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THE STRUCTURAL FINITE ELEMENT MODEL OF THE C-5A

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SUMMARY

A substructured NASTRAN model of the C-5A was analyzed for several different load conditions. The size of the model as well as the number of load cases used presented special problems in computer file and space management. This also resulted in revisions to the in-house NASTRAN code. Despite the problems encountered the analyses were completed with excellent results.

INTRODUCTION

The C-5A is a very large transport aircraft. The primary structure of the aircraft is composed of frames connected by stringers and covered by skin panels in the fuselage and of ribs and spars covered by integrally stiffened skin panels in the wing. The C-5A contains a cargo floor and a second floor to carry troops. It has a hinged visor at the forward end which opens upward and a large cargo door at the aft end. Hinged ramps and removeable ramp extensions on either end permit drive-through loading of this unique aircraft.

During the late 1960's the C-5A was modeled using a Lockheed-developed finite element analysis program called FAMAS. The analysis used a force method. The FAMAS program limited the size of a model more severely than NASTRAN does. Thus the original model was substructured into relatively small modules. The forward fuselage was idealized as a full model (left and right sides) as was the aft fuselage. The center fuselage and wing were represented as a half model since that portion of the aircraft is essentially symmetric about the center line. Since FAMAS uses a left handed coordinate system, only the left side was actually modelled. The center fuselage substructures and the wing were also coupled. However, a complete coupling of forward, aft and center sections was never carried out. To reduce the size of individual substructures, the FAMAS model contained much lumping, both for frames and stringers.

In order to provide an improved quality of the predicted stresses and stress distributions for damage tolerance and durability analyses, to provide compatibility with detail structural models of the C-5A, and to ensure a modern, state-of-the-art analysis tool, the FAMAS C-5A model was converted to a NASTRAN model. The basic substructure configurations of the FAMAS model were retained with the exception of a 360-inch-long section of the forward fuselage. This section had previously been represented by repeated couplings of a 40-inch barrel section and was converted into two completely new substructures. Further changes include geometry alterations where structural modifications had been incorporated, a switch to a Lockheed-developed semi-monocoque element to represent skin-stringer combinations, and flexibility changes where errors were detected or material or structural changes had occurred.

NASTRAN Model Geometry

The NASTRAN C-5A model has two levels of substructures. The model is divided into 27 basic substructures which are grouped into 3 sections. Section 1, the forward fuselage, contains substructures one through twelve; Section 2, the aft fuselage, contains substructures 18 through 27; and the center fuselage, Section 3, contains substructures 13 through 17 including substructure 14 which represents the entire outer wing. The reason for grouping the substructures into sections will be explained later.

The model is composed of rod, beam, shear, triangular membrane, and rigid elements all of which are standard NASTRAN elements, and the previously mentioned Lockheed-developed semi-monocoque element for skin-stringer combination representation. Rods and beams are used primarily to represent fuselage frames, longitudinal beams, wing spars and ribs, and intercostals. Shear elements represent beam webs, bulkhead webs, spar webs, and in a few instances, skin panels. Rigid elements represent extremely stiff structural members usually found in fittings. Triangular membrane elements occur both as isotropic and anisotropic elements - the anisotropic elements represent stringers and overlay isotropic elements representing the skin panels in the same location. Finally, the semi monocoque elements represent skin-stringer combinations and specify stringer size, spacing and orientation and percentage of skin effectivity.

The C-5A NASTRAN model retains one of the FAMAS model idiosyncracies - the pseudoframe. Normally, if a substructure boundary falls at a frame location, in a substructured model, the frame would appear in both substructures with half of the area represented for that frame in each substructure. In this instance, the full frame is contained in one substructure while only the skin-stringer connecting grid points appear in the adjoining substructure, creating a phantom - or pseudoframe. This method creates some problems in specifying the degrees of freedom which are coupled between substructures since, for example, the substructure containing the frame could react bending forces while the substructure containing the pseudoframe could not. It was deemed simpler to keep the FAMAS configuration, however, than to create a new frame for the pseudoframe substructure and change the appropriate properties and connectivities in the two affected substructures.

