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IMPLEMENTATION OF ELASTIC-PLASTIC STRUCTURAL ANALYSIS INTO NASTRAN †

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SUMMARY

Elastic-plastic analytic capabilities have been incorporated into the NASTRAN program. The present implementation includes a general rigid format and additional bulk data cards as well as two new modules. The modules are specialized to include only perfect plasticity of the CTRMEM and CROD elements but can easily be expanded to include other plasticity theories and elements. The practical problem of an elastic-plastic analysis of a ship's bracket connection is demonstrated and compared to an equivalent analysis using Grumman's PLANS program. The present work demonstrates the feasibility of incorporating general elastic-plastic capabilities into NASTRAN.

INTRODUCTION

A feasibility study on incorporating state-of-the-art nonlinear capabilities into NASTRAN has been conducted and reported on in ref. 1. It was pointed out that each class of nonlinear behavior has a "best" solution strategy. For an elastic-plastic analysis, the "initial-strain" approach is the most efficient finite element analytic method. In this approach, an incremental pseudo-load vector is formulated assuming an initial strain equal to the sum of the estimated plastic strain for the current increment and an equilibrium correction term which corrects for the difference between the resulting plastic strain and assumed plastic strain of the previous incremental step. This method, characterized by the plastic behavior being incorporated into an incremental pseudo-load vector, leaves the stiffness matrix unaltered from step to step. Thus, the stiffness matrix need only be decomposed once. Consistent with the initial-strain approach, ref. 2 provides the pseudo-load vector formulation due to plastic behavior for a number of elements in the NASTRAN library. The general approach is to transfer the integral form of the pseudo-load vector into a numerical representation by utilizing various integration schemes. For many of the finite elements the choice of the number and type of integration points is left to the user. The choice of integration points for the integration of the pseudo-load vector determines the allowable variation of the plastic strain within each element. This allowable variation can be changed by choosing a different set of integration points. This may eliminate the costly process of changing the

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finite element idealization if the plastic strain variation was more complex than originally modeled for. One may only have to change the choice of integration points. A more complete discussion of these methods is given in ref. 3.

The initial-strain approach, as outlined above, has been incorporated into the NASTRAN program. This has been done by writing a new rigid format along with two new modules. Also included are three new bulk data cards. Although the methods are general, only perfectly-plastic behavior of a membrane and a rod element have been initially considered. This first step is sufficient to examine the feasibility and efficiency of the implemented techniques within the NASTRAN framework.

The practical problem of an elastic-plastic structural analysis of a ship's bracket connection has been carried out using the implemented NASTRAN program and the results have been compared to those obtained from the PLANS finite element computer program (ref. 4). The results are in exact agreement and the cpu time and associated costs are approximately the same.

ELASTIC-PLASTIC FORMULATION

The initial-strain method is chosen to solve small displacement plasticity problems. The governing equation, derived from energy principles, is written in incremental form as follows:

$$[K]\left\{\Delta U\right\}_i = \left\{\Delta P\right\}_i + \left\{\Delta Q\right\}_i + \left\{R\right\}_i \tag{1}$$

where

$[K]$ ≡ elastic stiffness matrix

$\left\{\Delta U\right\}_i$ ≡ incremental displacement of i^{th} step

$\left\{\Delta P\right\}_i$ ≡ incremental external load of i^{th} step

$\left\{\Delta Q\right\}_i$ ≡ incremental pseudo load based on predicted inelastic strain of i^{th}step

$\left\{R\right\}_i$ ≡ equilibrium correction term representing any balancing force due to drift from equilibrium during the incremental application of the load

The elastic stiffness matrix is found to be

$$[K] = \int [B]^T [E] [B] \, dV \tag{2}$$

where $[B]$ is obtained from the strain-displacement relation

$$\left\{\Delta e\right\}_i = [B]\left\{\Delta U\right\}_i \tag{3}$$

and [E] is obtained from the stress-strain relation

$$\left\{\Delta\sigma\right\}_i = [E]\left(\left\{\Delta e\right\}_i - \left\{\Delta\epsilon^P\right\}_i\right) \qquad (4)$$

with

$\left\{\Delta\sigma\right\}_i$ ≡ incremental stress

$\left\{\Delta e\right\}_i$ ≡ incremental total strain

$\left\{\Delta\epsilon^P\right\}_i$ ≡ incremental plastic strain

Plasticity enters the analysis through the increment in plastic strain, $\Delta\epsilon^P$. These as well as other path dependent quantities depend on the implemented plasticity theory.

The predicted pseudo-load vector for the $(i+1)^{st}$ step is found to be

$$\left\{\Delta Q\right\}_{i+1} = \frac{\delta_{i+1}}{\delta_i}\int [B]^T [E] \left\{\Delta\epsilon^P\right\}_i dV \qquad (5)$$

where δ_{i+1} and δ_i correspond to the $(i+1)^{st}$ and i^{th} step sizes respectively. We can expect the successive linearization procedure to drift from a true equilibrium position for the nonlinear response. This drifting is a combined result of truncation, the successive linearization procedure and the fact that information not yet available is required for a true solution (in Eq (5) the predicted pseudo-load vector is based on the incremental plastic strains of the preceding step rather than on the current step). The simplest corrective procedure involves the introduction of an equilibrium correction term that may be added as a load vector in the incremental procedure. The equilibrium correction term is defined as

$$\left\{R\right\}_{i+1} = \int [B]^T [E]\left(\left\{\Delta\epsilon^P\right\}_i - \left\{\Delta\epsilon^P\right\}_{i-1}\right) dV \qquad (6)$$

This is a simpler method than a complete iterative scheme and in effect the equilibrium correction term represents a one step iteration.

The pseudo-load vector is computed by various integration schemes (e.g., trapezoidal and Gaussian) in which Eqs (5) and (6) are combined and written as

$$\left\{\Delta Q\right\}_{i+1} + \left\{R\right\}_{i+1} = \sum_{J=1}^{n} A_j \left[B(\tau_j)\right]^T \left[E(\tau_j)\right]\left(\left(1+\frac{\delta_{i+1}}{\delta_i}\right)\left\{\Delta\epsilon^P\right\}_i - \left\{\Delta\epsilon^P\right\}_{i-1}\right) \qquad (7)$$

where n represents the number of integration points, τ_j represents the spatial location of the j^{th} integration point and A_j corresponds to an integration weight factor for the jth integration point. The derivation of the pseudo-load vector for many of the NASTRAN elements is presented in ref. 2. The present study utilizes only the triangular membrane element (CTRMEM) and the extensional rod element (CROD).

IMPLEMENTATION OF ELASTIC-PLASTIC ANALYSIS INTO NASTRAN

Elastic-plastic capabilities have been incorporated into the NASTRAN program. A flow diagram, representing the intital-strain method, is shown in Appendix A. The function of each step in the flow diagram is explained. A corresponding rigid format was written as a modification to rigid format 1 (Level 17.0). The ALTER package and resulting new rigid format are shown in Appendices B1 and B2, respectively.

