MULTI-SPRING REPRESENTATION OF FASTENERS FOR MSC/NASTRAN MODELING

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ABSTRACT

The paper describes a particular modeling approach for 3-dimensional representation of fastener joints developed for MSC/NASTRAN. Different physical properties of plate-fastener systems are analyzed separately and interaction between them is established. Calculations of the system properties are shown, as well as the technique of their application in models. Description of a program automating generation of additional cards required by the method is included. The procedure is illustrated with an example showing both an application of the method and results of FEA based on its implementation.

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INTRODUCTION

Generally, distribution of loads through the structure depends not only on the mechanical properties of selected materials and dimensions of its components but also on stiffness of the fasteners connecting them. Therefore, more realistic finite element analysis results can be obtained when components of a model are connected by elements representing stiffness of the joints.

The procedure below describes the stiffness analysis and modeling technique for 3-dimensional fastener joint representation, including description of a program for generation of additional bulk data.

The traditional approach to modeling fastener joints is based on calculations of a single spring rate representing joint flexibility for a particular combination of fastener and plate properties. Such approach, though quite adequate for 1- or 2-dimensional joint models, cannot be used for 3-dimensional joint models when reference planes of connected plates do not coincide at fastener locations.

The presentation below describes an approach designed specifically for joints with connected elements modeled by plates without offsets at their actual mid planes.

Models of this type are used for strut modeling at Boeing Commercial Airplane Group, with average model size of approximately 250,000 DOFs.

The approach is based on definition of independent components contributing to a joint flexibility, analysis of each component, and their assembly to represent a complete plate-fastener system of the joint.

The approach can be extended to different types of models, by quantitative definition of factors contributing to the flexibility of joints.

The method does not account for the effects of fastener pretension and fit.

STIFFNESS ANALYSIS OF FASTENER JOINTS

In the calculation of a fastener joint stiffness, Fig. 1, the following stiffness components are considered:

- plate bearing stiffness;
- fastener bearing stiffness;
- fastener shear and bending stiffness.

The plate *i* bearing flexibility

$$C_{bpi} = \frac{1}{E_{cpi} * t_{pi}}$$

where: E_{cpi} – plate *i* material compression modulus;
t_{pi} – plate *i* thickness.

The fastener bearing flexibility at plate *i*

$$C_{bbi} = \frac{1}{E_{cb} * t_{pi}}$$

where: E_{cb} – fastener material compression modulus.

Combined fastener and plate bearing flexibility at plate *i*

$$C_{bi} = C_{bpi} + C_{bbi}$$

Combined bearing stiffness at plate *i*

$$S_{bi} = \frac{1}{C_{bi}}$$

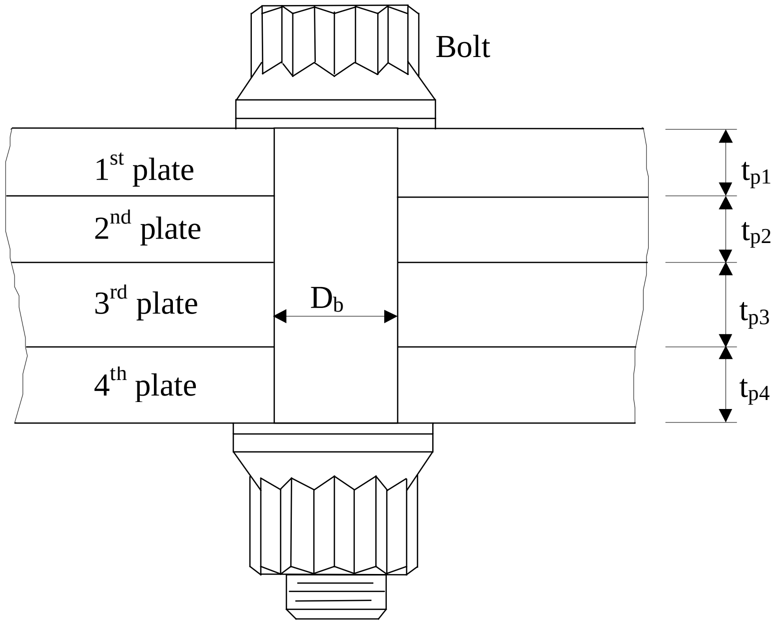


Figure 1. Bolt joint

The fastener shear flexibility between mid planes of plates *i* and *i*+1

$$C_{s(i,\,i+1)} = \frac{t_{pi} + t_{p(i+1)}}{2\,A_b * G_b}$$

where: G_b – fastener material shear modulus;

t_{pi}, $t_{p(i+1)}$ – thickness of plates *i* and *i*+1 in the joint;

A_b – area of fastener cross section,

$$A_b = \frac{\pi D_b^2}{4}$$

D_b – fastener diameter.

