

# **Methodology for Connecting Strut Loads Calculations during Assembly and Launch Sequence of Two Space Station Modules**

by

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## **Abstract**

This paper outlines the solution method for calculating residual loads in the connecting members (struts) of two space station modules during assembly and launch process using MSC/NASTRAN geometric nonlinear capability. Use of geometric nonlinear capability is essential since, the assembly and launch process the loads and boundary conditions are changing at each step causing the energy redistribution during the process. The process is demonstrated using a small problem and a realistic looking space structure.

## 1. Introduction

Many of the aerospace engineering challenges are associated with space exploration. These processes often involve fabrication and assembly of the components on the ground in 1-g environment and subsequently launching these components in space in 0-g environment. Likeness of the spacestation modules and connecting struts are shown in figure 1. Assembly and Launch process introduces residual loads in the connecting components. The task at hand is made inconvenient by the inherent nature of the process where loads, boundary conditions and the structure itself are changing during each step of the process. The finite element models associated with such structure are often large which further complicates the analysis process. Due to changing loads and boundary conditions, the structural stiffness is changing between load cases. Moreover, the strain energy stored in the structure in a load case is redistributed in subsequent load case. MSC/NASTRAN nonlinear capability allows these type of interactions between loadcases where loads can be added and constraints can be removed in a continuous manner allowing the energy transfer to take place during process. This is done by appropriately selecting load sets, single-point-constraint set and multi-point constraint set for each loadcase. It is important to note that in deformed grid can not be constrained in the deformed position in the subsequent subcase. Constraining the deformed grid in later subcase will force the deformation of the grid to zero. Multi-point-constraints are linear equations connecting one degree of freedom displacement to one or more degree of freedom displacements.

This paper demonstrates the single step procedure for finding residual loads in connecting struts of two space-station modules at various stages of the assembly and launch sequence. The process consists of several loadcases for each step of the assembly and launch process. These are identified in figure 2. These loadcases are identified by distinct subcases in MSC/NASTRAN terminology.

Schematic of typical space station modules showing the Connecting struts.