A further legacy from the FAMAS model are the half models in the center fuselage section. Since the FAMAS model was never completely coupled through from nose to tail, the existence of half models only in the center fuselage presented no problems in the FAMAS analysis and served to reduce the model size significantly. In the NASTRAN analysis the half models result in an extra step in the Phase 2 analysis. The half models must be equivalenced and mirror imaged, then coupled to each other before the coupled center fuselage section can be combined with the full model aft and forward sections.

The complete C-5A model is reacted externally in six degrees of freedom on three points in substructure 13 in the center fuselage. Since all the points lie on coupling boundaries, and since substructure 13 is a half model, the reaction points are actually located in 6 equivalenced and coupled substructures. In checking the external reaction forces against internal loads this distribution caused a problem in retrieving all the data since so many numbers were involved.

APPLIED LOADS

The C-5A NASTRAN model was analyzed with three different systems of applied loads. During the first iteration a system of loads referred to as SRS loads was applied. SRS loads are single reference station unit loads which are applied at 6 locations on the airplane. Six components of a load are applied at each location. An additional load case consists of a unit internal pressure applied to all elements within the pressure boundary of the airplane. SRS loads were, until recently, used to determine stress/load ratios for use in fracture analysis. The disadvantage to SRS loads is that answers can be considered accurate for a given load only at a point relatively far removed from the point of load application.

During the second iteration of the analysis, two design loads which had previously been applied to the FAMAS model and had also been used in actual specimen testing were applied to the C-5A NASTRAN model. The results were compared to previous answers to assess the NASTRAN model accuracy and locate possible problem areas or errors.

During the third and most important iteration of the analysis a system of loads called MRS (multiple reference station) loads were applied to the C-5A NASTRAN model. This system of loads was recently developed at Lockheed and involves both a new loading approach and a new computer program for calculating load distributions. Previous repeated loads analyses utilized a very limited definition of external (SRS) loads. Stress spectra for use in fracture analyses were generated using, at most, six load components near the analysis area of interest. This approach is adequate for simple loading conditions and in situations where all external loads are remote from the area of interest. However, in a complicated structure such as the center fuselage of an aircraft where complex load sources (aerodynamic, landing gear, cargo, etc.) affect the structure this approach may be inaccurate. Furthermore, historical repeated loads analyses were limited to six load components by load phasing constraints. This problem has been solved in the MRS system by allowing the combination of many external loads in a repeated loads system and resulting in more accurate internal loads. No new technology was required in the FEM analysis. However a much larger number of unit load conditions applied to the FEM model are required to generate stress/load ratios for all external load sources. A total of 733 separate load cases are applied during the MRS NASTRAN analysis of the C-5A model. This unusual number of load cases (at least at Lockheed) caused problems with the NASTRAN code - the limits on the number of load cases that could be applied had to be extended. Furthermore, checking the output for that many load cases for possible errors became a monumental task for the 27 substructures involved. To check external reaction forces against internal loads a special DMAP (direct matrix abstraction program) was written to sum the reaction loads contained in the various substructures for all load cases. In order to streamline the recovery of stress/load ratios by future users the output was also written to tape and then stored in a separate Relational Information Management (RIM) database for user access.

DATA MANAGEMENT

A model with 27 substructures, each of which contains from 150 to 1400 grid points, requires quite a bit of data management. Automated substructuring analysis requires access to geometry and property data, load data, SOF (Substructure Operating File) files, output files and restart tapes. In order to simplify the bookkeeping, a separate file for geometry and property data was assigned to each substructure. Since several engineers were involved in the analysis, another file was established to contain the runstreams for all analysis stages for all substructures. This was done so that any one engineer could easily locate the appropriate information for making any NASTRAN run. A separate loads file was also established for each substructure.

SOF files presented a challenge. Because the SOF files needed to be manipulated separately we tried to keep them relatively small. This was not a problem for the first two iterations. With the initiation of the MRS iteration the problem of establishing a size which could accommodate the 733 load cases surfaced. Largely by trial and error we eventually ended up with SOF files which required 317,000 kilobytes (kb) of mass storage.

Because we wanted to take advantage of graphic display capabilities for both geometry and output such as deflections and stresses, the output for the first two iterations was stored in another set of files. Because of space limitations this was not possible for the MRS iteration.

Along with some intermediate files required for the Phase SOLVE step the total amount of computer mass storage for all the required files for the MRS iteration came to 421,000 kb! In addition, 27 restart tapes and 36 output tapes were required for the MRS analysis.