The fastener shear stiffness between mid planes of plates *i* and *i*+1

$$S_{s(i,i+1)} = \frac{1}{C_{s(i,i+1)}}$$

MODELING OF FASTENER JOINTS

General

The method presented addresses two main concerns in modeling of a fastener joint:

1. Improved idealization of fastener behavior in a joint, and, at the same time,
2. Generation of output easily readable by an analyst with minimum post-processing required.

Idealization of a plate-fastener system should account for the following:

i. Elastic bearing deformations of plate and fastener at contact surface;

ii. Bending and shear deformations of fastener shank;

iii. Compatibility of displacements of fastener and connected plates at the joint.

The method below represents a solution that exhibits realistic in situ fastener behavior and generates easy to understand output.

The modeling process required by the method may be summed up in two basic steps:

a. Separate modeling of fastener, and
b. Modeling of the interaction between the fastener and plates connected by it.

The method creates fastener-plate system model as illustrated in Fig. 2.

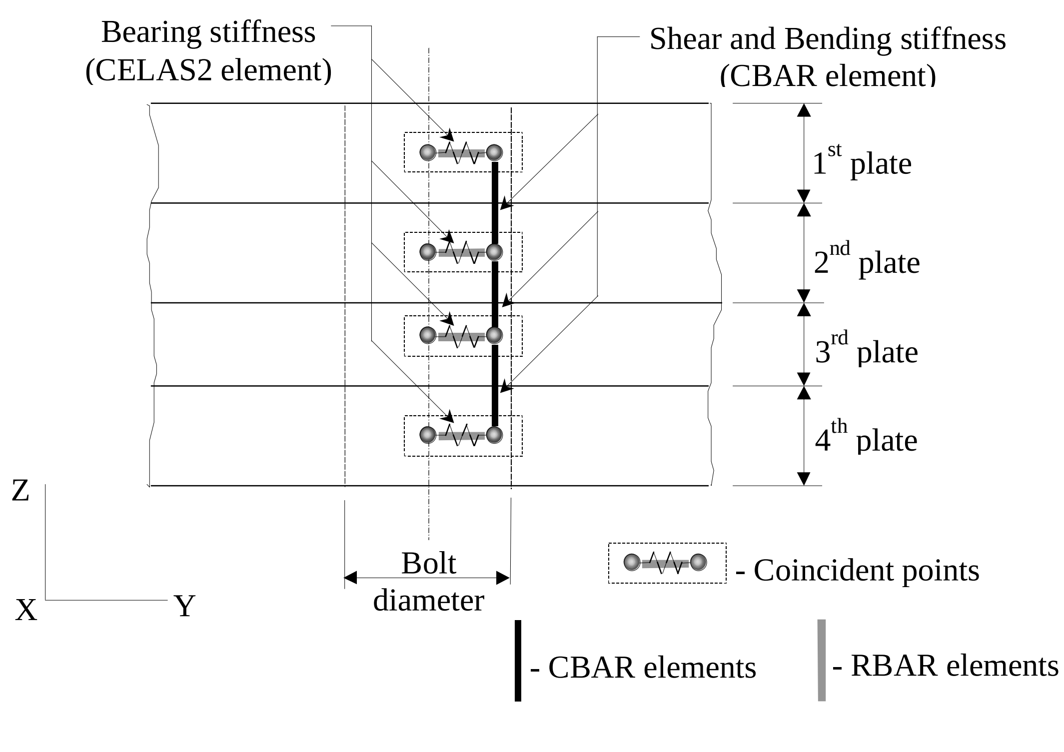


Figure 2. Bolt Joint Modeling

Modeling of Fasteners

A fastener is modeled by BAR elements [1] using for connectivity a separate set of grid points coincidental with corresponding plates grid points (see also Fig. 2).