Some of the important features of the new rigid format will be mentioned. Firstly, two new modules have been written, PLANS1 and PLANS2. PLANS1 determines the critical load, i.e., the lowest load amplitude for which at least one element stress point has become plastic. In addition a new table, PLI, is initialized. This table contains the last known field quantities such as stress, strain and plastic strain. PLANS2 implements the elastic-plastic constitutive equations for incremental stress, strain and plastic strain. Initially only perfect plastic behavior of the CTRMEM and CROD elements have been included. In addition PLANS2 updates the PLI table and forms the pseudo-load vector the the next plastic increment. The calculations needed to perform an elastic-plastic analysis are divided into those that are performed one time and those that are performed in each incremental step. Among those that are performed once are all the usual functions necessary in an elastic finite element analysis, i.e., reading input, all global functions such as setting up data tables, and solving for the elastic displacement field. These functions are performed by the operational sequence currently in rigid format 1 and are represented by the first block of the flow diagram. In addition, the critical load calculation and some preliminary plastic analysis definitions are carried out as shown in the flow diagram above LOOPA, which is the start of the plasticity loop. The calculations performed during each incremental step are contained in the plasticity loop as shown in the flow diagram. During each pass through the plasticity loop the SSG3 module solves for the incremental displacements due to the plastic pseudo-load only. The incremental displacement due to the external load or prescribed displacements are known and are added to the incremental displacements due to the pseudo-load vector. The plasticity constitutive equations are implemented and the new pseudo-load vector, to be used in the next incremental step, is formed (PLANS2). The plasticity loop is repeated for each incremental step.

Three new bulk data cards have been added for later use in a general elastic-plastic analytic capability program. These are described in Appendix C. The MATS2 bulk data card defines the plastic material properties; the PLFAC2 bulk data card defines the load history and step size information; and the TABLEY1 bulk data card defines the yield stress as a function of accumulated plastic strain.

SAMPLE PROBLEM

In order to validate the implemented NASTRAN capability an elastic-plastic analysis of a typical structural detail of a ship, namely a bracket connection, was performed using NASTRAN and the Grumman PLANS program. Figure 1 shows the intersection of a horizontal girder with a transverse bulkhead. The shaded area represents the structural component that was analyzed. Loads and boundary displacements on this section were provided from a finite element model of the entire structure. The finite element model consisted of 657 membrane triangles for the webs, 103 rod elements for the flanges (shown as dotted lines in Fig. 3) resulting in 704 degrees of freedom with a semi-band width of 40. Figures 2 and 3 show the details of the finite element model. Figure 4 shows the resulting growth of the plastic region of the highest stressed section.

The NASTRAN analysis was performed on a CDC cyber 172 computer and required 20 cpu seconds for each incremental step. The PLANS program,run on an IBM 370/3033 computer, used 5 cpu seconds for each incremental step. The results from each program were identical. Taking into account the difference between computational speed of each computer (about 5:1), the running time for the NASTRAN program is competitive with the PLANS program.

CONCLUSIONS

The present work demonstrates the feasibility of incorporating elastic-plastic capabilities into NASTRAN. The present implementation included a general new rigid format and bulk data cards as well as two new modules. The modules are specialized to include only perfect plasticity of the CTRMEM and CROD elements.

An extension of these capabilities to include general plastic behavior of the complete NASTRAN element library should present no new pitfalls and will be briefly outlined. Firstly, an extension to the flow chart and ALTER package would include one new module, PLA5, used to accumulate the total displacements (Table UGVPAC) as well as stress, strain and plastic strain (Table PLIAC) at the end of each increment. It would apear as

```
PLA5   UGVP, PLI/UGVPAC,PLIAC/V,N,PLACOUNT/V,N,P
```

In addition, new tables would be set up in PLANS1 and would contain element integration point information. To form these tables, user specified information would be supplied on bulk data cards through new element property cards.

Module PLANS2 must be generalized to build a pseudo-load vector, Eq (7), from the new tables set up in PLANS1. In addition, the plasticity theory contained in PLANS2 should be expanded to include, in addition to perfect plasticity, linear strain-hardening, nonlinear strain-hardening using either a Ramberg-Osgood function or a stress-strain table, or any other theory consistant with the initial strain approach that the developer wants to incorporate.

REFERENCES

1. Levy, A., and Pifko, A.B., "Feasibility Study for the Incorporation of Nonlinear Capability into NASTRAN," Grumman Research Department Report, RE-593, Grumman Aerospace Corporation, January 1980.

2. Crouzet-Pascal, J., and Levy, A., "Pseudo-Load Formulation for NASTRAN material Nonlinear Analysis using Initial-Strain Method," Grumman Research Department Report, RE-594, Grumman Aerospace Corporation, March 1980.

3. Levy, A., and Pifko, A.B., "On Computational Strategies for Problems involving Plasticity and Creep," International Journal for Numerical Methods in Engineering, Vol. 17, pp. 747-771 (1981).

4. Pifko, A.B., Levine, H.S., Armen, Jr., H., and Levy, A., "PLANS - A finite element program for nonlinear analysis of structures," ASME Preprint 74-WA/PVP-6(1974).