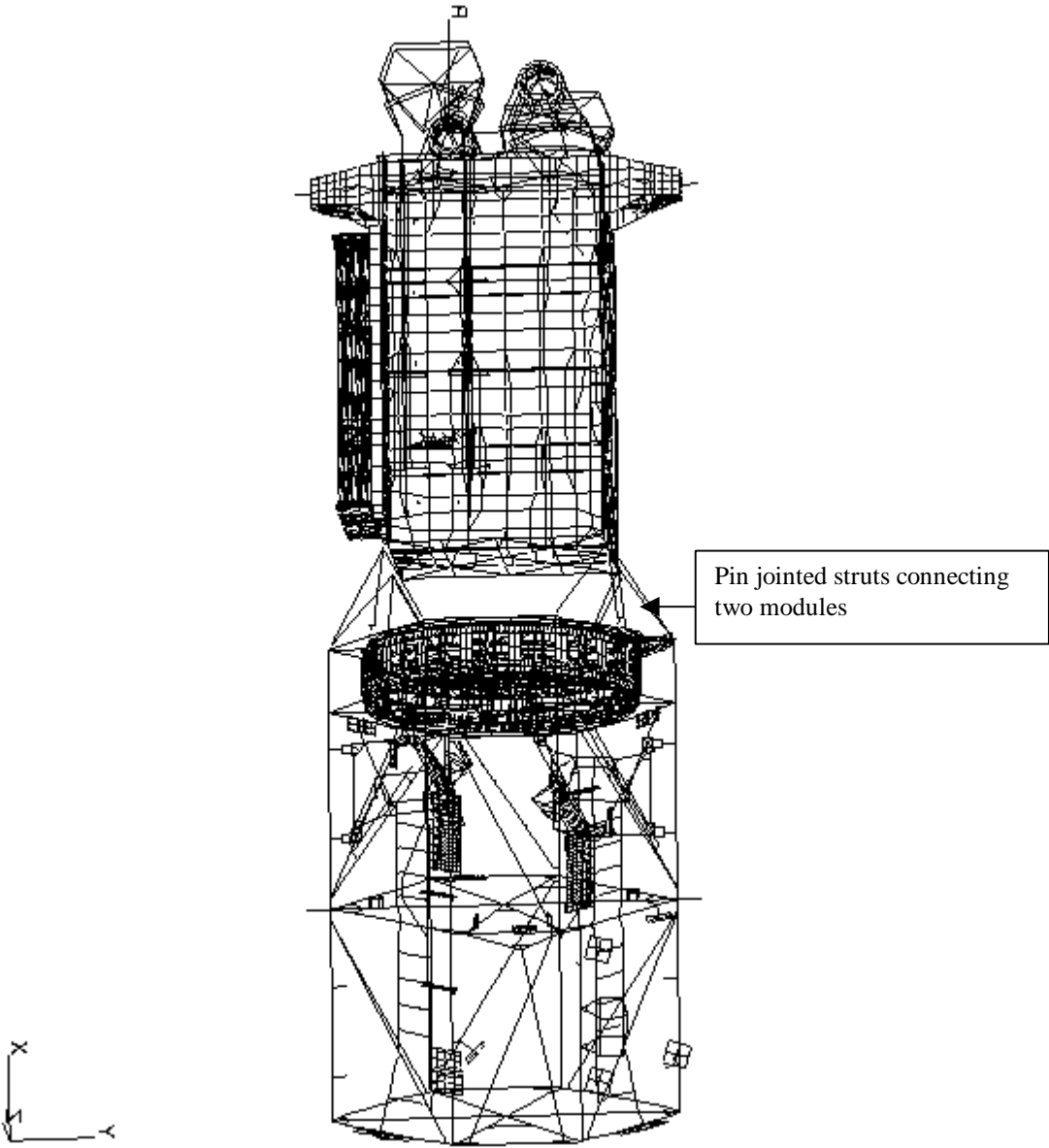
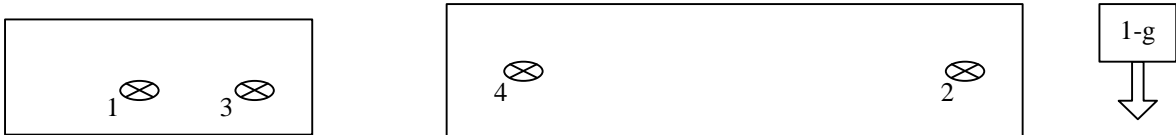


Figure 1: Spacestation module assembly

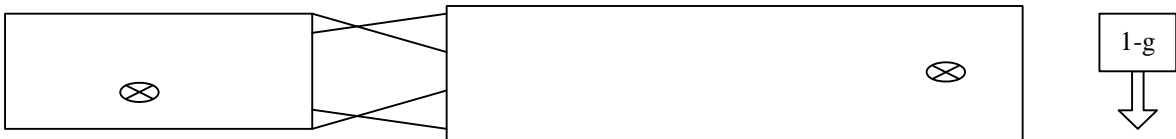
⊗ : Constraint Locations

↓ : Loading Condition

Step 1 Bring both modules under 1g loading prior to connecting struts



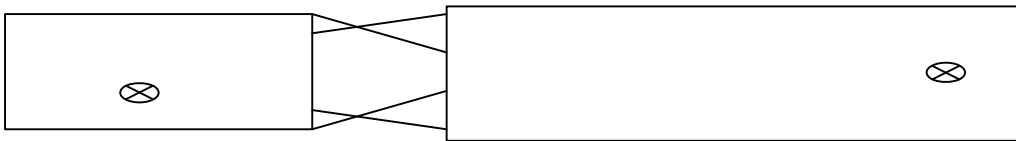
Step 2 Connect struts between two modules and remove the two interior constraints



Step 3,4 Place both modules in to shuttle cargo bay and switch 1g direction



Step 5 Shuttle reaches orbit: remove loading



Step 6 Modules are place in orbit: remove constraints



Figure 2: Schematic showing various events of a launch process during which strut loads are calculated.