All BAR elements representing the same fastener reference the same PBAR card [1] with the following properties:

1. MID to reference the actual fastener material properties.
2. Fastener cross-sectional area
   $A_b = \pi D_b^2 / 4;$ where D_b is the fastener diameter;
   as per Sect. "Stiffness Analysis of Fastener Joints" above.
3. Moments of inertia of the fastener
   $I_1 = I_2 = \pi D_b^4 / 64.$
4. Area factors for shear
   $K_1 = K_2 = 1.0.$

Then the required fastener shear flexibility $C_{s(i,i+1)}$ defined in Sect. "Stiffness Analysis of Fastener Joints" is obtained as follows:

- $(t_{pi} + t_{p(i+1)}) / 2$ is modeled by positioning of reference grid points at plates mid planes;
- a finite value of fastener shear rigidity A_bG_b is created by entering appropriate value of G_b on MAT1 card for the fastener, calculation of the actual A_b (see above), and giving area factors for shear value of 1.

Additionally, fastener axial and bending flexibility is also accounted for.

An example of BAR element definition for a 0.375" dia. fastener is shown below.

CBAR	**EID**	**PID**	**GA**	**GB**	**X1**	**X2**	**X3**
CBAR	21	206	1011	2011	1.0	0.0	0.0

PBAR	**PID**	**MID**	**A**	**I1**	**I2**	**J**	**NSM**
PBAR	206	2	0.11	9.7E-4	9.7E-4		
	C1	**C2**	**D1**	**D2**	**E1**	**E2**	**..**
	0.0	0.0					
	K1	**K2**	**I12**				
	1.0	1.0					

Modeling of Interaction between Fasteners and Plates

Connectivity cards for plates and fasteners reference two separate sets of coincident grid points.

The connection between each pair of the coincident points should account for combined bearing flexibility of each plate and the fastener, and compatibility of the fastener and the plates deformations.

The combined bearing flexibility of the fastener and the plates is defined as C_{bi} in Sect. "Stiffness Analysis of Fastener Joints". Its value is entered as a spring rate on CELAS2 cards [1] in two directions defining fastener shear plane, for each pair of the coincident points as above. It should be noted that though CELAS2 element is used in this presentation use of CELAS1, with the same K, is equally possible (see ref. [1]).

To define a fastener shear plane and axial direction correctly a coordinate system with one of its axes parallel to the fastener axis must exist in the bulk data. All grid points defining connectivity of plates and fasteners with the same orientation must reference this coordinate system in field 7.

Compatibility of fastener-plate system displacements is enforced by this method as follows:

- a plate cannot “slide” along the fastener; and
- a plate and the fastener have the same slope under bending.

The requirements are satisfied by writing RBAR elements between each pair of the coincident grid points, for the DOFs as described here.

The above is illustrated for a fastener connecting two plates. The fastener and the plates in the example have the coincident pairs of grid points 1005 and 2005, and 1006 and 2006. Spring rate K is calculated as 1.6E+7. The fastener axis is parallel to Z-axis of a local coordinate system defined in the bulk data. The relevant cards are listed below.

CELAS2	**EID**	**K**	**G1**	**C1**	**G2**	**C2**	
CELAS2	210	1.6E+7	1005	1	2005	1	
CELAS2	211	1.6E+7	1005	2	2005	2	
CELAS2	212	1.6E+7	1006	1	2006	1	
CELAS2	213	1.6E+7	1006	2	2006	2	

RBAR	**EID**	**GA**	**GB**	**CNA**	**CNB**	**CMA**	**CMB**
RBAR	310	1005	2005	123456			345
RBAR	311	1006	2006	123456			345

If the fastener axis were parallel to Y-axis of a local coordinate system RBAR cards would be written as:

RBAR	310	1005	2005	123456			246
RBAR	311	1006	2006	123456			246

In the examples of RBAR elements, only the DOFs discussed are entered into **CMB** field for clarity only. All three rotations can be listed in the field without changing the nature of the interaction.

FEM_joint PROGRAM

The program **FEM_joint** analyzes stiffness of fastener joints and generates grid points and elements following the procedure as described above.

The program automates the approach presented here by

- Generating additional sets of coincident grid points for the modeling of fasteners;
- Generating CBAR elements for modeling fasteners; and
- Writing interface conditions between fasteners and plates in form of CELAS2 and RBAR elements.