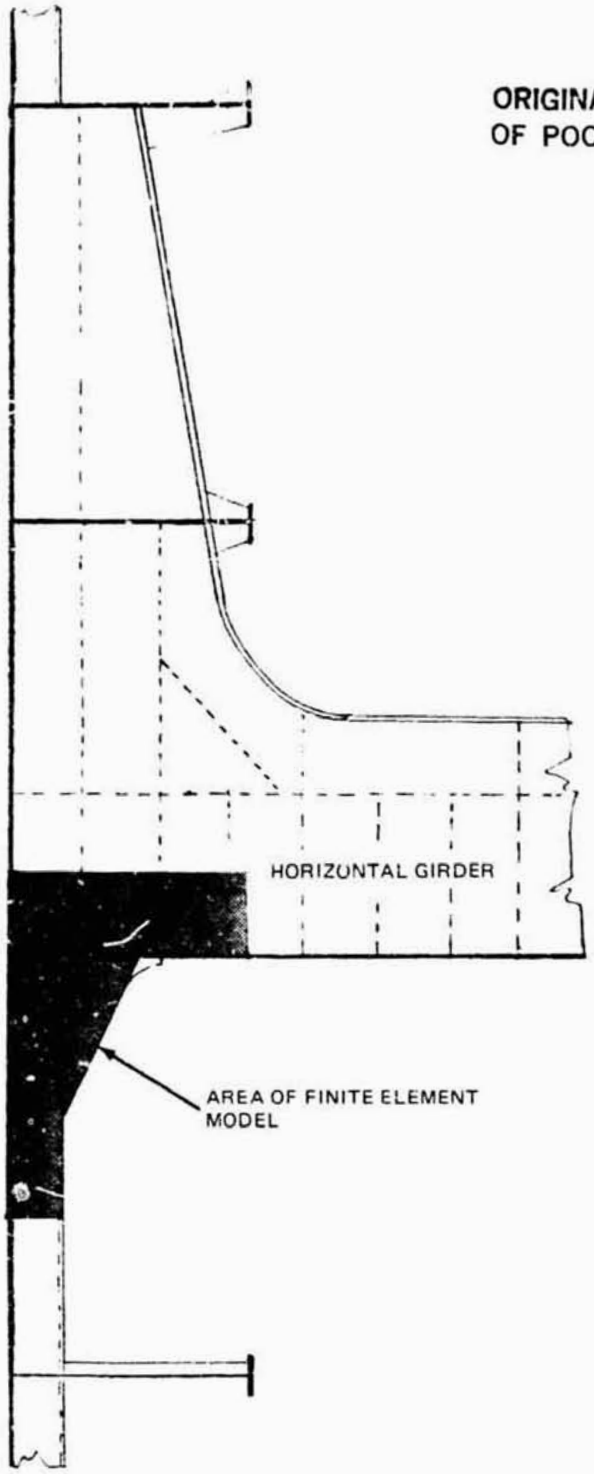
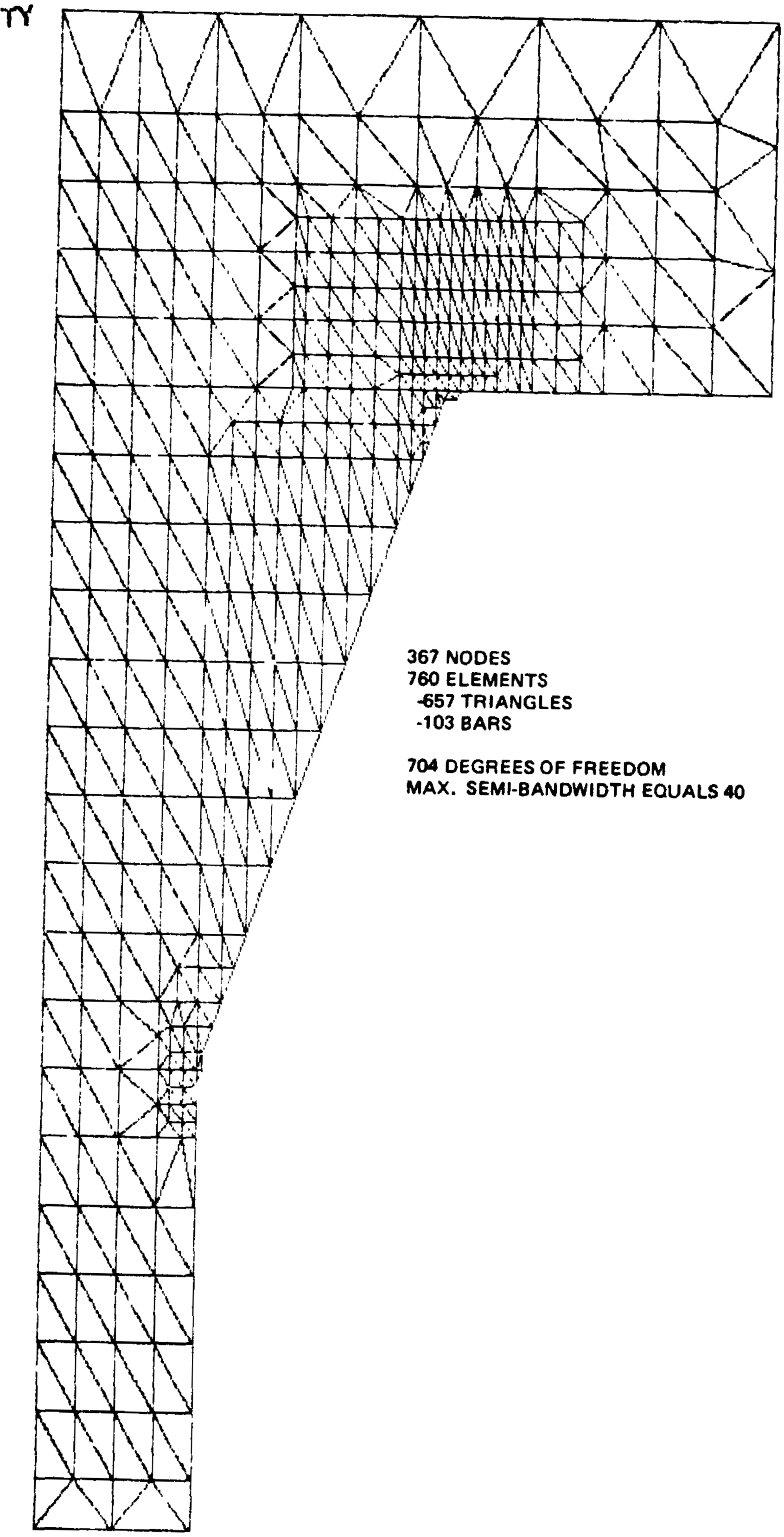