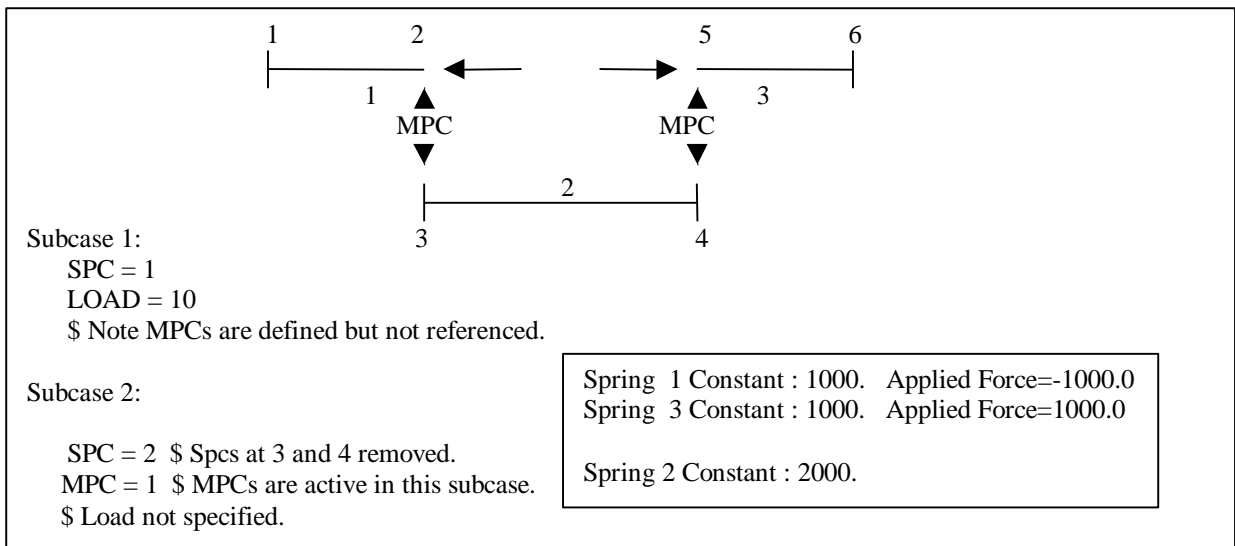
## **2. Solution Method:**

MSC/NASTRAN nonlinear static solution sequence (SOL 106) will be used for the problem. It continuously, accounts for modification of loads, boundary condition and multi-point constraint equations between subcases. (i.e. converged solution at the end of a subcase forms an initial conditions for the next subcase). Multiple subcases provide tool for applying distinct loads and boundary conditions, which are part of a load history for the analysis under consideration. Within a subcase loading and boundary conditions can be subdivided into number of increments to assist the convergence process. The number of load increments and iteration methods are specified on the NLPARM bulkdata entry, which is selected within each subcase. Thus, subcases in nonlinear analysis provide partitioning of a load history where each step of the loading history can be controlled independently. For the present problem, response of the structure is linear for the given loading and incremental load steps are not required.

In step-1 described above both modules are loaded in 1-g configuration as they are supported by the rigid assembly frame in subcase 1. The assembly process of step 2 is modeled by connecting ends of the struts to the connection point of the modules via multi-point constraint (MPC) equations. Purpose of MPCs is to linearly relate the two or more degree of freedoms. In subcase 2 these multi-point constraint equations are activated by MPC case control request and the supports at locations 3 and 4 are removed. Since continuity between subcases is maintained, the multipoint constraint equations will use the displacement values obtain at the end of the first or previous subcase. This will cause redistribution of strain energy stored in the modules to be redistributed thru the structure and the struts will take up some of this energy. Note that in subcase 2 some of the constraints are removed, the multipoint constraints equations are added and no changes in the external loads are introduced. This concept of removing loads, constraints and including new structure during an analysis can be shown by a simple example shown in next section.

### 3. Demonstration of concept:

It is invaluable to illustrate and validate the analysis under consideration prior to attempting it on an actual problem. This is done here using simple three-spring model, which is conceptually similar to problem under investigation that has a close form solution. In this sample problem three co-linear springs are considered. Objective of the analysis is to fit the middle spring between the two outer springs and calculate the loads in the assembled structure. Two outer springs are constrained at the opposite ends and compressed to fit the middle spring. Subsequently, compression causing external forces from the two outer springs are released and load in the middle spring is observed. The MSC/NASTRAN nonlinear solution result for the problem described in figure 3 is compared to closed form solution obtained via principle of minimum potential energy in the following table 1. Theoretical formulation is shown on next page and MSC/Nastran input file is shown in appendix A.



