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# PRESERVATION AND UTILIZATION OF FINITE ELEMENT MODELS OF USAF AIRCRAFT STRUCTURES

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## NOTICE



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The problem addressed by this report is that the Air Force is not getting full value for the resources expended in the development of finite element models of USAF aircraft structures, both directly and by contractors. Models developed by airframe contractors are usually not made available to the Air Force. Models that are available are often inadequately documented or verified, or their existence may be unknown to those who need them. The problem was assessed by a survey of Air Force organizations and was attacked in three ways. First, software called FEM-X was developed for storage and retrieval of finite element model data along with descriptive information about the data. The software could be used by an Air Force Finite Element Model Center. A proposal for establishment of this Center is the second aspect of modification, and distribution of aircraft models. The third subject addressed by the report is a Mil Standard that is proposed for delivery of finite element models by Air Force contractors.

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## FOREWORD

This is the final report for the Phase II SBIR effort conducted by CSA Engineering, Inc. under Air Force contract F33615-89-C-3205, entitled "Finite Element Models for the Supportability of USAF Aircraft." CSA was assisted by its subcontractors, Aerospace Structures, Inc. and Applied Technology, Inc. The report covers work performed during the period 9 Mar 89 through 31 Dec 90. Lt Steven Rasmussen was the Air Force project monitor for WL/FIBR.

Portions of the text of this report appeared in the Phase I report entitled "Finite Element Models for the Supportability of USAF Aircraft," CSA Report 88-03-01, especially Sections 2, 3, 4, and Appendix A. Mr. Gordon "Nick" Negaard assisted in the preparation of this report.

Prepared by: ______________________

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# 1. Introduction and Executive Summary

## 1.1 The Promise of Finite Element Analysis

The finite element method has become a standard for design analysis of aerospace structures. It is an irreplaceable tool for all aerospace organizations, and for the Air Force itself. While emphasis has shifted somewhat toward commercial software packages, most aerospace firms also devote significant resources to in-house finite element software development, evaluation, and training. Finite element analysis promises faster and more accurate analysis, more efficient designs, and less dependence on costly and time-consuming tests.

## 1.2 The Promise Unfulfilled

The prevalence of finite element analysis in many industries is testimony to its effectiveness. Yet in some ways the promise of the method remains unfulfilled. Considerable resources are devoted to finite element models, and the return on these resources is not what it should be. Many models die a premature death because they were not adequately documented, verified, publicized, archived, or made available to organizations that could have made use of them.

Within the Air Force, this problem was perceived by Dr. V. B. Venkayya, Dr. James Olsen, and others in the Structures Division of the Flight Dynamics Laboratory who have been leaders in developing methods of structural analysis and optimization for many years. Briefly, the problem is that the Air Force is getting nowhere near full value for the finite element models that are developed either directly or by contractors. Generally speaking, contractors are not required to deliver the models they develop as a part of their aircraft structural design analysis work. There are many circumstances in which the Air Force could benefit from having these models after the aircraft have been put into service. When such circumstances arise, Air Force personnel have no good choices. They either develop models themselves (labor-intensive), pay a contractor to develop a model (expensive and difficult to fund), or do without (losing valuable opportunities).

The idea behind this SBIR program is that these problems might be remedied by establishment of a centralized operation dedicated to identifying, collecting, documenting, verifying, storing, modifying, and disseminating finite element models of Air Force aircraft. In addition, a specification is proposed that could be used for future procurement programs so that contractors were required to deliver models to the Air Force. The specification would primarily address documentation and format requirements. A draft Mil-Standard appears in Appendix B of this report.

## 1.3 Goals

The Phase I feasibility study was intended to do the following:

1. Evaluate current practices in finite element analysis among selected Air Force organizations.
2. Outline a military standard that could eventually be used to specify requirements for delivery of finite element models by aircraft development contractors to the Air Force.
3. Propose a plan of operation for an Air Force center where models would be collected, documented, verified, modified, stored, retrieved, and distributed, with emphasis on potential cost savings.
4. Investigate supporting software that could be used in the operation of this Center.

The Phase II goals were as follows:

1. Develop and demonstrate database software for finite element models.
2. Draft a prototype Mil-Standard for delivery of finite element models.
3. Produce a Plan of Operation for an Air Force Finite Element Model Center.

## 1.4 Findings of Phase I

The findings of the Phase I study may be summarized briefly as follows:

### 1.4.1 Survey Confirms FDL Suspicions

The Air Force is not getting full benefit from the finite element models of aircraft structures that are developed by contractors. The perceptions of FDL engineers and others that this is so are supported by the survey reported in Appendix A and by the authors' personal experience. This is partly a management problem and partly a technical problem. That is, there are few if any organized procedures for acquiring, documenting, modifying, and distributing these models. This report shows that these problems are costing the Air Force a lot of money and many lost opportunities.

### 1.4.2 Lack of Model Delivery Requirements: the Consequences

Contractors are not currently required to deliver the finite element models they develop while designing aircraft. Our survey showed several cases where Air Force organizations needed models that perhaps should have been delivered when the aircraft were procured. In these cases they either paid for another model to be created, or did without. There have probably been many cases where Air Force organizations recognized a need for a model but immediately dismissed the idea, believing that the obstacles to finding or creating the model they needed were too great.

### 1.4.3 Mil-Standard Needed

It will not be sufficient to simply insert a new CDRL item in future contracts to require delivery of models. A standard is necessary to specify the format of the data, and the form and content of supporting documentation. A discussion of this requirement is presented in Section 5 of this report, and a draft Mil-Standard appears in Appendix B.

### 1.4.4 Documentation is Crucial

The importance of documentation supporting finite element models is difficult to overstate, no matter where the models come from. Undocumented raw data can be very difficult (even dangerous) to use. Documentation is especially important when several variations of a basic model exist, as shown in the case study described in Section 3. Another case study, showing well-documented models, appears in Section 4.

## 1.5 Accomplishments of Phase II

A finite element database software package called FEM-X has been developed. The software runs on Unix workstations under the X Window System, and uses the CADDB engineering database software that was developed for ASTROS. Although FEM-X was developed on a Sun-4 workstation running the MIT distribution of the X Window System (X11, Release 4), it was designed for porting to other Unix systems that support the X Window System. The development of FEM-X is discussed in Section 6 of this report, and detailed user information may be found in an accompanying volume, *FEM-X User's Guide*.

A draft Mil-Standard has been prepared and is presented in Appendix B of this report. It is anticipated that a version of this document will be adopted so that the Air Force can get full value for the effort expended by contractors in developing and using finite element models of the aircraft that they produce.

A Plan of Operation for the proposed Air Force Finite Element Model Center appears in Section 7. The plan explains in detail how the Center will acquire, validate, document, and distribute finite element models to Air Force users and contractors.

# 2. Statement of the Problem

With each new Air Force aircraft system that has been developed, finite element analysis (FEA) has played a greater role in the structural design analysis process. Older aircraft such as the B-52 that were designed entirely by hand have also been the subject of finite element analysis in recent years. Certainly FEA is now irreplaceable in aircraft structural design and analysis. However, as Drs. Venkayya and Olsen point out in their paper [1], the Air Force is not getting full value for the resources that are spent either directly or by contractors on FEA.

Before defining the problem in more detail, it will be useful to review the evolution of finite element analysis and to summarize the current state of affairs in this field.

## 2.1 Evolution of Finite Element Analysis

The finite element method evolved in parallel with the rise of digital computers. Because of intensive matrix computations, a computer is necessary for even the simplest models. Twenty years ago, FEA was much different than it is today. NASTRAN had not yet appeared, and most organizations supported their own in-house codes. Card decks were standard, and a big model had a thousand degrees of freedom. Pen plotters were the state of the art in graphics.

At first, attention was naturally focused on basic methods: issues like element formulations and equation solution methods. Later, software reliability and expanded problem sizes were addressed. In recent years, considerable effort has been expended on graphical pre- and post-processors. Perhaps the present effort will turn out to be part of another shift in focus in the industry, this time toward protecting investments in models by organized efforts to verify, document, preserve, and disseminate these models.

## 2.2 Costs of Finite Element Analysis

The costs of developing a finite element model can be staggering. One of the engineers whom we contacted in our survey (Section A.1 of Appendix A) quoted a cost of $500,000 for development of a model they wanted. While this was an off-the-cuff remark, it probably reflects the order of magnitude of the costs that can be incurred in modeling.

There are three major components of the overall cost: (1) computer hardware, (2) computer software, and (3) engineering manpower.

It is common knowledge that the hardware cost of performing a unit of computation has dropped spectacularly in recent years. But demand has kept pace with the falling unit costs so that hardware expenditures have fallen only slightly in absolute terms, perhaps more in percentage terms. However, these costs can still be substantial. In large organizations, finite element analysis tasks can consume much of the power of a multi-million dollar supercomputer.

Engineering software effectiveness has increased more slowly, but again demand has more than offset gains here.

Engineering manpower productivity has increased most slowly. Most of the manpower productivity gains have come about with the introduction of graphics pre- and post-processing software. In both absolute and percentage terms, manpower costs in FEA have risen substantially.

Thus manpower is certainly the most important consideration in FEA costs. Two keys to controlling manpower costs are (1) to be sure that expensive engineers are working on the right problem, and (2) that they are not duplicating someone else's work. This is where dissemination and documentation play a key role. Clearly, if an Air Force organization can acquire the right model rather than reinvent it, considerable time and funds will be saved. If the model is properly documented, engineers will be sure of what they are working on.

## 2.3 Air Force Needs for Finite Element Models

All developers of Air Force aircraft use finite element analysis in the structural design process. Considerable resources (computer hardware and software costs; engineering manpower) are devoted to the development, verification, and use of these models. These resources are all provided, at least indirectly, by the government, and so it would seem that these models ought to belong to the government. However, contractors only deliver what their contract requires them to deliver.

There are many reasons why Air Force organizations such as ASD, AFLC, and AFWAL might need such models, such as

- Providing support for repair and maintenance operations,
- Investigating new versions of aircraft (e.g., F15A - F15E),
- Investigating modifications to existing aircraft (new weapons systems, performance enhancements, etc.),
- Validation of contractors' analyses, and
- Provision of realistic test problems for validation of new technology. New capabilities added to the ASTROS [2] software, for example, need to be evaluated on realistic problems. Models of existing systems are ideal for this purpose.

Since there has been no requirement for delivery of models in past system developments, models have been obtained under less than satisfactory conditions, if at all:

- Models have been acquired from the developers through informal requests, usually with little or no supporting documentation,
- Models are sometimes purchased (twice, in effect) from the original system developers,
- Contracts are sometimes let to third parties to create new models.

The Air Force does not have the manpower to devote to creating complex models, so until now, these three approaches have been the only means of obtaining the required models.

Getting contractors to deliver models means more than just another item added to a CDRL. It will be necessary to provide specific requirements regarding documentation, verification, and data formats. This subject is addressed in some detail in Section 5. This specification expands on the ideas presented by Dr. Venkayya in his DID [4] and in his conference paper [1].

## 2.4 Need for Documentation

The authors know from personal experience the importance of documentation of finite element models. This becomes dramatically apparent to an analyst who is given an undocumented model and asked to make modifications. In the worst case, without even any comments in the bulk data, the analyst must begin a laborious process of plotting and running the model. Plots are necessary to find out node point and element locations, and to relate element properties and material types to specific areas of the structure. Test runs must be made to validate the model for statics and dynamics.

Documentation issues are addressed in Section 5, which outlines requirements for delivery and documentation of models, and in Section 6 which documents the FEM-X database software that would not only preserve existing documentation and make it accessible, but also encourage users to provide additional documentation.

# 3. F-16 Case Study: Consequences of Poor Documentation

Some of the difficulties and frustrations experienced in working with a model obtained with little or no documentation can be illustrated with the following case study which was performed for FDL.

## 3.1 Evaluating the Finite Element Models

A finite element analysis was requested to quantify and evaluate the effects of real damage caused by live firings on an F-16 wing. Two finite element models were located and obtained. One model was an MSC/NASTRAN model freshly obtained from General Dynamics. This model was very extensive, containing over 7,000 grid points and an immense amount of structural detail. The other model had been around the Flight Dynamics Laboratory for several years, so long that its origin had been forgotten. This model contained around 400 grid points and over 1,000 elements. Plots of the two models may be seen in Figures 1 and 2. Note that the coarse model shown includes some elements within the fuselage, presumably for modeling the wing root stiffness.

Neither model had any documentation, so it was necessary to run the models, obtain plots, and study the results in order to gain an understanding of each model, its structure, constraints, and materials. The larger model had to be converted to COSMIC NASTRAN, and then debugged before it could be run. All this preliminary work used up considerable engineering manpower and computer time without producing any directly applicable results.

It would have been desirable to use the more detailed model, but the required time and manpower would have been excessive. This was partly because so much of the budget was consumed in preliminary activities. It therefore seemed necessary to use the coarse model. From the preliminary work, the coarse model appeared acceptable, since it seemed to represent a fully configured wing. But before it could be used with confidence, it had to be validated in some way.

## 3.2 Verifying the Coarse Model

When the same static load was applied to each model, the predicted deflections were very similar. This gave evidence that the two models had essentially the same bending stiffness. However, when computed deflections were compared to measured deflections obtained from a test having ostensibly the same loads, the results disagreed by over 100 percent. This was found to be due to flexibility in the test fixture jig at the wing root. It should have been possible to introduce flexibility into the root area of the wing model so that predicted deflections could be made to match the test