Fig. 1 Structural Detail of Bracket Connection



367 NODES
760 ELEMENTS
-657 TRIANGLES
-103 BARS

704 DEGREES OF FREEDOM
MAX. SEMI-BANDWIDTH EQUALS 40

Fig. 2 Finite Element Model of Bracket Detail - CTRMEM Elements

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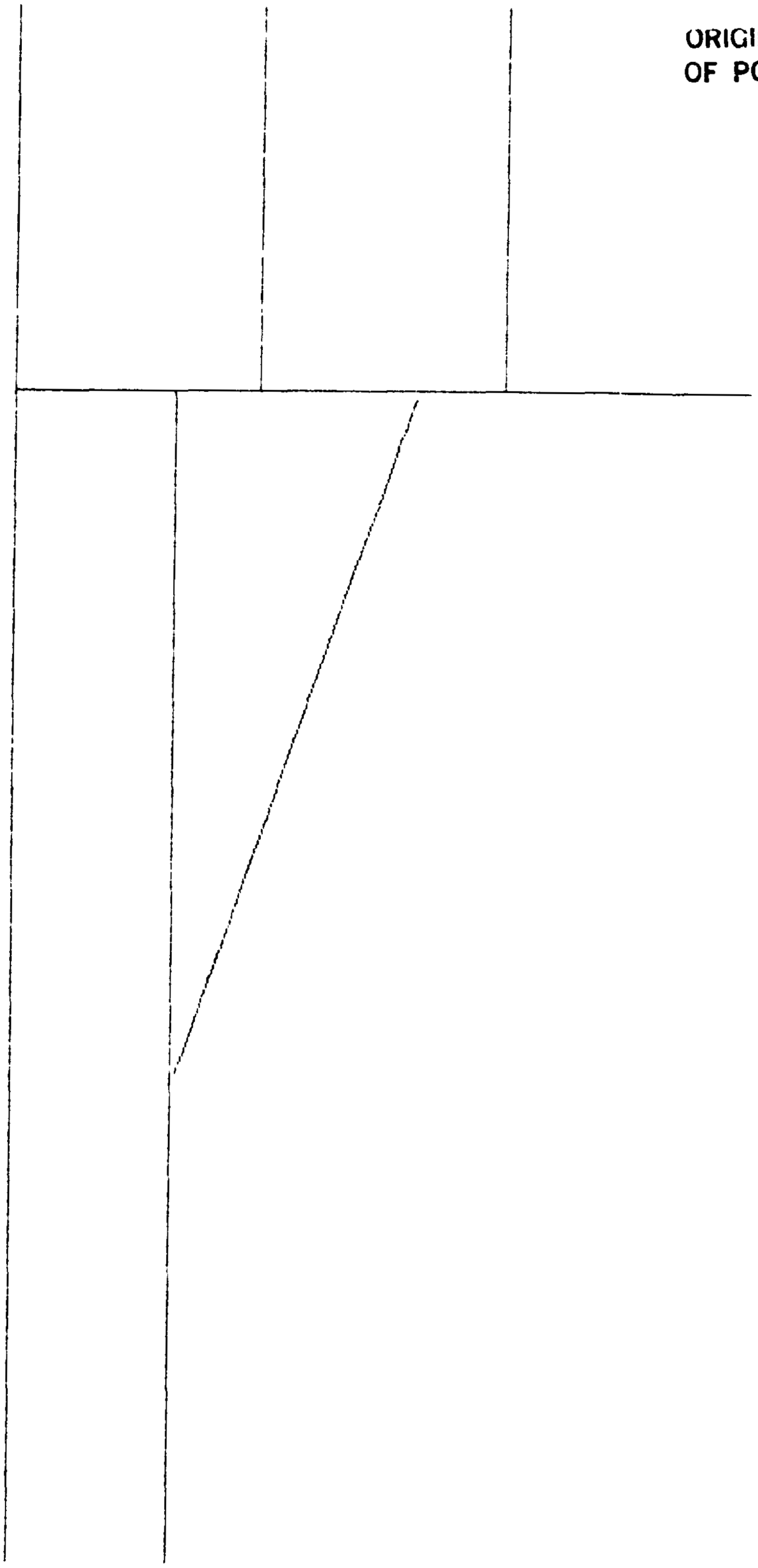
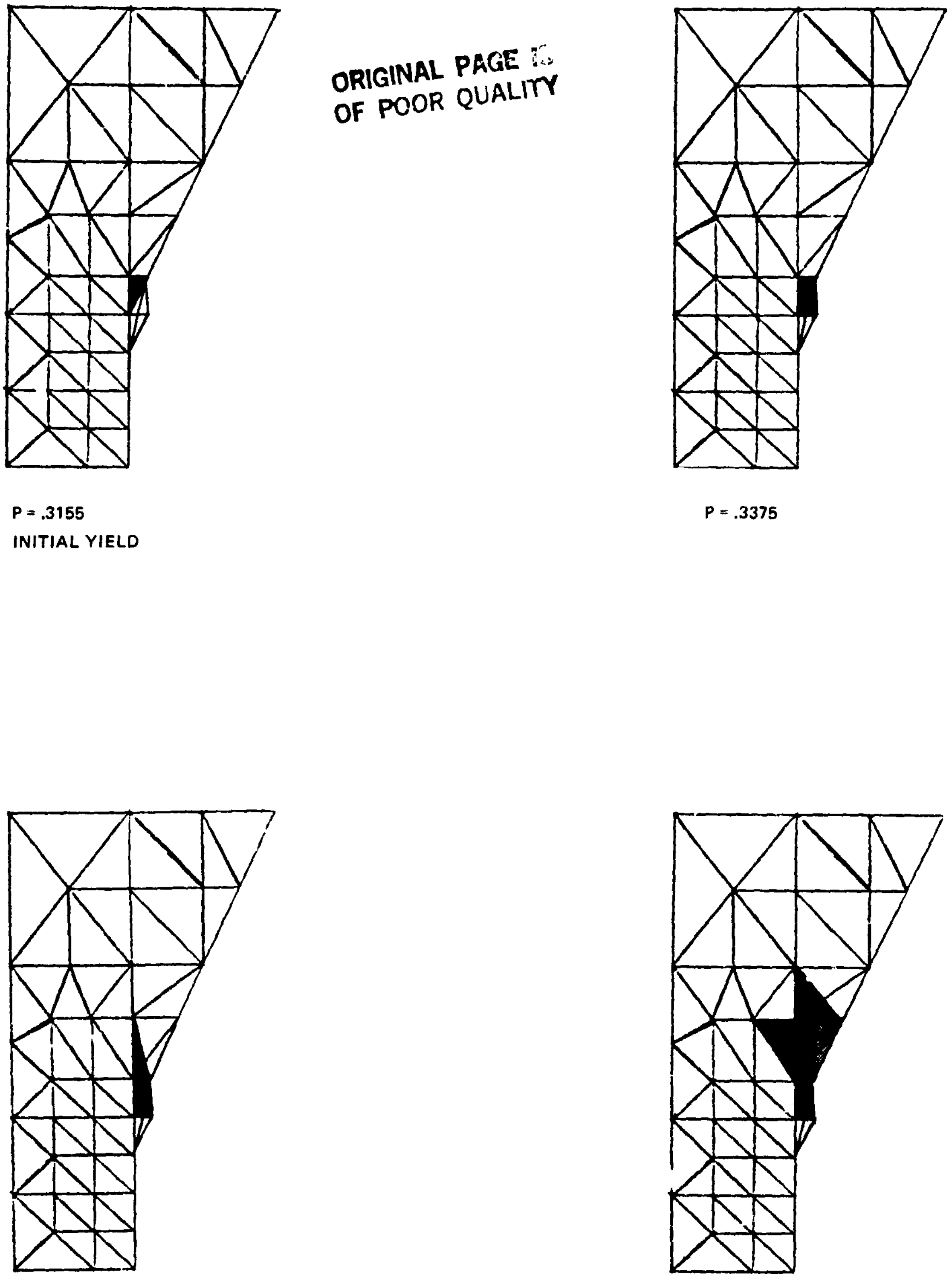


