

USER'S MANUAL FOR

B : **BEGINNING-CONCEPT**
E : **EFFICIENT**
S : **STRUCTURAL**
T : **TOPOLOGY**
O : **OPTIMIZATION**
P : **PROGRAM**

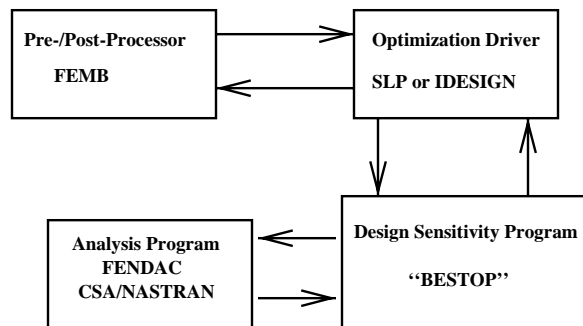
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DESCRIPTION OF THE COMPUTER CODE BESTOP

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BESTOP is a modular software package written to solve for beginning concept designs of linear elastic continuum type structures. The resulting optimal beginning concept designs then form the basis for further detailed design of the structure using fixed topology shape and size optimization methods. Topology optimization of continuum structures requires the integrated action of: an optimization driver; a design sensitivity analyzer; a structural analysis program; and a topology visualization program. Strictly speaking, **BESTOP** is simply the design sensitivity analyzer which interacts with the remaining functional parts as shown below.



BESTOP is based on a continuum formulation of the structural topology optimization problem which uses hybrid combinations of classical Voigt and Reuss mixing rules, and powerlaw mixing rules. Among the many features and capabilities of **BESTOP** are the following:

- Static compliance minimization of structures loaded by prescribed force loadings.
- Treatment of multiple/single loading cases and restraint conditions.
- Tailoring of multiple vibrational eigenvalues.
- Multi-disciplinary optimization involving both static compliance and vibrational eigenvalues.
- Design of structures with compliant/flexible mechanisms.
- Geometric symmetry control and design variable reduction.
- Spatial design variable filtering to provide anti-checkerboarding stability.
- Structural analysis with CSA/NASTRAN, MSC/NASTRAN, or FENDAC.
- Visualization of structural topologies in X-Windows.

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1.0 BRIEF OVERVIEW OF BESTOP INPUT

Before attempting to perform structural topology optimization, it is assumed that the user has generated a working NASIRAN or FENDAC FEM model of the structure to be optimized. For simplicity, a pre- and post-processing package such as FEMB facilitates creating the extensive bulk data that is required, but this is not required. In NASIRAN data files, those lines beginning with the \$ in the first column are perceived by NASIRAN as comment lines and are thus ignored. Control data for BESTOP should be placed at the top of the NASIRAN execution input data file, and each line should begin with a \$ in the first column. Thus BESTOP reads the \$ lines, while NASIRAN reads the non-\$ lines of the input file which should be named *bestop.data*

2.0 MODE CONTROL

2.1 Alternative modes of execution

There are two modes in which to run BESTOP : execution mode and data check mode. Invariably, before executing BESTOP in execution mode, one should execute the program at least once for a given problem in data-checking mode. There are a number of operations and data structures that must be established in the data-checking mode in order for the program to run efficiently and properly in execution mode. For example, in data checking mode BESTOP enforces symmetry control by creating a local ascii file called *DESVAR_MAP* which provides a mapping correspondence between specific finite elements in the structural model and specific design variables. Also, in data checking mode, BESTOP establishes data structures for Haber's perimeter control (ascii file *CBOARD_STRUC*) and data structures for spatial filtering of design variables (ascii file *CHECKB*).

For most structural topology problems, the number of design variables depends upon the specification of designable/ non-designable regions and on the symmetry reductions and enforcements. After BESTOP has been run in data check mode, the number of design variables is printed at the head of the ascii file *DESVAR_MAP*.

2.2 Keyword

The input of the mode control parameter commences on the line immediately following the line beginning with the keyword **\$BESTOP** in the data set.