ANALYSIS FLOW

The analysis of the model followed the normal NASTRAN automated substructuring analysis with a few twists. The first step consisted of the checkout of each individual substructure. The checkout procedure included both computer program checks which search the geometry and property data for format errors as well as graphic display checks. Visual display of geometry allows checking connectivity data and locating missing or duplicate elements. Visual display of properties allows checking of property data accuracy, property trends and continuities between substructures. Possibly the most time consuming check concerns the A-Sets for the boundaries, particularly for substructures which connect to four or five other substructures. Once each substructure has been checked, the Phase 1 runs can begin.

As mentioned earlier, the model was not only substructured but divided into three primary sections. One of the reasons for this further subdivision was the allocation of SOF files. Since we wished to keep the size of the SOF files small and since NASTRAN allows a maximum of 10 physical SOF files, the SOF files used in Phase 1 were assigned to the primary sections. One set of SOF files was used for substructures in the forward fuselage, one set for substructures in the aft fuselage, and one set for substructures in the center fuselage. Because the load cases applied differed from substructure to substructure, the PG (static applied loads) matrix for each substructure in Phase 1 was written out onto a PG loads file. Beyond these changes, the Phase 1 runs were normal for an automated substructuring static analysis.

The Phase 2 runs, again, followed normal Phase 2 procedure for the substructures in Sections 1 and 2. In Section 3, the individual substructures required equivalencing and mirror imaging first, then coupling with the mirror images before they could be coupled to other substructures. Once all substructures in each Section were combined and reduced an intermediate step was taken before the SOLVE could be accomplished. All matrices for the last pseudo structure in each Section were read into an intermediate SOF file. Using this intermediate file the SOLVE was then accomplished along with the BRECOVER for the three last pseudo structures. The matrices for these pseudo structures were then copied back into their respective Section SOF files.

Phase 3 could then be accomplished. Since a different set of load cases was applied to each substructure originally, the PG matrix written out during Phase 1 was read back in during Phase 3. This was our solution to the NASTRAN logic problem which prohibits load case number incompatibility between Phases 1 and 3. Although we had a total number of applied load cases of 733, not every case was applied to every substructure during Phase 1. However, during the SOLVE operation in Phase 2, all the load cases were combined with LOAD C cards. During Phase 3, the load case number compatibility once again had to be restored and thus the Phase 1 PG matrix was read in externally. A Restart RECOVER was then performed for each individual substructure. In the case of the first two iterations the OCQ1, OES1 and OUGV1 matrices were output on a file for later graphic display. During the MRS iteration, the EST and OES1 matrices were written out to tape for storage in the stress/load ratio database.

SPECIAL PROBLEMS

The first two analysis iterations presented few special problems except for the intermediate Phase 2 steps described above. The major problems arose with the MRS analysis and its 733 load cases. As mentioned before, changes had to be made in the code to accommodate this many load cases. A small problem, but an annoying one, was the huge volume of the output. Although only an average of 50 load cases was actually recovered for each substructure, the volume of paper that this generated for the 27 substructures was enormous. Keeping all the output separated and properly bound and labeled became a chore especially since several errors detected after completed runs necessitated reruns. Our work areas soon became labyrinths made up of stacks of computer output.

A new problem surfaced when we tried to limit output size by including sets for certain substructures. We discovered a limit on the number of elements which could be included in a set and this limit had to be eliminated in the code.

When the MRS iteration began we tried to determine how much space would be required for the SOF files and found no accurate method of determing SOF file sizes. It became a matter of trial and error to find the required size and also brought to light the fact that once a size for a SOF file has been used, the physical file cannot be reduced in size without creating havoc.

Our most aggravating problem, however, was the space requirement that this model had for the MRS iteration. Our NASTRAN analyses are run using a UNIVAC 1100 main frame computer. Our FEM group is allocated approximately 1,000,000 kb mass storage.

As mentioned above, the model required 412,000 kb of storage space. Moreover, several substructures required 120,000 kb HICORE allocation to run which severely crimped the space available to other users of the system. The amount of mass storage used also created space binds for other models concurrently in the works. This space bind caused a very close monitoring of file sizes all during the analysis.