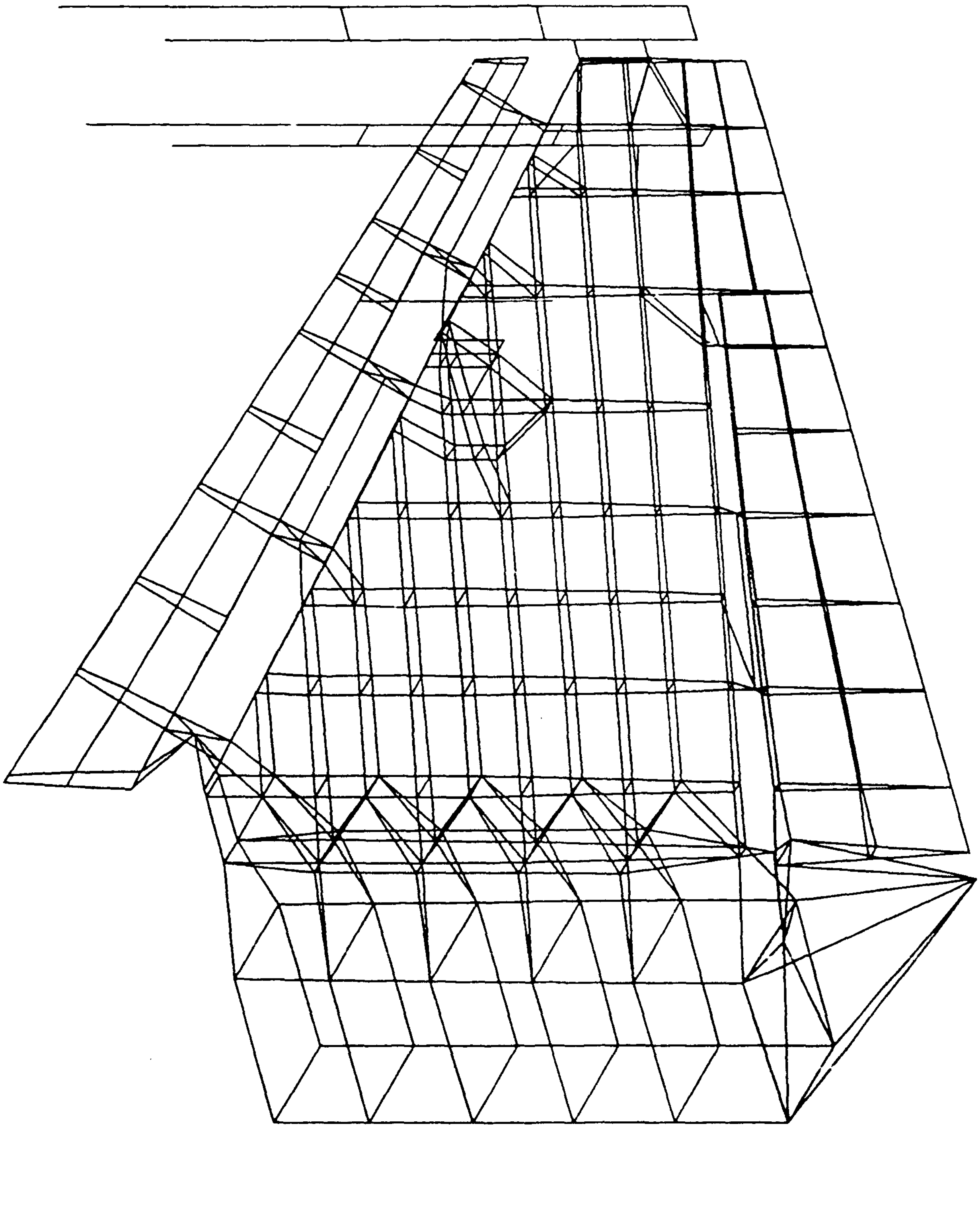

Figure 1: F16 Coarse Model

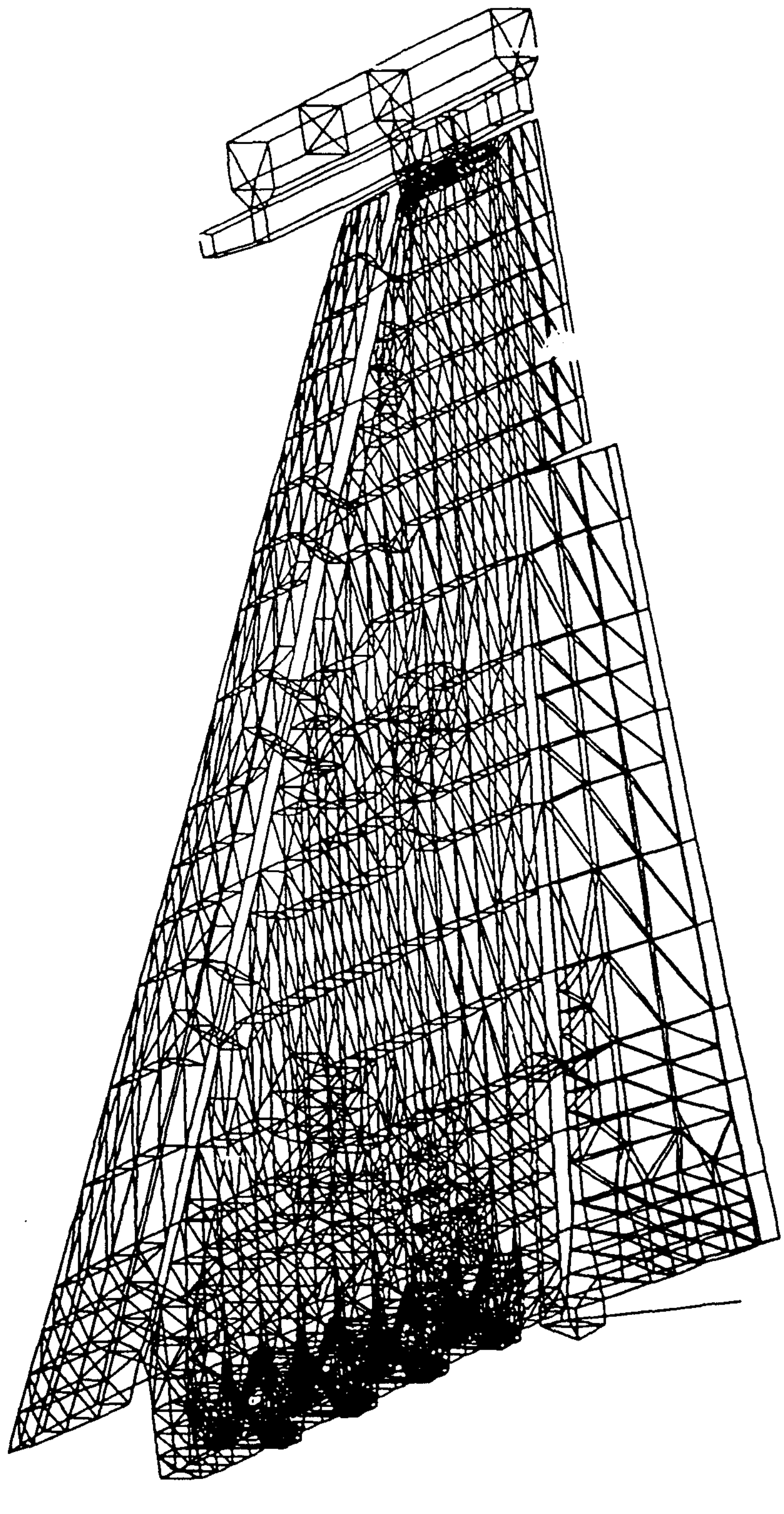

Figure 2: F16 Fine Model

results. Again, time and manpower constraints did not allow this. It appeared that a comparison of dynamic results would be easier, and this was undertaken instead.

First, the fully configured FDL finite element model was compared to the results of an FDL ground vibration test on a similarly configured wing on an actual aircraft. The first two natural modes matched quite well.

The next step was to compare the model to vibration tests of the test wing, since these tests would be conducted several times between firings in order to evaluate changes in the dynamics of the wing. Since the test wing was stripped of all external structure, it was necessary to remove all items such as the front and rear flaps, missiles, and pylons from the model. This was a time-consuming task due to the lack of documentation. The predicted weight was still about 200 pounds greater than the measured weight, so it was necessary to remove a percentage of the nonstructural mass included in the model. After the weight had been adjusted to within a few pounds, the first four natural modes predicted by the model matched the vibration tests within a few percent.

This correlation was considered close enough to proceed with the damage study. Each damage case was modeled and static and dynamic characteristics were tabulated before and after each shot in order to assess residual strength degradation from damage. Ten damage cases were analyzed for the study. Since the test wing was repaired after each test, these repairs also had to be modeled.

## 3.3 Cataloging the Models

Ten damage cases with two models each resulted in twenty configurations, along with four configurations of the undamaged model. (Three test wings were used for the tests, each varying slightly in configuration and weight, depending on the structure removed.) A dynamic and a static analysis was made with each model. As a result, there were 48 NASTRAN decks in use. The differences between decks varied from a few dozen cards to a few hundred. Bookkeeping became very important in keeping track of each model and in preventing errors from propagating.

For similar analyses done in the early 1970's, the CDC UPDATE utility was used. The original model was kept on permanent file, and a separate update deck in punched card format was kept for each case. These decks could be marked and written on in order to keep them straight.

For the F-16 study, complete decks were kept on permanent files. The CDC permanent file system allows only seven characters for file names, so a shorthand system had to be devised and a manual log book kept. After models were no longer actively needed they were archived to the Central File System (CFS). The CFS allows file names up to about 30 characters long so that descriptive titles could be used. The approach used here was superior to the old UPDATE method because the engineer could use a screen editor instead of the cumbersome line-oriented directives required by UPDATE. However, one advantage of UPDATE was lost. When one model is derived from anotner, the UPDATE method provides an explicit indication (in the form of correction sets) of the differences between the two models. No such direct comparison is possible when separate files are kept for all models.

Comment cards were inserted in the various decks to describe the changes that were made.

## 3.4 How a Database might have Helped

If FEM-X had been available when this study was done, it could have helped in three ways. it could have provided a better starting point for the effort, smoother procedures during the effort, and an end product that would be more accessible to future users.

If a well-documented and verified model had existed prior to this effort, a savings of at least 25% of the labor would have been possible, according to the engineer who did the work. The work would have been easier because it would not have been necessary to track models and file names manually. FEM-X would have provided automated tracking of models, with tracing of the derivation of one model from another. It would have provided both the convenience of a screen editor and the traceability of UPDATE. It would have encouraged him to provide adequate documentation at every step, while providing reversibility of all changes. Finally, although the CFS works well when it is up, it goes down frequently (or did when the study was done). This aggravation would have been avoided with a database implemented on a VAX. In summary, while the job got done, the engineer likened it to using a hand saw in comparison to a power saw.

The same engineer has stated that he would be able to find the files and notes and continue the study with relatively little difficulty if he were called on to do so. He also stated that it would be virtually impossible for anyone else to do so without his assistance.

# 4. B-1 and F-15E Case Studies: Well-Documented Models

In this section, two large finite element aircraft analysis programs are reviewed. They were selected because they provide examples of well-documented models.

## 4.1 B-1 Model for an Airloads Research Study

Rockwell International developed a model of the B-1 aircraft number two (A/C-2) for NASA/Dryden Research Facility in the early 1980's [5]. The purpose of the study was to utilize flight data acquired during B-1 flights and perform analyses of these data beyond the scope of Air Force requirements. Specifically, the structural model was to be used to calculate influence coefficients which would then be passed to the NASA aerodynamics code, FLEXSTAB. Although detailed models were available at Rockwell, it was decided to develop coarse models so that the aerodynamic studies could be executed efficiently. Seven substructures were modeled (wing, forward fuselage, aft fuselage, horizontal and vertical stabilizers, fairings, and nacelle) with a total of about 3520 grid points. The report appeared in five volumes (NASTRAN model plans; horizontal stabilizer, vertical stabilizer, and nacelle structures; wing structure; fuselage structure; and fairing structure).

This report is cited because it represents a thoroughly documented finite element model. The introduction begins by explaining the reason for the model, i.e., providing flexibility matrices of sufficient complexity for use with FLEXSTAB, an aeroelastic code. This is followed by brief physical descriptions of the aircraft as a whole, and each component.

There is an explanation of the DMAP code that was written to provide the required matrices for interfacing with FLEXSTAB. Following this is a package of engineering drawings that were used in developing the model.

Separate volumes are provided for each substructure. The wing volume, volume III, for example, begins with some engineering drawings and then gives an explanation of NASTRAN input, consisting of several pages copied from the User's Manual. This would probably be unnecessary today with NASTRAN having become so well known. There is a page that explains the numbering scheme that was used (e.g., grid number XXYY lies on rib XX and spar YY). Similar conventions are given for element numbers.

Following this is an exhaustive series of plots generated by NASTRAN. It appears that every grid point and every element is labelled in at least one plot. For example, see Figures 3 through 6 which show all grid and element numbers for the outboard wing lug area.

The text asserts that the model was checked for continuity, constraints, etc., using