2.3 Execution Mode Parameter

On the line in the data file immediately after this line BESTOP reads in the variable MODE in the following format:

Columns	Variable	Description
2-10	MODE	Execution mode: 0 for data check; 1 for normal execution;

3.0 OBJECTIVE AND CONSTRAINT DEFINITIONS

3.1 Keyword

The specification of the objective function and global constraints for topology optimization commences on the line immediately following the line beginning with the keyword **\$TOPOLOGY** in the data set.

3.2 Expected format for input data

BESTOP expects to read in descriptive data for one **objective** function, and descriptive data for up to ten global **constraint** functions. The first function read in is taken to be the **objective** and subsequent ones are treated as constraints. To tell BESTOP how many constraint functions will be used in defining the optimization problem, the user must first input the variable $NFUNCT \leq 10$ on a separate line, followed by at least $(NFUNCT+1)$ lines of data describing the prescribed functionals.

3.2.1 Input of control parameter NFUNCT

The expected format for input of the parameter NFUNCT is **1x,i5** on a separate line immediately following the keyword **\$TOPOLOGY**.

3.2.2 Specifying the functionals

After reading in the parameter NFUNCT, BESTOP then expects to read in the appropriate number of lines of data, each having the format (**1x,3I5,2F10**). There must be at least one line of data (and perhaps more) for each function used in the optimization problem. The required variables have the following meanings:

Columns	Variable	Description
2- 6	IFUNC(I,1)	Primary function descriptor If 1, global volume fraction function If 2, global strain energy function If 3, global eigenvalue function If 6, "perimeter" function
7-11	IFUNC(I,2)	Secondary functional descriptor Consult Table 3.2
12-16	IFUNC(I,3)	NASIRAN Subcase control descriptor Consult Table 3.3
17-26	CVAL(I)	Scalar constant which is subtracted from the computed function value
27-36	SVAL(I)	Scalar constant by which the computed function value is multiplied.

Table 3.1 Functional data employed in topology optimization.

BESTOP uses the secondary functional descriptors to provide additional information for each functional. The meaning and usage of the secondary descriptors is as listed below in Table 3.2.

PRIMARY DESCRIPTOR IFUNCT(I,1)	FUNCTIONAL TYPE	SECONDARY DESCRIPTOR IFUNCT(I,2)
1	Global volume fractions	If ≤ 1 : $\mathcal{F}_I = \langle \phi \rangle$ If 2: $\mathcal{F}_I = \langle \phi(1 - \phi) \rangle$
2	Global strain energy	If 0 or 1: Force-controlled
3	Global eigenvalues	If > 0 , gives the eigenvalue number If < 0 , composite eigenvalue function BESTOP expects to read abs[NFUNCT(I,2)] lines of data (1x,i5,f10) specifying the eigenvalue # and weighting parameter
6	Perimeter function	Unused.

Table 3.2 Secondary functional descriptors.

PRIMARY DESCRIPTOR IFUNCT(I,1)	FUNCTIONAL TYPE	SUBCASE DESCRIPTOR IFUNCT(I,3)
1	Global volume fractions	unused
2	Global strain energy	If > 0 , Subcase for single load/spc conditions If < 0 , composite compliance function BESTOP expects to read abs[NFUNCT(I,3)] lines of data (1x,i5,f10) specifying the subcase # and weighting parameter
3	Global eigenvalues	> 0 , gives the subcase number associated with the eigenvalue function
6	Perimeter function	Unused.

Table 3.3 Subcase descriptors.

The subcase control descriptor is associated only with performance functionals such as strain-energy or eigenvalues. For strain energy functions, a positive value of the subcase number IFUNCT(I,3) indicates that the strain energy is to be computed for that sub-case. For strain energy functions, a negative value of the subcase number IFUNCT(I,3) indicates that a composite strain energy function is to be employed, that is $\mathcal{F}_E = \sum_{k=1}^N \beta_k \mathcal{F}_{E_k}$ where $N = \text{abs}[\text{IFUNCT}(I,3)]$ and \mathcal{F}_{E_k} is the strain energy associated with the specified k^{th} subcase and β_k is the weighting parameter for the specified k^{th} subcase. When BESTOP reads a negative IFUNCT(I,3), it then expects to read abs[IFUNCT(I,3)] lines of data (format **1x,i5,f10**) specifying the subcase number and the weighting parameter β_k . For eigenvalue functions,

IFUNCT(I,3) should be positive, and specifies a subcase number giving the restraints on the structural domain.