CONCLUDING REMARKS

The NASTRAN automated substructuring analysis of the C-5A was successfully completed for three different loading systems. Correlation of stresses between the original FAMAS model and the converted NASTRAN model was very good where direct comparison was possible. The NASTRAN analysis resulted in better correlation with actual test data and provided better and more complete results. For example, stresses in triangular elements are now available and stringer stresses are output directly - no complicated delumping process is required. Grid point loads for use as load input for detail models are now available and the NASTRAN model now reflects all major structural changes incorporated since the FAMAS analysis was completed.

The analysis process in its third iteration uncovered several problems in the NASTRAN code of which anyone attempting a substructured model of this scale should be aware. For a model requiring a large number of load cases, the code must be altered to accommodate the load cases. If output for a large model is to be limited with a set definition card, the set number limitation in the NASTRAN code must first be removed.

A further consideration in constructing very large models is the availability of mass storage space. Space requirements dictate that a very large model must be analyzed using a large main frame computer. In addition, a good data management system is essential for a successful analysis of a large substructured model.

The system of grouping the substructures of a large model into larger sections is very efficient since it allows several engineers to work on a single model independently of each other while totally maintaining the integrity of the model. Finally, mechanizing the modeling process, from geometry generation to geometry and property plots to force summation to deflection, load and stress plots, is an invaluable asset to completing an analysis of a large substructured model with many applied load cases in an efficient and timely manner.

TABLE 1 - C-5A MODEL STATISTICS

Substruct.	Grid Points	Elements	DOF	A-set G.P.	A-set DOF
01	352	1160	1070	63	173
02	627	2033	2065	145	389
03	597	2093	1909	115	304
04	152	658	595	8	18
05	557	2100	1360	21	44
06	647	2205	1747	41	97
07	468	1330	1408	99	263
08	362	957	1042	117	337
09	292	750	794	136	399
10	296	838	721	135	398
11	738	1808	1573	128	397
12	578	1369	1296	112	342
13*	399	1229	982	114	364
14*	1380	4216	4184	32	96
15*	497	1382	1423	160	499
16*	562	1590	1504	147	467
17*	143	368	337	65	217
18	232	574	689	107	336
19	416	1085	1178	101	290
20	479	1339	1283	97	292
21	326	975	759	107	273
22	247	610	779	74	210
23	301	797	929	63	175
24	688	1790	2362	52	148
25	600	1897	1581	26	78
26	401	1271	1286	41	59
27	243	784	773	18	20
	12,580 (15,561)**	37,208 (45,993)**	35,626 (44,056)**		