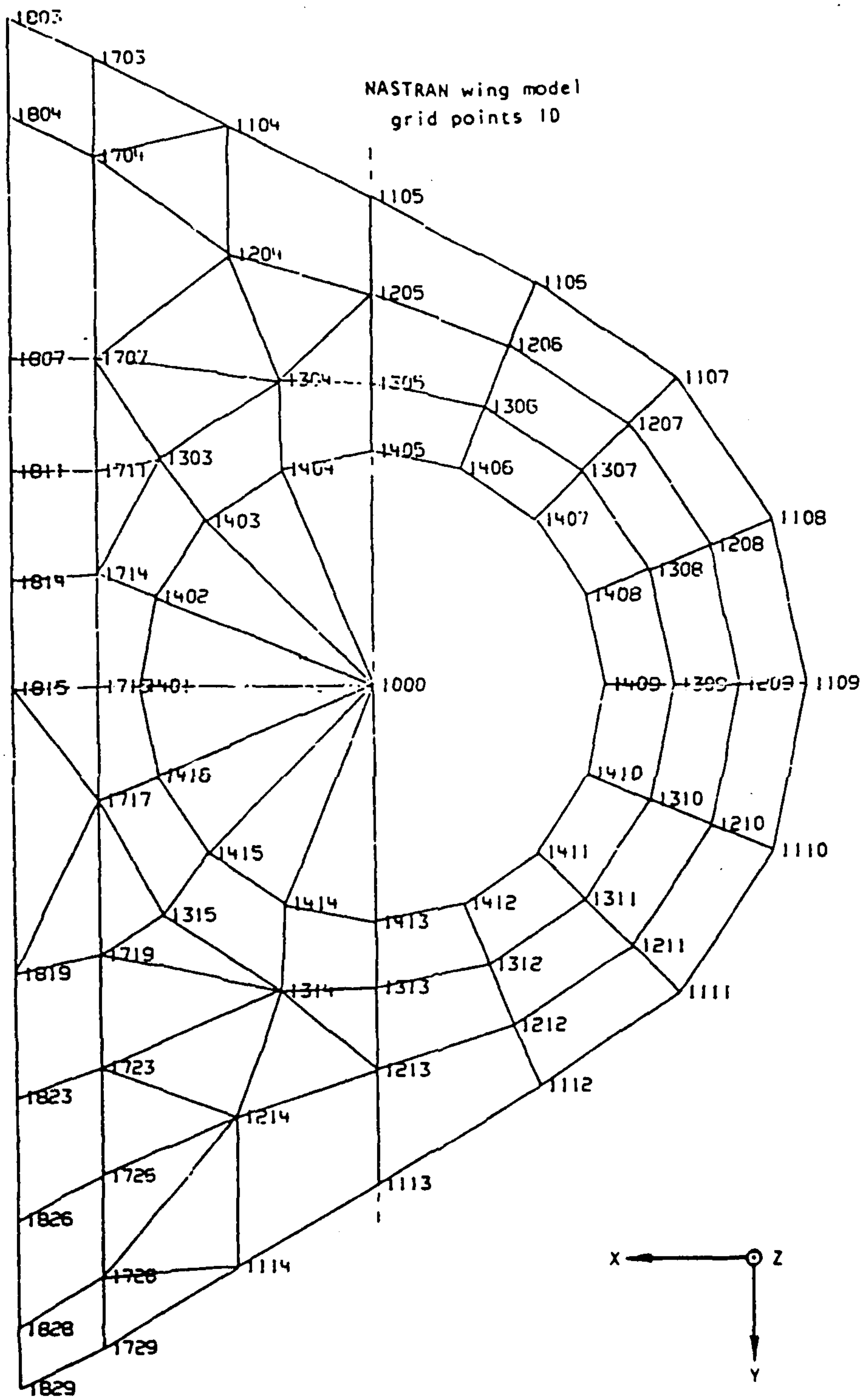


Figure 3: Upper Outboard Wing Pivot Lug Grid Points

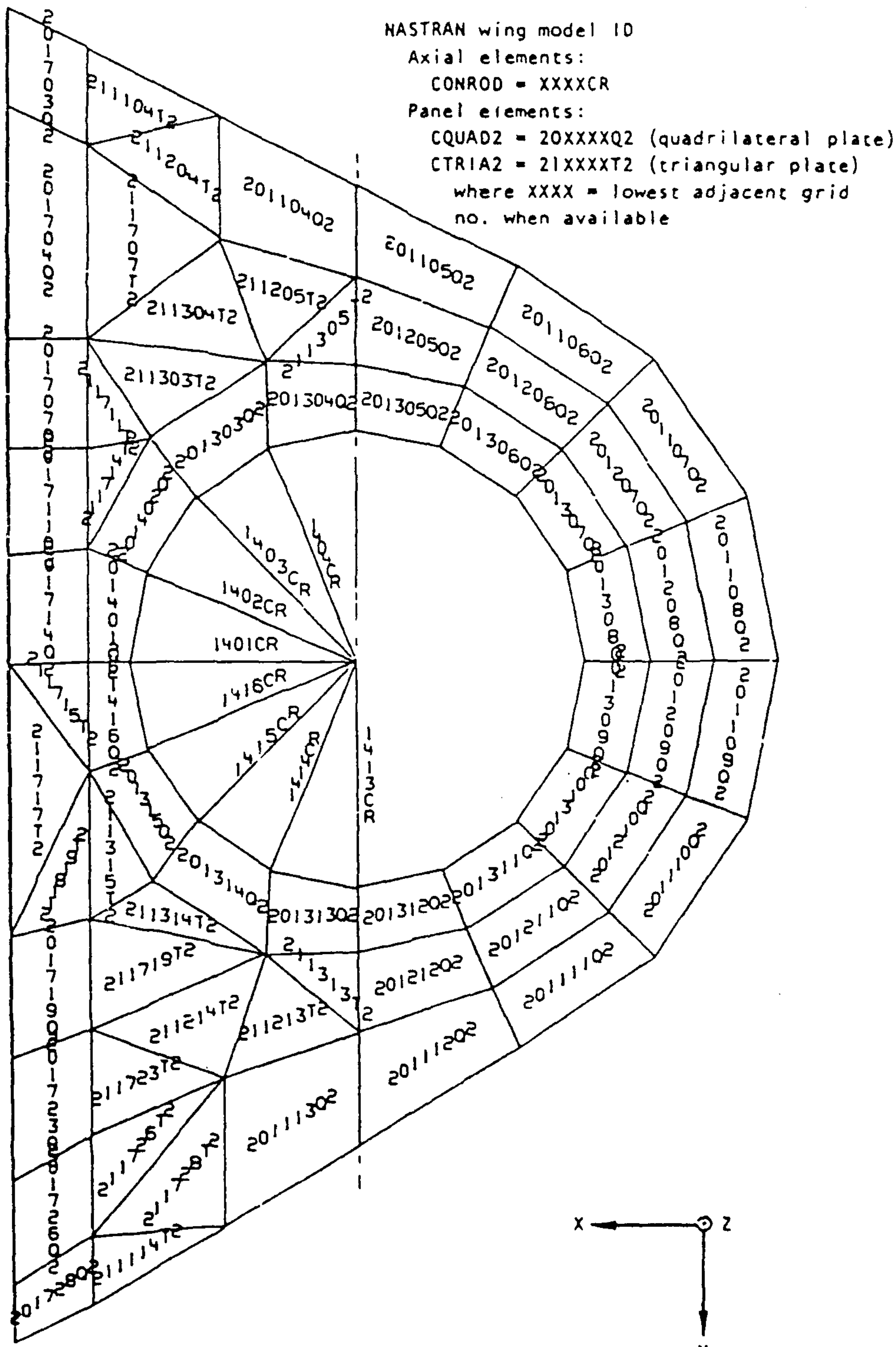


Figure 4: Upper Outboard Wing Pivot Lug Elements

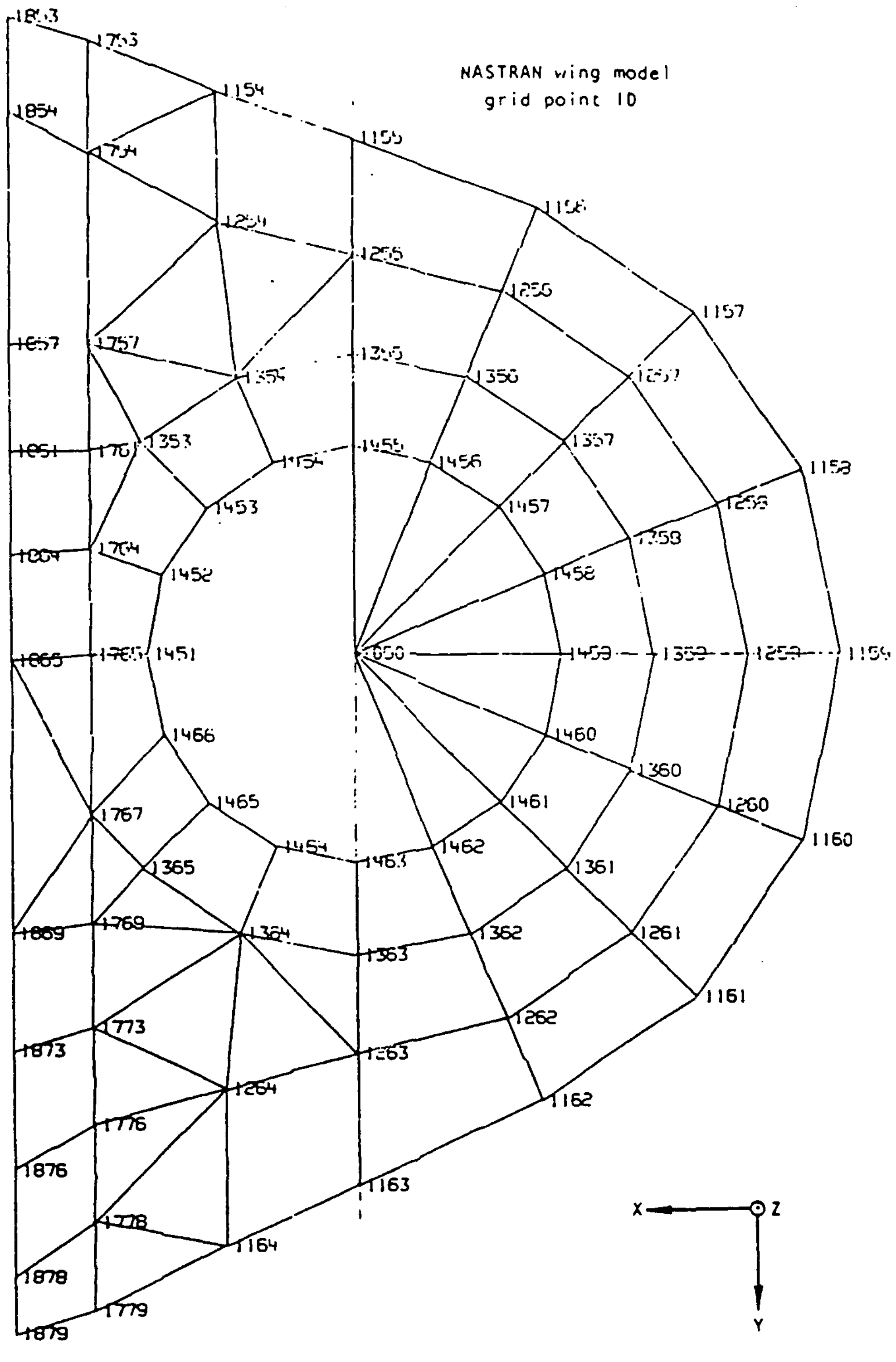


Figure 5: Lower Outboard Wing Pivot Lug Grid Points

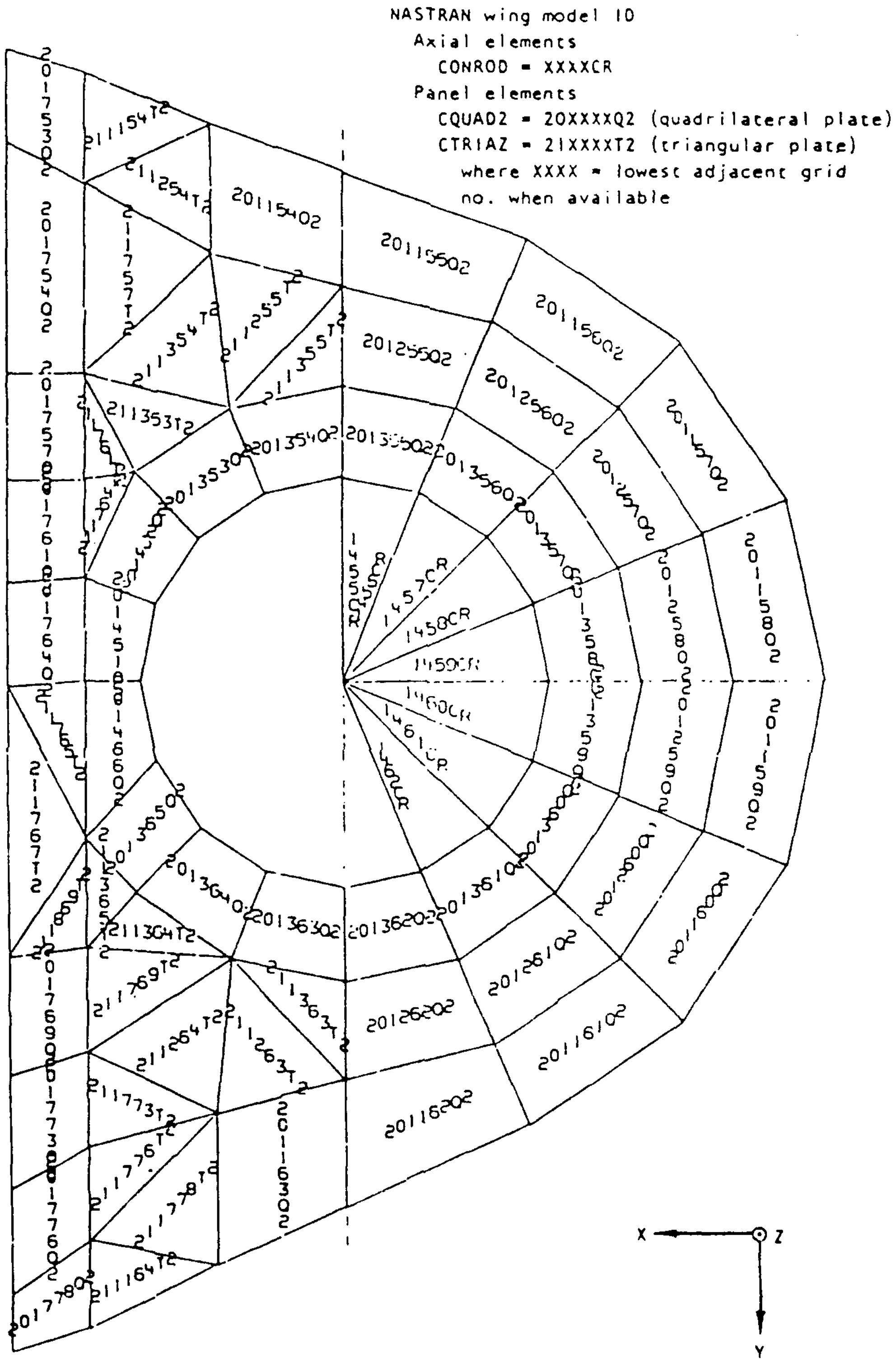


Figure 6: Lower Outboard Wing Pivot Lug Elements

an interactive graphics code. Results are presented for unit loading at each of a number of selected influence coefficient points. Plots show selected displacements plotted versus results predicted by the detailed B-1 model. Good agreement is shown.

Finally, a sorted bulk data echo of over 4000 cards is given.

Thus, the report presents practically all the information that would be needed by an analyst assigned to pick up this model and use it. Engineering drawings are given, complete plots are presented, the numbering scheme is explained, and evidence of verification is given. The only category not covered is documentation of loads. There were no loads *per se*, since the purpose of the study was to develop influence coefficients.

As an aside, one wonders whether the project would be undertaken at all if it were proposed today. If the detailed model referenced in the report were available from Rockwell, and given today's tradeoff between engineering labor costs and computer costs, it might be better to simply run with the complex model. Second, one wonders whether any contractor other than Rockwell could have done the job. This would depend on whether the detailed model (which was of course created by Rockwell) could have been obtained by another contractor, and if so, whether it would have been documented adequately.

## 4.2 F-15E Model

Another contractor report is cited as an example of good documentation of loading conditions. This is the stress report for the F15-E aircraft, [6], specifically, section 11.9.2, Loading Conditions.

The section on loading conditions begins with a discussion of factors of safety, ultimate loads, thermal effects, and conservative combinations of engine thrust loads, flight loads, and cockpit pressures. Crash loads and pilot applied loads are also considered. The computer program used to develop load distributions is referenced.

Table 1 (copied from table 11.9.2-1 of the report) shows a listing of load conditions that were selected as critical for the forward fuselage. Each line of the table indicates the condition number used in NASTRAN, the engine thrust (max or min), Mach number, altitude, a brief description of the condition, limit load factors, cockpit pressure, a description in terms of the the effects on the structure, and an indication of the areas that are critical for the particular condition. This last item would be especially useful for someone picking up the model for the first time, intending to use it in an optimization study, for example.

| COND NO. | F.E.M. COND NO. | ENG. THRUST | MACH NO. | ALT. FEET | DESCRIPTION | LIMIT LOAD FACTORS | ULT COCKPIT PRESSURE | TYPE LOADING | CRITICAL ITEMS OR AREAS |
|---|---|---|---|---|---|---|---|---|---|
| 53 | 1-1 | | | S.L. | Cockpit Burst Pressure | | 11.8 psi | Cockpit Pressure | Cockpit Frames, Floors, Tension Tie, Aft Cockpit Deck |
| 54 | 1-2 | Max | 1.20 | S.L. | Steady State Pull Up | $N_y = 0$ $N_z = 9.00$ | 0 psi | Down Bending & Shear | Upper & Lower Longerons, Vertical Shear Panels |
| 55 | 1-3 | Max | 1.20 | S.L. | Steady State Pull Up | $N_y = 0$ $N_z = 9.00$ | 8.85 psi | Down Bending & Shear with Cockpit Pressure | Cockpit Longerons, Frames, Skins, etc. |
| 56 | 1-4 | Min | 1.20 | S.L. | Steady State Pull Up | $N_y = 0$ $N_z = 9.00$ | 0 psi | Down Bending & Shear | Upper & Lower Longerons, Vertical Shear Panels |
| 57 | 1-5 | Min | 1.20 | S.L. | Steady State Pull Up | $N_y = 0$ $N_z = 9.00$ | 8.85 psi | Down Bending & Shear with Cockpit Pressure | Cockpit Longerons, Frames, Skins, etc. |
| 58 | 1-6 | Max | 1.13 | S.L. | Steady State Push Down | $N_y = 0$ $N_z = -3.00$ | 0 psi | Up Bending & Shear | Compression in Upper Longeron |
| 59 | 1-7 | Max | 1.13 | S.L. | Steady State Push Down | $N_y = 0$ $N_z = -3.00$ | 8.85 psi | Up Bending & Shear with Cockpit Pressure | Compression in Upper Longeron |
| 60 | 1-8 | Min | 1.13 | S.L. | Steady State Push Down | $N_y = 0$ $N_z = -3.00$ | 0 psi | Up Bending & Shear | Compression in Upper Longeron |
| 61 | 1-9 | Min | 1.13 | S.L. | Steady State Push Down | $N_y = 0$ $N_z = -3.00$ | 8.85 psi | Up Bending & Shear with Cockpit Pressure | Compression in Upper Longeron |
| 62 | 1-10 | Max | 0.90 | S.L. | L/H Rolling Pull Out | $N_y = .47$ $N_z = 7.24$ | 0 psi | Combined Bending, Shear & Torque | Side Longeron, Horizontal Shear Panels |

Table 1. Forward fuselage design loading conditions

| COND NO. | F.E.M. COND NO. | ENG. THRUST | MACH NO. | ALT. FEET | DESCRIPTION | LIMIT LOAD FACTORS | ULT COCKPIT PRESSURE | TYPE LOADING | CRITICAL ITEMS OR AREAS |
|---|---|---|---|---|---|---|---|---|---|
| 63 | 1-11 | Max | 0.90 | S.L. | L/H Rolling Pull Out | $N_y$ = .47 $N_z$ = 7.24 | 8.85 psi | Combined Bending, Shear & Torque with Cockpit Pressure | Side Longerons, Horizontal Shear Panels |
| 64 | 1-12 | Min | 0.90 | S.L. | L/H Rolling Pull Out | $N_y$ = .47 $N_z$ = 7.24 | 0 psi | Combined Bending, Shear & Torque | Side Longerons, Horizontal Shear Panels |
| 65 | 1-13 | Min | 0.90 | S.L. | L/H Rolling Pull Out | $N_y$ = .47 $N_z$ = 7.24 | 8.85 psi | Combined Bending, Shear & Torque with Cockpit Pressure | Side Longerons, Horizontal Shear Panels |
| 66 | 1-14 | Max | 0.90 | S.L. | R/H Rolling Pull Out | $N_y$ = −.47 $N_z$ = 7.24 | 0 psi | Combined Bending, Shear & Torque | Side Longerons, Horizontal Shear Panels |
| 67 | 1-15 | Max | 0.90 | S.L. | R/H Rolling Pull Out | $N_y$ = −.47 $N_z$ = 7.24 | 8.85 psi | Combined Bending, Shear & Torque with Cockpit Pressure | Side Longerons, Horizontal Shear Panels |
| 68 | 1-16 | Min | 0.90 | S.L. | R/H Rolling Pull Out | $N_y$ = −.47 $N_z$ = 7.24 | 0 psi | Combined Bending, Shear & Torque | Side Longerons, Horizontal Shear Panels |
| 69 | 1-17 | Min | 0.90 | S.L. | R/H Rolling Pull Out | $N_y$ = −.47 $N_z$ = 7.24 | 8.85 psi | Combined Bending, Shear & Torque with Cockpit Pressure | Side Longerons, Horizontal Shear Panels |
| 70 | 1-18 | – | – | – | Canopy Jettison | – | – | Maximum Canopy Remover Load | Canopy Jettison Mechanism |
| 71 | 1-19 | – | – | – | NLG Retract Actuation | – | – | NLG Retract Actuator | Actuator Support, F.S. 373.5 Floor Beam, Aft Cockpit Floor |

Table 1. Forward fuselage design loading conditions (Continued)

| COND NO. | F.E.M. COND NO. | ENG. THRUST | MACH NO. | ALT. FEET | DESCRIPTION | LIMIT LOAD FACTORS | ULT COCKPIT PRESSURE | TYPE LOADING | CRITICAL ITEMS OR AREAS |
|---|---|---|---|---|---|---|---|---|---|
| 72 | 1–20 | – | – | – | 40 G Crash<br>Fwd & Right | – | – | Inertia | Aft Cockpit Deck,<br>Seat Rail Supports |
| 73 | 1–21 | – | – | – | 20 G Crash<br>Down | | – | Inertia | Aft Cockpit Deck,<br>Seat Rail Supports |
| 74 | 1–22 | – | – | – | 1 – Cosine Dip<br>(Dynamic Taxi Cond) | | – | Nose Gear | Not Critical |
| 75 | 1–23 | – | – | – | Unsymmetric Braking<br>L/H –Aft C.G. | | – | Nose Gear | Not Critical |
| 76 | 1–24 | – | – | – | Unsymmetric Braking<br>L/H –Fwd C.G. | | – | Nose Gear | Keel Web,<br>Trunnion Fitting |
| 77 | 1–25 | – | – | – | Unsymmetric Braking<br>R/H –Aft C.G. | | – | Nose Gear | Not Critical |
| 78 | 1–26 | – | – | – | Unsymmetric Braking<br>R/H –Fwd C.G. | | – | Nose Gear | Keel Web,<br>Trunnion Fitting |
| 79 | 1–27 | – | – | – | 0° Tow Aft @ NLG<br>0° Swivel | | – | Nose Gear | Keel Web,<br>Drag Brace Fitting |
| 80 | 1–28 | – | – | – | 0° Tow Aft @ NLG<br>180° Swivel | | – | Nose Gear | Keel Web,<br>Drag Brace Fitting |
| 81 | – | – | – | – | Jacking @ NLG | | – | Nose Gear | Trunnion Fitting |

Table 1. Forward fuselage design loading conditions (Continued)

# 5. Standards for Delivery of Finite Element Models

The reasons why the Air Force should require its contractors to deliver finite element models developed in the course of their work have already been noted. In order to implement this requirement for the delivery of future systems, a Mil-Standard must be developed. This section presents some information on finite element models, preprocessors, and NASTRAN as a standard. This background information leads into a preliminary outline of a Mil-Standard directed toward delivery of finite element models.

## 5.1 Background on Finite Element Models and Their Use

This section begins with a general discussion of finite element modeling as background for the subsequent discussion of delivery requirements for finite element models. More information on finite element analysis may be obtained from a standard finite element text such as [7] or from the handbook series published by MacNeal-Schwendler [8] [9] [10] [11] [12].

In finite element structural analysis, we are solving some kind of matrix equation which can be stated in a general way as

$$f\left(\mathbf{K}(\mathbf{U},\theta,\omega),\mathbf{M},\mathbf{B},\mathbf{U}(t),\dot{\mathbf{U}}(t),\ddot{\mathbf{U}}(t),t\right) = \mathbf{P}(\mathbf{K},\mathbf{M},\mathbf{U},t,\theta,\omega) \tag{1}$$

Here the stiffness, mass, and damping matrices are denoted by $\mathbf{K}$, $\mathbf{M}$, and $\mathbf{B}$; displacements by $\mathbf{U}$, loads by $\mathbf{P}$, time by $t$, frequency by $\omega$, and temperature by $\theta$, showing that stiffness may be a function of displacement, temperature, or frequency, and that loads may be functions of stiffness, mass, displacement, time, frequency, or temperature. Thus, the familiar linear static analysis would be just

$$\mathbf{KU} = \mathbf{P} \tag{2}$$

whereas a geometrically nonlinear transient analysis with follower forces would be written

$$\mathbf{K}(\mathbf{U})\mathbf{U} + \mathbf{B}\dot{\mathbf{U}} + \mathbf{M}\ddot{\mathbf{U}} = \mathbf{P}(t,\mathbf{U}) \tag{3}$$

This example shows that nonlinearity is usually introduced implicitly (i.e., $\mathbf{K}$ and $\mathbf{P}$ are shown as functions of the independent variable $\mathbf{U}$). This leads to iterative solutions of the equations.