4.0 SYMMETRY CONTROL

4.1 Explanation

Geometrical symmetry can be imposed upon the layout design by specifying an arbitrary number of spatial symmetry planes about which the design will be symmetrical. In data checking mode **BESTOP** enforces symmetry control by creating a local ascii file called *DESVAR_MAP* which provides a mapping correspondence between specific finite elements in the structural model and specific design variables.

4.2 Keyword

The input of the symmetry control data commences on the line immediately following the line beginning with the keyword **\$SYMPLANES** in the data set.

4.3 Number of Symmetry Planes

Immediately following the keyword **\$SYMPLANES**, **BESTOP** expects to read an integer variable telling how many symmetry planes will be employed. The format for the variable **NPLANES** is as follows:

Columns	Variable	Description
2-10	NPLANES	Number of symmetry planes 0 no planes; >0 NPLANES will be used;

4.4 Input of Symmetry Plane Definitions

Upon reading in the variable **NPLANES**, **BESTOP** expects to read in $3*NPLANES$ lines of additional data, each having the format **(1x,3f10)**. Since each plane is defined by three points that lie in the plane, the three data lines per plane are for the coordinates points defining the plane.

5.0 DESIGNABLE/NON-DESIGNABLE REGIONS

5.1 Explanation

It is possible to perform topology optimization over the entire structural domain Ω_s , or to perform topology optimization only over a subset of the structural domain. Portions of the structural domain in which the material layout is fixed are said to be non-designable, whereas portions of Ω_s in which the material layout remains to be determined are denoted as designable. **BESTOP** performs topology optimization using **NASIRAN**'s **CTRIA3**, **CQUAD4**, **CHEXA**, **CPENTA** and **CTETRA** elements. Associated with each **CTRIA3** and **CQUAD4** element is a **PSHELL** id number, and associated with each **CHEXA**, **CPENTA**, and **CTETRA** element is a **PSOLID** id. By default the elements belonging to the various **PSHELL** and **PSOLID** id groups are not designable. The user must indicate to **BESTOP** which **PSHELL** and **PSOLID** element groups are to be designable. The input data in this sub-section describes how to convey this information to **BESTOP**.

5.2 Keyword

The input of the data which specifies designable and non-designable regions commences immediately following the line beginning with the keyword **\$DESIGNABLE** in the data set.

5.3 Designable PSOLID groups

Immediately following the keyword **\$DESIGNABLE**, **BESTOP** expects to read a data line of the format **(a8,i10)**. The data expected on this line conveys the following information:

Columns	Variable	Description
1- 8	NAME1	Should be '\$PSOLID '
9-18	NPSOLIDS	Number of designable PSOLID groups If >0, then NPSOLIDS lines of data should follow.

Table 5.1 Input of number of designable PSOLID groups.

Each of the **NPSOLIDS** lines of data that follows is of the format **(1x,i5)** and specifies a **PSOLID** group number which will be designable.

5.4 Designable PSHELL groups

Immediately following the input of the designable **PSOLID** data, **BESTOP** expects to read another data line of the format **(a8,i10)**. The data expected on this line is analogous to that of the **PSOLID** data and conveys the following information:

Columns	Variable	Description
1- 8	NAME2	Should be '\$PSHELL '
9-18	NPSHELLS	Number of designable PSHELL groups If >0, then NPSHELLS lines of data should follow.

Table 5.2 Input of number of designable PSHELL groups.

Each of the NPSHELLS lines of data that follows is of the format **(1x,i5)** and specifies a PSHELL group number which will be designable.

6.0 CHECKERBOARD CONTROL

Many topology formulations, especially those using low-order finite elements, are prone to checkerboarding instabilities. To ameliorate these instabilities, spatial filtering of design variables can be employed. The default mode for **BESTOP** is to run with spatial filtering of design variables turned off. Filtering can be turned on, however, as is discussed below.

6.1 Keyword

The input of the data which specifies whether checkerboard stabilizing filtering is to be used commences immediately following the line beginning with the keyword **\$FILTER** in the data set.