The program does not generate cards required for definition of local coordinate systems and PBAR cards.

Program input consists of three files:

1. List file:
   The file contains list of user input files to be processed by the program.
   The file names must include full path from the location of the run initialization.
   Number of user input files is not limited by the program.

2. Bulk data file:

   The file must contain all relevant GRID cards in 8-character field format. Other cards can be written in any legal format.

3. User input file(s):

   User input file is described in detail below.

User input file contains instructions required for generation of all the additional cards as described above.

Each input file defines one group of fasteners having common properties as follows:

i. Identical fasteners and fastener orientation;

ii. Identical number of plates connected by the fasteners, plate gauges and materials, and relative order in the plates in the joint.

A user input file has fixed number of records arranged in a sequence that defines record contents, as shown below.

Record Number	Contents	Values	Type	Format	Remarks
1	Title 1	Any	Character	N	60 characters max.
2	Title 2				
3	Title 3				
4	Number of fasteners n_f	Any	Integer	N	
5	Number of plates n_p	Any	Integer	N	
6	Bolt diameter	Any	Real	Y	
	Bolt material	A, T, S	Character		
7 to (n_p+6)	Plate thickness	Any	Real	Y	One record per plate
	Plate material	A, T, S	Character		
(n_p+7) to (n_p+n_f+6)	List of grid points at fasteners	Any	Integer	N	List in order of plate input at each fastener, n_p entries per record
n_p+n_f+7	Direction normal to plates	X, Y, Z	Character	N	

Notes: 1. **Record Number**: n_p is number of plates, n_f is number of fasteners.

2. **Value** column shows the choices of permitted input values as follows:
   Any – any value of the type indicated in **Type** column can be input;
   A, T, S – material choices for aluminum, titanium and steel, respectively;
   X, Y, Z – coordinate axes choices.

3. **Format**: N – no formatting is required, Y – 8-character field format is required.

EXAMPLE OF MODELING AND ANALYSIS

Description of Structure and FEM

The structure modeled for the example represents part of a joint containing one fastener only for clarity. The model is not intended for a discussion of load transfer through a joint and illustrates the modeling method and the automated procedure for fastener representation only.

The joint consists of three plates, aluminum plate t = 0.200”, titanium plate t = 0.120”, and steel plate t = 0.080”. The plates are attached by 0.19” dia. titanium fastener. The fastener shear plane is defined by rectangular coordinate system ID = 1. Fastener properties are written on PBAR 203.

Load transfer in the joint is approximated by loads applied to the middle plate while two outer plates are constrained in the direction of applied loads.

Continuity of the joint members omitted in the simplified model is simulated by boundary conditions for guided free edges of the plates.

The plates are identified by GRID and element IDs as follows:

- Plate 1, steel: 1 to 9;
- Plate 2, titanium: 11 to 19;
- Plate 3, aluminum: 21 to 29.

All GRID points and elements generated for fastener representation have IDs starting at 100.

The complete model is shown in Fig. 3.