	End of Subcase 1		End of Subcase 2	
	Nastran	Theory	Nastran	Theory
Displacement A	-1.0	-1.0	-.8	-.8
B	1.0	1.0	.8	.8
Element forces 1	1000.	1000.	800.	800.
2	0.0	0.0	800.	800.
3	1000.	1000.	800.	800.

Table 1: Comparison of a Test case with MSC/Nastran nonlinear solution.

Theoretical Formulation:

The potential energy of the system can be written as

$$U = \frac{1}{2} k_1 x_1'^2 + \frac{1}{2} k_2 x_2'^2 + \frac{1}{2} k_3 [ (x_1 - x_1') + (x_2 - x_2') ]^2$$

Where,

$x_1, x_2$  = deformation of the outer springs prior to load release.

$x_1', x_2'$  = deformation at equilibrium

$k_1, k_2, k_3$  = spring stiffness of springs 1,2, and 3.

Using principle of minimum potential energy,

$$\begin{aligned} dU/dx_1 &= 0 \\ dU/dx_2 &= 0 \end{aligned}$$

following equations can be obtained

$$(x_1' / x_2') = (k_2 / k_1)$$

$$x_2' = [k(x_1 - x_1')] / [k_2 + k_3 + (k_1 k_2 / k_3)]$$

### **Strut loads analysis:**

In this example, two structures depicting spacestation modules are first subjected to 1g condition simulating assembly environment in subcase 1. Secondly, two modules are connected by ten connecting struts and interior constraints were removed under 1g condition. Thus, subcase 2 simulated module placement in shuttle bay in horizontal position. These struts are expected to carry axial loads only due to the pinned connections simulated by beam elements with pinflags. Here, it is assumed that change in length of the connecting struts is small compare to initial length and will not have significant affect on the critical strut loads. In subcase 3 strut loads were calculated in vertical position prior to launch. In subcase 4 strut loads were calculated under 10g loading simulating acceleration during launch. Then, in subcase 5 loads were removed simulating in orbit configuration. Lastly, all the constraints were removed in subcase 6. Complete MSC/NASTRAN input file is shown in appendix B.

It is important to note that complete model existed in the bulk data file including the modules and the struts. The activating appropriate MPC, SPC and LOAD sets in the case control allowed for changing of structure, constraints and loading to simulate various steps of the launch process as described above.

Coincident nodes existed at the connection points of struts and modules. The nodes associated with struts were constrained in first subcase and struts were assumed massless throughout the analysis. In the second subcase, the connection of the struts was established by removing the set of constraints associated with struts in first subcase and activating the multi point constraint equations. At the same time inboard constraints were also removed from the modules.

Results for each case were checked by observing forces in the beam elements and comparing resultant load output against the reaction resultants for each subcase. Convergence for nonlinear analysis was observed for each subcase. For each case, resultant load output agreed with reaction resultants and no moment, shears or torque forces were observed in the connecting struts confirming correct connection of struts with the modules. Element force output for each subcase is shown in figure 3. The multi-point constraint force output was



also compared with the element force output and no inconsistencies were found.

