# Establishing New Methodologies With MSC SOFTWARE Products to Develop a 747SP Finite Element Model for FAA Certification of Airframe Design Modification

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## ABSTRACT

Raytheon Systems Company Waco has developed a MSC/NASTRAN finite element model from drawings of the Boeing 747SP in support of the SOFIA program. SOFIA (Stratospheric Observatory For Infrared Astronomy) is an airborne observatory housing a 2.5 meter infrared telescope (the largest ever airborne). The SOFIA airborne observatory will take a team of NASA scientists, engineers, and educators above 41,000 feet placing the aircraft above 99% of the earth's obscuring water vapor and providing a view of the universe superior to any earth bound observatory. The 747SP finite element model is playing a significant role in the structural substantiation of the design modifications to the 747SP. There are three phases of finite element model development: the baseline model representing the baseline configuration of the Boeing 747SP, the section 46 design model characterizing all of the design changes reflected in the SOFIA design modification, and the certification model with the final SOFIA design modification incorporated into the full 747SP finite element model. These models are MSC/PATRAN databases defined within MSC/SuperModel. MSC/SuperModel has been used to maintain configuration control of the MSC/PATRAN databases and to establish the pedigree of the model by maintaining the history of the model assembly. Throughout the certification process CAE tools and methods have significantly enhanced productivity and have been used to provide an integrated method of data management and analysis. This paper illustrates the finite element process from airframe modification design to the design certification process, and how the Methods & Finite Element Group at Raytheon Waco has utilized MSC software products to enhance the certification process.

## INTRODUCTION

Because of the difficulty of developing a complete baseline 747SP finite element model from drawings, combined with a finite element characterization of a major design modification to the 747SP fuselage, and due also to tight schedule requirements, it was evident that a significant change to the finite element process was required. The Methods & Finite Element Analysis group had to establish a new approach to model development and integrate new methodologies into the finite element process to make more productive use of the finite element model in the substantiation of the airframe modification. A significant change to the finite element process was the establishment of the MSC/PATRAN database as the master definition of the finite element model. The finite element model master database has had a profound impact on improving productivity, and has had far reaching effects on integrating methodologies which have redefined the process of the finite element model development and analysis. The master database has eliminated many inefficiencies in the modeling process; database methodology has eliminated the use of the bulk data file for all functions but the transparent translation performed by MSC/Analysis Manager upon job submittal to MSC/NASTRAN. After loads have been defined within the database, loads validation such as shear and bending moment and load summation checks are performed within the database. The requirement to use the bulk data file with annotated comment cards to denote key information critical to maintaining the model pedigree has been replaced with the electronic association of model history maintained within the MSC/PATRAN database. Numbering schemes used to define the location of grids and elements were abandoned in favor of an interactive database approach to model development. Though numbering schemes are very useful when working with only bulk data files and f06 files, the master database provides much greater accessibility to the model parameters than do ASCII files. The master database is a more useful and logical presentation of the finite element characterization of airframe structure.

The finite element master database is maintained within the MSC/SuperModel file management system. Configuration control of all files used to develop the model is maintained within the MSC/SuperModel file hierarchy. MSC/SuperModel has provided an integrated method of data management, and a means by which new engineering methodology can be integrated into the master database.

This paper chronicles the development of the 747SP finite element model, and how MSC software applications have been integrated into the finite element process to establish methodologies that have made the finite element model central to the substantiation of the 747SP design modification.

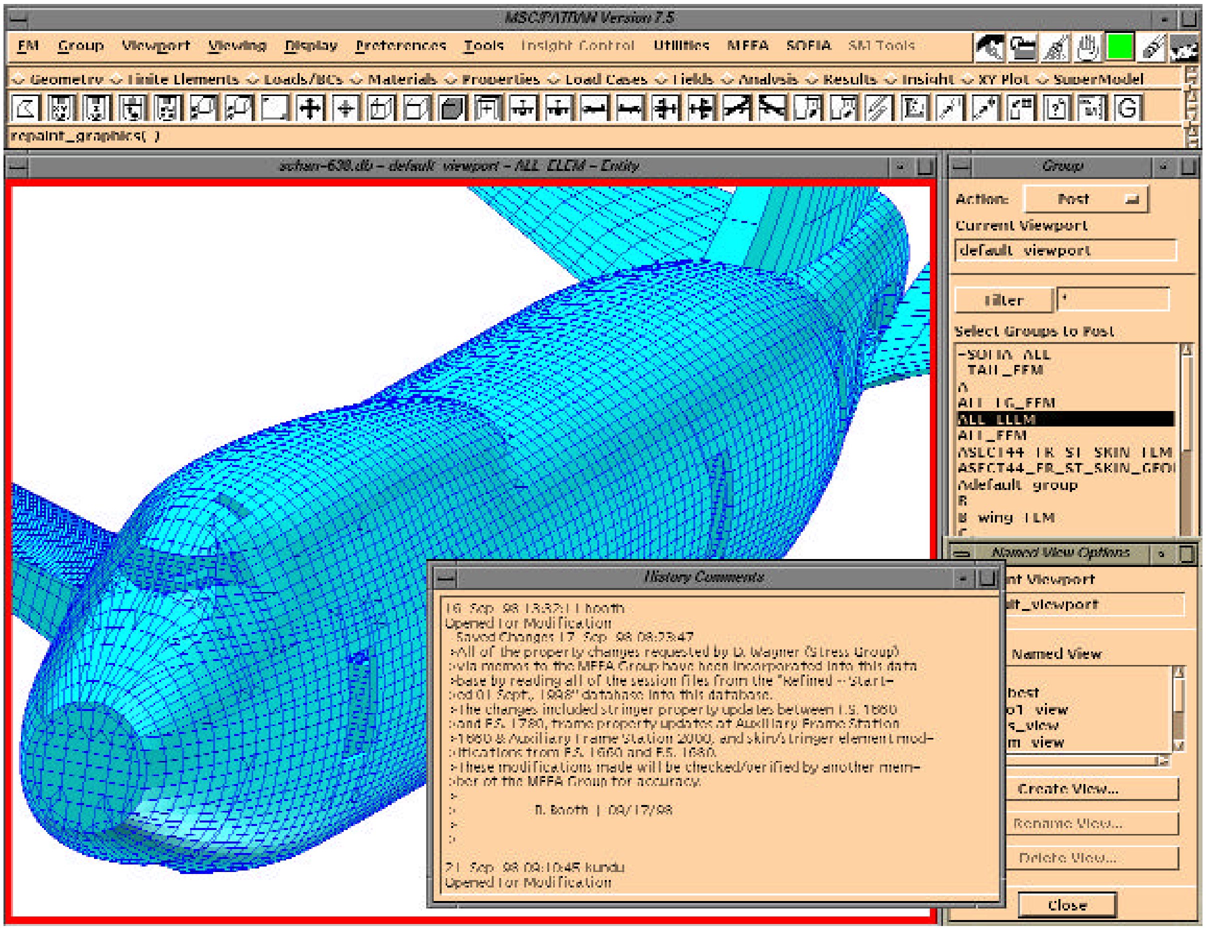
## SUPERMODEL

Implementing database methodology for all aspects of the finite element process was critical to successfully meeting the technical and schedule requirements of the SOFIA program. Central to the database methodology is the master finite element model database. The heart of the master databases of the 747SP baseline, design and certification model is MSC/SuperModel. MSC/SuperModel provides a means to manage all the components of the master databases.