The initial bulk data file is listed below.

```
ASSIGN OUTPUT2='example1.op2' UNIT=12 UNKNOWN
$
SOL 101
TIME 1
CEND
TITLE=3-D JOINT EXAMPLE PROBLEM
SUBTITLE=3 PLATE JOINT
SPC=1
DISP=ALL
SPCF=ALL
ELFO=ALL
MPCF=ALL
GPFO=ALL
LOAD=1
BEGIN BULK
CORD2R  1               0.      0.      0.      0.      -1.     1.
        1.      0.      0.
CQUAD4  1       1       1       2       5       4
CQUAD4  2       1       2       3       6       5
CQUAD4  3       1       4       5       8       7
CQUAD4  4       1       5       6       9       8
CQUAD4  11      2       11      12      15      14
CQUAD4  12      2       12      13      16      15
CQUAD4  13      2       14      15      18      17
CQUAD4  14      2       15      16      19      18
CQUAD4  21      3       21      22      25      24
CQUAD4  22      3       22      23      26      25
CQUAD4  23      3       24      25      28      27
CQUAD4  24      3       25      26      29      28
FORCE   1       17      1       1000.           1.
FORCE   1       18      1       1000.           1.
FORCE   1       19      1       1000.           1.
GRID    1       1       2.      0.      0.      1
GRID    2       1       1.      0.      0.      1
GRID    3       1       0.      0.      0.      1
GRID    4       1       2.      1.0     0.      1
GRID    5       1       1.      1.0     0.      1
GRID    6       1       0.      1.0     0.      1
GRID    7       1       2.      2.      0.      1
GRID    8       1       1.      2.      0.      1
GRID    9       1       0.      2.      0.      1
GRID    11      1       2.      0.      -.1     1
GRID    12      1       1.      0.      -.1     1
GRID    13      1       0.      0.      -.1     1
```

```
GRID    14      1       2.      1.0     -.1     1
GRID    15      1       1.      1.0     -.1     1
GRID    16      1       0.      1.0     -.1     1
GRID    17      1       2.      2.      -.1     1
GRID    18      1       1.      2.      -.1     1
GRID    19      1       0.      2.      -.1     1
GRID    21      1       2.      0.      -.3     1
GRID    22      1       1.      0.      -.3     1
GRID    23      1       0.      0.      -.3     1
GRID    24      1       2.      1.0     -.3     1
GRID    25      1       1.      1.0     -.3     1
GRID    26      1       0.      1.0     -.3     1
GRID    27      1       2.      2.      -.3     1
GRID    28      1       1.      2.      -.3     1
GRID    29      1       0.      2.      -.3     1
MAT1    1       3.E+7           .28
MAT1    2       1.6E+7          .30
MAT1    3       1.E+7           .33
PBAR    203     2       .02835  6.4E-5  6.4E-5
        0.
        1.      1.
PSHELL  1       1       .08     1               1
PSHELL  2       2       .12     2               2
PSHELL  3       3       .2      3               3
SPC1    1       1       1       11      17      21
SPC1    1       23      1       2       3
SPC1    1       23      21      22      23
SPC1    1       45      1       2       3
SPC1    1       45      7       8       9
SPC1    1       45      11      12      13
SPC1    1       45      17      18      19
SPC1    1       45      21      22      23
SPC1    1       45      27      28      29
ENDDATA
```

<u>List file</u> contains the name of a single user input file listed below.

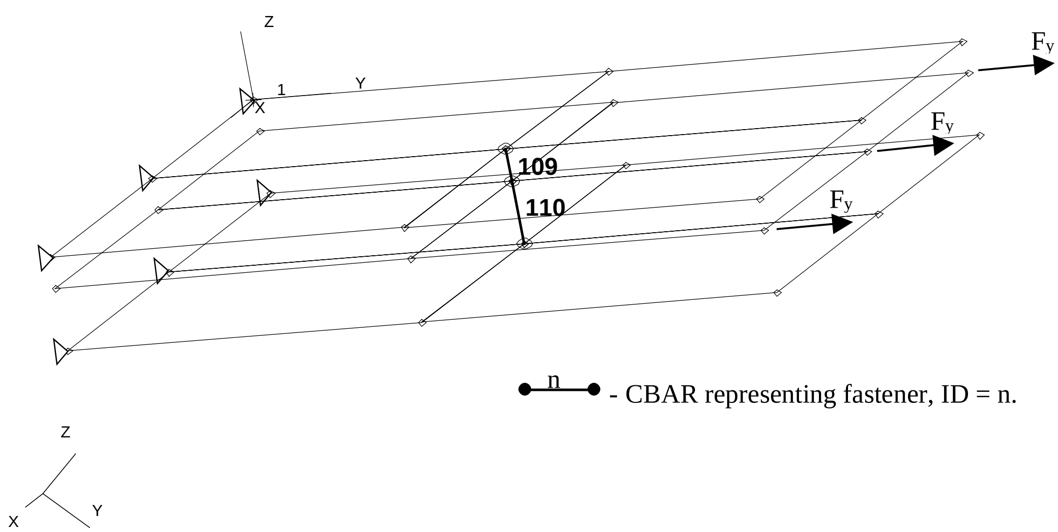


Figure 3. Model, Boundary Conditions and Applied Loads

User Input File

```
Example problem
3 plate joint with one fastener
0.19" Ti fastener, 0.08" S, 0.12" T, 0.20" A plates
1
3
.19     T
.08     S
.12     T
.2      A
5       15      25
Z
```