* Half Model Only
**Full Model

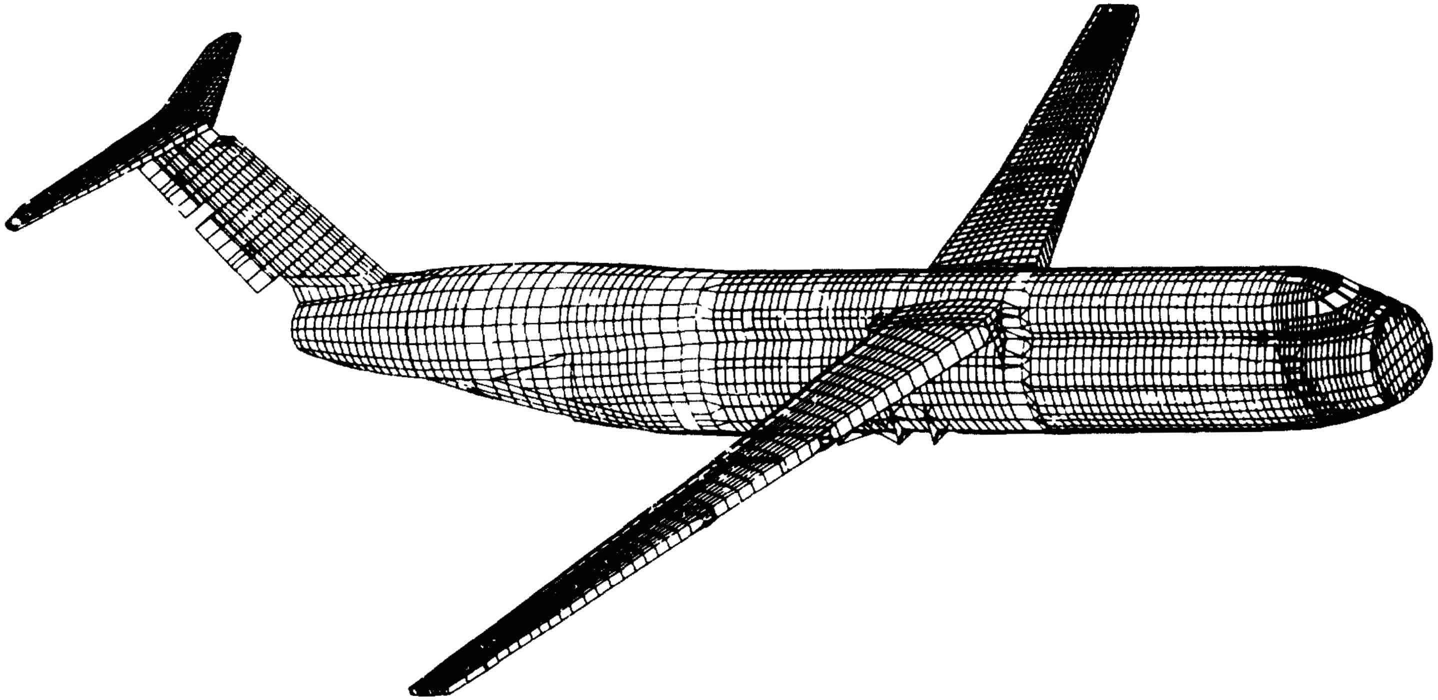

FIGURE 1: COMPOSITE PLOT OF SUBSTRUCTURED C-5A MODEL

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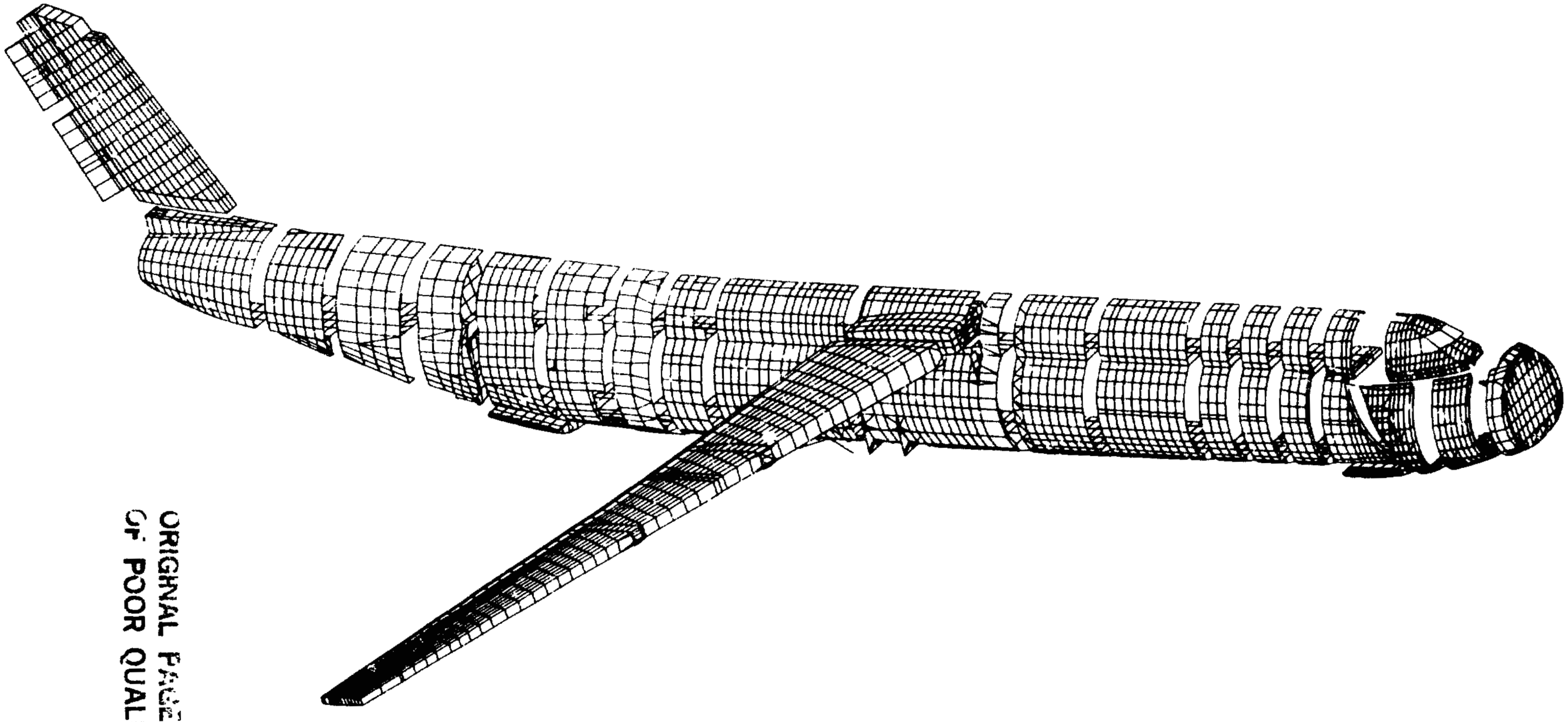