Configuration management was of vital importance throughout the development of the 747SP model. Within MSC/SuperModel a file hierarchy is established. Within that hierarchy branches are established which delineate the sections of the 747SP structure. Within each section in MSC/SuperModel resides the data relevant to the section. Items such as the Single Geometry Model and other CAD part files are maintained with respect to their specific section of the airframe. Within each section in MSC/SuperModel resides the distinct MSC/PATRAN database representing that section of the 747SP airframe structure. The interface of these databases is maintained within the MSC/SuperModel hierarchy.

The distinct databases of each section of the 747SP coupled with common interfaces between the baseline and certification section 46 models have facilitated the model development process. The interchangeability of these two sections requires that only one database of each section of the 747SP model be maintained. Productivity gains were achieved by managing one database that represents the components of both the baseline and certification finite element model.

To maintain the pedigree of the databases it was required to establish the history of the model assembly. To indicate the work completed within each database session an entry input to the history form is made upon saving the database. This form is electronically associated to the database, and can be viewed at any time to evaluate the status of the model. Additionally the text in this form was captured and e-mailed to provide an automated means of tracking status of the model development. Figure 1 illustrates the history form electronically associated to the database.



repaint_graphics( )

schan-630.db - default_viewport - ALL_ELLM - Entity

Action: Post

Current Viewport: default_viewport

Filter: *

Select Groups to Post:

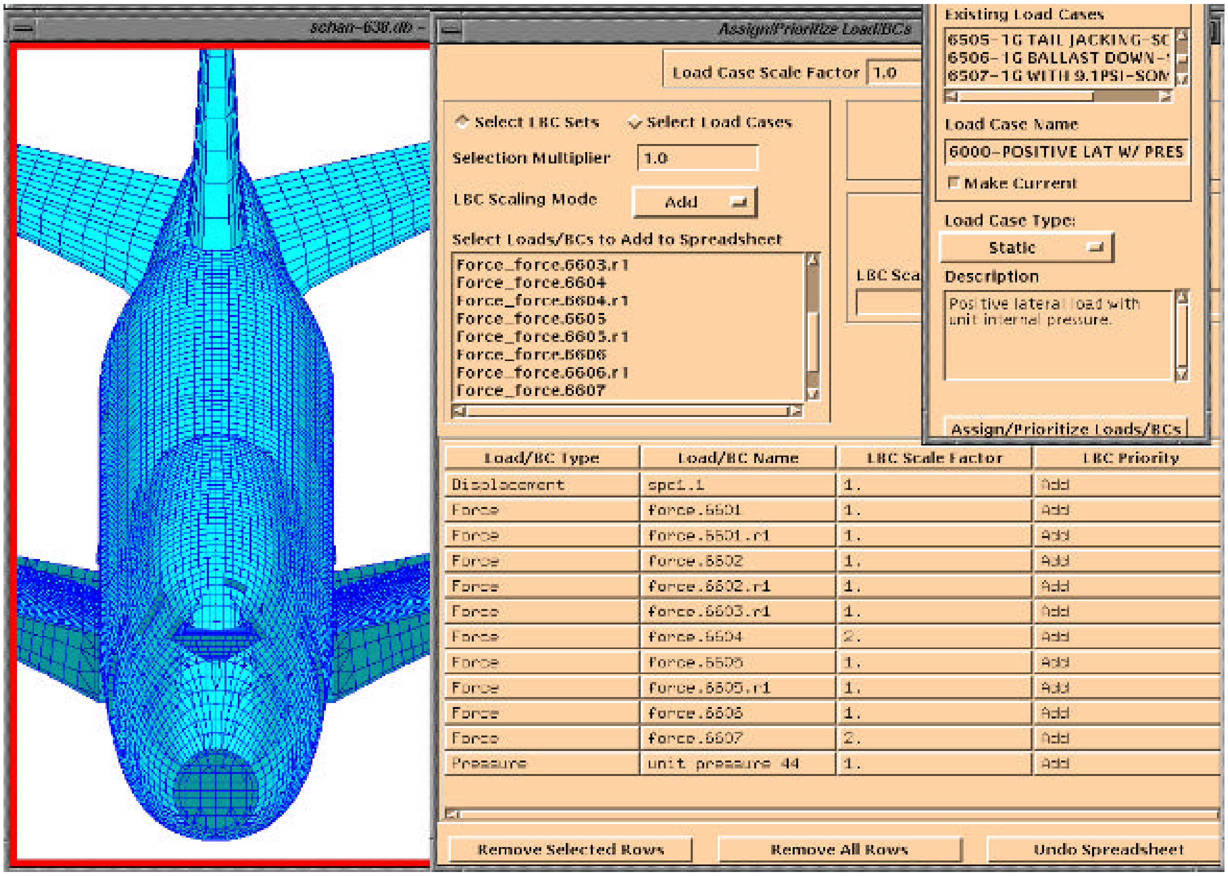
```
-SOFIA_ALL
 TAIL_FFM
A
ALL_LG_FFM
ALL_ELLM
ALL_FFM
ASECT44_FR_ST_SKIN_FEM
ASECT44_FR_ST_SKIN_GEOI
Adefault_group
B
B_wing_FEM
```

```
16 Sep 98 13:32:11 booth
Opened for Modification
  Saved Changes 17 Sep 98 08:23:47
 >All of the property changes requested by D. Wagner (Stress Group)
 >via memos to the MFEA Group have been incorporated into this data
 >base by reading all of the session files from the "Refined -- Start-
 >ed 01 Sept., 1998" database into this database.
 >The changes included stringer property updates between F.S. 1660
 >and F.S. 1780, frame property updates at Auxiliary Frame Station
 >1660 & Auxiliary Frame Station 2000, and skin/stringer element mod-
 >ifications from F.S. 1660 and F.S. 1680.
 >These modifications made will be checked/verified by another mem-
 >ber of the MFEA Group for accuracy.
 >
 >            R. Booth | 09/17/98
 >
 >

21 Sep 98 09:10:45 kundu
Opened for Modification
```

Figure 1 – The History Form

The finite element graphical representation of the airframe structure enhanced every aspect of the finite element process. Visualization of the finite element model coupled with direct access to all parameters within the master database eliminated the requirement for numbering schemes for grids, elements and properties. All load conditions are integral to the database. Figure 2 shows a load case defined within the MSC/PATRAN database. From within the MSC/PATRAN database the loads are evaluated to ensure that each load case is balanced and that the shear and bending moments match the original external load conditions. From the database the model is submitted to MSC/NASTRAN and the resultant internal loads are delivered to the master database.



Existing Load Cases
6505- 1G TAIL JACKING-SC
6506- 1G BALLAST DOWN-
6507- 1G WITH 9.1PSI-SON

Load Case Name: 6000-POSITIVE LAT W/ PRES

☐ Make Current

Load Case Type: Static

Description: Positive lateral load with unit internal pressure.