Based on this general formulation, we may state three basic questions facing the modeler:

1. What equations are to be solved; i.e., what is $f$? Is this a static or dynamic problem, steady-state or transient, linear or nonlinear?

2. How to develop **K**, **M**, and **B**. This is determined by the layout of grids and elements, and by element types. These questions in turn are governed primarily by the objective of the analysis. Geometric symmetry may be used to advantage in laying out the model.

3. How to represent the load **P**. Is it static, transient, or steady-state? Does it vary with temperature, displacement, etc.?

Engineering expertise is needed to answer these questions, based on the nature of the structure, the excitations, and the physical phenomenon being modeled. Each of these questions is now discussed in turn.

### 5.1.1 Six Kinds of Finite Element Models

The kind of mesh that is chosen (coarse or fine) and the types of elements are determined primarily by the objective of the analysis. We may identify five kinds of NASTRAN finite element models which are distinguished mainly by the kind of elements that are used and the density of the mesh. The classifications are rather broad and overlap substantially, as will be seen. For aircraft structures, only three kinds are typically used:

1. Static models
2. Dynamic models
3. Aeroelastic models

Two other kinds are less common in aircraft modeling:

4. Heat transfer models
5. Acoustic cavity models

and one is not used at all:

6. Electromagnetic models

**Static models** are designed to provide stress and deflection predictions. A high degree of mesh refinement is generally required for stress analysis for two basic reasons: (1) high stress gradients are commonly observed, and (2) when displacements are the independent variables, as is the case in all modern finite element codes, stresses are computed by differentiating the approximate displacements, thus introducing additional error which must be compensated for by increased refinement.

**Dynamic models** are generally used to compute natural frequencies and mode shapes. They may also be used to compute transient or steady-state displacements and accelerations. Such analyses require considerably less detail than static models since mode shapes are usually distributed widely over the structure and are thus insensitive to local variations. Two exceptions may be noted: first, when gravity loads are included, there must be sufficient accuracy in the mass distribution to produce accurate loads. Second, dynamic stresses may also be of interest. In this case more detail must be introduced, at least locally. Also, if a dynamic analysis is desired but only a static model is available, it may be more economical to pay for the additional computer time required to carry out dynamic analysis with a static model than to expend the manual or semi-automated effort required to simplify the static model.

**Aeroelastic models** involve a mathematical model of the aerodynamics as well as a structural model. Aerodynamic models may be used to predict static aeroelastic stability using a real eigenvalue solution, and for dynamic aeroelastic stability. Aerodynamic models must be coupled with structural models in order to predict aeroelastic effects. Since the meshes for the two models do not coincide, interpolation must be used. Interpolation is not a trivial matter, but several methods are available.

**Heat transfer models** are generally similar to static models with regard to the geometry of elements. Heat transfer analysis capabilities are included in NASTRAN as a sort of byproduct of the structural analysis capability. The same elements are used, but NASTRAN generates heat capacitance and conductance matrices instead of stiffness and mass matrices, temperatures in place of displacements (thus only one degree of freedom per node), and heat sources and sinks in place of loads. Prediction of accurate internal heat flux distributions is similar to prediction of accurate stresses in that generally fine meshes are required.

**Acoustic cavity models** appeared in NASTRAN as something of an adjunct capability which is not particularly relevant to aircraft analysis, but is mentioned here only for completeness. The method is intended for analysis of structure-acoustics interaction in rocket motors with axisymmetric geometry.

**Electromagnetic models** are used to determine the magnetic fields in and about ferromagnetic bodies. A finite element approximation to Maxwell's equations is developed and solved.

### 5.1.2 Symmetry

Most finite element models are general three-dimensional models. Others exhibit special symmetries which can be exploited by NASTRAN. Reflective symmetry is handled by simple constraints applied at points on symmetry planes. Cyclic symmetry is handled by special solution methods in NASTRAN. This category covers situations having rotational symmetry; that is, the structure looks the same after rotation about an axis through a given angle (which must divide 360 degrees evenly). Axisymmetry is a limiting case of cyclic symmetry. It is still supported in NASTRAN by special elements based on Fourier series expansions in the circumferential direction, but these special elements may be considered obsolete since the introduction of the more general cyclic symmetry capability.

It is not necessary that loads be symmetric in order to exploit geometric symmetry. In the case of reflective symmetry about the plane $x = 0$, for example, a general load $\mathbf{P}$ is decomposed into symmetric and anti-symmetric components; i.e.,

$$\mathbf{P}(x,y,z) = \mathbf{P}_S(x,y,z) + \mathbf{P}_A(x,y,z) \tag{4}$$

where

$$\begin{aligned} \mathbf{P}_S(x,y,z) &= \mathbf{P}_S(-x,y,z) \\ \mathbf{P}_A(x,y,z) &= -\mathbf{P}_A(-x,y,z) \end{aligned} \tag{5}$$

A static solution may be obtained by solving

$$\mathbf{K}_S\mathbf{U}_S = \mathbf{P}_S$$

and

$$\mathbf{K}_A\mathbf{U}_A = \mathbf{P}_A$$

and recovering the total solution

$$\mathbf{U} = \mathbf{U}_S + \mathbf{U}_A$$

for the $x \geq 0$ side, or

$$\mathbf{U} = \mathbf{U}_S - \mathbf{U}_A$$

for the $x \leq 0$ side. Even though two solutions are required, the cost is less than a solution of the full model because the matrix decomposition time will be less by a factor of about four.

Similar derivations are possible for solution of general loads acting on cyclic symmetric structures [8].

### 5.1.3 Equation Types

The simplest form of structural analysis is static analysis in which we solve the linear matrix equation shown in Eq. 2. Static analysis is justified when the loads change only slowly. In most cases, flight maneuver loads, for example, are treated as quasi-static.

In linear eigenvalue analysis we solve

$$(\mathbf{K} - \omega^2\mathbf{M})\mathbf{U} = 0 \tag{6}$$

to obtain natural frequencies $f_i = \omega_i/(2\pi)$ and mode shapes $\mathbf{U}_i$. This kind of analysis is very important because frequencies and mode shapes tell a lot about the dynamics of a structure.

Static stability analysis is almost never required in aircraft analysis, but is mentioned here for completeness. The eigenvalue buckling problem

$$(\mathbf{K} + \lambda \mathbf{K}^d)\mathbf{U} = 0 \tag{7}$$

is formed in terms of the "differential stiffness" $\mathbf{K}^d$, and solved for the lowest root $\lambda$. $\mathbf{K}^d$ is the linearized incremental stiffness associated with a particular applied load.

Dynamic loads may be classified as transient or steady-state. Transient problems are solved by forward integration of the equations of motion. Steady-state problems are important in the analysis of random excitations. Both problems are usually formulated in terms of modal superposition in which multipliers of a selected set of normal modes are used as independent degrees of freedom rather than node point displacements.

Most structural analysis is based on linearized equations of motion and linearized stress-strain laws. Nonlinearity is encountered more frequently in heat-transfer analysis, as when temperature-dependent thermal properties or nonlinear radiation laws are specified. In some cases, which are seldom encountered in aircraft analysis, one or both of these assumptions may not unjustified. In these cases special iterative analysis methods must be employed. Nonlinear analysis is usually difficult and time-consuming, requiring an analyst with special skills.

### 5.1.4 Definition of Loads

Definition of loads for aircraft analysis is basically a matter of defining the flight conditions to be used. Loads usually represent a certain load factor, altitude, airspeed, gross weight, store loads and many other considerations. Ground loads for taxi or landing landing impact may also have to be simulated. Obtaining these loads may require running other computer codes such as aerodynamic or taxi programs. Ideally a finite element model would come with a series of such loads representing the conditions which are critical for the design of the aircraft. Unfortunately, different loads are critical for different parts of the structure. A rolling pullout may drive the design of one component, while a different maneuver may be more important to another.

The manufacturer's stress report generally lists the criteria used in the design of each component and shows how the stress analysis was performed. These stress reports form a valuable adjunct to a finite element model, but they are usually published in limited quantities (only a few copies of each volume, while the volumes may run to a hundred or more) and are usually not available to most engineers. It is recommended that the Model Center have a copy of the stress reports available. Loads for a limited number of well-defined loading conditions should be part of the model.

## 5.2 NASTRAN as a Standard

NASTRAN was developed originally for NASA by contractors. Subsequently, commercial versions appeared, among which MSC/NASTRAN is predominant. While several other commercial finite element codes exist, none of them competes seriously in the aerospace industry. COSMIC NASTRAN, the original NASA version, still exists and is being maintained, modestly enhanced, and marketed. While it is used at a few government installations, we know of no aerospace companies that use it. Some aerospace companies continue to use in-house finite element codes, but nearly all use NASTRAN at least as an adjunct to their in-house code. FDL's ASTROS program also uses NASTRAN input format. These facts make it reasonable to specify NASTRAN format in the proposed Mil-Standard, and also to adopt NASTRAN format for storage of models in the Model Center.

The question remains as to whether a particular form of NASTRAN input should be required for model delivery. The various versions of NASTRAN have diverged to some extent as new enhancements have been added. The divergences have mainly taken the form of new capabilities, each of which generally brings with it a few new bulk data cards or new fields on existing cards. In a few circumstances, old capabilities have been dropped (e.g., the QUAD2 element has been dropped from MSC/NASTRAN). Also, some new bulk data formats have been added (free format options). Perhaps as a result of conservatism and inertia in the engineering community, these changes have not been overwhelming. Typically, an aircraft structural model rarely uses features that are not common to all versions, so that translation is can be be performed without ambiguity. When aeroelastic features are used, there is some difficulty, but again typically not insurmountable. It is expected that the translator prepared as part of this effort (see Section 6.2.4) will make the debate about COSMIC versus MSC format immaterial. The translator automates conversion of bulk data files among any of three formats (COSMIC, MSC, ASTROS). It translates unambiguous entries without comment. Where there is some ambiguity or lack of overlap, the translator either makes an assumption or makes no translation, flagging the situation so the analyst can make a judgement.

It light of the forgoing, it is recommended that files prepared for any publicly or commercially available version of NASTRAN be acceptable. At present, these include COSMIC NASTRAN, MSC/NASTRAN, UAI/NASTRAN, and CSA/NASTRAN. Although the latter two versions are not currently supported by the translator, files in these formats could be dealt with in either of two ways: (1) translate them as COSMIC files, or (2) add UAI/NASTRAN or CSA/NASTRAN to the translator. The translator is designed to facilitate addition of new codes in that no source code modification is necessary; instead, the ASCII template file which drives the translator is modified by somewhat with knowledge of NASTRAN, without any modification to the translator source code.

## 5.3 Pre- and Post-Processors

Finite element pre-processors are programs (usually graphics-oriented) that can be used to generate finite element models in a semi-automated manner. Generally speaking, users define certain key nodes (at corners, for example) and then specify that a mesh of interior nodes and elements is to be filled in according to certain specifications.

Automatic mesh generation is convenient when applicable, but geometric irregularities in a structure may limit its usefulness. In these cases manual definition of many nodes and elements will still be necessary. In these cases, pre-processors are still valuable for the ability to view the model with interactive control of rotation, zoom, hidden surface removal, etc.

Pre-processors generally accept commands either from the keyboard or from command files. Since keyboard commands are not recorded permanently, command files are the best way to generate models in production work. In these cases the user may not pay much attention to the bulk data file that is generated by the pre-processor, considering the pre-processor command file to be the real source of the model and the focus of his effort. In other cases, however, manual editing of the bulk data may be necessary. If a user makes nonrepeatable (or difficult-to-repeat) changes to a bulk data deck, he has then invalidated the pre-processor command file, making it difficult or impossible to go back to the pre-processor and make changes at that level. This also leads to the possibility that some unsuspecting future user may assume that the command file is still current. Thus we may distinguish three situations in the use of pre-processors:

1. Where little or no editing of the bulk data is required, the pre-processor command file should be considered the source of the model. Any editing of the bulk data should be done in a repeatable manner.

2. Where extensive editing of the bulk data is required, it may be best to "burn bridges," abandoning the pre-processor once extensive changes to the bulk data have been made.

3. Borderline cases have to be handled with judgement, but it must always be clear whether the pre-processor command file is current or not.

NASTRAN has been selected as a standard finite element code for this effort. No such choice is possible for pre-processors, however, since no one code has reached the position of prominence that NASTRAN has reached among finite element codes. Therefore, no attempt will be made to develop standards that relate to pre-processing codes.

## 5.4 Validation of Models

It is very important to establish confidence in a finite element model, especially one obtained from another organization. Validation of models is by no means an exact science, but depends partly on experience and judgement. Nor is validation a simple yes/no judgement. For example, a static model may (deliberately) predict accurate stresses in one region and not another. Dynamic models must be judged in terms of the highest frequency that should be accepted. They may also be set up to suppress unwanted modes such as in-plane modes.

As was mentioned in Section 5.1, there are some mathematical theorems regarding convergence of finite element models with increasing mesh refinement. Only recently, with the advent of commercial versions of the so-called *p-version* of finite element analysis such as MSC/PROBE, have these theorems begun to have practical application. The p-version of FEA is a systematic approach to model refinement wherein the order of the shape functions of certain elements is increased in response to stress gradient data. (In the h-version, by contrast, accuracy is enhanced by adding more elements with unchanged shape function order.) However, in aircraft structures there is often little choice about where to locate node points. Having defined node points at all the places dictated by the geometry of the structure (i.e., at stiffeners, cutouts, thickness changes, etc.), the analyst often finds his "budget" of node points exhausted, or nearly so.

There are a number of diagnostic checks performed by NASTRAN that should be checked as a first step in validating a model. Assuming a model is free of simple format errors and typos, the next validation step would be generation of plots. These can be used to check visually for elements that are misshapen, node points out of place, etc. Plots are best generated with a pre-processing program, but NASTRAN's plot capability can also be used. Also, the diagnostic program called RATS can be used to check models for unacceptable or borderline values of aspect ratio, interior angle, and skew. Next, simple static loads can be applied. NASTRAN prints several diagnostic messages that can help uncover errors in element connections, poor constraint sets, etc. Simple node point singularities are detected automatically. More complex mechanisms or near-mechanisms can be detected by a matrix conditioning number (ratio of maximum factor diagonal to matrix diagonal). Acceptable values for this nondimensional ratio range from $10^5$ to $10^7$. A residual error ratio which is calculated for static analysis can also point to stiffness singularities. In dynamic analysis, spurious strain energy in rigid body modes can indicate improper constraint sets. All these diagnostics should be checked where applicable.

Loads often provide a good standard with which to validate models. A set of known loads that provide a set of known or measured displacements for the actual structure provide a benchmark that can be used to check the model for continuity, connectivity, and constraints. Correlation of such data provides confidence that the model is an accurate representation of the real structure. Confidence in the model is a very important factor in finite element analysis, since there can be errors that are not easy to detect. Another method of providing loads to run a check on a model is the use of structural influence coefficients using point loads as was done during the creation of the the B-1A model. This is useful if there are sufficient data to check against. If vibration data are available, from a ground vibration test for example, a normal modes analysis of the model can help verify the stiffness of the model if the mass is known to match.

In dynamic problems, mode shapes should be checked thoroughly by generating plots. Improper stiffness and masses will often show up as unrealistic mode shapes. Also, the diagnostic messages that are provided with the various eigenvalue solution methods should be checked to insure that no roots have been skipped.

Validating a model can require a great deal of effort. As the survey results reported in Appendix A indicate, Air Force agencies receiving models from contractors often have no practical choice but to assume that the contractor has created a good model. It can be argued that manufacturers have the best data and knowledge of the structure and so the models they create ought to be good. Of course, a major goal of the present effort is to make it unnecessary to accept models on faith, by requiring evidence of validation along with delivery of models.

## 5.5 Supporting Documentation

The value of a finite element model depends heavily on the availability of supporting documentation, especially when a model is delivered from one organization to another. Documentation may include reports, plots, sketches, and comments in the bulk data deck.

## 5.6 Mil-Standard for Delivery of Finite Element Models

The need for a standard to require developers of Air Force aircraft to deliver the finite element models that they generate has already been discussed in section 2. In this section we discuss the proposal for a standard in more detail. The Mil-Standard presented in Appendix B was based largely on Venkayya's proposal [1]), but with some additional ideas and a somewhat different arrangement.

### 5.6.1 Background on Mil-Standards

Typically a standard imposes requirements and performance standards and recommends techniques for compliance. Structural requirements for aircraft are contained in two basic documents, Mil-A-87221 and Mil-Std-1530A. A Mil-Standard for the acquisition of finite element models should ideally be a separate document, although it could conceivably be made part of Mil-A-87221, during its next review and update cycle. The requirements of such a Mil-Standard have been addressed by the Air Force. A sample Data Item Description was drafted in 1985 [4] and addresses in detail the type of data that must be supplied.