FIGURE 2: EXPLODED VIEW OF SUBSTRUCTURED C-5A MODEL, RIGHT SIDE

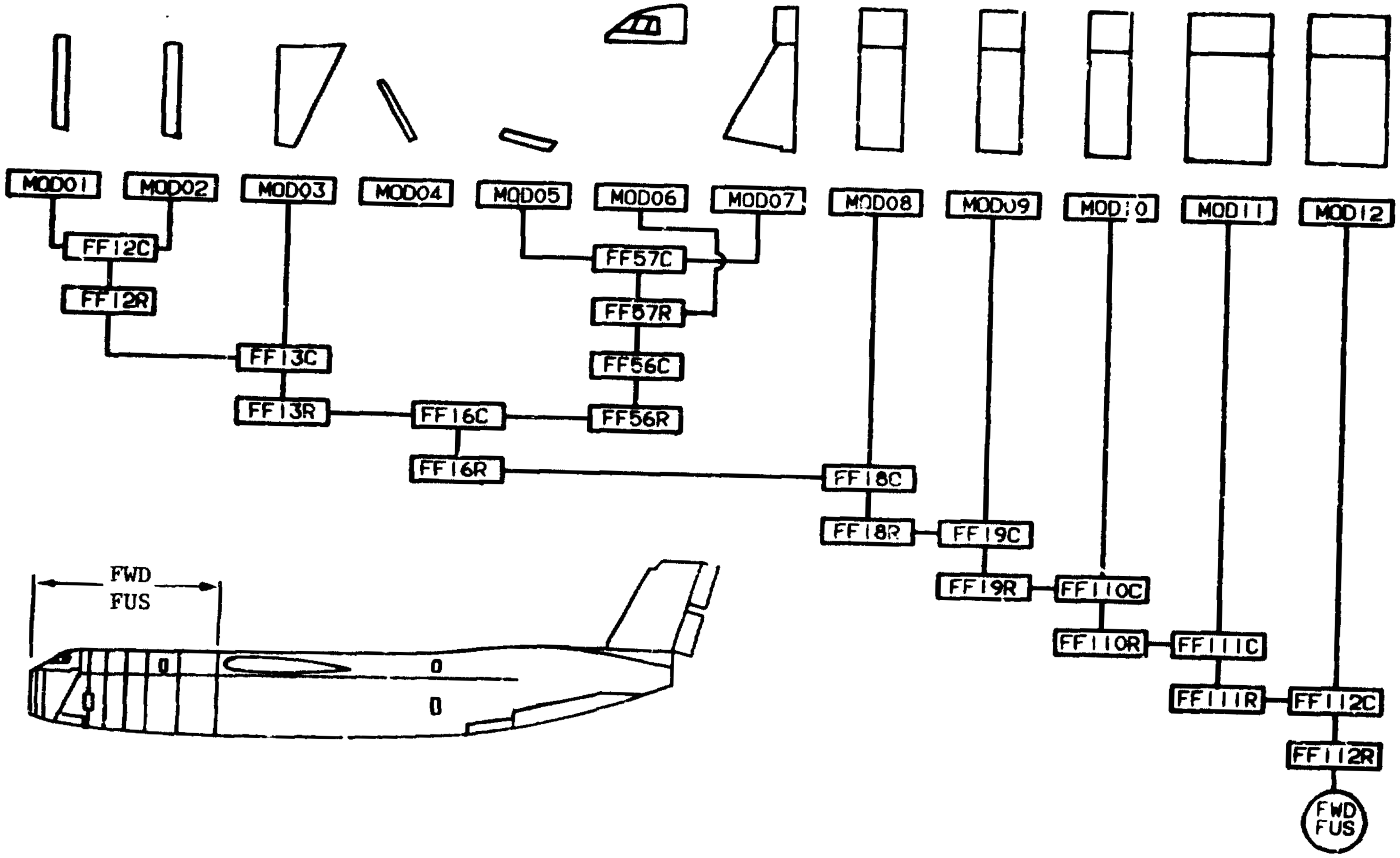