Load Case Scale Factor: 1.0

Selection Multiplier: 1.0

LBC Scaling Mode: Add

Select Loads/BCs to Add to Spreadsheet
Force_force.6603.r1
Force_force.6604
Force_force.6604.r1
Force_force.6605
Force_force.6605.r1
Force_force.6606
Force_force.6606.r1
Force_force.6607

| Load/BC Type | Load/BC Name | LBC Scale Factor | LBC Priority |
|---|---|---|---|
| Displacement | spc1.1 | 1. | Add |
| Force | force.6601 | 1. | Add |
| Force | force.6601.r1 | 1. | Add |
| Force | force.6602 | 1. | Add |
| Force | force.6602.r1 | 1. | Add |
| Force | force.6603.r1 | 1. | Add |
| Force | force.6604 | 2. | Add |
| Force | force.6605 | 1. | Add |
| Force | force.6605.r1 | 1. | Add |
| Force | force.6606 | 1. | Add |
| Force | force.6607 | 2. | Add |
| Pressure | unit pressure 44 | 1. | Add |

Figure 2 – Load Case Defined Within MSC/PATRAN

MSC/SuperModel has provided an integrated method of data management. Raytheon Systems Company Waco has implemented MSC/SuperModel to create a master database, while achieving parallel model development, file management, and maintaining a history of model assembly and results. This concept is illustrated by figure 3.

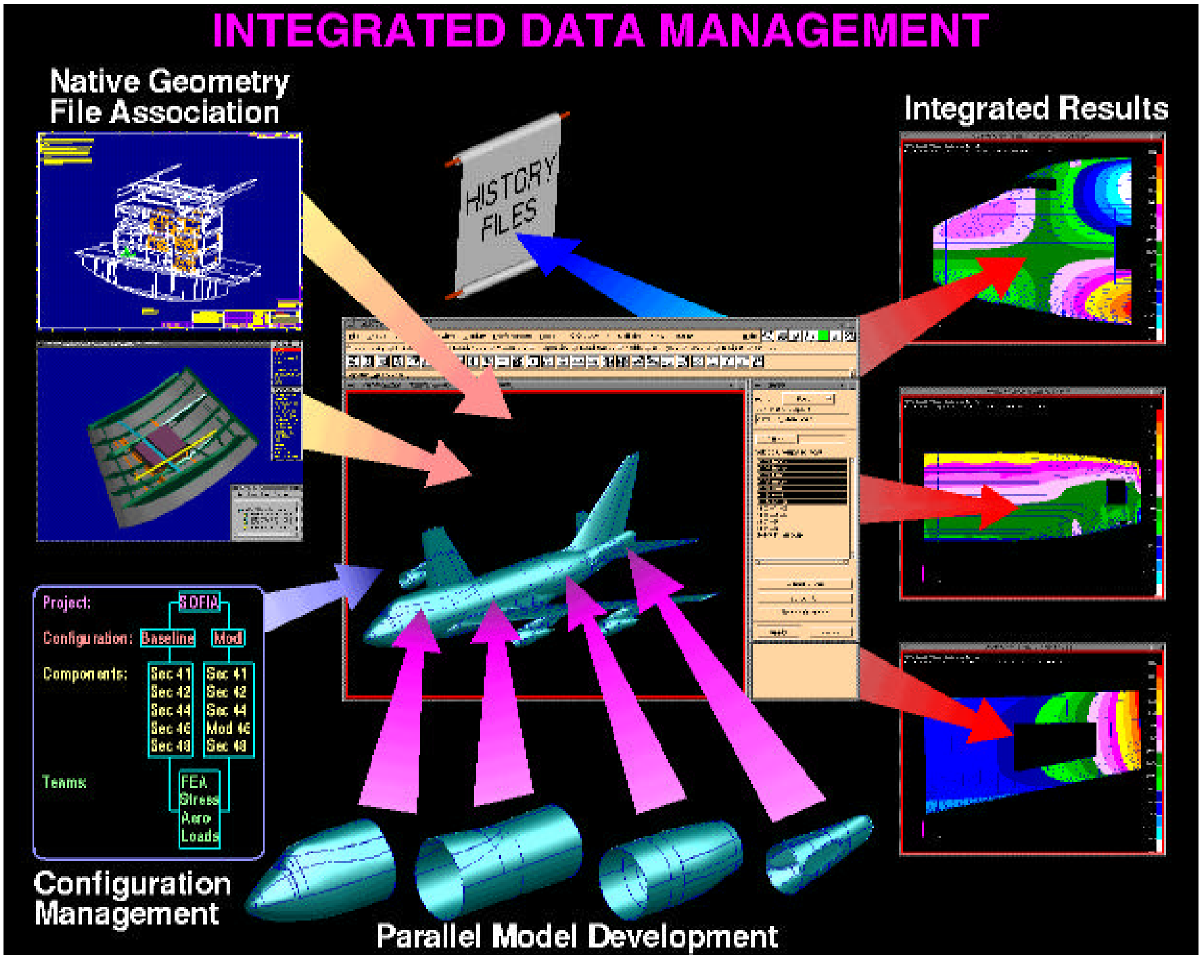


Figure 3 – Integrated Data Management

## SINGLE GEOMETRY MODEL

The Single Geometry Model was used to facilitate the development of the 747SP finite element model. The usefulness of the single geometry model is that different engineering disciplines can share the same geometry to enhance productivity and meet engineering objectives. The Aerodynamic group of Flight Sciences Raytheon Systems Company Waco developed geometry to define fuselage skin IML (Inner Mold Line) of the 747SP from Boeing Master Dimension Drawings for aerodynamic analysis. Curves defining the stringer locations were also developed from the Master Dimension Drawings. This curve geometry was projected onto the fuselage IML surface geometry to define the location of the stringers. This IML surface and stringer geometry was used as the basis for the finite element development of the fuselage skins and stringers. The geometry developed for the aerodynamic analysis was also used by Design engineers to help define the CAD geometry for SOFIA. Figure 4 illustrates the concept of the Single Geometry Model used by various engineering disciplines at Raytheon Systems Company Waco.