Through the MIL-PRIME program, the Air Force has been working to streamline the acquisition process by improving the quality of specifications and standards applied to individual contracts. The goal is to eliminate overspecification by tailoring documents to specific weapons systems. Each MIL-PRIME document consists of a specification or standard tailored to the specific situation. An associated handbook contains rationale, guidance, and lessons learned for each requirement and its associated verification. By the end of 1987, fifty-four MIL-PRIME development documents were available for program use [13]. In the past, delivery of finite element models has generally not been a requirement, even though the contractor may have been paid for the work involved. If such delivery is to made a requirement, a stringent Mil-Standard must be developed to ensure that models contain all the documentation needed to insure their usefulness. The requirements of this Mil-Standard should be such that it would not require or even accept tailoring to an individual program. The temptation to water down the model requirements must be avoided.

### 5.6.2 Comments on the Mil-Standard

Appendix B of this report presents a Draft Mil-Standard on Requirements for Delivery of Finite Element models. The Standard was formatted along the lines of Mil-Standard 1530. This document would of course be subject to review and editing before it could be published as an official Mil-Standard.

Typical Mil-Standards are only four to eight pages in length. The Mil-Standard in Appendix B was deliberately kept short, also. Mil-Standards are meant to be flexible documents, to be tailored to the needs of a particular contract.

The subjects of acoustic cavity analysis and electromagnetic analysis, were omitted, even though they can be solved with finite elements, were omitted from the Mil-Standard because they are not relevant to aircraft structures. Neither were metamodels (input to finite element pre-processors) included because they are not suitable for standardization at this time.

### 5.6.3 Costs

It must be understood that these requirements will impose costs upon contractors which will ultimately be reflected in their bids. Superficially, it might seem that the only costs involved would be writing a tape, bundling up some documents, and shipping them, and these would be nominal. In fact, the real costs would result from contractors' perceptions (real or imagined) that they were being subject to increased exposure and liability. They would thus expend extra effort in verifying and documenting any models that were to be delivered.

It is very difficult to quantify such costs. They would certainly be considerably less than the costs that would be expended if the Air Force should have to go out on contract for the purpose of creating a finite element model of an existing system, which has happened.

Another relevant point is the benefits that would accrue to both the contractor and the Air Force as a result of these requirements, aside from the delivery *per se*. The authors know from long experience that having to explain a model to a colleague is one of the most effective ways of debugging it. This is so even when the colleague merely sits and listens. Another fact of life is that developers, having invested so much energy in a model, tend to assume it is complete before there have been sufficient checks. It is quite likely that in documenting and verifying a model in preparation for delivery, contractors would discover shortcomings that had previously not come to light. Such discoveries could prevent potentially catastrophic problems with the models. In any event, the additional efforts would increase the contractor's confidence in his own model.

Another way to approach the costs issue is to assume for a moment that delivery requirements had been in effect all along and that someone was proposing eliminating them in order to save money. They would have to argue that contractors would bid lower because they could take less care in their modeling and could skip some of the documentation and verification efforts. Such arguments would not likely be taken seriously. This would be especially true if the proposed Model Center had been in existence for some time, and if models delivered by contractors had been used to advantage by the Air Force.

# 6. FEM-X Database Management System

FEM-X is the finite element database management system that was developed as part of this contract. In accordance with the terms of the contract, the delivered software is considered a prototype version. Thus, while the developers have taken great pains to produce a robust and useful system, FEM-X, like any substantial software product, needs to undergo a period of independent or *beta* testing to flush out errors or shortcomings. Detailed instructions on the use of FEM-X may be found in the accompanying *FEM-X User's Guide*. This section briefly reviews the operation and organization of FEM-X, and discusses some of the software design decisions that were made.

The software is intended to address a specific need in finite element analysis: the need for procedures to provide storage, identification, and tracking of finite element models. It is not intended to compete with graphics software used for generation and display of finite element models and therefore does not provide such displays, not any X-Y plots.[1] Neither does FEM-X do any significant checking of finite element data. It is assumed that the user has the skill and the resources (e.g., a computer running NASTRAN) to perform validation tasks. Because it provides a convenient framework for documentation and storage of models, it is expected that FEM-X will *encourage* users to perform and document validation runs.

Most successful software packages provide users with a framework for exercising their own creativity. Examples include spreadsheets with formula-building tools and macro languages, NASTRAN with its DMAP matrix manipulation language (which is arguably the most important reason for NASTRAN's longevity), or ASTROS with its MAPOL language, user-callable relational database, and its system generation utility. It is hoped that FEM-X will encourage user productivity and innovations in two ways: First, the software is rather flexible in that it provides users with a number of text fields whose names suggest what the contents should be, but nevertheless allow users wide latitude in actually entering data. Second, the use of CADDB as the underlying database manager may encourage users to develop applications for manipulation of bulk data stored in FEM-X. This is because of the wide range of options available for manipulating CADDB data through ICE (the interactive interface to CADDB databases, described in [14]) or the Fortran interface.

While FEM-X is designed to be user-friendly, it is also meant to encourage more discipline on the part of its users. Finite element analysts, like software developers, often neglect documentation chores. FEM-X will encourage documentation in parallel with development or modification of models. For users of and developers of finite element models, FEM-X will provide functionality reminiscent of that provided by

[1]But because it works under the X Window System, FEM-X will harmonize well with graphics software that also runs under X. Users will be able to view finite element graphics in one window and FEM-X in another, on the same screen. Major finite element graphics packages are now beginning to provide support for X.

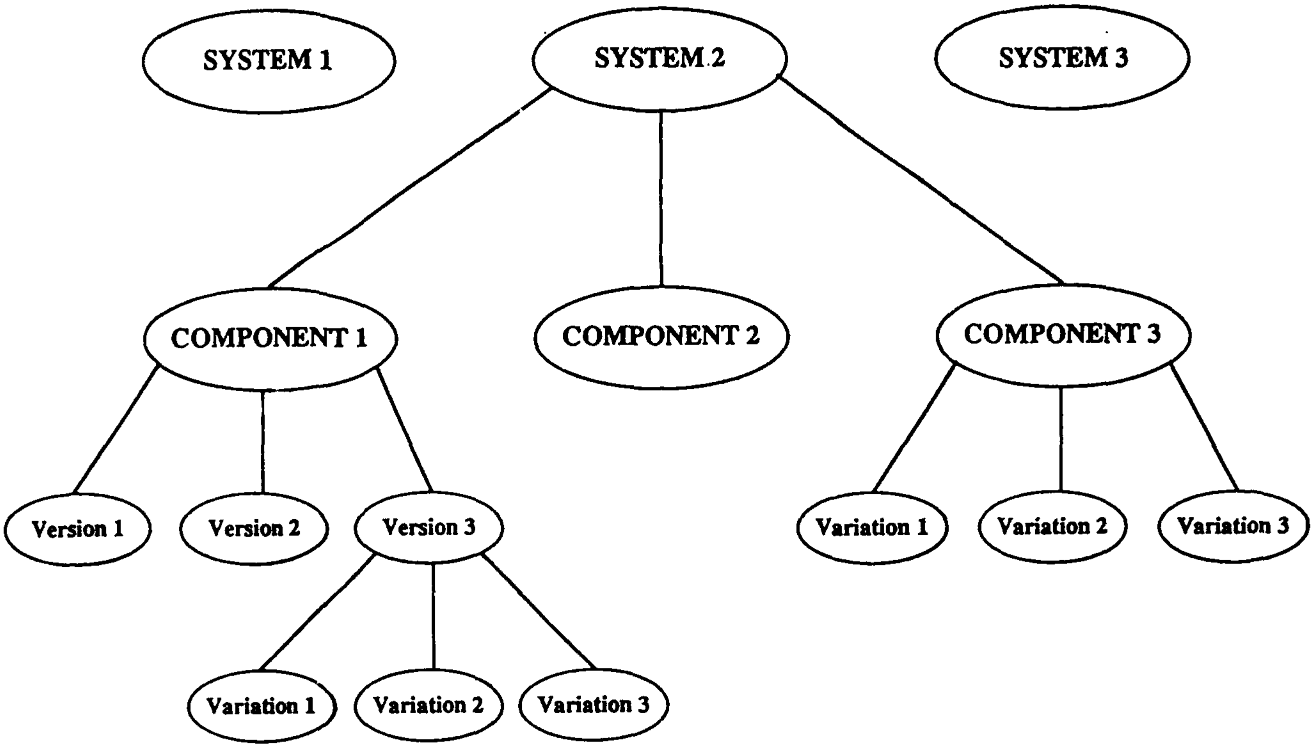


Figure 7: Hierarchy of Information in FEM-X

CA.E tools[1] for software developers.

The primary purpose of FEM-X is to support the proposed Air Force Finite Element Model Center (Section 7). The users at the Center will not be expected to create finite element models, although they may modify them. However, FEM-X should also be useful to analysts who are creating models. Its provisions for documentation should be useful for keeping a work log and for maintaining significant versions of their models that are generated as the design changes, loads change, etc.

## 6.1 Organization of Information in FEM-X

The information in the FEM-X database is organized in a hierarchical fashion, as shown in Figure 7. The items that constitute the hierarchy (systems, components, versions, and variations) are explained in the following paragraphs. Users move up and down the hierarchy and are always located at a particular position which determines the options available to them. That is, they start by selecting a system, then may move down to a component, down to a version, back up to the original system level, sideways to a new system, etc.

[1]Computed-Aided Software Engineering

### 6.1.1 Systems and Components in FEM-X

FEM-X is designed to support finite element analysts who are working with models of airframes. Although it is hoped and expected that the software will be useful to engineers working with other kinds of FE models, there is one aspect of aircraft models that had particular influence on the design of the software. This is the fact that models of individual sections or "components" of aircraft are more common than single models of an entire aircraft. Therefore, finite element models in FEM-X are assumed to represent a single component, and components are grouped under the heading of a "system." Thus, for example, the database might contain a number of models of portions of the B1-B airframe. Under "systems," there would be an entry called "B1-B." In addition to some brief text about the B1-B, there could be a number of component entries such as "Wing Carry-through," or "Forward Landing Gear." For each of these components, there would not only be a finite element model but a wide variety of descriptive information as well.

The system-component arrangement does not preclude a single model of an entire aircraft, or any other structure. In this case, the user would have a system with just one component which would constitute the entire model.

### 6.1.2 Versions and Variations in FEM-X

In working with finite element models, analysts invariably make a number of changes in a model. Some changes are for debugging purposes. Other changes are part of the normal course of developing and checking out a model (e.g., an initial static analysis may be used to verify the "sanity" of the model, perhaps followed by calculation of a few natural frequencies, followed by more natural frequencies). Some changes, especially those made for debugging purposes, are transient in nature and are properly discarded after they are run through the analysis code. Other changes may not have much bearing on the final purpose of the model, but would be of some interest for future review of the steps undertaken by the analyst. Other changes warrant careful documentation, such as new load conditions, design changes, etc. FEM-X provides two modes for handling the various kinds of model changes that may be made: versions and variations.

A version is a substantial change in a model, typically undertaken for engineering purposes. A variation is a minor change, such as a local refinement, a change in boundary conditions, etc. It is entirely up to the user to classify a particular change as a version or a variation.

### 6.1.3 Results and References in FEM-X

FEM-X provides for text entries under the heading "Results." It is expected that these fields will be used for entry of summary remarks about the results produced by a particular FE model (e.g., maximum stresses, natural frequencies, etc.). Users may also wish to use the cut-and-paste facility of X to extract small portions of the output file of the finite element code, such as eigenvalue tables or the summary information that appears when X-Y output is requested in NASTRAN and place these portions in the "Results" field

As an example of the use of the "results" field, consider a user who was computing natural frequencies and mode shapes of a structure. FEM-X would be open in one window on the screen. The user could open another window and scroll through NASTRAN's "print" file in another. Upon reaching the eigenvalue summary table, he would use the mouse to cut the frequencies from the NASTRAN output file and paste them into the FEM-X "results" field. He would then open a post-processing program in another window to display deformed shape plots for several natural frequencies. He would use these displays to characterize each mode and enter remarks such as "first bending mode" next to the corresponding natural frequency in the "results" window.

An area labelled "references" is provided for entry of information about supporting documents such as drawings, reports. It could also contain brief notes, transcripts of telephone conversations, etc.

### 6.1.4 Scripts

CADDB is a relational database offering sophisticated means for users to extract, view, or compare data. There are two ways for users to perform these functions: by writing Fortran or C code that calls library routines that are provided in object code format with the ASTROS distribution (and described in Volume IV of [2]), and by using the interactive interface code called ICE (Interactive CADDB Environment, [14]). ICE implements a query language called CQL (CADDB Query Language), a counterpart of the well-known SQL language for business database applications. Because sequences of CQL commands can be quite complex, users often enter them in script files and play them through ICE in a semi-interactive mode. FEM-X provides a mechanism for users to create, store, and execute ICE scripts. The users have complete liberty to write any ICE script. FEM-X does not check the syntax or usefulness of a user's script; it merely provides means to store, identify, and execute scripts. The uses for which scripts might be employed are limited only by users's imaginations. However, it is expected that scripts will be used primarily to extract portions, or subsets, of a bulk data file. Typically, a user script would include a `SET INTERFACE` command for the purpose of writing selected data to an ASCII file. This file could then be edited and used to refine or modify a model.

Following is an example of a hypothetical script file whose purpose is to identify and write out all of the nodes and elements (specifically, GRID, CQUAD4, and CTRIA3 records) near the engine mount of an aircraft wing model. Although the CQL commands appearing here are fairly self-explanatory, readers unfamiliar with ICE will want to consult the ICE manual [14] for complete explanations of what each command does. The commands are numbered for reference in the following discussion:

```
 1.  CREATE VIEW ENGINEGRIDS AS
         SELECT ID,X,Y,Z FROM GRID WHERE
             X > 143.2 AND X < 157.8;
 2.  SET INTERFACE TO 'ENGINE.GRID';
 3.  INTERFACE ON;
 4.  INTERFACE FORMAT '(''GRID'',I12,8X,3F8.4)';
 5.  SELECT ID,X,Y,Z FROM ENGINEGRIDS;
 6.  SET INTERFACE TO 'ENGINE.CQUAD4';
 7.  INTERFACE FORMAT '(''CQUAD4'',T9,6I8)';
 8.  SELECT EID,PID,G1,G2,G3,G4 FROM CQUAD4 WHERE
         G1 IN (SELECT ID FROM ENGINEGRIDS) OR
         G2 IN (SELECT ID FROM ENGINEGRIDS) OR
         G3 IN (SELECT ID FROM ENGINEGRIDS) OR
         G4 IN (SELECT ID FROM ENGINEGRIDS);
 9.  SET INTERFACE TO 'ENGINE.CTRIA3';
10.  INTERFACE FORMAT '(''CTRIA3'',T9,5I8)';
11.  SELECT EID,PID,G1,G2,G3 FROM CTRIA3 WHERE
         G1 IN (SELECT ID FROM ENGINEGRIDS) OR
         G2 IN (SELECT ID FROM ENGINEGRIDS) OR
         G3 IN (SELECT ID FROM ENGINEGRIDS);
```

The region near the engine mount is identified by $143.2 < x < 157.8$. Line 1 creates an entity called `ENGINEGRIDS` which consists of the ID and coordinates of all the nodes that lie in that range. Line 2 opens a file that will receive selected data, line 3 activates writing to this file, and line 4 is a Fortran format statement for writing GRID data. Line 5 causes all the data in ENGINEGRIDS to be written to the interface file. Lines 7 through 11 extract all the QUAD4 elements that have at least one node in `ENGINEGRIDS`, and the final set does the same for TRIA3 elements.

Two shortcomings of ICE may be noted in passing. First, there is no provision for comment lines. Second, each `INTERFACE FORMAT` statement causes any information previously written to the interface file to be lost. Hence the example above was set up to write to three different files. The authors view the latter situation as a bug in ICE which should be fixed.

As the foregoing example indicates, scripts can be rather complex. It is expected that users will develop scripts interactively, and only when they are seen to produce the required results will they be entered in FEM-X. FEM-X, ICE, and the X Window environment will provide users with a number of options for developing scripts. One scenario is as follows: the user types ICE commands into the window provided for FEM-X scripts. (This window provides virtually all the features of the **xedit** screen editor that accompanies X.) When the user wants to try the script, he simply picks the EXECUTE button on the screen, at which time his script is played through ICE and the results shown on an additional window that is created for that purpose. If the results are not satisfactory, the user can edit the script and repeat its execution. In another scenario, the user can be running ICE in a separate `xterm` window, having issued the `SET ARCHIVE` command to cause all commands that are entered to be saved on a file. Once satisfied with the results, the user can insert the archive file into the FEM-X script window with a simple command. Unwanted lines can then be removed from the script.

## 6.2 Finite Element Model Data

Section 5 of this report stipulated that COSMIC NASTRAN should be the format in which contractors deliver finite element model data to the Air Force. However, many models exist in ASTROS and MSC/NASTRAN data formats as well. Therefore, FEM-X has been designed to support all three of these formats. All finite element model data that are entered into FEM-X are tagged to indicate whether it conforms to ASTROS, COSMIC NASTRAN, or MSC/NASTRAN format. FEM-X does a modest amount of checking of bulk data that are entered, equivalent to the checking that ASTROS or NASTRAN do in their first pass over the bulk data: checks for required fields, data type, and limited checks of values (such as numbers that are supposed to be positive).