Fig. 3 Finite Element Model of Bracket Detail - CROD Element for Flanges



P = .3155
INITIAL YIELD

P = .3375

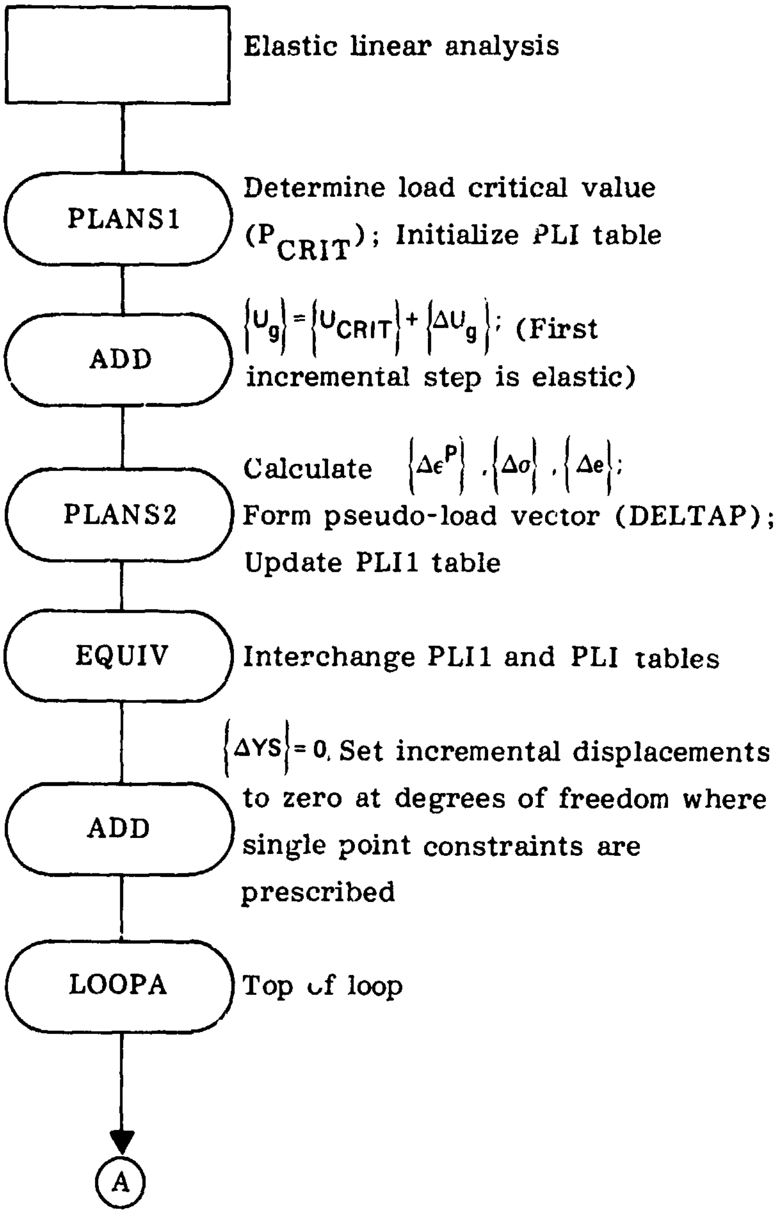
P = .3786

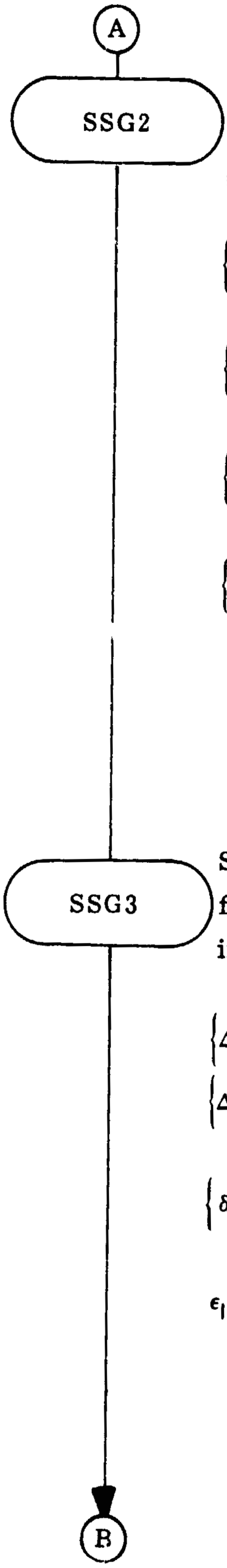
P = .4417
INITIAL PLASTICITY IN FLANGE

Fig. 4 Growth of the Elastic-Plastic Boundary in Region of Largest Stress

APPENDIX A

FLOW DIAGRAM OF MAIN FEATURES OF ELASTO-PLASTIC ANALYSIS





Apply constraints to incremental pseudo-load vector (DELTAP $\equiv \{\Delta P_g\}$),

$$\{\Delta P_g\} = \left\{\frac{\Delta \bar{P}_n}{\Delta P_m}\right\}, \quad \{\Delta P_n\} = \{\Delta \bar{P}_n\} + [G_m]\{\Delta P_m\}$$

$$\{\Delta P_n\} = \left\{\frac{\Delta \bar{P}_f}{\Delta P_s}\right\}, \quad \{\Delta P_f\} = \{\Delta \bar{P}_f\} - [K_{fs}]\{\Delta YS\}$$

$$\{\Delta P_f\} = \left\{\frac{\Delta \bar{P}_a}{\Delta P_o}\right\}, \quad \{\Delta P_a\} = \{\Delta \bar{P}_a\} + [G_o]^T\{\Delta \bar{P}_o\}$$

$$\{\Delta P_a\} = \left\{\frac{\Delta P_l}{\Delta P_r}\right\}$$

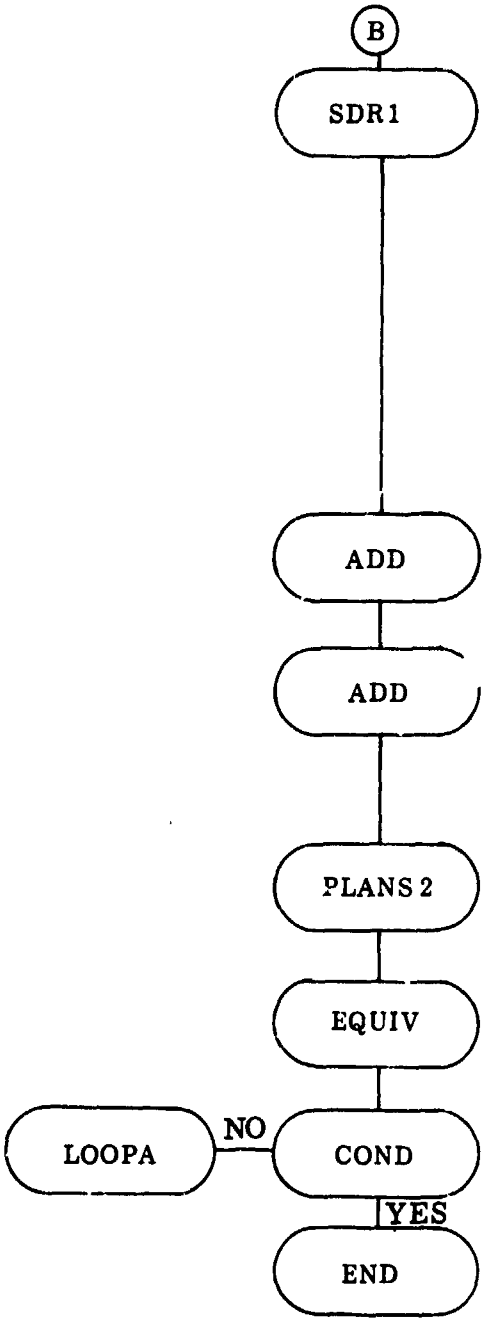
Solve for independent degree of freedom displacements due to incremental pseudo-load,

$$\{\Delta U_l\} = [K_{ll}]^{-1}\{\Delta P_l\}$$

$$\{\Delta U^{o}_{o}\} = [K_{oo}]^{-1}\{\Delta P_o\}$$

$$\{\delta \Delta P_l\} = \{\Delta P_l\} - [K_{ll}]\{\Delta U_l\}$$

$$\epsilon_l = \frac{\{\Delta U_l\}^T\{\delta \Delta P_l\}}{\{\Delta U_l\}^T\{\Delta P_l\}}$$



Recover dependent incremental displacements due to incremental pseudo-load,

$$\left\{\frac{\Delta U_l}{\Delta U_r}\right\} = \left\{\Delta U_a\right\},\ \left\{\Delta U_o\right\} = [G_o]\left\{\Delta U_a\right\} + \left\{\Delta U_o^o\right\}$$

$$\left\{\frac{\Delta U_a}{\Delta U_o}\right\} = \left\{\Delta U_f\right\},\ \left\{\frac{\Delta U_f}{\Delta YS}\right\} = \left\{\Delta U_n\right\}$$

$$\left\{\Delta U_m\right\} = [G_m]\left\{\Delta U_n\right\},\ \left\{\frac{\Delta U_n}{\Delta U_m}\right\} = \left\{\Delta U_g\right\}^p$$

Form total incremental load,

$$\left\{\Delta U_g\right\} = \left\{U_{nit}\right\} \bullet \left\{\frac{\Delta P}{P_{unit}}\right\} + \left\{\Delta U_g\right\}'$$

Update total displacement,

$$\left\{U_g\right\} = \left\{U_g\right\} + \left\{\Delta U_g\right\}$$

Calculate $\left\{\Delta\epsilon^p\right\}, \left\{\Delta\sigma\right\}, \left\{\Delta e\right\}$;
Form pseudo-load vector (DELTAP);
Update PLI1 Table

Interchange PLI1 and PLI tables

Bottom of loop; PLAST <1 ? If YES then last step and end, if NO then not last step and continue