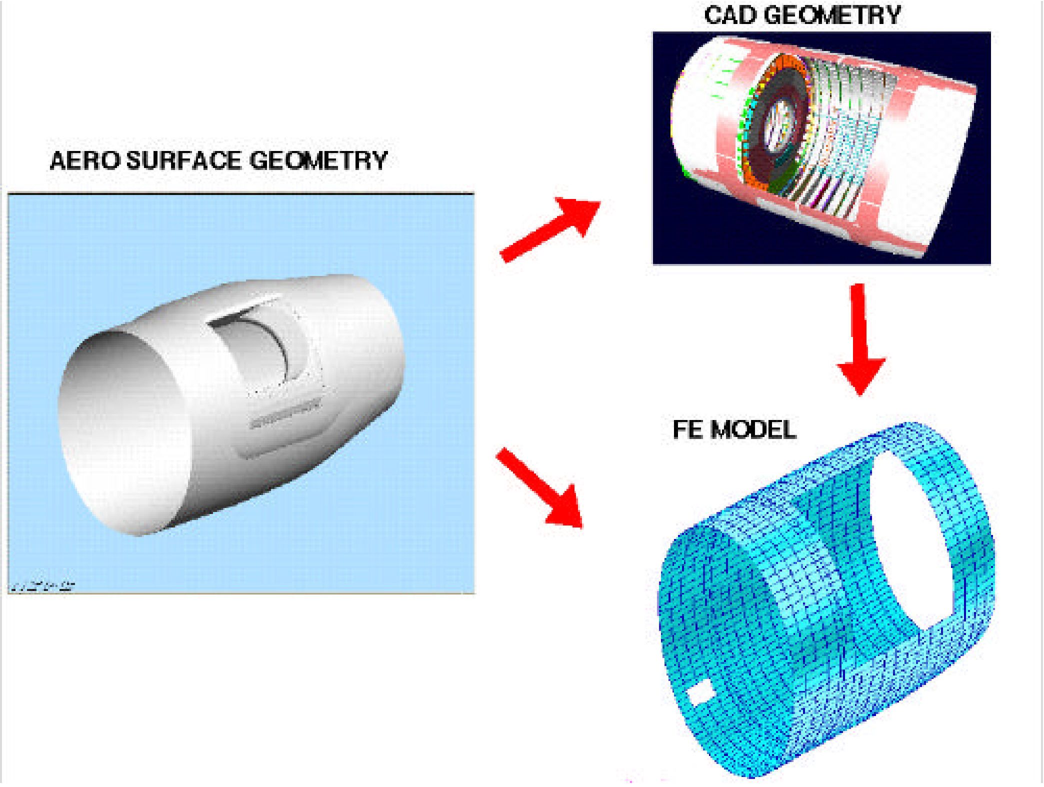


Figure 4 – Single Geometry Model

## BASELINE MODEL

A finite element model of the baseline Boeing 747SP configuration was developed from drawings. This model is an internal loads model used to define the primary load paths of the airframe structure and to develop the internal loads characteristics of the 747SP for all load conditions. The baseline finite element model consists of 50,000 grids, 150,000 elements and over 250,000 degrees of freedom defining the fuselage, wing and empennage structure. The 747SP finite element model consists of more than 90 frames and bulkheads which are represented in the model as built-up structure. Attention to detail in defining the primary load paths was maintained in the development of each section of the model: to represent the fuselage door surround structure built-up door sills and auxiliary frames were included in the model. Main and upper deck floor structure and nose wheel well are modeled in the nose section (section 41). The keel beam, intercostals, crease and floor beams in the fuselage center section (section 44), and ribs stringers mid-spars in the wing and wing center section, are all defined in the model as built-up structure. Built-up structure was used to provide an efficient means of recovering the airframe structure internal loads directly from the components of the built-up structure, such as axial load from cap, shear load from web elements and so on. For the frames, elements defining the inner chord frame caps and the frame fail-safe angles were physically off-set in the model to the neutral axis to accurately represent frame stiffness.

Membrane elements (CQUAD4) with in-plane and shear stiffness are used to define the fuselage skin. The fuselage skin elements are located at the fuselage skin IML. Rod elements with only axial stiffness define the fuselage stringers.

The 747SP model was developed in sections consistent with Boeing nomenclature of the airframe structure defining section 41 as the section nose, section 42 as the forward, section 44 as fuselage center section, and so on. The master databases defining the sections of the airframe structure (submodels) are distinct MSC/PATRAN databases maintained within the MSC/SuperModel file hierarchy.

These submodels were developed independently. The template geometry used to define the built-up sections of the model was created in MSC/PATRAN and Parametric Technologies Corporation's Pro/ENGINEER. Some of the sections were divided into sub-sections to improve model development time. This technique was made practical by use of the import database function in MSC/PATRAN. The submodel master databases of the baseline 747SP are shown in figure 5, and the baseline 747SP finite element model is shown in figure 6.