### 6.2.1 Prefaces

All three finite element codes accept data from ASCII files in very similar formats. Preliminary information, (executive control, case control, etc.) appears in relatively free format, followed by the actual finite element model data in bulk data format (mostly numeric, entered in 8-character fields). We have grouped this preliminary information under the heading "prefaces" in FEM-X. Prefaces are stored separately from bulk data and are also tagged as having either ASTROS, COSMIC NASTRAN, or MSC/NASTRAN format. FEM-X does not perform any kind of checking to validate preface data, however.

The contents of prefaces for the various finite element packages are as follows:

**ASTROS**

| | |
|---|---|
| DEBUG packet | Debug output control |
| MAPOL packet | MAPOL matrix language source code |
| SOLUTION packet | selections of solution type, loads, support conditions, output requests, solution methods, etc. |

**COSMIC NASTRAN**

| | |
|---|---|
| NASTRAN card | Miscellaneous operating parameters |
| Executive control | Choice of solution type, etc. |
| Substructure control | Control of substructuring operations |
| Case control | Selection of loads, support conditions, output requests, solution methods, etc. |

**MSC/NASTRAN** (version 65 and earlier)

| | |
|---|---|
| NASTRAN card | Miscellaneous operating parameters |
| Executive control | Choice of solution type, etc. |
| Case control | Selection of loads, support conditions, output requests, solution methods, etc. |

**MSC/NASTRAN** (version 66 and later)

| | |
|---|---|
| NASTRAN card | Miscellaneous operating parameters |
| File management section | Database control |
| Executive control | Choice of solution type, etc. |
| Case control | Selection of loads, support conditions, output requests, solution methods, etc. |

### 6.2.2 Entry of New Models

In order to enter a new finite element model into FEM-X, the user provides a few simple items of information by filling in blanks in a screen like that shown in Figure 8. The software then reads the file indicated by the user and splits it into a preface (as explained in Section 6.2.1) and the actual bulk data. The bulk data are read into CADDB relations by executing a special "rump" version of ASTROS. There are three special versions of ASTROS: one for ASTROS data, one for COSMIC NASTRAN, and one for MSC/NASTRAN. The word "rump" indicates that the standard MAPOL sequence of ASTROS has been replaced with a truncated version that does nothing more than read, check, and store bulk data. Input values are checked with respect to type and in some cases ranges of allowable values. The three versions of ASTROS were generated using the SYSGEN capability of ASTROS, which creates executable code and a system database based on descriptive files that may be modified by knowledgeable users. Complete descriptions of all the bulk data cards possible in COSMIC NASTRAN and MSC/NASTRAN were coded into these files, along with relational schema used to store this data. More details on this process may be found in the *FEM-X User's Guide*.

### 6.2.3 Extraction of Bulk Data

Extraction of bulk data is available through a screen designed for that purpose. "Extraction" simply means writing the bulk data to an ASCII file, along with an optional

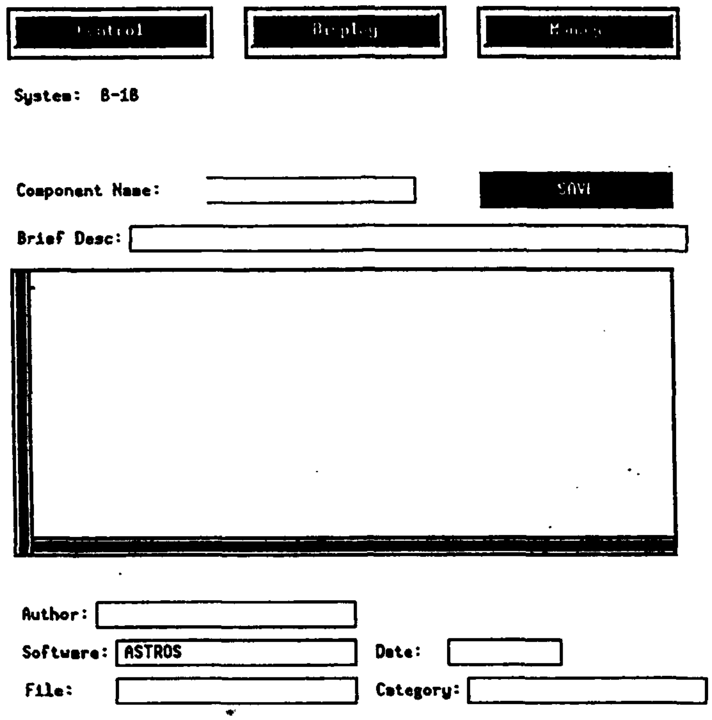


Figure 8: FEM-X Screen for Entry of a New Finite Element Model

preface. The user decides what to do with the ASCII file after it is created, but presumably it will serve as input to NASTRAN or ASTROS, perhaps being edited first. (After editing and running the bulk data, the user may choose to re-enter it in the database as a version, variation, or even a new component model. The bulk data that will be provided is determined by the user's current context or position in the hierarchy (i.e., what component, version, etc., is currently accessed). The user is allowed to select a preface from the list of prefaces, or to obtain the bulk data without any preface. The user is also offered a translation option, and two formatting options for MSC/NASTRAN files: space or tab delimiters, and explicit continuation symbols or implied continuations.

### 6.2.4 Translation of Bulk Data

As a convenience to users, a translator function is provided with FEM-X. Users can request that bulk data be translated from any of the three supported formats to any of the others. Preface data are not translated. Not all data types are supported by all three codes. When there is some ambiguity or an assumption to be made, the translator makes a choice and enters a note in a commentary file. When no translation can be performed, the translator simply skips the data, enters a note, and proceeds. The choices made by the translator regarding individual record types as well as individual fields types are governed by a "template file" which can be modified by careful users to change the way certain records or fields are translated, or to update the translator in response to release of a new version of NASTRAN or ASTROS.

The translator is built into FEM-X and is also available in a stand-alone version called TRANSNAS. Detailed information on the translator may be found in the accompanying *FEM-X User's Guide.*

## 6.3 Design Decisions in the Development of FEM-X

The following discussion centers on some of the issues and policies that came up prior to and during the development of FEM-X.

Two software systems were chosen for use with FEM-X: CADDB for database management and the X Window System for the user interface. Since these choices were so important for the development of FEM-X, they are discussed in some detail here.

### 6.3.1 Database Software

FEM-X is principally a database application. Its basic function is to store, retrieve, and display information related to finite element models, as well as the bulk data for the models. The choices available at the time this project was initiated were as follows:

1. Use a commercial database package such as Oracle.
2. Write our own database software.
3. Use CADDB, the database software written as part of the ASTROS [2] development project.

It was not necessary to choose the same database software or approach for these two classes of information; thus, the approach to storing text data is discussed separately from the approach to storing bulk data. For both purposes, commercial database software was considered undesirable because of the added cost, and because it would be a hindrance to distribution of FEM-X (i.e., there would be license agreements and fees both for the development work and for each distributed copy of the final product). It seemed unreasonable to expend resources on writing our own software if existing software could be used. CADDB was already being used to store bulk data for ASTROS, and it appeared to offer reasonable facilities for storing text data as well. CADDB was the leading candidate because (1) it is Air Force property, controlled by the same organization that will control FEM-X (Wright Laboratory/Flight Dynamics Directorate), (2) it seemed to offer the required capabilities, and (3) it had already been ported to several computers, and it was expected that subsequent ports would not be difficult.

### Text Data

In hindsight, custom database software for text strings might have been just as good a choice as CADDB for storing text data. This statement is based on the following considerations:

1. The database operations required by FEM-X are not particularly complicated.

2. It is somewhat awkward (from a programming point of view) to store and retrieve long text strings (i.e., paragraphs) using CADDB.

3. Although CADDB functions correctly when properly utilized, with only very minor exceptions, it has an unfortunate tendency to crash or corrupt the user's database when utilized improperly (i.e., when illegal values are passed to CADDB subroutines).

4. CADDB generates database files that seem excessive in size, i.e., their size is a large multiple of the number of bytes of actual data they contain.

The most likely alternative to CADDB would be storage of text data in ASCII files, relying on the Unix hierarchical file system for organization of these files. But there would have been drawbacks with this approach, also, mainly the proliferation of a large number of small files in user directories, and the increased likelihood that files would be lost because users or system managers would not recognize them and would delete them.

### Bulk Data

FEM-X has been programmed for storage of bulk data in CADDB relations. The reasons for this choice are as follows:

1. Users can use ICE to query or manipulate the bulk data as they see fit. Users may compile sequences of ICE commands into files called "scripts" which may be retained in the FEM-X database (Section 6.1.4). It is expected that users will make use of scripts to identify particular portions of an aircraft structure, but other uses may be found as well.

2. Advanced users may wish to write Fortran programs that interface to the CADDB database. For example, a simple plot program was written to display a model in a FEM-X database in an X Window. This program is documented in the *FEM-X User's Guide*.

There are drawbacks to this approach, however:

1. First, user comments are lost when bulk data are converted to CADDB format. However, our policy is that descriptive data belong in the FEM-X database where it can be reviewed and edited conveniently. Comments from the bulk data should be copied into the windows provided for commentary. General commentary can be entered in the descriptive text fields provided for individual components. Comments relative to particular sets of cards can be handled by making subsets out of those card sets, using scripts (Section 6.1.4) and entering the commentary in the descriptive fields provided for scripts. Users can open the ASCII bulk data file in one window and FEM-X in another. Using the mouse, they can cut comments out of the bulk data and paste it into FEM-X rather easily.

2. When a user wants to reconstitute an ASCII bulk data file from an FEM-X database, the file that is written will not be identical to the original from which the database version was generated. We expect that the differences will be cosmetic (field alignment, continuation symbols, etc.) and that the data will be identical in terms of the results that NASTRAN or ASTROS produce when operating on that data. However, the following problems could occur:

   (a) At present, FEM-X writes only single fields (8 characters), even though the data may have been entered using NASTRAN's or ASTROS' double-field (16 character) option. To counteract possible loss, code is set up to provide maximum precision for floating-point data within eight characters. At worst, three significant digits are provided (e.g., $-1.234567 \times 10^{-12}$ would be written as `-.123-13`). This worst case only occurs with negative numbers smaller than $10^{-10}$ in magnitude. Most engineering data are not accurate beyond three digits, so there should be no problem in the vast majority of cases. Usually, extra precision in input data is required only for matrix input (GENEL, DTI, and DMI cards). This consideration plus the complexity of these cards led us to define all the data on these card types in COSMIC and MSC/NASTRAN as character data. For such cards, the real numbers will be stored as ASCII characters thus eliminating any truncation problems.

   (b) There is a wide variety of card types, and some of the card types allow for a variety of data configurations. Although the code has been tested extensively, it is possible that some obscure card configurations may be improperly handled.

There is a very small probability that significant data would be lost by the format translation process. None of the models that have been exercised with FEM-X to date have presented any such problem. Therefore it has been decided to retain the original bulk data file in addition to the CADDB relations. The prototype version of FEM-X, as delivered with this report, offers users a choice of two methods of extracting bulk data from the database for use with NASTRAN or ASTROS. They can either request that the bulk data in the database be written to a file of their choice, or that the original bulk data file be copied to their file.

ASTROS, in addition to reading ASCII files, writes its bulk data on CADDB databases. It would be possible to make use of existing ASTROS bulk data in a CADDB database, but we will not do so. The reason is that we would either have to use the existing database that ASTROS created, adding our own descriptive entities to that database, or create our own database and copy all the bulk data relations from the ASTROS user database to our new database. The former seems inadvisable because we would have one database with two software packages manipulating it (ASTROS and FEM-X), with the attendant danger that the database will be destroyed or moved, and the latter is awkward because there is no simple COPY function that copies a whole entity from one DB to another.

In summary, the main consideration that favors CADDB for storing bulk data is the flexibility offered by the interactive query language that is implemented in ICE, and by the Fortran subroutine library. These factors enhance the opportunities for creative users to generate new capabilities that build on FEM-X. Of course, only time will tell whether such extensions will be developed.

## 6.4 The X Window System

The second critical choice was the use of the X Window System[1] for the user interface. The alternative to X or another window system would have been a command line interface such as that provided with ICE. The X Window System was chosen because windowing systems had become very popular with Macintosh users and were starting to become available for IBM-type personal computers, engineering workstations, minicomputers, and even Cray supercomputers. This popularity was not simply due to the "warm feeling" experienced by users of window systems, but was in fact a matter of genuine productivity gains. Any Macintosh user knows the benefits of a windowing system:

- Instead of consulting a manual or searching one's memory to decide what to do next, one simply points and clicks at symbols on the screen that show what

[1] *X Window System* is a trademark of the Massachusetts Institute of Technology. The X Consortium, the organization responsible for the development and distribution of the X Window System, requests that the following names be used when referring to this software:

X Window System
X Version 11
X Window System, Version 11
X11

The best reference work is the series by O'Reilly and associates [3]. Volume III, *X Window System User's Guide* is best for those who will be users, not programmers. Computer magazines are also a good source of information about the X Window System.

actions are available and meaningful in the present context. A "help" button is always available in well-designed applications to assist users when they are stuck. Erroneous entries are met with a friendly indication that something is wrong.

- Multiple overlapping windows can be open on the screen. Users can thus refer back and forth between windows showing related documents or information. A "cut and paste" facility allows users to copy text fields between applications that support this facility (such as FEM-X), even though the applications may be running on different host computers.

Very little prescience is required to project a time in the near future when users will demand and expect window environments and will have lost patience with command-driven software. Thus the use of a windowing system for FEM-X could be expected to extend its useful life considerably.

Computer manufacturers had begun to offer proprietary windowing systems tied to their own hardware, such as Sunview on Sun workstations or WorkSpace on Silicon Graphics workstations. The advantages of X over these proprietary systems are as follows:

1. X was designed to work on virtually any computer that provides a bitmapped graphics display and one of several networking protocols (TCP/IP, DECnet). Applications that use X could, at least in theory, run on any machine to which X had been ported.

2. X was designed from the beginning to function in a network environment. It is possible to run an application (the "client") on one machine and the associated display on another (the "server").[1] No effort is required on the part of the application programmer to take advantage of this facility. The display for an application can be made to appear on any properly equipped workstation with no modification or recompilation of the application source code required.

The X Window System is freely available from MIT in source code format, with machine-specific display server code provided for most major workstations. CSA chose to use this version of X in writing FEM-X.

Increasingly, vendors are providing software environments that are compliant with the X specification (principally, Open Look on Sun workstations and Motif on Digital Equipment workstations). The proliferation of the X Window System in the workstation world has validated our decision to use X. One need only look around the Flight Dynamics Directorate or the ASD Computer to see the predominance of window systems, more and more of which are based on the X Window System. The choice of X

[1] Unfortunately, many people think of the "server" as the machine doing the computing and the "client" as the machine doing the display. In X terminology, these terms have the opposite meaning.

has also taken its toll on this project, however. Considerable resources were expended early on in learning to program with X. Initially, Release 3 of Version 11 of X was used, and there were some difficulties with that release. Later, X11 Release 4 was adopted, and these difficulties were cleared up. Also, until all proprietary window systems achieve compliance with X11 R4, it may not be possible to install FEM-X on some workstations. For example, the IBM RS/6000 workstation currently provides a version of Motif that is not compliant with X, but the next release, due in the first half of 1991, is supposed to be compliant.

## 6.5 Computers that can run FEM-X

This section discusses the kinds of computers on which FEM-X can be run, in terms of both hardware and supporting software. As indicated in the preceding discussion, the X Window System makes it possible to run FEM-X on one machine and the display on another, with no changes to the code. This allows many choices in a large organization like WRDC. The ASD computer center has an extensive network that connects a number of workstations and computers both at Building 676 and in other buildings. Seated at a workstation in the Flight Dynamics Laboratory, for example, a user can run an application on a computer at the Computer Center, a half mile away, and see the application's display in front of him. This works well in practice, not just in theory.

Devices called X Terminals have been available for the past 2 to 3 years and are currently priced from $995 up. These are bit-mapped display terminals that incorporate the X server software in local firmware but have no other local computing capabilities nor any local disks. They must be connected over a network to a workstation, mini-computer, or mainframe running X applications ("clients"). An X Terminal can be thought of as a compromise between a "dumb terminal" like a VT100 and a low-end workstation like a SPARCstation. CSA used an X Terminal for development of FEM-X and found no problem in running it using this terminal, except that it is somewhat slow.

A computer on which FEM-X is to be installed as a client must have the following attributes:

| | |
|---|---|
| Operating system | Unix |
| Compilers | C (standard with all Unix systems)<br>Fortran (f77) |
| Database | ASTROS object library |
| Window System | Compatible with X11, Release 4 |
| Main memory | Requirement unknown, but unlikely to be a problem in practice |
| Disk storage | 100M desirable |

Any display device (workstation or X terminal) must be capable of handling input to and output from an application written for X11, Release 4. CSA's X Terminal, which implements X11 R3 server software, handles FEM-X and other R4 displays with no problem.

# 7. Plan of Operation for the Finite Element Model Center

This plan of operation provides detailed projections for the establishment and operation of the Air Force Finite Element Center. The purpose of the Finite Element Model Center is to collect, evaluate, store, and disseminate finite element model information to qualified users, primarily to other Air Force organizations or their contractors. The overall objective of the Center is to ensure that finite element models of aircraft and aerospace structures are made available in a form that maximizes their usefulness to these users. It will support Logistics Centers with respect to modifications or repair and maintenance of operational aircraft. The Center will also provide assistance to SPO's in enforcing the standards for delivery of finite element models of new aircraft (Section 5), assuming this standard becomes a contractual requirement. Thirdly, models will be available for developing derivatives of the aircraft and for research purposes.