FIGURE 3: FORWARD FUSELAGE COUPLING TREE

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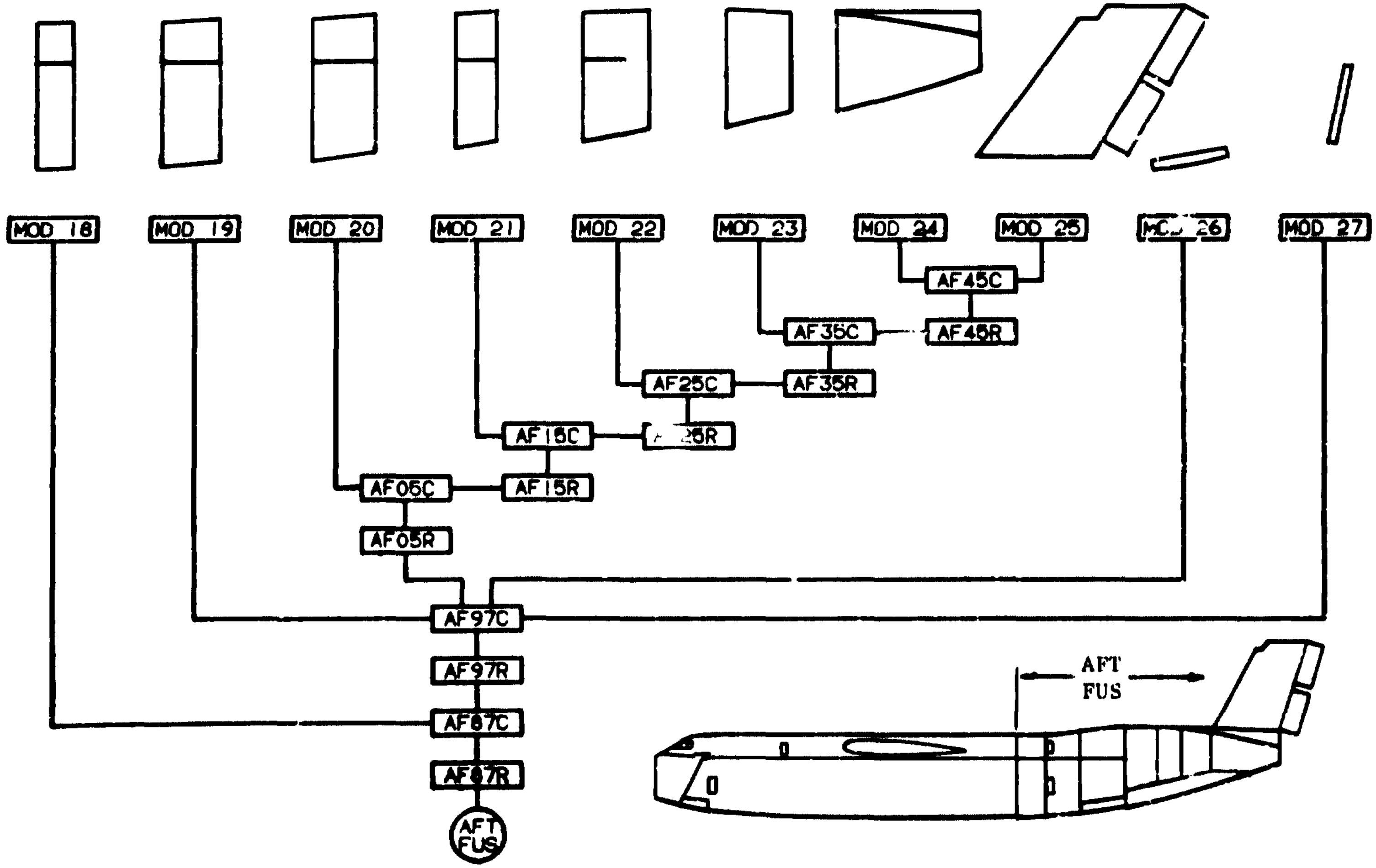