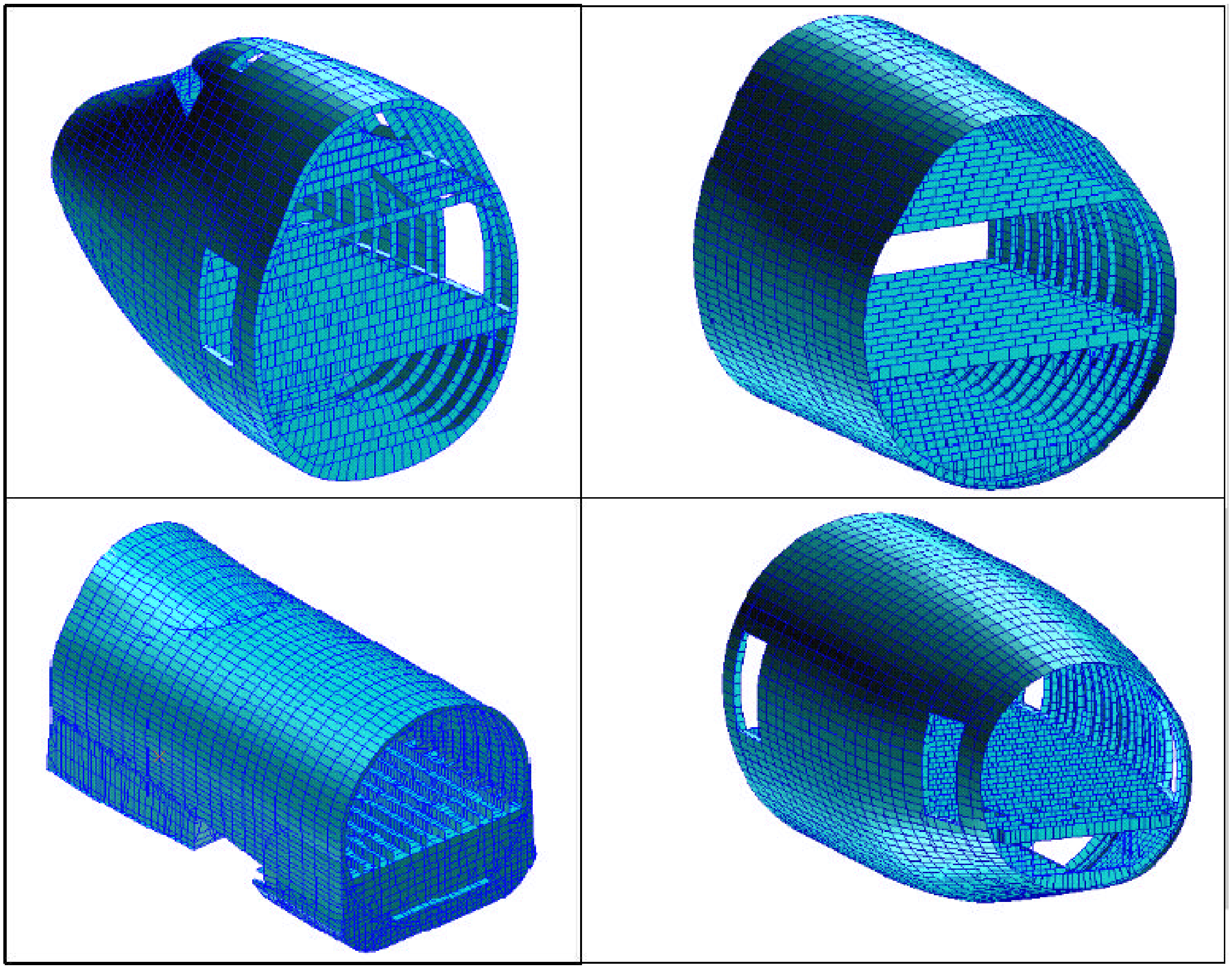


Figure 5 – Submodel Master Databases

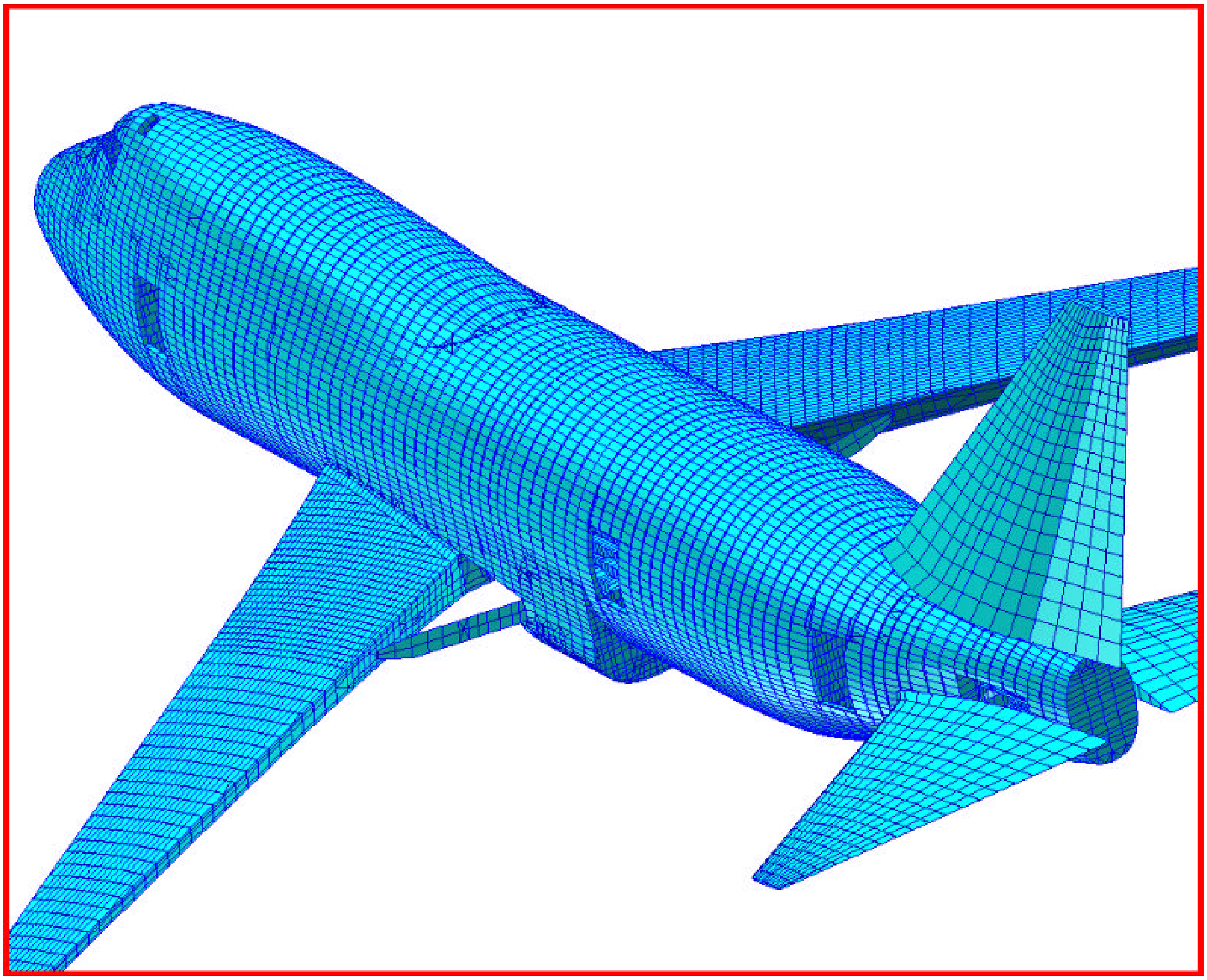


Figure 6 – 747SP Finite Element Model

## DESIGN MODEL

A finite element design model was developed to provide a means for initial sizing and a feasibility analysis of the SOFIA design. It was necessary that this model support design studies as well as develop internal loads for preliminary static strength analysis. The design model was maintained as a simplified finite element representation of the SOFIA design changes to the section 46 fuselage, so detailed features such as built-up frames were not included in this model. The design model was derived from the baseline model. Usable existing structure defined in the baseline model such as fuselage skin, stringer and frame elements were imported into the design model database. Five frame bays forward of section 46 were included in the design model to provide characteristic compliant fuselage structure and to minimize the effects of the boundary conditions on the design area. The design features of the SOFIA modification were incorporated into the finite element design model. These features include a nine bay cutout and the surround structure, framing over the cargo door and door #3, new forward and aft bulkheads, and floor modifications. Figure 7 depicts the finite element design model.