## 7.1 Location of the Center; Contractual Arrangements

The Finite Element Model Center will be located in the Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB, Ohio. The Model Center could be established as a separate organization or it could be integrated into the Aerospace Structures Information Analysis Center (ASIAC). If organized separately, the Center would be a contractor-operated government facility. Integration with ASIAC would offer the following advantages:

- The technical skills required for ASIAC engineers are very similar to those required for the Model Center.
- ASIAC routinely receives finite element models or information about models, and also receives requests for models.
- The ASIAC newsletter could be used as a publicity medium for the Center.
- A single contract could cover both activities.

There would be some potential disadvantages, however:

- If it were not identified by a separate organizational name (the Model Center), but only as an ASIAC task, it could lose visibility.
- Personnel charged with working on Model Center tasks could be diverted to other ASIAC tasks.
- Cooperation with the other anticipated auxiliary centers (discussed below) would be more difficult if the center were not autonomous.

No recommendation is made at this time as to whether the Model Center should be part of ASIAC, since this issue hinges on so many factors that are beyond the technical considerations covered in this report.

### 7.1.1 Auxiliary Centers

Auxiliary Centers may be established at other Air Force Bases also. These would be independent operations, separately funded and operated. The organizations selected below all provide support for particular aircraft (with the exception of the Armament Laboratory). They are most cognizant of the current status of their particular aircraft, and are in contact with the contractor that built the aircraft. They would have their own copy of FEM-X, maintain their own database, and provide their own funding and facilities. The costs associated with each auxiliary center would be minimal, since most of them would likely have a suitable workstation available, or could obtain one at minimal cost. An existing engineer with finite element skills could be trained in the use of FEM-X and could take responsibility for the auxiliary Center. The main Center's primary engineer could visit each establishment for about a week and provide setup, training, and publicity.

The auxiliary centers are not envisaged as full replicas of the main Center. They would not engage in acquisition of models except for their particular aircraft, nor would they generally distribute their models. They would keep contact with the main Center and would feed their new models or updates to the main Center. Communication would be handled primarily by electronic mail.

Possible locations of auxiliary centers are as follows:

| Site | Organization | Specialty |
|---|---|---|
| Eglin AFB | Air Force Armament Laboratory | |
| Hill AFB | Ogden Air Logistics Center | F-4, F-16 |
| Kelly AFB | San Antonio Air Logistics Center | C-5A, C-5B, C-9, C-17, F-5 |
| McClellan AFB | Sacramento Air Logistics Center | A-7, A-10, F-117A, F/FB/EF-111 |
| Robins AFB | Warner Robins Air Logistics Center | F-15, C-130, C-141 |
| Tinker AFB | Oklahoma City Air Logistics Center | B-1B, B-2A, B-52G/H |

It is anticipated that the Armament Laboratory at Eglin AFB and the organizations at Wright-Patterson AFB will ordinarily be users of the models maintained at the AFLC organizations and that any models developed or modified by these research organizations will be of interest primarily to specialized users. As a secondary goal, the center will attempt to collect and maintain such research models and at a minimum will try to track and be aware of the existence of these models.

## 7.2 Operating Procedures

The following sections outline the procedures that would be followed in the daily operation of the center, as well as the initial startup period.

### 7.2.1 Acceptance of Models

Section 5 of this report presents a proposed set of standards for delivery of finite element models by contractors who are building aircraft for the Air Force. It is hoped that such a set of standards will be adopted as a contractual requirement for new aircraft. As these standards begin to take effect (which will take some time), the Center will be called upon to assist the SPO's in enforcing the standards and in actually taking delivery of the models. In order to fulfill this function, the finite element analyst assigned to the Center will have to be thoroughly familiar with the standard and will have to document his efforts on behalf of the SPO.

The Center's activities will not be confined to models that are being accepted on behalf of SPO's, however. The Center will also actively seek models from other sources: from within the Flight Dynamics Laboratory, from other Air Force organizations, from contractors, and elsewhere. The Center will of course be unable to impose any "delivery standards" on these organizations but will in most cases have to take what it can get. In the process of seeking out models and associated documentation, the Center's finite element analyst will therefore be called upon to exercise diplomatic and public relations skills in addition to technical skills.

Electronic mail has become very common as a means of communication among computer users, and this will be the preferred communication medium for the Center. All that is necessary is to obtain an official e-mail address which is an administrative task. Wright-Patterson has the required network facilities for world-wide e-mail. The Center will also be prepared to accept models in various tape formats. For this purpose, accounts will be required on other computers on the Base so that tapes of various kinds can be read and the files transferred over the local network.

### 7.2.2 Validation of Models

The importance of validation will be difficult to overestimate. The Center's reputation and credibility would suffer mightily if ever a model that had been distributed by the Center, with its stamp of approval, were found to be defective and led to erroneous results, wasted time, or perhaps even to faulty structural design decisions. (However, the Center may choose to distribute unverified models in special circumstances, clearly marked "as is" by means of comments included both in the text that is delivered with the model and in the bulk data.)

Again the mode of operation will be different depending on whether the Center is acting on behalf of a SPO in accepting new finite element models from a contractor, or accepting a model that the Center has actively solicited. In the former case, the burden lies on the contractor to demonstrate that the delivery requirements, including evidence of validation, have been met. The Center's obligation in this case is to verify to the SPO that the requirements are being met, both through documentation and independent validation exercises performed on the models by the Center.

When solicited models are accepted by the Center, validation will be especially important because the organization providing the model will typically not be under any obligation to the Center, and may not be responsive to requests for assistance in understanding the model. Thus the Center's analyst will have to have the skills necessary to evaluate a model without any outside assistance. Experience and judgement are required in assessing the quality of solutions produced by finite element software, and the limitations of a model, particularly with respect to its frequency bandwidth in dynamic analysis.

### 7.2.3 Delivery of Models

The first consideration in processing a request for delivery of a model is the requestor's need to know. Elaborate administrative procedures will not be required, since distribution of Classified models is not anticipated. A letter from the requesting organization should suffice.

In most cases, distribution will consist of an ASCII bulk data file along with supporting documentation, also in an ASCII file. These can both be obtained as output from FEM-X. Transmission can be accomplished most easily via e-mail, but tapes can be written instead.

A record will be kept of all distributions as well as acceptance of new models. This can be done using a modest database or journal file on the Center's workstation.

## 7.3 Computer Hardware Requirements

Section 6 discussed the computer hardware and software environment required to run FEM-X. Two options are possible for the Center. The first would be a minimal configuration using an X Terminal to access a remote machine on which FEM-X was installed. At least 40Mb of disk space would be required on the remote machine.

The second option would have a dedicated workstation with a 300-Mb disk, with FEM-X installed locally. A standard 19-in black-and-white monitor would be sufficient – color would be unnecessary. This is the preferred option for several reasons:

1. A low-end workstation does not cost much more than an X Terminal.[1]

[1] For example, CSA recently obtained two Sun 386i model 150 workstations. They are somewhat out of date, but they provide local processing in addition to X server functions at a price that was less than the price of a new X Terminal.

2. Computer Center personnel sometimes purge user files on the machines that they control. This would not be a problem with a dedicated machine under complete control of the Center.

3. The Center would not be vulnerable to network outages.

A printer would be desirable and has been included in the cost figures given below. This option might be skipped if a printer were available on the network at a location convenient to the Center. A scanner would also be useful but has not been included in the cost figures. For one thing, we are not aware of scanning hardware and software that is compatible with Unix. Access to scanners elsewhere on the Base may be possible.

## 7.4 Publicity

If the Center is to achieve its potential, it will have to be publicized. A brochure will be prepared that explains the functions of the Center to potential users. The brochure can be prepared inexpensively using a desk-top publishing package running on the Center's workstation, or at the Contractor's home facility. It should be printed professionally on high-quality paper.

Word of mouth will be an important means of publicity. FIBR personnel can assist in informing their colleagues in various Air Force organizations about the Center's services.

## 7.5 Phasing in the Center

There will be a startup or phase-in period for the Center. During this period of perhaps a month, it is anticipated that an engineer from the Contractor's organization would work on-site. He or she would be responsible for:

1. Hiring a full-time engineer and a part-time secretary.
2. Procuring and setting up the workstation.
3. Installing FEM-X and other software.
4. Training the engineer in the use of FEM-X.
5. Doing some initial solicitation and gathering of models.
6. Publicizing the Center.

Resources should be allocated for maintenance and enhancement of FEM-X. This is a normal part of any software project of this size. These activities would probably be performed at the contractor's home office and not at the Center. Distribution of FEM-X, if authorized by the Air Force, would also require a small part of the budget.

## 7.6 Staffing Requirements

The work involved in operating the Center may be broken down as follows:

1. Coordinating with engineers in other organizations: soliciting models and supporting documentation, answering inquiries, distributing models and documentation, setting up auxiliary centers (as described above), and distributing copies of FEM-X.

2. Performing finite element analysis work, (e.q., modeling structural changes, new loads, etc.).

3. Managing the local workstation.

4. Writing reports and doing other paperwork.

Items 1 and 2 require an engineering professional. There is some clerical work entailed in item 4. Managing a workstation is not particularly difficult; a clerical person could be taught to do tasks such as backup. The workstation might be set up under the supervision of an expert from the Computer Center or from the contractor's organization, who could provide some training in the use of the X Window System.

In light of these considerations, the staffing proposed for the Center consists of a full-time finite-element analyst and a part-time secretary (with some computer aptitude).

## 7.7 Cost of Operation; Government-Furnished Equipment.

Estimated costs for establishing and maintaining the Finite Element Model Center are given here. It is assumed that space and office furniture for the Center will be provided on-base in a manner similar to the Aerospace Structures Information and Analysis Center (ASIAC). Following are the estimated costs, fully burdened.

Government-furnished equipment includes office space suitable for two people and a workstation, plus office equipment (desks and chairs, file cabinets, bookshelves, workstation desk). A commercial telephone line is assumed; a base phone could also be installed.

## 7.8 Security Procedures

It is not anticipated that any of the finite element models in the model center will be classified; however, some information may be sensitive in nature and precautions will have to be provided for appropriately safeguarding the data. The tape drive specified in the computer hardware section will be helpful in this regard.

As a government contractor located on a military base, Center personnel comply with both the local security regulations and with the provisions of the Industrial Security Manual. As a Visitor Group on a military base, all personnel of the center will be required to attend the security briefings scheduled by the host organization, in addition to complying with the security provisions of the contractor organization.

| On-site startup costs | |
|---|---|
| Computer hardware | |
| Workstation | $15,000 |
| Printer | 3,000 |
| Cartridge Tape Drive | 2,500 |
| Office equipment and startup supplies | 2,000 |
| Total startup cost | 22,500 |
| **Annual on-site costs** | |
| Salary, full-time finite-element analyst | 90,000 |
| Half-time secretary | 21,000 |
| Telephone, Supplies, etc. | 5,000 |
| Total annual cost | 116,000 |
| **Annual off-site costs** | |
| Maintenance, enhancement, and possible distribution of FEM-X | $26,000 |
| Contract administration | 4,000 |
| Total annual off-site cost | 30,000 |

# References

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[2] Johnson, E. H., Venkayya, V. B., Neill, D. H., Herendeen, D. L., and Hoesly, R. R., "Automated Structural Optimization System (ASTROS)," AFWAL-TR-88-3028, December 1988. Volume I – Theoretical Manual, Volume II – User's Manual, Volume III – Applications Manual, Volume IV – Programmer's Manual.

[3] O'Reilly & Associates, *Guides to the X Window System*, 1990.

[4] Venkayya, V. B., "Data for Finite Element Models of Aerospace Structures," Internal Flight Dynamics Laboratory Data Item Description.

[5] Mock, W. D., and Latham, R. A. (Rockwell International, Los Angeles Division) "NASTRAN Model of a Large Flexible Swing-wing Bomber," NASA Contractor Report 170392, September 1982.

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[7] Zienkiewicz, O. C., *The Finite Element Method in Engineering Science*, McGraw-Hill, New York, 1971.

[8] MacNeal-Schwendler Corp., *Handbook for Linear Analysis*, August 1985.

[9] MacNeal-Schwendler Corp., *Handbook for Dynamic Analysis*, June 1983.

[10] MacNeal-Schwendler Corp., *Handbook for Thermal Analysis*, November 1986.

[11] MacNeal-Schwendler Corp., *Handbook for Aeroelastic Analysis*, November 1987.

[12] MacNeal-Schwendler Corp., *Handbook for Numerical Methods*, April 1990.

[13] *Air Force Magazine*, January 1988.

[14] Herendeen, D. L., and Ludwig, M. R., "Interactive Computer Automated Design Database (CADDB) Environment User's Manual," AFWAL-TR-88-3060, August 1988.

# Appendix A: Interview Transcripts

This appendix presents interviews that were conducted with six Air Force organizations and one NASA organization. The following organizations were surveyed: ASD/ENFS (WPAFB), Eglin AFB, 4950th Test Wing (WPAFB), Warner-Robbins ALC, Hill AFB, Sacramento ALC (McClellan AFB), and NASA/Dryden. One transcript is provided for each organization, following a standard format.

## A.1 ASD/ENFS, WPAFB

Interviewer: G. Negaard (in person)

Persons interviewed: Hugh Griffis, Robert Moore

### Organizational mission:

Review contractors' structural analysis including finite element analysis. Perform hardness assessments, look at flutter problems.

### Organizational capability:

**Personnel:** Two people in the vulnerability group, three in the flutter group. Other ASD structures personnel are scattered among the SPO's.

**Expertise:** Novice to intermediate, able to understand contractors' work and perform some FE analysis.

**Equipment:** CDC and VAX, Tektronix terminals; PATRAN, NASTRAN. They have developed the DATANET code which uses FASTGEN, MOVIE.BYU, and TRACELINKS to do animation of large models. They are getting NAVGRAF (a new package which encompasses graphic pre-processing, COSMIC NASTRAN, and graphic post-processing). They are having a ballistics and laser vulnerability capability put into ASTROS.

### Organizational use of finite element models:

They review contractors' analysis, check some of it.

Use NASTRAN and thermal codes. Perform 1-D thermal analysis to check for exceeding elastic limits. Panel analysis for overpressures.

Did T-46 flutter analysis using NASTRAN to get natural frequencies and modes shapes, then FACES for flutter analysis.

**Acquisition methods:**

How are models obtained?

Via S.O.W. where possible, otherwise by "begging, borrowing, or stealing".

How are such models verified and understood?

By contractors only, to any real degree.

How are they archived and retrieved?

Not really archived at all.

Lessons learned in this area?

Need a system to obtain and keep models.

**Existing or potential needs for FE models:**

F-15E model coming. Will be in McDonnell-Douglas format, will have to be converted to NASTRAN.

Have an F-15C/D model in McDonnell-Douglas format, with numerous errors.

Have a need for the dual role fighter model (F-16E?)

HALE (High Altitude Long Endurance) aircraft coming up

**Awareness of FE models developed by contractors:**

GLCM (Ground-Launched Cruise Missile). Launcher, truck, and trailer.

B-52 (on paper ... needs tying in)

KC-135 (on paper ... needs tying in)

**Response to the idea of a model center:**

They favor the idea, suggest that AFWAL draft a letter to each Program Office asking them for a model with necessary documentation.

**How they would like to see a Model Center work:**

They would like someone to take paper listing of models, put them up, verify, and make them available as needed.

There is no real need for quick response. A few days or weeks is quick enough for their needs.

**Estimate of funds or time that might be saved if a Model Center existed:**

Paraphrasing: "When you have to go to the contractor for a model, it's going to take a year or more, so if something has to be done in a timely manner, it doesn't get done. Having a model available would allow analysis of problems that often are not attempted due to time constraints."

As for funds, the F-15C/D model was obtained for $50,000 from the contractor. This procurement was tacked on to a larger contract. The model was actually "free"; it was the documentation that cost $50,000. However, if the contractor were asked to create a model it would cost at least $500,000.

## A.2 Eglin AFB

Interviewer: G. Negaard (telephone)

Persons interviewed: Jim Robinson, Wayne Ingraham

Phone number: AV 88-872-2748/3017

**Organizational Mission:**

Store certification for aircraft and stores.

**Organizational capability:**

**Personnel:** Three people in flutter analysis, three in loads.

**Expertise:** Mostly in flutter. Loads people have two entry level engineers, one more experienced analyst.

**Equipment:** Cyber 176 mainframe, MSC/NASTRAN only.

**Organizational use of finite element models:**

To analyze flutter with stores.

**Acquisition methods:**

How are models obtained?

They have usually gone to contractors for models. They do not do any modelling of their own. They typically use stick models for dynamic analysis.

How are such models verified and understood?

Apply allowable loads. If wing torsion or wing bending exceed allowable limits at any station, they go back to the contractor for additional analysis.

How are they archived and retrieved?

They have no system.

**Existing or potential needs for FE models:**

F-111 (future)

A-10, F-4 flutter models

F-15 A/B/C/D models (now on hand)

Getting F-16 model from GD in a month - primarily wing, fuselage and empennage represented by gross elements. The model will have 100-200 elements for dynamic analysis.

**Awareness of FE models developed by contractors:**

F-15 models

F-16 model

**Response to the idea of a model center:**

No response; not knowledgeable.

**Estimate of funds or time that might be saved if a Model Center existed:**

They had no idea but felt they could benefit.

## A.3 4950th Test Wing

Interviewer: G. Negaard (in person)

Persons interviewed: Lloyd Matson, George Perley

### Organizational Mission:

Design and build modifications to existing aircraft. They are presently converting several old commercial 707's to C-18's.