FEM_joint Program Output File

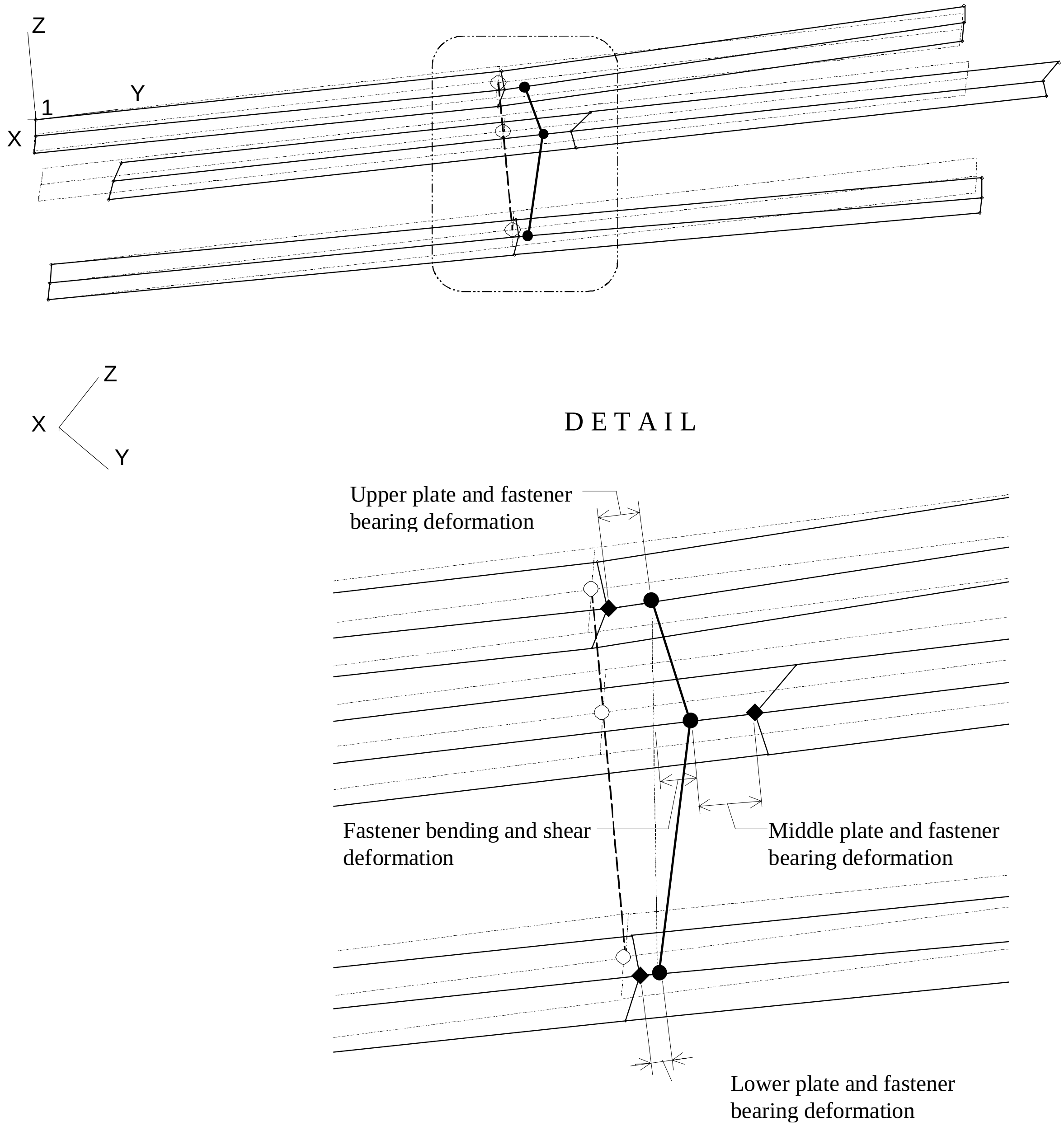
```
$ Example problem
$ 3 plate joint with one fastener
$ 0.19" Ti fastener, 0.08" S, 0.12" T, 0.20" A plates
$
$  ADDITIONAL GRID POINTS
$
GRID         1001       1.      1.0     0.      1
GRID         1011       1.      1.0     -.1     1
GRID         1021       1.      1.0     -.3     1
$
$  RBAR ELEMENTS CONNECTING COINCIDENT POINTS
$
RBAR         100       5     100 123456                 3456
RBAR         101      15     101 123456                 3456
RBAR         102      25     102 123456                 3456
$
$  CELAS2 ELEMENTS
$
CELAS2      103  824889.       5       1     100       1
CELAS2      104  824889.       5       2     100       2
CELAS2      105  960000.      15       1     101       1
CELAS2      106  960000.      15       2     101       2
CELAS2      107 1267924.      25       1     102       1
CELAS2      108 1267924.      25       2     102       2
$
$  CBAR ELEMENTS CONNECTING PLATES
$
CBAR         109     203     100     101      1.      0.      0.
CBAR         110     203     101     102      1.      0.      0.
$
$
```