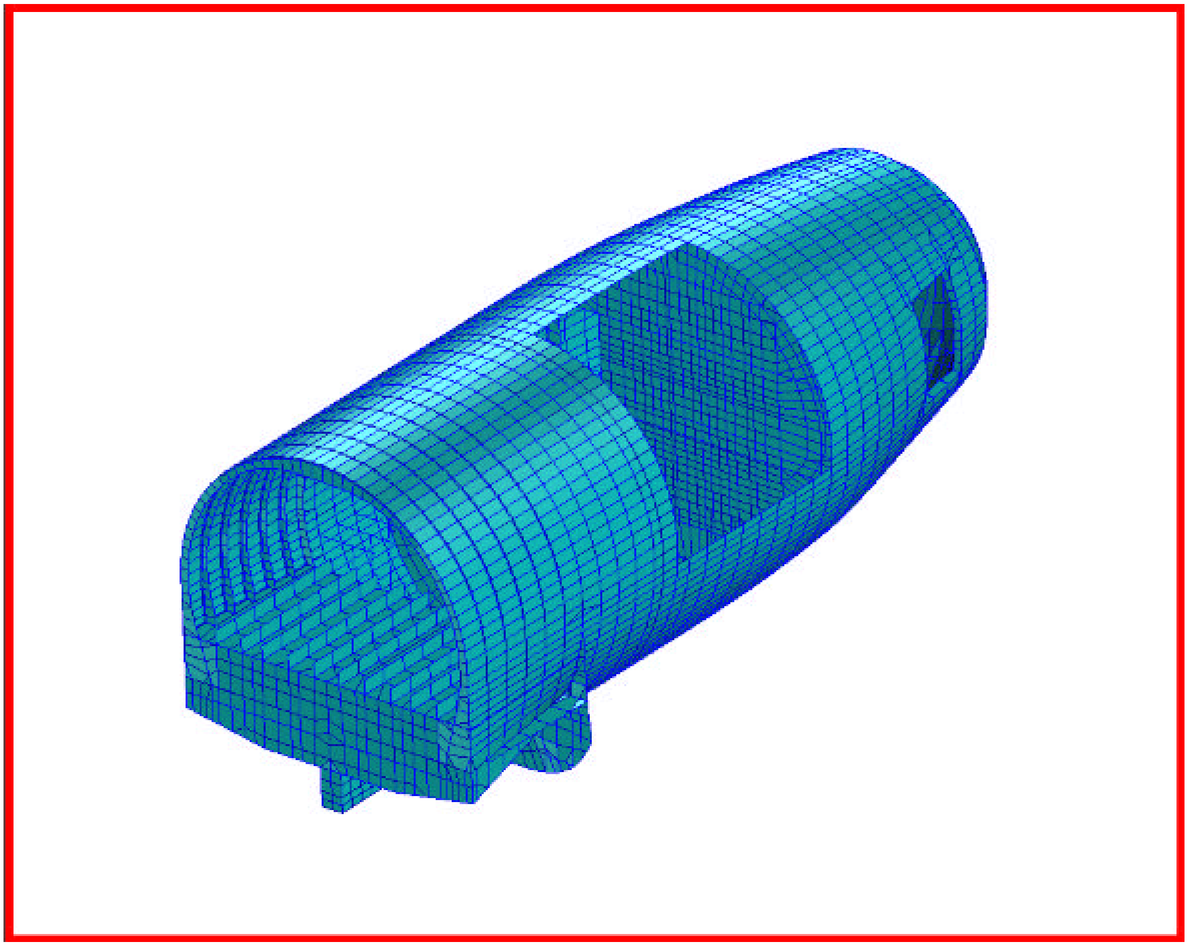
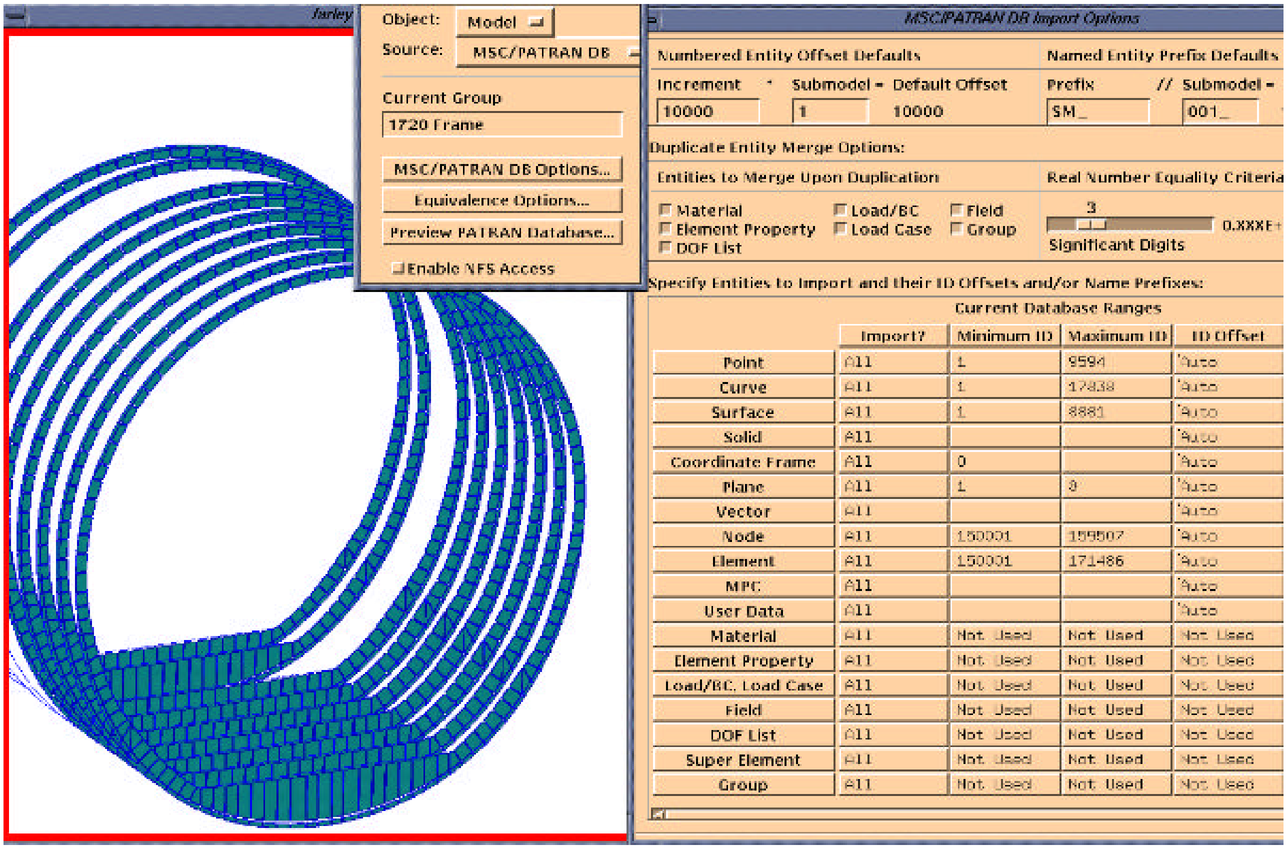


Figure 7 – Finite Element Design Model

## CERTIFICATION MODEL

The certification finite element model is the complete 747SP finite element model including the design modification to section 46 to characterize the SOFIA modification. The function of this model is to provide internal loads for the static strength analysis for the substantiation of the SOFIA design modification to section 46.

Section 46 of the certification model shares some features with the baseline model. The existing finite element structure common to both the baseline and certification models was imported into the certification model database. Figure 8 illustrates how existing finite element data from the baseline model database was directly imported into the certification model database by use of the database import option in MSC/PATRAN. The import feature proved to be instrumental in the model development process of the section 46 certification modification. It enabled the Methods & Finite Element group to divide the section 46 model for certification into sub-sections, at which point features of the design modification were modeled in independent MSC/PATRAN databases. Though there is a practical limit to the division of the databases for model development, parallel sub-section model development of large primary structure has enhanced the model development. Figure 9 provides and example of partitioned databases for parallel model development of the SOFIA design modification. Upon completion of the sub-section models the databases were imported into the section 46 master database representing the SOFIA design modification. The importation of databases and maintenance of database interfaces within MSC/SuperModel is fundamental to the model development process. The section 46 databases of the baseline and certification model adhere to the same model interface within MSC/SuperModel. The section 46 portions of the baseline and certification model are interchangeable. This interchangeability of the two databases with regard to interfacing with the adjacent sections (section 44 and section 48) is critical to the supermodel methodology. All of the databases that define the 747SP model whether baseline or certification are maintained within the MSC/SuperModel file hierarchy.