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APPENDIX B1

"ALTERS" TO RIGID FORMAT 1 FOR ELASTO-PLASTIC ANALYSIS

```
ALTER 1,3
BEGIN      $  ELASTIC-PLASTIC ANALYSIS - - DEVELOPED BY GAC FOR NSRDC
ALTER 33,35
ALTER 37.38
ALTER 41.41
ALTER 65.66
ALTER 128,133
ALTER 137,140
PARAM     //C,N,ADD/V,N,PLACOUNT/C,N,1/C,N,0      $
PLANC1    EST,MPT,DIT,UGV/PLI/V,Y,PPCT/V,N,PCRIT      $
SAVE      PPCT,PCRIT      $
CHKPNT    PLI      $
MATPRT    UGV//      $
PARAMR    //C,N,MPY/V,N,DELP/V,Y,PPCT/V,N,PCRIT      $
PARAMR    //C,N,ADD/V,N,P11/V,N,PCRIT/V,N,DELP      $
PARAMR    //C,N,COMPLEX//V,N,P11//V,N,P11C      $
PARAMR    //C,N,COMPLEX//V,N,PCRIT//V,N,PCRITC      $
PARAMR    //C,N,COMPLEX//V,N,DELP//V,N,DELPC      $
PARAMR    //C,N,ADD/V,N,P/V,N,PCRIT//      $
ADD       UGV,/DELTAUGP/V,N,DELPC      $
ADD       UGV,/UGVP/V,N,P11C      $
CHKPNT    DELTAUGP,UGVP      $
PARAM     //C,N,ADD/V,N,PLACOUNT/V,N,PLACOUNT/C,N,1      $
EQUIV     PLI,PLI1/NEVER      $
PLANS2    PLI,MPT,EST,DELTAUGP,DIT/PLI1,DELTAP/V,N,PLACOUNT/V,N,PLAST/
          V,N,PRINTINC/V,N,P/V,N,DELP/V,Y,PMAX      $
SAVE      PLAST,PRINTINC,P      $
EQUIV     PLI1,PLI/ALWAYS      $
CHKPNT    PLI,DELTAP      $
COND      N22,PRINTINC      $
PRTPARM   //C,N,0/C,N,P      $
MATPRT    UGVP//      $
LABEL     N22      $
ADD       YS,/DELTAYS/C,N,(0.0,0.0)      $
CHKPNT    DELTAYS      $
```

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$
$         TOP OF LOOP
$
LABEL     LOOPA     $
SSG2      USET,GM,DELTAYS,KFS,GO,DM,DELTAP/DELTAQR,DELTAPO,DELTAPS,
          DELTAPL     $
CHKPNT    DELTAQR,DELTAPO,DELTAPS,DELTAPL     $
SSG3      LLL,KLL,DELTAPL,LOO,KOO,DELTAPO/DELTAULV,DELTAUOOV,DRULV,DRUOV/
          V,N,OMIT/V,N,IRES=-1/V,N,NSKIP/V,N,EPSI     $
SAVE      EPSI     $
CHKPNT    DELTAULV,DELTAUOOV,DRULV,DRUOV     $
COND      L22,IRES     $
MATGPR    GPL,USET,SIL,DRULV//C,N,L     $
MATGPR    GPL,USET,SIL,DRUOV//C,N,O     $
LABEL     L22     $
SDR1      USET,DELTAP,DELTAULV,DELTAUOOV,DELTAYS,GO,GM,DELTAPS,KFS,KSS,
          DELTAQR/DELTAUGV,DELTAPLG,/C,N,1/C,N,STATICS     $
CHKPNT    DELTAUGV,DELTAPLG     $
ADD       UGV,DELTAUGV/DELTAUGT/V,N,DELPC     $
ADD       DELTAUGT,UGVP/UGVPT/     $
EQUIV     UGVPT,UGVP/ALWAYS     $
CHKPNT    UGVP     $
PARAM     //C,N,ADD/V,N,PLACOUNT/V,N,PLACOUNT/C,N,1     $
EQUIV     PLI,PLI1/NEVER     $
PLANS2    PLI,MPT,EST,DELTAUGT,DIT/PLI1,DELTAP/V,N,PLACOUNT/V,N,PLAST/
          V,N,PRINTINC/V,N,P/V,N,DELP/V,Y,PMAX     $
SAVE      PLAST,PRINTINC,P     $
EQUIV     PLI1,PLI/ALWAYS     $
CHKPNT    PLI,DELTAP     $
COND      N21,PRINTINC     $
PRTPARM   //C,N,0/C,N,P     $
MATPRT    UGVP//     $
LABEL     N21     $
COND      LOOPED,PLAST     $
REPT      LOOPA,20  $
$
$         BOTTOM OF LOOP
$
LABEL     LOOPED     $
ALTER    ,164
ALTER 166,167
ALTER 174,175
ENDALTER
```

APPENDIX B2

"ALTERED" RIGID FORMAT FOR ELASTO-PLASTIC ANALYSIS

```
LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING


 3  BEGIN     $  ELASTIC-PLASTIC ANALYSIS - - DEVELOPED BY GAC FOR NSRDC
 4  GP1       GEOM1,GEOM2,/GPL,EQEXIN,GPDT,CSTM,BGPDT,SIL/V,N,LUSET/  V,N,
              NOGPDT/V,N,ALWAYS=-1 $
 5  SAVE      LUSET $
 6  CHKPNT    GPL,EQEXIN,GPDT,CSTM,BGPDT,SIL $
 7  GP2       GEOM2,EQEXIN/ECT $
 8  CHKPNT    ECT $
 9  PARAML    PCDB//C,N,PRES/C,N,/C,N,/C,N,/V,N,NOPCDB $
10  PURGE     PLTSETX,PLTPAR,GPSETS,ELSETS/NOPCDB $
11  COND      P1,NOPCDB $
12  PLTSET    PCDB,EQEXIN,ECT/PLTSETX,PLTPAR,GPSETS,ELSETS/V,N,NSIL/   V,N,
              JUMPPLOT=-1 $
13  SAVE      NSIL,JUMPPLOT $
14  PRTMSG    PLTSETX// $
15  PARAM     //C,N,MPY/V,N,PLTFLG/C,N,1/C,N,1 $
16  PARAM     //C,N,MPY/V,N,PFILE/C,N,0/C,N,0 $
17  COND      P1,JUMPPLOT $
18  PLOT      PLTPAR,GPSETS,ELSETS,CASECC,BGPDT,EQEXIN,SIL,,ECT,,/PLOTX1/V,N,
              NSIL/V,N,LUSET/V,N,JUMPPLOT/V,N,PLTFLG/V,N,PFILE $
19  SAVE      JUMPPLOT,PLTFLG,PFILE $
20  PRTMSG    PLOTX1// $
21  LABEL     P1 $
22  CHKPNT    PLTPAR,GPSETS,ELSETS $
23  GP3       GEOM3,EQEXIN,GEOM2/SLT,GPTT/V,N,NOGRAV/V,N,NEVER=1 $
24  SAVE      NOGRAV $
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LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING

