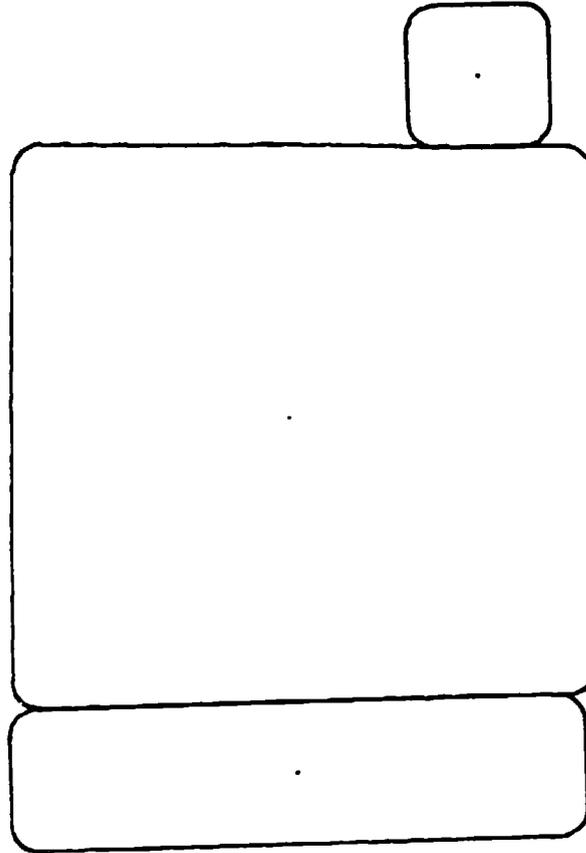
(OUTER
BOUNDARY)

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	6.500E+03	-3.254E+03	1.555E+03
(RIGID)												
301	1	1	3.355E+01	1.500E+01	3.000E+05	8.125E+06	3.857E-02	-2.511E-09	-7.424E-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	-1.850E+04	-1.704E+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	3.045E+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	5.284E-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 C=1E6 BULK=2E6
PROP MAT=2 D=10000 KN=1E8 KS=1E8 FRIC=.1 C=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
```

PROBLEM NO. 3 INPUT FILE

)/STAKT

PROGRAM UDEC: UNIVERSAL DISTINCT ELEMENT CODE (VERSION 1.2)

```

THIS IS A START RUN
)/PROP MAT=1 D=2000 KM=1E8 KS=1E8 FRIC=.1 C=1E6 BULK=2E6
)/PROP MAT=2 D=10000 KM=1E8 KS=1E8 FRIC=.1 C=1E8 BULK=1E8
)/ROUND = 0.2
)/BLOCK 2,2 2,8 4,8 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 4 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
)/FTX 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	POL. MOM.	X,Y,THETA VELOCITIES			X,Y,THETA FORCES		
195	1	1	4.000E+00	2.500E+00	3.000E+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	4.194E+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

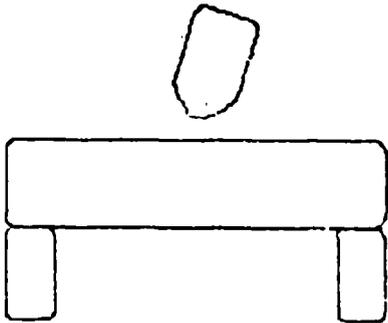
ZONE	GRID-POINTS			SIGMA-11	SIGMA-12	SIGMA-22	MASS
1237	411	642	897	1.736E+03	1.466E+02	7.710E+03	5.000E+02
1246	483	495	897	1.222E+04	3.225E+03	-3.302E+02	5.000E+02
1255	411	897	495	6.214E+03	2.237E+03	1.292E+04	5.000E+02
606	456	807	615	4.303E+03	-1.475E+03	-1.838E+04	5.000E+02
1264	483	615	807	1.927E+04	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	-3.458E+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

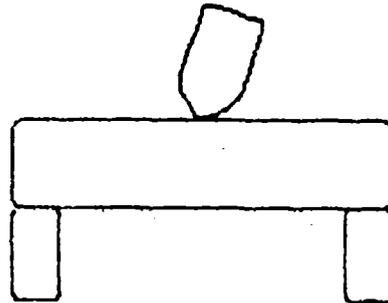
)STOP

Sample Problem No. 4

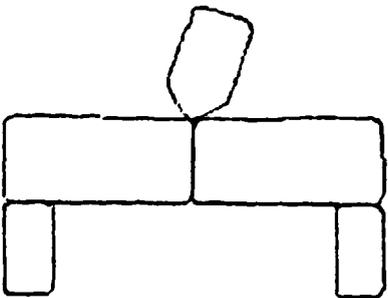
A projectile hits a beam and breaks it into two (fracture based on Griffith theory).