Object: Model

Source: MSC/PATRAN DB

Current Group: 1720 Frame

Numbered Entity Offset Defaults

Increment * Submodel = Default Offset

10000 * 1 = 10000

Named Entity Prefix Defaults

Prefix // Submodel =

SM_ // 001_

☐ Material
☐ Element Property
☐ DOF List
☐ Load/BC
☐ Load Case
☐ Field
☐ Group

Significant Digits: 3 0.XXXE+

| | Import? | Minimum ID | Maximum ID | ID Offset |
|---|---|---|---|---|
| | | Current Database Ranges | | |
| Point | All | 1 | 9594 | Auto |
| Curve | All | 1 | 17838 | Auto |
| Surface | All | 1 | 8881 | Auto |
| Solid | All | | | Auto |
| Coordinate Frame | All | 0 | | Auto |
| Plane | All | 1 | 3 | Auto |
| Vector | All | | | Auto |
| Node | All | 150001 | 159507 | Auto |
| Element | All | 150001 | 171486 | Auto |
| MPC | All | | | Auto |
| User Data | All | | | Auto |
| Material | All | Not Used | Not Used | Not Used |
| Element Property | All | Not Used | Not Used | Not Used |
| Load/BC, Load Case | All | Not Used | Not Used | Not Used |
| Field | All | Not Used | Not Used | Not Used |
| DOF List | All | Not Used | Not Used | Not Used |
| Super Element | All | Not Used | Not Used | Not Used |
| Group | All | Not Used | Not Used | Not Used |

Figure 8 – Database Import

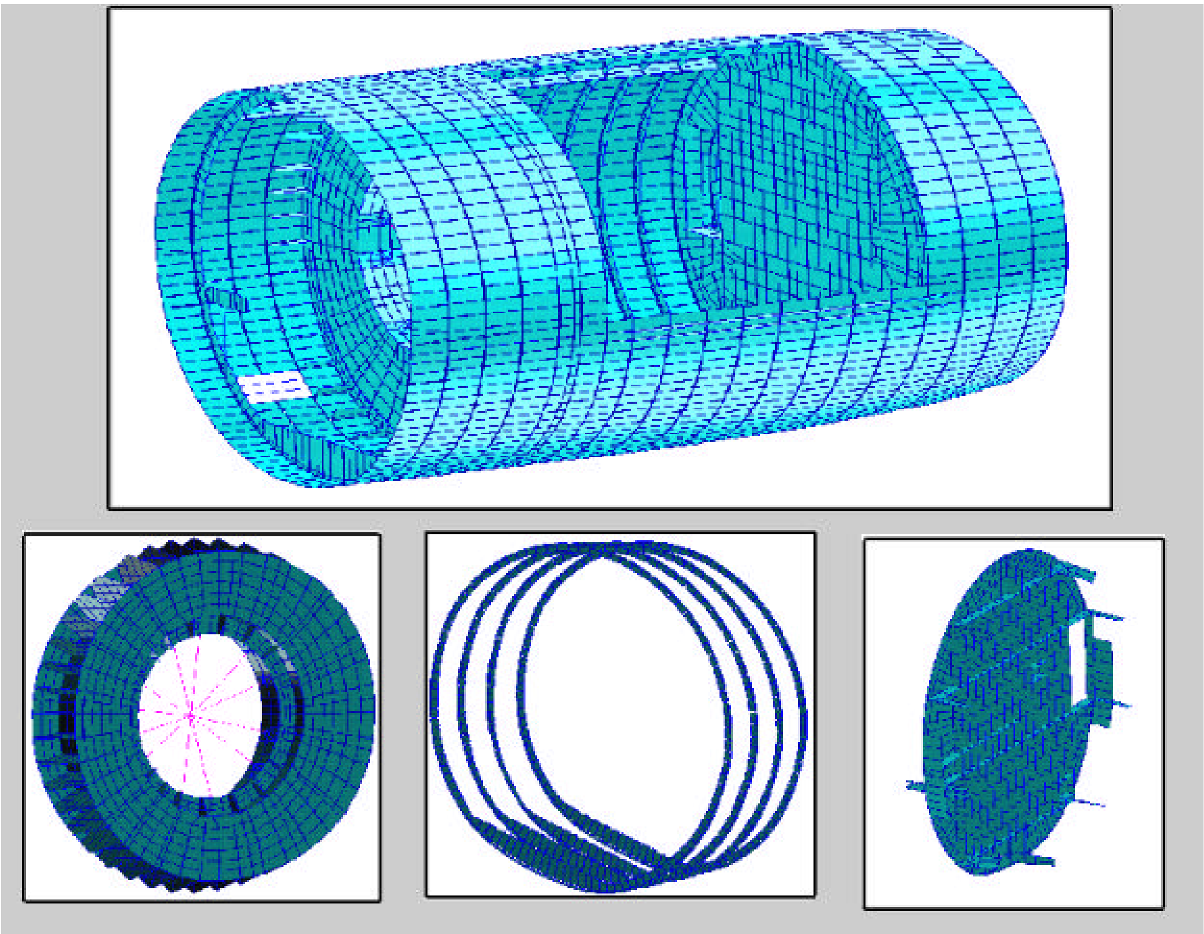


Figure 9 – Partitioned Databases

The requirement established by Methods & Finite Element Analysis group was to maintain only one database that defines each section of the 747SP. One of the functions of MSC/SuperModel is to perform database management of the models databases required to define the certification and baseline models. With all the databases maintained within the MSC/SuperModel file hierarchy the user need only indicate which databases are to be used for submitting the models to MSC/NASTRAN. If the section 46 SOFIA design modification database is selected as part of the 747SP finite element model to be executed by MSC/NASTRAN, upon submission, MSC/SuperModel will combine all of the selected databases into one model. The assimilated database becomes the certification finite element model. If the baseline section 46 database is selected as part of the database to be submitted to MSC/NASTRAN the assimilated database becomes the baseline model. Figure 10 illustrates how submodels are assimilated by MSC/SuperModel to become a baseline or certification model.

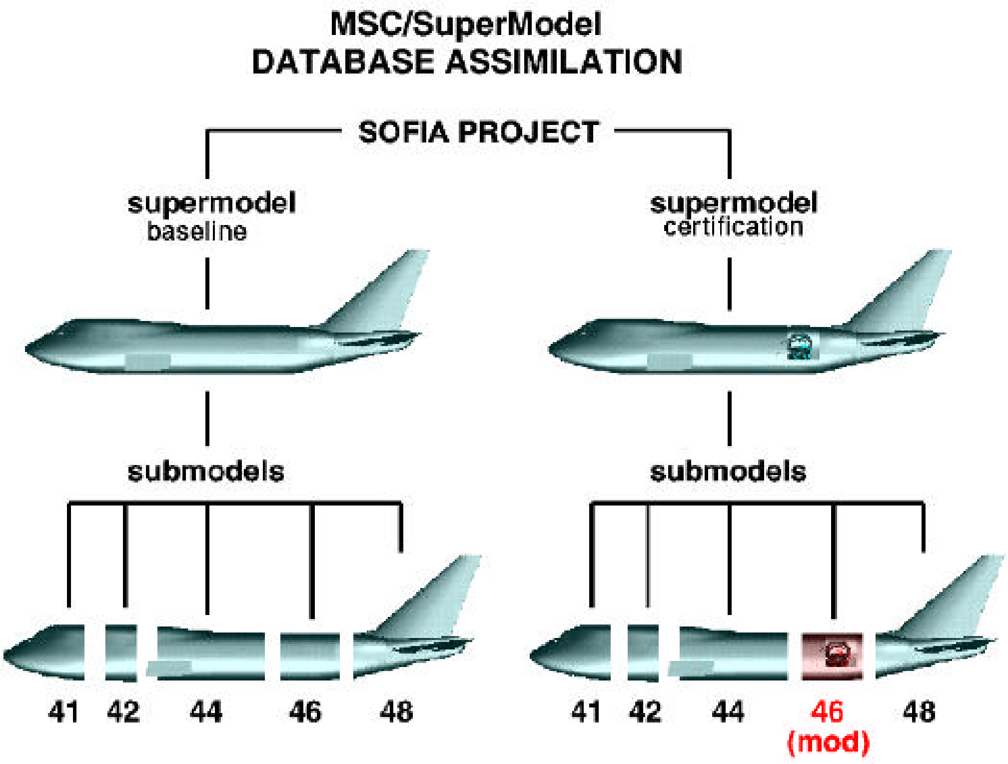


Figure 10 – Assimilated Submodels

## PANEL BUCKLING

To establish the correct internal loads within a finite element model a model is required which accounts for fuselage skin panel buckling. The fuselage skin panels buckle when subjected to high compressive and or shear loads. Upon buckling the loads carrying capability of the skin is reduced. This reduction in load carrying capability of the buckled fuselage skin shifts the neutral bending axis of the airframe structure effecting the stiffness of the structure and the internal loads.