6.2 Filtering Mode Parameter

On the line in the data file immediately following **\$FILTER**, **BESTOP** reads in the variable **IFILTER** in the following format:

Columns	Variable	Description
2-10	IFILTER	Filtering mode: 0 filtering turned off; 1 filtering turned on;


```
CEND
TITLE=BEAM10
DISPLACEMENT (PUNCH) = ALL
MAXLINES=10000
ECHO=NONE
SUBCASE 1
SPC = 1
LOAD = 1
BEGIN BULK
PSHELL 1 1.100E+01 1.100E+01 1.833E+00.000E+00WING
CQUAD4 1 1 1 6 7 2
CQUAD4 2 1 2 7 8 3
CQUAD4 3 1 3 8 9 4
CQUAD4 4 1 4 9 10 5
CQUAD4 5 1 6 11 12 7
CQUAD4 6 1 7 12 13 8
CQUAD4 7 1 8 13 14 9
CQUAD4 8 1 9 14 15 10
MAT1 1.200E+12 .300E+00.100E+01.000E+00.000E+00.000E+00WING
GRID 1 0.000 0.000 0.000 0 0
GRID 2 10.000 0.000 0.000 0 0
GRID 3 20.000 0.000 0.000 0 0
GRID 4 30.000 0.000 0.000 0 0
GRID 5 40.000 0.000 0.000 0 0
GRID 6 0.000 10.000 0.000 0 0
GRID 7 10.000 10.000 0.000 0 0
GRID 8 20.000 10.000 0.000 0 0
GRID 9 30.000 10.000 0.000 0 0
GRID 10 40.000 10.000 0.000 0 0
GRID 11 0.000 20.000 0.000 0 0
GRID 12 10.000 20.000 0.000 0 0
GRID 13 20.000 20.000 0.000 0 0
GRID 14 30.000 20.000 0.000 0 0
GRID 15 40.000 20.000 0.000 0 0
SPC 1 1 123456 0.0
SPC 1 2 456 0.0
SPC 1 3 456 0.0
SPC 1 4 456 0.0
SPC 1 5 23456 0.0
SPC 1 6 456 0.0
SPC 1 7 456 0.0
SPC 1 8 456 0.0
SPC 1 9 456 0.0
```

```
SPC      1  10  456  0.0
SPC      1  11  456  0.0
SPC      1  12  456  0.0
SPC      1  13  456  0.0
SPC      1  14  456  0.0
SPC      1  15  456  0.0
FORCE    1   2   0  1.00.00E+00-.10E+070.00E+00
FORCE    1   3   0  1.00.00E+00-.10E+070.00E+00
FORCE    1   4   0  1.00.00E+00-.10E+070.00E+00
ENDDATA
```

7.2 Sample Data File #2

The small sample data file listed below is for a structural topology optimization problem having 16 CQUAD4 elements. Features of the topology problem are:

- BESTOP is being run in “execution” mode (MODE=1).
- There is one objective function and there are three constraint functions.
- The objective is a composite eigenvalue function (IFUNCT(1,1)=3) consisting of two eigenvalues (IFUNCT(1,2)=-2), and subcase 3 (IFUNCT(1,3)=3) provides the restraints on the structural domain for the eigenvalue problem. The scaling factor for the objective function is -1.0 (SVAL(1)=-1.0) and the subtracted factor is 0 (CVAL(1)=0.0). The objective function is the weighted sum of the structure’s first two eigenvalues, with the first weighted by 10.0 and the second weighted by 1.0.
- The first constraint function is a global volume fraction (IFUNCT(2,1)=1) constraint of 50% (SVAL(2)=1.0, CVAL(2)=0.50) on the solid material phase .
- The second constraint is a composite strain energy function (IFUNCT(3,1)=2) from two load subcases (IFUNCT(3,3)=-2). The scaling factor for this constraint function is 1.0 (SVAL(3)=1.0) and the subtracted factor is 100 (CVAL(3)=100.0). The strain energy function is the weighted sum of the strain energy from load cases 1 and 2, where the weighting factors are 1.0 and 1.0.
- The third and final constraint is the strain energy (IFUNCT(4,1)=2) associated with load case 3 (IFUNCT(4,3)=3) with a scaling factor of 1.0 (SVAL(4)=1.0) and a subtracted factor of 150 (CVAL(4)=150.0).
- A fourth constraint of type 6 (perimeter) is also listed in the data file, but will be ignored.
- There are 3 symmetry planes for the structure defined by 9 points.
- There are no designable PSOLID elements in the problem, and all of the elements with a PSHELL id of 1 are considered to be designable.
- Finally, this problem is being run without any filtering to stabilize against checkerboarding.