### Organizational capability:

**Personnel:** Ten people

**Expertise:** Static, dynamic, and flutter analysis. Considerable expertise, ranging from a few years to ten or more.

**Equipment:** Cray, CDC, and VAX, Tektronix terminals; PATRAN, NASTRAN. Access to MSC/NASTRAN via Cybernet. One Evans & Sutherland graphics system. They have three VAXes of their own, and four or five MicroVAXes. They are going out for a CAD/CAM/ CAE system – Sun, Apollo, or Intergraph.

### Organizational use of finite element models:

Usually to check static strength for aircraft modifications such as radomes or equipment racks. They are also working on a project called ECCM/ARTB (Electronic Countermeasures/Advanced Radar Test Bed) which requires cutting holes in the top of a C-141 fuselage to mount radomes.

### Acquisition methods:

*How are models obtained?*

They often build their own models but sometimes go out on contract. Rockwell, for example, just made them a model of a 450-inch fuselage section of a C-141.

*How are such models verified and understood?*

By comparing to existing models or similar data. Also with hand calculations. For example, the Rockwell C-141 fuselage model showed negative margins of safety in several places, and the original Lockheed analysis did not. However, these points are places where the C-141 has had fatigue problems, which helped verify the Rockwell model.

*How are they archived and retrieved?*

Cards, tape, hard-copy printout. No system for permanent storage.

*Lessons learned in this area?*

They need a system to catalog and keep track of models.

**Existing or potential needs for FE models:**

C-18 (Boeing 707) fuselage to aid in fatigue analysis

C-135

C-141

T-39

A-37

A-7D

**Awareness of FE models developed by contractors:**

C-141 done by Rockwell

**Response to the idea of a model center:**

They favor the idea, if the procedure can be quick and painless.

**How they would like to see a Model Center work:**

They would like to be able to pick up the phone, interrogate a database, pull up a pictures of models, then order the components decided upon.

**Estimate of funds or time that might be saved if a Model Center existed:**

They have no idea, because their needs are so special that they generally have to start from scratch and build their own models. (Note: the 4950th was unaware of the C-141 COSMIC NASTRAN model that Warner-Robbins has. We gave them a contact to call there.)

## A.4 Warner-Robbins ALC

Interviewer: G. Negaard (telephone)

Persons interviewed: Robert Wade, Lt Randy Jansen

Phone number: AV 88-468-2525

**Organizational Mission:**

Depot maintenance for C-141, C-130, F-15, and H-53 aircraft.

**Organizational capability:**

**Personnel:** Seven engineers and a manager.

**Expertise:** Mostly static analysis.

**Equipment:** Dedicated VAX-11/785, Tektronix terminals, MSC/NASTRAN, Supertab.

**Organizational use of finite element models:**

Usually to check static strength for aircraft modifications or repairs. They use large models to get internal loads which are then used for stress analysis on small parts. They also look at fatigue problems.

**Acquisition methods:**

How are models obtained?

They usually build the component models they need.

How are such models verified and understood?

"As best one can." Hand calculations, for example.

How are they archived and retrieved?

On tapes and on the VAX.

**Existing or potential needs for FE models:**

They have C-130 and C-141 COSMIC NASTRAN models.

They are getting an F-15E model in MacAir format; need to convert it to NASTRAN.

**Awareness of FE models developed by contractors:**

F-15 Models

**Response to the idea of a model center:**

Not much need for large models except to get loads for components. For small models, they go straight to the drawings, work off the drawings as needed, or take measurements from parts.

**How they would like to see a Model Center work:**

Moderate interest, not sure how they would benefit.

**Estimate of funds or time that might be saved if a Model Center existed:**

No idea.

## A.5 Hill AFB (MMSR, MMAR, MMMDR, MMIR)

Interviewer: M. James (in person)

Persons interviewed: Bret Hamblin, Tim Sorensen, Bruce Burgon

Phone number: (801) 777-7072

**Organizational Mission:**

Perform fatigue analysis on various parts of the F-4 and F-16 aircraft. Hill AFB is the central depository for all aircraft landing gear technology throughout the Air Force.

**Organizational capability:**

**Personnel:** MMSR: 8 civilian, 3 military; MMAR: 10 civilian, 2 military; MMMDR: 4 civilian, 1 military

**Expertise:** Novices in the use of both NASTRAN and CRACKS 85. The longest experience of any individual is two years. Contractors supply the necessary expertise, as a rule.

**Equipment:** Two clustered VAX-11/785's, Tektronix 4109 and 4129 terminals.

**Organizational use of finite element models:**

They develop finite element models for fatigue analysis, primarily, but also do some design and repair work. The models are usually created in-house with some assistance from contractors (BYU and General Dynamics), or by outright purchase (F-16 from General Dynamics).

**Acquisition methods:**

How are models obtained?

Purchased from manufacturer or created in-house.

How are such models verified and understood?

No verification yet!

How are they archived and retrieved?

Models are stored on VAX disks and backed up on magnetic tape.

Lessons learned in this area?

Disk crashes have resulted in a loss of time and effort. No crash has been bad enough to endanger the models totally but a few days' worth of work was lost at times!

**Existing or potential needs for FE models:**

F-16 and F-4 aircraft for fatigue analysis. Hill AFB is the depository for all aircraft landing gear, including models.

**Awareness of FE models developed by contractors:**

MacAir has an F-4 model.

General Dynamics has a complete model of the F-16. (They are rumored to have an F-16E model as well.)

**Response to the idea of a model center:**

They are very receptive. They do express a concern that the repository may get tangled in the typical government red tape, however. It must be run by contractors and it must be "user-friendly."

**How they would like to see a Model Center work:**

A pictorial display of the model using an MSC/NASTRAN database of superelements of the entire aircraft. All models must be completely verified to be worth while!

**Estimate of funds or time that might be saved if a Model Center existed:**

A lot of money may be saved by ensuring that all models being used throughout the Air Force are keyed to the current revision of the aircraft. The other armed services should be consulted regarding models they have so as to reduce redundant efforts in model building and verification.

## A.6 Sacramento ALC

Interviewer: W. Gibson (in person)

Persons interviewed: Mr. Sal Alestra

Phone number: (916) 643-5300

**Organizational Mission:**

F-111 and A-10 aircraft. Mostly stress analysis with concentration on durability and damage tolerance assessments.

**Organizational capability:**

**Personnel:** Five engineers and a manager.

**Expertise:** Mostly static analysis.

**Equipment:** VAX-11/780. MSC/NASTRAN, GIFTS.

**Organizational use of finite element models:**

They use F-111 and A-10 models primarily for analysis of damage and corrosion. However, due to manpower problems, they are largely in a reactive mode.

**Acquisition methods:**

How are models obtained?

They "found" three A-10 models.

Are paying for two F-111 models; will procure six more.

Model deliver will be a future contractual requirement.

How are such models verified and understood?

GD provides them with GIFTS steering files. They use GIFTS interactive viewing commands to gain understanding of models.

How are they archived and retrieved?

On the VAX, with backup tapes.

**Existing or potential needs for FE models:**

They are getting new F-111 models from GD.

**Awareness of FE models developed by contractors:**

Strong awareness of F-111 and A-10 models developed by GD

**Response to the idea of a model center:**

They do not favor the idea. They say they are the only Air Force organization doing analysis on the F-111 aircraft.[1] Therefore they should be in charge of all F-111 models. They see requirements for them to send models to the Center as an additional burden that would detract from their main mission.

**How they would like to see a Model Center work:**

Use of COSMIC NASTRAN instead of MSC/NASTRAN would be a "kiss of death" for the Center.

## A.7 NASA/Dryden

Interviewer: M. James (telephone)

Persons interviewed: Alan Carter, Larry Shuster

Phone Number: (805) 258-3311 ext 3919

[1]However, Warner-Robbins personnel expressed an interest in an F-111 model. See section A.4.

**Organizational Mission:**

Maintain finite element models of aircraft at NASA/Dryden and update those models when changes occur to either the structure and the stores.

**Organizational Capability:**

Expertise: Several experts in the field of structural analysis using codes such as COSMIC and MSC/NASTRAN.

Equipment: VAX's and an ELXI multiple processor system.

**Organizational use of finite element models:**

On-site development of finite element models to be used for stress, dynamic and loads analysis. Most models are made in-house but a few have been procured from contractors.

**Acquisition Method:**

How are models obtained?

Made in-house usually.

How are such models verified and understood?

In-house models are verified as they are made. The modeler must trust the drawings and other items used to make models. The understanding of the models is very great because the author of the model is at NASA/Dryden.

How are they archived and retrieved?

The models are constructed and placed in storage on the computer system. Paper writeups are available to identify models.

Lessons learned in this area?

The models must be backed up on computer tape to ensure that they are secure from loss. No problems otherwise.

**Existing or potential needs for FE models:**

NASA/Dryden has models of the B1-A and the X29 forward swept-wing aircraft. They see no need for other models as yet but as aircraft are added to the inventory at Dryden they will either acquire or build models of those aircraft.

**Awareness of FE models developed by contractors:**

NASA/Dryden has little contact with outside contractors in the modeling area except for COSMIC NASTRAN colloquia. Rockwell provided the B1-A model at Dryden and should have a B1-B model.

**Response to the idea of a model center:**

Larry Shuster seemed pleased to hear that a finite element model center is being talked about. He believes that the center would be a major step forward but the problems associated with the center could be great. The major problem will be cooperation from all the organizations involved.

**How would they like to see a model center work:**

Not sure that they would use the center except to possibly contribute models to the center!

**Estimate of funds or time that might be saved if a Model Center existed:**

Would not use center for retrieval of models but may participate after acceptance throughout the FEM community.

# Appendix B: Mil Standard Requirements for Finite Element Models

1. SCOPE

1.1. Scope. This standard establishes guidelines and requirements for the development and delivery of a finite element model of an aircraft structure.

1.2. Purpose. The purpose of this standard is to establish uniform practices for finite element model documentation, to ensure the inclusion of essential information, and to establish a practice of maintaining and updating the models.

1.3. Application. This standard may be applied at the discretion of the program manager to any system or major equipment program or project. When this standard is applied on a contract, the prime contractor may, at his option, or as specified by the Government, impose tailored requirements of this standard on subcontractors.

1.4. Implementation. This standard is intended to be used in preparing requirements for inclusion in solicitation documents and contract work statements during the development of an airframe for a particular weapon or support system. Waivers or deviations shall be specified in the contract specifications and shall have specific Air Force approval prior to commitment.

1.5. Tailoring. The Air Force will make the decision regarding application of this standard and may modify or tailor task statements to suit system needs. Tailoring takes the form of deletion, alteration or addition to the task statements. In tailoring the tasks, the depth of detail and level of effort required, and the intermediate and output engineering data expected must be defined. Subsequent tailoring may be done by the contractor and the Government during contract negotiations. The agreement reached shall be reflected in the resultant contract.

2. REFERENCED DOCUMENTS.

Military Specifications:

| | |
|---|---|
| MIL-A-87221 | General Specification for Aircraft Structures |

Military Standards:

| | |
|---|---|
| MIL-STD-483 | Configuration Management Practices for Systems, Equipment, Maintenance and Computer Software |
| MIL-STD-1521 | Technical Review and Audit for Systems, Equipment and Computer Software |
| MIL-STD-1587 | Materials and Processes Requirements for Air Force Weapon Systems |

Handbooks:

| | |
|---|---|
| MIL-HDBK-5 | Metallic Materials and Elements for Aerospace Vehicle Structures |
| MIL-HDBK-17 | Plastics for Aerospace Vehicles |
| MIL-HDBK-23 | Structural Sandwich Composites |

Air Force Systems Command Handbooks:

| | |
|---|---|
| DH-1-0 | General |
| DH-1-1 | General Index and References |
| DH-1-2 | General Design Factors |
| DH-2-0 | Aeronautical Systems |
| DH-2-1 | Airframe |
| DH-2-7 | System Survivability |

## 3. DEFINITIONS.

3.1. Airframe. The complete aircraft structure, including the fuselage, wing, empennage, landing gear, control systems and surfaces, engine mounts, structural operating mechanisms, and other components as specified in the contract specifications.

3.2. Structural Operating Mechanisms. Those operating, articulating, and control mechanisms which transmit structural forces during actuation and movement of structural surfaces and elements.

3.3. Finite Element Model. A structural model, wherein the distributed physical properties of a structure are represented by a finite number of idealized substructures or elements that are interconnected at a finite number of points.

## 4. GENERAL REQUIREMENTS.

The contractor shall create and submit a finite element model of the airframe capable of producing detailed analyses of the major components of the structure to demonstrate load paths and to perform stress calculations of primary and secondary components. The finite element model should provide the capability to analyze the airframe under both symmetric and anti-symmetric external loads and to generate internal design loads. It is anticipated that this finite element model will be the same model used by the contractor to perform the analytical determination of the structure's ability to support critical loads and to meet the specified strength requirements as well as for dynamic analyses. In this event, the stress analysis reports and other analysis reports will form part of the supporting documentation for the model. If the contractor has not used the model for this purpose, then sufficient documentation must be accomplished and included to serve to validate the model. For each model, a complete set of documentation will be required.

5. DETAILED MODEL REQUIREMENTS.

5.1. The contractor shall deliver to the Air Force all finite element models that were used in verifying the structural integrity of the aircraft, in its final configuration as delivered to the Air Force.

5.2. Contractors shall not be required to use any particular computer software in their finite element analysis work. Models shall be delivered in the format appropriate to the particular software that was used. If some code other than COSMIC NASTRAN is used by the contractor , a translated version of each model shall also be provided. The translated version will conform to the input requirements of COSMIC NASTRAN (specifically, the version of COSMIC NASTRAN current at the time of delivery).

6. DETAILED DOCUMENTATION REQUIREMENTS

6.1. For each model delivered, a complete set of documentation is required.

6.2. For each model, the name and configuration of the aircraft will be identified. A key diagram showing the location of the component being modeled in relation to the rest of the model will be included. The construction, arrangement, material, location (by coordinates) of load-carrying members, and other pertinent data shall be included. Adequate sketches shall be provided so as to minimize the necessity of referring to detailed drawings of the structure. Drawings to which the model corresponds will be identified. The drawings referenced in the model shall be provided if they are not otherwise available to the government.

6.3. Adequate identification of all aspects of the finite element model shall be included with the finite element model. Documentation shall indicate, individually or by groups, what part of the structure is represented by the nodes, elements, element properties, and materials. Coordinate systems shall be defined in terms of the primary aircraft coordinate system. Applied loads, support conditions, and rigid elements shall be explained. The output information shall include, but not be limited to, deflections, stresses, element forces, and restraint forces. Proprietary information should be so indicated.

6.4. The documentation will include a brief discussion of the physical phenomenon being modeled. The fineness or coarseness of the model will be discussed. The use of any special techniques such as symmetry (type and location) will be documented. A list of element types and the rationale for the use of each will be provided. Smearing approximations will be explained wherever they have been used. All material properties shall be explained and referred to appropriate Mil Standards, and reasons given for any deviations. Each set of boundary conditions or constraints will be explained.

6.5. The contractor shall explain how the model was validated. This discussion includes diagnostic messages from the finite element code, comparison to known or expected results, and reference to test data where it is available.

6.6. Documentation will include the following:

6.6.1. Static models. An explanation will be provided for each set of loads, including the category (distributed forces, concentrated forces, gravity loads, prescribed displacements, thermal forces, imposed deformations (strains), centrifugal loads, or special situations). Where load sets are to be combined, the combined sets must be documented. Where nonlinear analysis is used, information specific to the nonlinear aspects of the analysis must be presented, such as the nature of the nonlinearity (finite displacements, nonlinear elasticity, plasticity), and the reason why non-linear behavior was expected. Control parameters that were used in the iterative solution and evidence of convergence will be documented.

6.6.2. Dynamic models. Dynamic models include undamped normal modes, damped modes (complex eigenvalues), transient analysis, steady-state frequency response analysis, and random analysis. Documentation will include the frequency range over which the model is valid and the reduction process, if any, that was used. This may include subspace iteration, generalized dynamic reduction, Guyan reduction, or Ritz vectors. In the case of Guyan reduction, an explanation of the analysis-set degrees of freedom shall be provided. In the case of Ritz vectors, an explanation of the static loads used to start the process shall be provided. Nonstructural masses will be documented and explained. For dynamic response analysis, documentation shall include the source of the loading and the way in which its frequency distribution or time history were derived, the the kind of damping used (viscous or structural) and how values were arrived at. For either transient or steady-state analysis, where modal superposition is used, the frequency at which modes were truncated shall be justified, and the use of any special enhancement techniques such as residual flexibility explained. For transient analyses, the time step value that was chosen shall be justified. For steady-state frequency response analysis, an explanation of the frequency increment shall be provided.

6.6.3. Heat Transfer Analysis. This category includes linear steady state, nonlinear steady state, linear transient, and non-linear transient analysis. Documentation shall include derivation of the material properties with references to heat sources and sinks, boundary conditions, analysis type, and transfer of temperatures to static stress analysis models, if applicable.

6.6.4. Aeroelastic Models. Where aeroelastic analyses are performed, the aerodynamic theory employed will be described. The lifting surfaces for which the aerodynamics being modeled shall be enumerated and described physically. Aerodynamic parameters such as Mach number and altitude shall be listed. The kinds of force and displacement transformations between the structural grid and the aerodynamic grid shall be explained. Provisions for rigid-body modes will be explained. Where aeroservoelastic analysis is employed or anticipated, data must be presented in a state space formulation.

6.6.5. Special Analysis Types. A full explanation of the coupling method used for any special analysis types such as combined structure-control system analysis or fluid-structure interaction shall be provided.



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