For example, in a down bending condition skin on the belly of the fuselage will be in compression. If the combined internal loads within the skin reach a level which causes panel buckling the loads carrying capability of the skin is reduced. This change in stiffness causes a reduction in the inertia that can resist overall fuselage bending. As a result the neutral bending axis of the fuselage shifts up. This shift in neutral axis affects the internal fuselage loads. To establish the correct internal loads within a finite element model and to characterize the panel buckling of the airframe structure a model is needed which accounts for fuselage skin panel buckling. Such a model is referred to as an up & down bending model. Without a methodology to evaluate the stability of the fuselage skin panels an assumption must be made to define the behavior of the fuselage skin panels under ultimate load conditions. A simplified approach may be established in defining which panels have buckled. It is difficult to establish which skin panels have buckled without evaluation of the stability of each panel. Panel behavior is unique to the internal loads and the characteristics of the skin panel. The internal loads are a function of neutral bending axis and the airframe stiffness. This interdependence relationship between stiffness and internal loads can be resolved by characterizing the differential stiffness on the airframe as the panels buckle.

To address this issue MSC/PATRAN PCL (PATRAN Command Language) has been integrated into the finite element process to evaluate the stability of each fuselage skin panel on a load case by load case basis. The function of the PCL is to provide an automated method to evaluate the internal loads of each panel and determine whether the fuselage skin panels have buckled based on company defined algorithms for fuselage skin panel buckling.

The evaluation of the fuselage skin panels is initiated upon submittal of the airframe model defined within the PATRAN database for execution to MSC/NASTRAN. The results are automatically returned to the MSC/PATRAN database which will be subsequently used to evaluate the stability of the fuselage skin panels. From within the PCL, buckling groups of elements are selected to specify which elements are to be evaluated for buckling. The PCL form provides two options for redefining the reduced load carrying capability of the buckled skin panel. Option one is to redefine all buckled CQUAD4 as CSHEAR. Option two is to maintain the element definition of the skin panel as a CQUAD4 , but reference MAT2 on the PSHELL. The PCL will automatically manipulate the MAT2 material property matrix components, G11, G22, G13, and G23 consistent with the effective load carrying capability of a buckled panel. The shear component is set to the original CQUAD4 thickness.

The effective load carrying capabilities of the buckled skin panel is removed from the skin panel elements. The properties of the stringers elements and frame caps are adjusted to add the effective load capability of the buckled skin panel. The PCL output request form enables the user to review the output in report form or in database form. This output includes parameters such as critical shear buckling, critical compressive buckling and permanent buckling stress for each element within the selected group.

The elements involved in the evaluation of the buckled skin panels are put into three groups: Checked 1 (all elements selected for evaluation), Buckled 1 (all buckled elements), and Unbuckled. These groups are immediately posted upon completion of the buckling routine. The finite element model with its adjusted skin panel elements and stringers is resubmitted to MSC/NASTRAN and is iterated upon until it has converged to a solution. Figure 11 shows the PCL output request form and the buckled and unbuckled elements within the database.

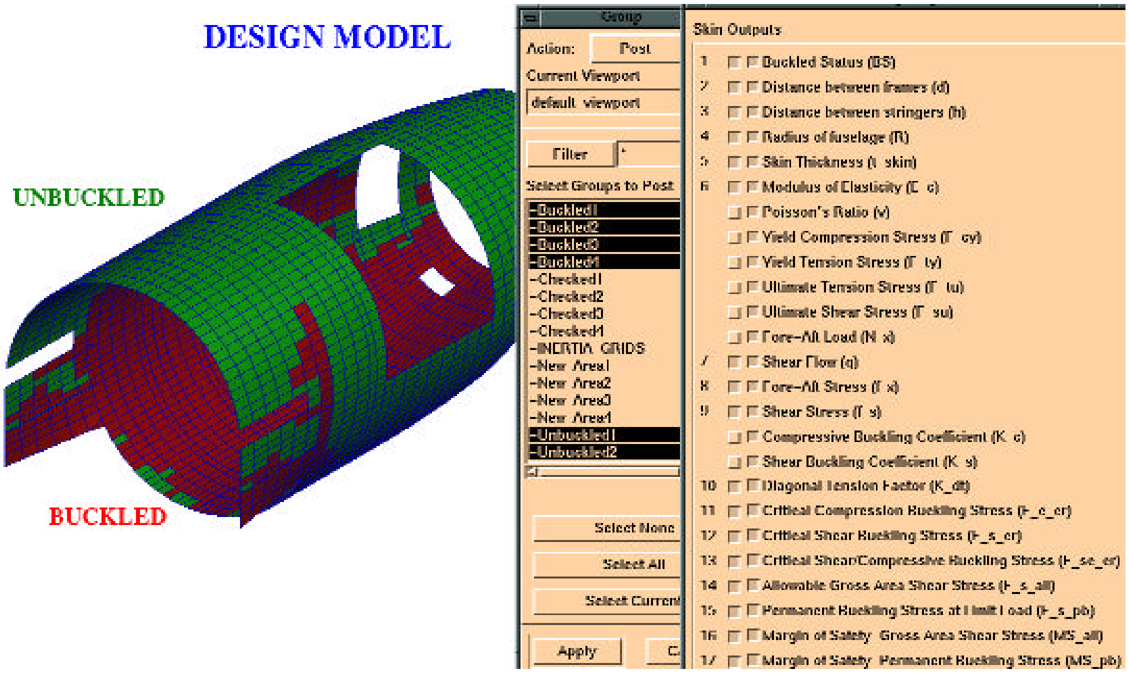


Figure 11 – Buckled Fuselage Skin Elements & PCL Output Request Form

## SUMMARY

A finite element model has been developed from drawings of a 747SP to support the design modification for the SOFIA program. There were three phases of model development: the baseline model to represent the baseline configuration of the 747SP, the design model to support design studies as well as develop internal loads for preliminary static strength analysis, and the certification model to characterize the SOFIA modification and to provide internal loads for the static strength analysis for the substantiation of the SOFIA design modification to section 46. A master database of all models was maintained within MSC/SuperModel. Configuration control of the databases is maintained by the MSC/SuperModel file hierarchy. Within the file hierarchy parallel model development history of model assembly is maintained. To meet the technical and schedule requirements of SOFIA MSC applications have been integrated into the finite element process. Implementing these applications and integrating methods into database finite element methodology, the finite element model has become central to the structural substantiation of the 747SP design modification.

## Acknowledgements

I would like to take this opportunity to thank the members of the Methods & Finite Element Analysis group, Robert Booth, Simon Chan, Ajit Kundu, Al Somanath, and Arlen Work, for their efforts in implementing the required methodology and developing the 747SP finite element model on schedule.