\$

\$BESTOP

\$ 1

\$TOPOLOGY

\$ 3 4

\$ 3 -2 3 0.000 -1.0e-00

\$ 1 10.000

\$ 2 1.0000

\$ 1 0 0 0.500 1.0e+00

\$ 2 0 -2 1.0e2 1.0e-00

\$ 1 1.0000

\$ 2 1.0000

\$ 2 0 3 1.5e2 1.0e-00

\$ 6 0 1.000 0.0055556

\$SYMPPLANES

\$ 3

\$ -5.000 0.000 0.000

\$ 0.000 0.000 5.000

\$ 5.000 0.000 0.000

\$ 0.000 -5.000 0.000

\$ 0.000 0.000 5.000

\$ 0.000 5.000 0.000

\$ -5.000 -5.000 0.000

\$ 0.000 0.000 5.000

\$ 5.000 5.000 0.000

\$DESIGNABLE \$

\$PSOLID 0 \$

\$PSHELL 1 \$

\$ 1

\$FILTER

\$ 0

\$

ID STATIC,EIGENVALUE

TIME 100

SOL 3

CEND

TITLE=PLATE

DISPLACEMENT (PUNCH) = ALL

MAXLINES=10000

SEDR=ALL

SEALL=ALL

ECHO=NONE

```
SUBCASE 1
SPC = 1
LOAD = 1
SUBCASE 2
SPC = 1
LOAD = 3
SUBCASE 3
SPC = 4
LOAD = 8
BEGIN BULK
EIGRL 3 5
PSHELL 1 1.100E+01 1.100E+01 1.833E+00.000E+00PLATE
CQUAD4 1 1 1 6 7 2
CQUAD4 2 1 2 7 8 3
CQUAD4 3 1 3 8 9 4
CQUAD4 4 1 4 9 10 5
CQUAD4 5 1 6 11 12 7
CQUAD4 6 1 7 12 13 8
CQUAD4 7 1 8 13 14 9
CQUAD4 8 1 9 14 15 10
CQUAD4 9 1 11 16 17 12
CQUAD4 10 1 12 17 18 13
CQUAD4 11 1 13 18 19 14
CQUAD4 12 1 14 19 20 15
CQUAD4 13 1 16 21 22 17
CQUAD4 14 1 17 22 23 18
CQUAD4 15 1 18 23 24 19
CQUAD4 16 1 19 24 25 20
MAT1 1.700E+10 .333E+00.100E+04.000E+00.000E+00.000E+00PLATE
GRID 1 -5.000 -5.000 0.000 0 0
GRID 2 -2.500 -5.000 0.000 0 0
GRID 3 0.000 -5.000 0.000 0 0
GRID 4 2.500 -5.000 0.000 0 0
GRID 5 5.000 -5.000 0.000 0 0
GRID 6 -5.000 -2.500 0.000 0 0
GRID 7 -2.500 -2.500 0.000 0 0
GRID 8 0.000 -2.500 0.000 0 0
GRID 9 2.500 -2.500 0.000 0 0
GRID 10 5.000 -2.500 0.000 0 0
GRID 11 -5.000 0.000 0.000 0 0
GRID 12 -2.500 0.000 0.000 0 0
GRID 13 0.000 0.000 0.000 0 0
GRID 14 2.500 0.000 0.000 0 0
```