25   PARAM    //C,N,AND/V,N,NOMGG/V,N,NOGRAV/V,Y,GRDPNT=-1 $
26   CHKPNT   SLT,GPTT $
27   TA1      ECT,EPT,BGPDT,SIL,GPTT,CSTM/EST,GEI,GPECT,/V,N,LUSET/   V,N,
              NOSIMP/C,N,1/V,N,NOGENL/V,N,GENEL $
28   SAVE     NOSIMP,NOGENL,GENEL $
29   PARAM    //C,N,AND/V,N,NOELMT/V,N,NOGENL/V,N,NOSIMP $
30   COND     ERROR4,NOELMT $
31   PURGE    KGGX,GPST/NOSIMP/OGPST/GENEL $
32   CHKPNT   EST,GPECT,GEI,GPST,OGPST $
36   PARAM    //C,N,MPY/V,N,CARDNO/C,N,0/C,N,0 $
39   COND     LBL1,NOSIMP $
40   PARAM    //C,N,ADD/V,N,NOKGGX/C,N,1/C,N,0 $
42   EMG      EST,CSTM,MPT,DIT,GEOM2,/KELM,KDICT,MELM,MDICT,,/V,N,NOKGGX/ V,
              N,NOMGG/C,N,/C,N,/C,N,/C,Y,COUPMASS/C,Y,CPBAR/C,Y,CPROD/C,Y,
              CPQUAD1/C,Y,CPQUAD2/C,Y,CPTRIA1/C,Y,CPTRIA2/  C,Y,CPTUBE/C,Y,
              CPQDPLT/C,Y,CPTRPLT/C,Y,CPTRBSC $
43   SAVE     NOKGGX,NOMGG $
44   CHKPNT   KELM,KDICT,MELM,MDICT $
45   COND     JMPKGG,NOKGGX $
46   EMA      GPECT,KDICT,KELM/KGGX,GPST $
47   CHKPNT   KGGX,GPST $
48   LABEL    JMPKGG $
49   COND     JMPMGG,NOMGG $
50   EMA      GPECT,MDICT,MELM/MGG,/C,N,-1/C,Y,WTMASS=1.0 $
51   CHKPNT   MGG $
52   LABEL    JMPMGG $
53   COND     LBL1,GRDPNT $
```

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```
    LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING

54  COND      ERROR2,NOMGG $
55  GPWG      BGPDT,CSTM,EQEXIN,MGG/OGPWG/V,Y,GRDPNT/C,Y,WTMASS $
56  OFP       OGPWG,,,,,// $
57  LABEL     LBL1 $
58  EQUIV     KGGX,KGG/NOGENL $
59  CHKPNT    KGG $
60  COND      LBL11A,NOGENL $
61  SMA3      GEI,KGGX/KGG/V,N,LUSET/V,N,NOGENL/V,N,NOSIMP $
62  CHKPNT    KGG $
63  LABEL     LBL11A $
64  PARAM     //C,N,MPY/V,N,NSKIP/C,N,0/C,N,0 $
67  GP4       CASECC,GEOM4,EQEXIN,GPDT,BGPDT,CSTM/RG,YS,USET,ASET/V,N,LUSET/
              V,N,MPCF1/V,N,MPCF2/V,N,SINGLE/V,N,OMIT/V,N,REACT/V,N,NSKIP/V,
              N,REPEAT/V,N,NOSET/V,N,NOL/V,N,NOA/C,Y,SUBID $
68  SAVE      MPCF1,MPCF2,SINGLE,OMIT,REACT,NSKIP,REPEAT,NOSET,NOL,NOA $
69  COND      ERROR3,NOL $
70  PARAM     //C,N,AND/V,N,NOSR/V,N,SINGLE/V,N,REACT $
71  PURGE     KRR,KLR,QR,DM/REACT/GM/MPCF1/GO,KOO,LOO,PO,UOOV,RUOV/OMIT/PS,
              KFS,KSS/SINGLE/QG/NOSR $
72  CHKPNT    KRR,KLR,QR,DM,GM,GO,KOO,LOO,PO,UOOV,RUOV,PS,KFS,KSS,QG,USET,RG,
              YS,ASET $
73  COND      LBL4,GENEL $
74  GPSP      GPL,GPST,USET,SIL/OGPST/V,N,NOGPST $
75  SAVE      NOGPST $
76  COND      LBL4,NOGPST $
77  OFP       OGPST,,,,,// $
78  LABEL     LBL4 $
```

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LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING

 79  EQUIV    KGG,KNN/MPCF1 $
 80  CHKPNT   KNN $
 81  COND     LBL2,MPCF2 $
 82  MCE1     USET,RG/GM $
 83  CHKPNT   GM $
 84  MCE2     USET,GM,KGG,,,/KNN,,, $
 85  CHKPNT   KNN $
 86  LABEL    LBL2 $
 87  EQUIV    KNN,KFF/SINGLE $
 88  CHKPNT   KFF $
 89  COND     LBL3,SINGLE $
 90  SCE1     USET,KNN,,,/KFF,KFS,KSS,,, $
 91  CHKPNT   KFS,KSS,KFF $
 92  LABEL    LBL3 $
 93  EQUIV    KFF,KAA/OMIT $
 94  CHKPNT   KAA $
 95  COND     LBL5,OMIT $
 96  SMP1     USET,KFF,,,/GO,KAA,KOO,LOO,,,,, $
 97  CHKPNT   GO,KAA,KOO,LOO $
 98  LABEL    LBL5 $
 99  EQUIV    KAA,KLL/REACT $
100  CHKPNT   KLL $
101  COND     LBL6,REACT $
102  RBMG1    USET,KAA,/KLL,KLR,KRR,,, $
103  CHKPNT   KLL,KLR,KRR $
```

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LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING

104  LABEL     LBL6 $
105  RBMG2     KLL/LLL $
106  CHKPNT    LLL $
107  COND      LBL7,REACT $
108  RBMG3     LLL,KLR,KRR/DM $
109  CHKPNT    DM $
110  LABEL     LBL7 $
111  SSG1      SLT,BGPDT,CSTM,SIL,EST,MPT,GPTT,EDT,MGG,CASECC,DIT/PG/V,N,
               LUSET/V,N,NSKIP $
112  CHKPNT    PG $
113  EQUIV     PG,PL/NOSET $
114  CHKPNT    PL $
115  COND      LBL10,NOSET $
116  SSG2      USET,GM,YS,KFS,GO,DM,PG/QR,PO,PS,PL $
117  CHKPNT    QR,PO,PS,PL $
118  LABEL     LBL10 $
119  SSG3      LLL,KLL,PL,LOO,KOO,PO/ULV,UOOV,RULV,RUOV/V,N,OMIT/V,Y,IRES=-1/
               V,N,NSKIP/V,N,EPSI $
120  SAVE      EPSI $
121  CHKPNT    ULV,UOOV,RULV,RUOV $
122  COND      LBL9,IRES $
123  MATGPR    GPL,USET,SIL,RULV//C,N,L $
124  MATGPR    GPL,USET,SIL,RUOV//C,N,O $
125  LABEL     LBL9 $
126  SDR1      USET,PG,ULV,UOOV,YS,GO,GM,PS,KFS,KSS,QR/UGV,PGG,QG/V,N,NSKIP/
               C,N,STATICS $
127  CHKPNT    UGV,PGG,QG $
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LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING

134  CHKPNT   CSTM $
135  GPFDR    CASECC,UGV,KELM,KDICT,ECT,EQEXIN,GPECT,PGG,QG/ONRGY1,UGPFB1/
              C,N,STATICS $
136  OFP      ONRGY1,UGPFB1,,,,// $
140  PARAM    //C,N,ADD/V,N,PLACOUNT/C,N,1/C,N,0        $
140  PLANS1   EST,MPT,DIT,UGV/PLT/V,Y,PPCT/V,N,PCRIT        $
140  SAVE     PPCT,PCRIT       $
140  CHKPNT   PLT        $
140  MATPRT   UGV//        $
140  PARAMR   //C,N,MPY/V,N,DELP/V,Y,PPCT/V,N,PCRIT        $
140  PARAMR   //C,N,ADD/V,N,P11/V,N,PCRIT/V,N,DELP        $
140  PARAMR   //C,N,COMPLEX//V,N,P11//V,N,P11C        $
140  PARAMR   //C,N,COMPLEX//V,N,PCRIT//V,N,PCRITC        $
140  PARAMR   //C,N,COMPLEX//V,N,DELP//V,N,DELPC        $
140  PARAMR   //C,N,ADD/V,N,P/V,N,PCRIT//        $
140  ADD      UGV,/DELTAUGP/V,N,DELPC        $
140  ADD      UGV,/UGVP/V,N,P11C        $
140  CHKPNT   DELTAUGP,UGVP        $
140  PARAM    //C,N,ADD/V,N,PLACOUNT/V,N,PLACOUNT/C,N,1        $
140  EQUIV    PLI,PLI1/NEVER        $
140  PLANS2   PLI,MPT,EST,DELTAUGP,DIT/PLI1,DELTAP/V,N,PLACOUNT/V,N,PLAST/
              V,N,PRINTINC/V,N,P/V,N,DELP/V,Y,PMAX        $
140  SAVE     PLAST,PRINTINC,P        $
140  EQUIV    PLI1,PLI/ALWAYS        $
140  CHKPNT   PLI,DELTAP        $
140  COND     N22,PRINTINC        $
```