The file is incorporated into the bulk data file as listed above.

FEA Results

The results of FEA shown in Fig. 4 for displacements are in good agreement with the expected behavior. The figure shows deformations due to combined plate and fastener bearing and, separately, deformations due to the fastener shear and bending.

Fastener shear and bending diagrams obtained directly from BAR element forces are shown in Fig. 5.



○ Plate and fastener nodes location before deformation.

◆ Plate node location after deformation.

● Fastener node location after deformation.

Undeformed shape.

Deformed shape.

Figure 4. Deformations

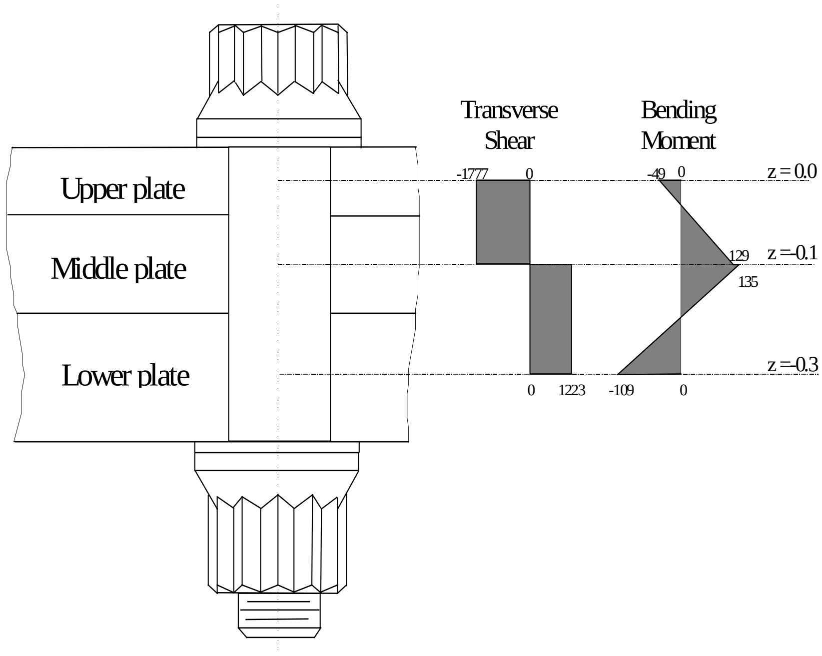


Figure 5. Fastener Loads

SUMMARY AND DISCUSSION

Basic characteristics of a joint model:

1. Plates:
   The plates have membrane, transverse shear and bending stiffness. The plates are modeled at their respective mid planes without offset.
2. Fasteners:
   Fasteners are modeled as BAR elements with the actual properties but without torsional stiffness. Additional set of grid points for the BAR elements connectivity must be created, coincident with respective plate grid points.
3. Fastener-plate interaction:
   Coordinate system with one of the axes parallel to fastener axial direction must exist;
   In-plane shear is transferred through two CELAS2, or similar (CELAS1), elements;
   Each plate is connected rigidly to the fastener in its axial and both bending directions.

Program limitations:

1. Max. number of plates = 8 per group of fasteners on user input file.
2. Max. number of fasteners = 500 per group of fasteners on user input file.

Application for alternative modeling technique:

Any element of the flexibility analysis and/or plate-fastener interaction as defined above can be used to model corresponding properties in any other type of FEM.

Application for alternative solution formats:

The models using the approach presented here for fastener representation are not limited to a particular solution format. However it should be noted that the method as is does not allow for modeling of non-linearity of fastener material and fastener-plate interaction without modifications.

REFERENCES

1. MSC/NASTRAN Quick Reference Guide.