GRID	15	5.000	0.000	0.000	0	0
GRID	16	-5.000	2.500	0.000	0	0
GRID	17	-2.500	2.500	0.000	0	0
GRID	18	0.000	2.500	0.000	0	0
GRID	19	2.500	2.500	0.000	0	0
GRID	20	5.000	2.500	0.000	0	0
GRID	21	-5.000	5.000	0.000	0	0
GRID	22	-2.500	5.000	0.000	0	0
GRID	23	0.000	5.000	0.000	0	0
GRID	24	2.500	5.000	0.000	0	0
GRID	25	5.000	5.000	0.000	0	0
SPC	1	1	1236	0.0		
SPC	1	2	36	0.0		
SPC	1	3	36	0.0		
SPC	1	4	36	0.0		
SPC	1	5	236	0.0		
SPC	1	6	36	0.0		
SPC	1	7	36	0.0		
SPC	1	8	36	0.0		
SPC	1	9	36	0.0		
SPC	1	10	36	0.0		
SPC	1	11	36	0.0		
SPC	1	12	36	0.0		
SPC	1	13	36	0.0		
SPC	1	14	36	0.0		
SPC	1	15	36	0.0		
SPC	1	16	36	0.0		
SPC	1	17	36	0.0		
SPC	1	18	36	0.0		
SPC	1	19	36	0.0		
SPC	1	20	36	0.0		
SPC	1	21	36	0.0		
SPC	1	22	36	0.0		
SPC	1	23	36	0.0		
SPC	1	24	36	0.0		
SPC	1	25	36	0.0		
SPC	4	1	123456	0.0		
SPC	4	5	123456	0.0		
SPC	4	21	123456	0.0		
SPC	4	25	123456	0.0		
FORCE	1	21	0	1.00.00E+000.50E+030.00E+00		
FORCE	1	22	0	1.00.00E+000.10E+040.00E+00		
FORCE	1	23	0	1.00.00E+000.50E+030.00E+00		

```

FORCE    3    23    0  1.00.00E+000.50E+030.00E+00
FORCE    3    24    0  1.00.00E+000.10E+040.00E+00
FORCE    3    25    0  1.00.00E+000.50E+030.00E+00
FORCE    8    13    0  1.00.00E+000.00E+001.00E+02
GRDSET,,,,,,6
ENDDATA

```

8.0 INPUT FOR SLP OPTIMIZATION DRIVER

Aside from providing input for the design sensitivity program **BESTOP**, input data is also required for the optimization program **SLP**. The input data requires one title line identifying the problem, and two lines of input, one consisting of integer parameters and the other of real parameters. The information that must be conveyed to the **SLP** optimization program in these two lines of data is described below:

8.1 Integer Parameters

Columns	Variable	Description
1- 5	NV	Number of design variables
6-10	NEQL	Number of global equality constraints
11-15	NIQL	Number of global inequality constraints
16-20	ITRS	Limit on number of optimization iterations

The number of design variables **NV** can be determined, after executing **BESTOP** in data checking mode, by looking at the head of the *DESVAR_MAP* file. The total number of constraints **NEQL** + **NIQL** should sum to the value of **NFUNCT** as specified in Section 3.2

8.2 Real Parameters

Columns	Variable	Description
1-10	ACV	Acceptable constraint violations
11-20	ACS	Acceptable tolerance for convergence parameter
21-30	DEL	Delta parameter used for finite difference DSA
31-40	ACT	Acceptable change in the cost function
41-50	DELM	SLP move limit value ($0 < DELM \leq 1$ 0.05 is the default value)
51-60	START	Uniform initial value of design variables if < 0 read binary DESIGN file, this facilitates re-starting; if ≥ 0 assign value of START
61-70	ALPHA	Voigt-Reuss hybridization parameter if 0, pure Reuss formulation if 1, pure Voigt formulation if $0 < ALPHA < 1$, hybrid formulation

8.3 Sample SLP Input Data File

For the sample input data file listed below, the optimization problem has the following characteristics:

- There are 210 design variables.
- There are 0 equality constraints and 2 inequality constraint.
- A maximum of 150 optimization iterations are permitted.
- $ACV = 1.0e-3$;
- $ACS = 1.0e-5$;
- $DEL = 1.0e-5$;
- $ACT = 1.0e-5$;
- $DELM = 0.05$ which corresponds to a SLP move limit of .05.
- $START = -1.0$, which means that the initial design state is being read from a binary DESIGN file;
- $ALPHA = 0.0$ which translates to a pure Reuss formulation;

Sample SLP Input Data File

BORON EPOXY SHEAR OPTIMIZATION 40% BORON

210 0 2 150

1.0000E-03 1.0000E-5 1.000E-05 1.0000E-5 0.0500 -1.00E+00 0.00E-02