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      LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING

 140  PRTPARM  //C,N,0/C,N,P     $
 140  MATPRT   UGVP//     $
 140  LABEL    N22     $
 140  ADD      YS,/DELTAYS/C,N,(0.0,0.0)     $
 140  CHKPNT   DELTAYS     $
 140  LABEL    LOOPA     $
 140  SSG2     USET,GM,DELTAYS,KFS,GO,DM,DELTAP/DELTAQR,DELTAPO,DELTAPS,
               DELTAPL     $
 140  CHKPNT   DELTAQR,DELTAPO,DELTAPS,DELTAPL     $
 140  SSG3     LLL,KLL,DELTAPL,LOO,KOO,DELTAPO/DELTAULV,DELTAUUOV,DRULV,DRUOV/
               V,N,OMIT/V,N,IRES=-1/V,N,NSKIP/V,N,EPSI     $

 140  SAVE     EPSI     $
 140  CHKPNT   DELTAULV,DELTAUOOV,DRULV,DRUOV     $
 140  COND     L22,IRES     $
 140  MATGPR   GPL,USET,SIL,DRULV//C,N,L     $
 140  MATGPR   GPL,USET,SIL,DRUOV//C,N,O     $
 140  LABEL    L22     $
 140  SDR1     USET,DELTAP,DELTAULV,DELTAUOOV,DELTAYS,GO,GM,DELTAPS,KFS,KSS,
               DELTAQR/DELTAUGV,DELTAPLG,/C,N,1/C,N,STATICS     $
 140  CHKPNT   DELTAUGV,DELTAPLG     $
 140  ADD      UGV,DELTAUGV/DELTAUGT/V,N,DELPC     $
 140  ADD      DELTAUGT,UGVP/UGVPT/     $
 140  EQUIV    UGVPT,UGVP/ALWAYS     $
 140  CHKPNT   UGVP     $
 140  PARAM    //C,N,ADD/V,N,PLACOUNT/V,N,PLACUUNT/C,N,1     $
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LEVEL 2.0 NASTRAN DMAP COMPILER - SOURCE LISTING

 140  EQUIV     PLI,PLT1/NEVER        $
 140  PLANS2    PLT,MPT,EST,DELTAUGT,DIT/PLI1,DELTAP/V,N,PLACOUNT/V,N,PLAST/
                V,N,PRINTINC/V,N,P/V,N,DELP/V,Y,PMAX            $
 140  SAVE      PLAST,PRINTINC,P      $
 140  EQUIV     PLT1,PLI/ALWAYS       $
 140  CHKPNT    PLT,DELTAP      $
 140  COND      N21,PRINTINC      $
 140  PRTPARM   //C,N,0/C,N,P      $
 140  MATPRT    UGVP//      $
 140  LABEL     N21      $
 140  COND      LOOPED,PLAST      $
 140  REPT      LOOPA,20   $
 140  LABEL     LOOPED      $
 165  JUMP      FINIS $
 168  LABEL     ERROR2 $
 169  PRTPARM   //C,N,-2/C,N,STATICS $
 170  LABEL     ERROR3 $
 171  PRTPARM   //C,N,-3/C,N,STATICS $
 172  LABEL     ERROR4 $
 173  PRTPARM   //C,N,-4/C,N,STATICS $
 176  LABEL     FINIS $
 177  END       $
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NEW BULK DATA CARDS

MATS2: Material Properties - defines stress-strain function for either Ramberg-Osgood representation, linear strain hardening or perfect plasticity.

	1	2	3	4	5	6	7	8
			TABLEY1	TABLES1	n	$\sigma_{0.7}$	α	
Ramberg-Osgood	MATS2	17			12	0.6+5		
Linear Hardening	MATS2	17					0.25	
Perfect Plasticity	MATS2	17					0.0	
Tabular	MATS2	17		100				

Field	Contents
MID -	Material identification number which matches the identification number on some basic MAT1 card (Integer > 0)
n -	shape parameter used in Ramberg-Osgood stress-strain function (Integer)
α -	E_T/E for linear strain hardening (Real)
$\sigma_{0.7}$ -	Ramberg-Osgood parameter (Real)
TABLES1-	Table number for Stress-strain function - TABLES1 Table (Integer)
TABLEY1-	Table number for yield stress vs. accumulated plastic strain, for near linear strain hardening (Integer)

Remarks: 1. Ramberg-Osgood representation: $\varepsilon = \frac{\sigma}{E} + \frac{3\sigma}{7E}\left(\frac{\sigma}{\sigma_{0.7}}\right)^{n-1}$

2. TABLEY1 may be used with any of the options listed.

PLFAC2: Load history and step size information

1	2	3	4	5	6	7	8	9	10
PLFAC2	SID	P1	N1	NLD1	P2	N2	NLD2	☒	+abc
PLFAC2	5	1.0	5	1	2.0	10	1		ABC

+abc	☒	P3	N3	NLD3	-etc-			☒	
+BC		3.0	5	2					

Field		Contents
SID	-	Set identification number (Integer > 0)
Pi	-	Load magnitude (Real)
Ni	-	Number of increments for current load (Integer ≥ 0)
NLDi	-	Load set reference (Integer)

Remarks:

1. Load history is contained with PLFAC2. Each Pi corresponds to total load for that set (NLDi).

2. One or Two sets of data may be included on each card. Fields 3, 4, and 5 must be used on each card, but fields 6, 7, and 8 may be omitted from any card even though continuation cards follow.

3. If Ni = 0, incrementation steps will be chosen automatically.

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TABLEY1: Yield stress vs. accumulated plastic strain

1	2	3	4	5	6	7	8	9	10
TABLEY1	SID	σ_{yt}	σ_{ys}	$\Sigma\varepsilon^p$	σ_{yt}	σ_{ys}	$\Sigma\varepsilon^p$	☒	+abc
TABLEY1	10								ABC

+abc	☒	σ_{yt}	σ_{ys}	$\Sigma\varepsilon^p$	-etc-			☒	
+BC									

<u>Field</u> <u>Contents</u>

SID - set identification number (Integer > 0)

σ_{yt} - yield stress in tension (Real)

σ_{ys} - yield stress in shear (Real)

$\Sigma\varepsilon^p$ - accumulated plastic strain (Real)

Remarks:

1. If accumulated plastic strain is less than first value in table then first values of σ_{yt} and σ_{ys} are chosen, if accumulated plastic strain is greater than last value in table than last values of σ_{yt} and σ_{ys} are chosen, otherwise a linear interpolation is used.
2. One or two sets of data may be included on each card. Fields 3, 4, and 5 must be used on each card, but fields 6, 7, and 8 may be omitted from any card even though continuation cards follow.