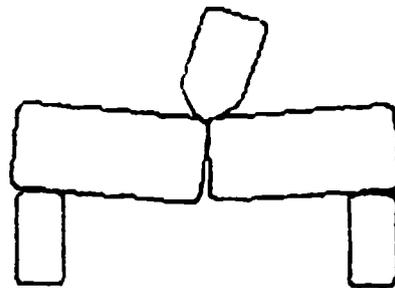
a. Initial State



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=1.0E8 KS=1.0E8 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 3.,3.35 3.,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 2.8,3.5 4,3.05
DELETE 1,2.5 1.9,3.3
DELETE 3.75,5 1.9,3.3
DELETE 2.8,3.4 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 -0.2E4 -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

```

Best Available Copy

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	POL. 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
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	8.651E-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 536, BLOCK 500, R-LINK 532
 CONTACT 166, BLOCK1 1373, BLOCK2 500 EDGE/CORNER
 CORNER 120, BLOCK 500, R-LINK 536
 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
KCBN Start of triple pointer to x,y,z coordinates
of block centroid.
KCD 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.
KEM 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.
KCL 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.

KBF Pointer to next face on this block.
KBH Pointer to host block.
KFP1 Pointer to first connecting face.
KFP2 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 MVER to denote a vertex.

KWV 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 MCON to denote a contact

KWC 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)
KCFV shear force vector (triple)

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).
LUMP Unit number for plotted output.

Number of words in data arrays

NVBL Block
NVFR Face
NVVR Vertex
NVCH Contact
NVDC Degenerate contact

Array limits

NTOP 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)

NRIG = 1 Rigid block
NSDEF = 2 Simply-deformable block
NFAC Face
NVVR Vertex
NVCH Contact

Contact codes

NCEE edge-to-edge
NCFV vertex-to-face
NCDC degenerate

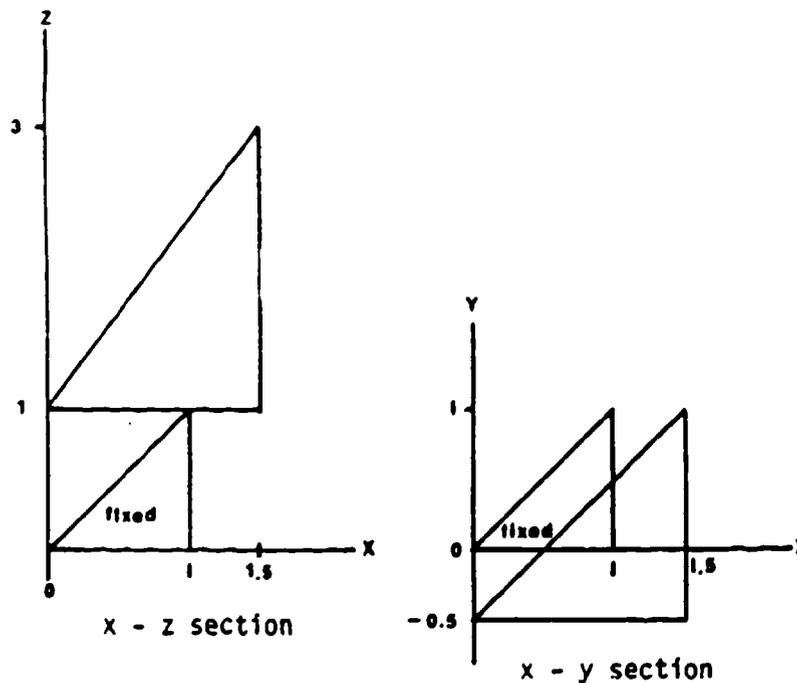
Main Common Block Variables

LINE(80) Buffer for current input line in AI 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 occurred.
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.
JNPSAU Index of last computed GOTO in MON.
NERR Error number.
JUNK Pointer to list of spare memory groups.
NFREE 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.
JRPGEN	Routing number for continuation line in GEN.
ALPHA	Mass damping coefficient.
BETA	Stiffness damping coefficient.
CON1	Damping factor $(1.0 - \text{ALPHA} * \text{TDEL} / 2.0)$
CON2	Damping factor $(1.0 / (1.0 + \text{ALPHA} * \text{TDEL} / 2.0))$
BOT	$\text{BETA} / \text{TDEL}$
ALPB	Internal mass damping coefficient for simply-deformable blocks.
C1B	Damping factor $(1.0 - \text{ALPB} * \text{TDEL} / 2.0)$
C2B	Damping factor $(1.0 / (1.0 + \text{ALPB} * \text{TDEL} / 2.0))$
DECRAD	$\text{PI} / 180$
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 friction 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.
GRW(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 EM=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 83: TEST-BED 3-8 DISTINCT ELEMENT CODE

THIS IS A START RUN

>PROP MAT=1 B=2000 IM=1EA KS=.5EA 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)	FM
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)	FM
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)	FM
184 (VERTEX-EDGE)		1	89	1.000E+00	0.000E+00	1.000E+00	2.653E+01	-2.653E+01	0.000E+00	8.149E+03
177 (DEGENERATE)		89	1							
BLOCK CODE	UXDOT	UYDOT	UZDOT	TXDOT	TYDOT	TZDOT				
89	0	1.307E-05	-1.307E-05	-3.395E-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			

>PROP