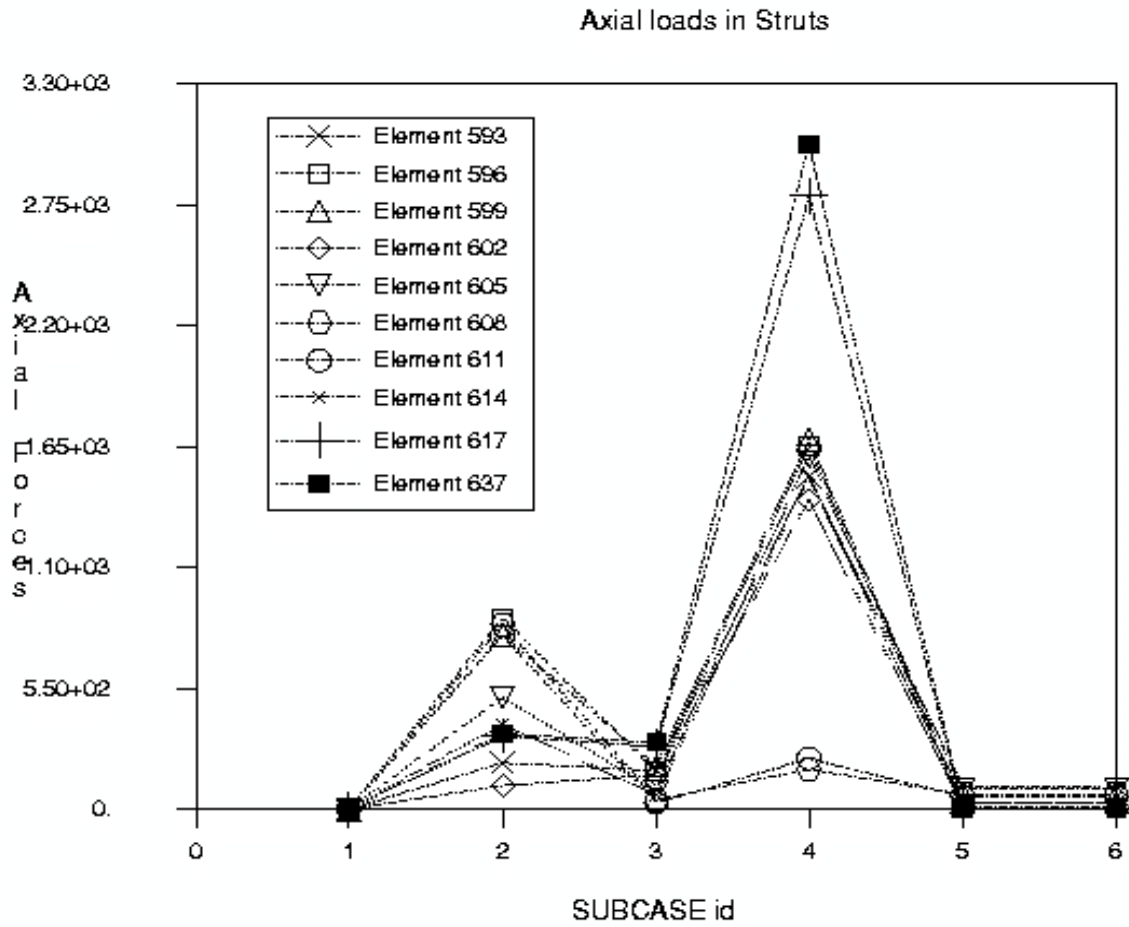


Figure 3: Axial loads in struts for six loadcases.

Most critical case for the struts loads is found in subcase4—acceleration phase during launch. It was observed that struts were not stress free in orbit.

## ***Conclusion***

This paper outlines the method to calculate loads in struts connecting two modules of a spacestation during launch sequence. As shown by the concept model, that the method can be used in variety of situations where changing structure, loads and constraints are part of the load history. In this example, constraints were only removed and not added to the deformed grid. This can also be accomplished by formulating the multipoint constraint equations appropriately. The model used the beam elements with pin flags to model only axial load carrying members. The MSC/NASTRAN version 70.5 has added a 1-D nonlinear element (cbush1d) with geometric and material nonlinearity which could also be used for this purpose.

## Appendix A

```

SOL 106
CEND
$
OLOAD=ALL
DISP=ALL
SPCFORCES=ALL
MPCFORCES=ALL
ESE = ALL
$
SUBCASE 1
  NLPARAM = 1
  LOAD = 1
  SPC = 1
$
SUBCASE 2
  NLPARAM = 2
  $ LOAD = 1          $ Unloading
  SPC = 2            $ Changing the SPC to include the middle spring
  MPC=1              $ Connecting outer springs to middle spring
BEGIN BULK
$ 1-----2          5-----6
$          mpc          mpc
$          3-----4
$
NLPARAM  1      1      AUTO  5      25      U      NO      +      G
+      G      .001  1.-7
$
CELAS2  10      1000.  1      1      2      1
CELAS2  20      2000.  3      1      4      1
CELAS2  30      1000.  5      1      6      1
$
MPC  1      4      1      1.      5      1      -1.
MPC  1      3      1      1.      2      1      -1.
$
GRID  6          10.
GRID  5          0.
GRID  4          0.
GRID  3         -4.
GRID  2         -4.
GRID  1        -14.
$
SPC1  1      1      1      6
SPC1  1      23456  1      2      5      6
SPC1  1      123456  3      4
$
$ Keeping the SPC the same for outside members.
$ Removing the SPC for the middle member.$
SPC1  2      1      1      6
SPC1  2      23456  1      THRU  6
$
FORCE  1      2          1000.0 -1.
FORCE  1      5          1000.0  1.
$
ENDDATA

```

## Appendix B

```
SOL 106
TIME 600
CEND
ECHO = NONE
SPCFORCE = ALL
MPCFORCE = ALL
SET 10 = 593,THRU,674
STRESS = 10
FORCE = 10
DISPLACEMENT(SORT1,REAL)=ALL
SUBCASE 1
  SUBTITLE=1g load two structures detached
  NLPARM = 1
  SPC = 2
  METHOD = 1
  LOAD = 2
SUBCASE 2
  SUBTITLE=1g load to structures attached inboard SPC removed
  MPC = 17
  SPC = 3
  LOAD = 2
  NLPARM = 2
SUBCASE 3
  SUBTITLE=1g load in z in the prelaunch configuration
  MPC = 17
  SPC = 3
  NLPARM = 2
  LOAD = 4
SUBCASE 4
  SUBTITLE=10g load in z in the during launch
  MPC = 17
  SPC = 3
  NLPARM = 2
  LOAD = 5
SUBCASE 5
  SUBTITLE=In orbit in shuttle bay
  MPC = 17
  SPC = 3
  NLPARM = 2
SUBCASE 6
  SUBTITLE=In orbit out of the shuttle bay
  SPC = 4
  MPC = 18
  NLPARAM = 2
PARAM   KDIAG   1.0
$
BEGIN BULK
PARAM   POST    -1
PARAM   PATVER  3.0
PARAM   COUPMASS -1
PARAM   K6ROT   100.
PARAM   WTMASS  1.
PARAM   PRTMAXIM YES
NLPARM  1       1       AUTO    5       25       UPW     NO     +     A
+      A .001   .001   1.-7
```

```

NLPARM 2 1 AUTO 5 25 UPW NO + B
+ B .001 .001 1.-7
$
PSHELL 1 1 .1 1 1
$
$ Elements and Element Properties for region : strut_h_pin
PBEAM 4 2 1.5 10. 10. 5. 10. + I
+ I + J
+ J YES 1. 1.5 10. 10. 5. 10. + K
+ K
$ "strut_h_pin" will be imported as: "pbeam.4"
CBEAM 593 4 3001 2001 1 + L
+ L 45 6
CBEAM 596 4 3002 2002 1 + M
+ M 45 6
CBEAM 599 4 3003 2003 1 + N
+ N 45 6
CBEAM 602 4 3004 2004 1 + O
+ O 45 6
CBEAM 605 4 3005 2005 1 + P
+ P 45 6
CBEAM 608 4 3006 2006 1 + Q
+ Q 45 6
CBEAM 611 4 3007 2007 1 + R
+ R 45 6
CBEAM 614 4 3000 2000 1 + S
+ S 45 6
$ Elements and Element Properties for region : strut_h_pin2
PBEAM 5 2 1.5 10. 10. 5. 10. + T
+ T + U
+ U YES 1. 1.5 10. 10. 5. 10. + V
+ V
$ Elements and Element Properties for region : strut_v_pin1
PBEAM 6 2 1.5 10. 10. 5. 10. + AE
+ AE + AF
+ AF YES 1. 1.5 10. 10. 5. 10. + AG
+ AG
$ "strut_v_pin1"
CBEAM 617 6 3003 2006 0. 0. 1. + AH
+ AH 6 45
CBEAM 637 6 3002 2007 0. 0. 1. + AI
+ AI 6 45
$
MAT1 1 1.+7 .3 .15
MAT1 2 1.+7 .3
$
include 'elements.inc'
include 'mpc.inc'
include 'grids.inc'
include 'spc.incl0'
$
GRAV 1 0 32.2000 0. -1. 0.
GRAV 6 0 32.2000 0. 0. -1.
GRAV 3 0 32.2000 0. 0. -10.
$
ENDDATA

```