FIGURE 4: AFT FUSELAGE COUPLING TREE

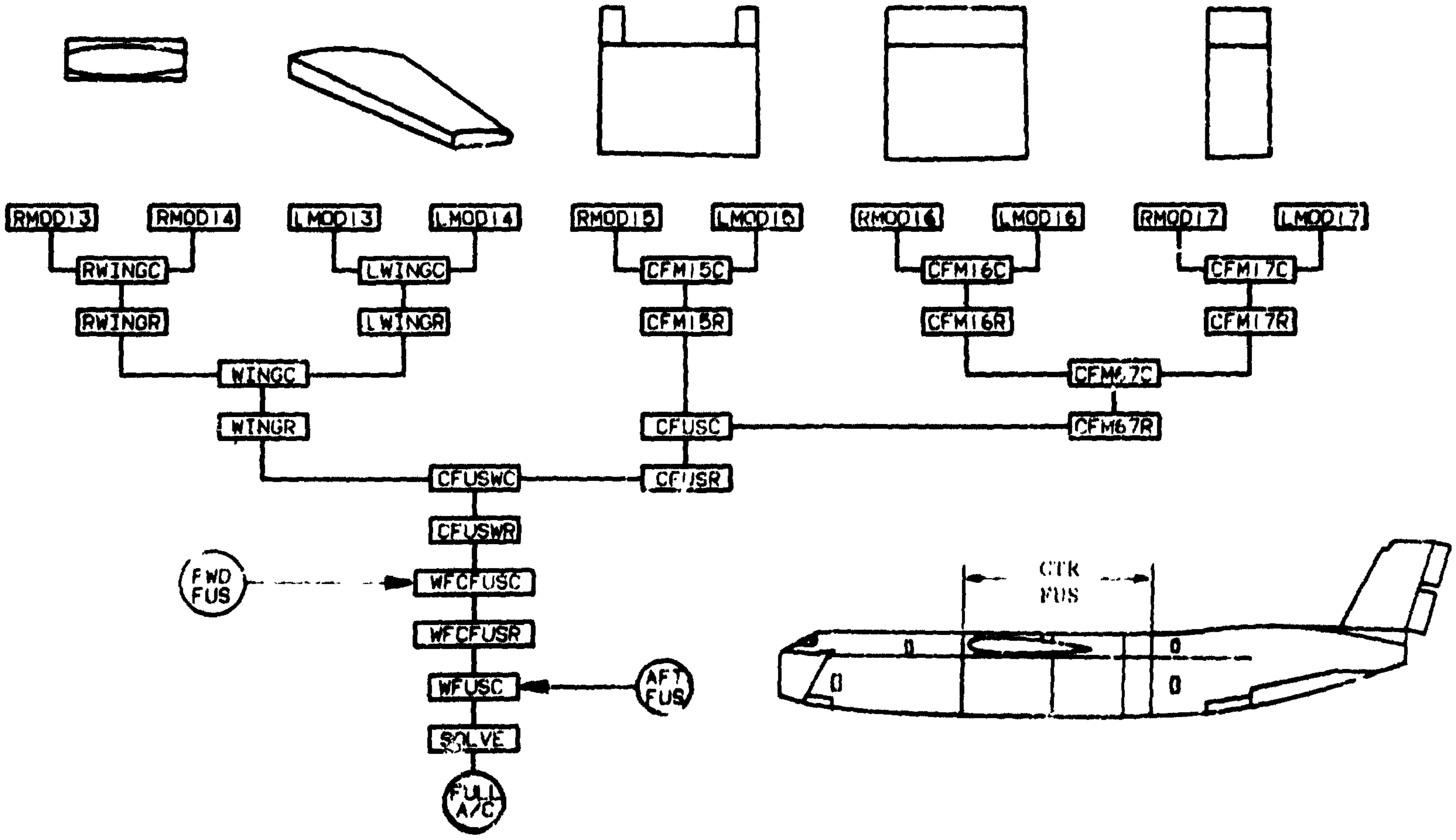

FIGURE 5: CENTER FUSELAGE/AIRCRAFT COUPLING TREE

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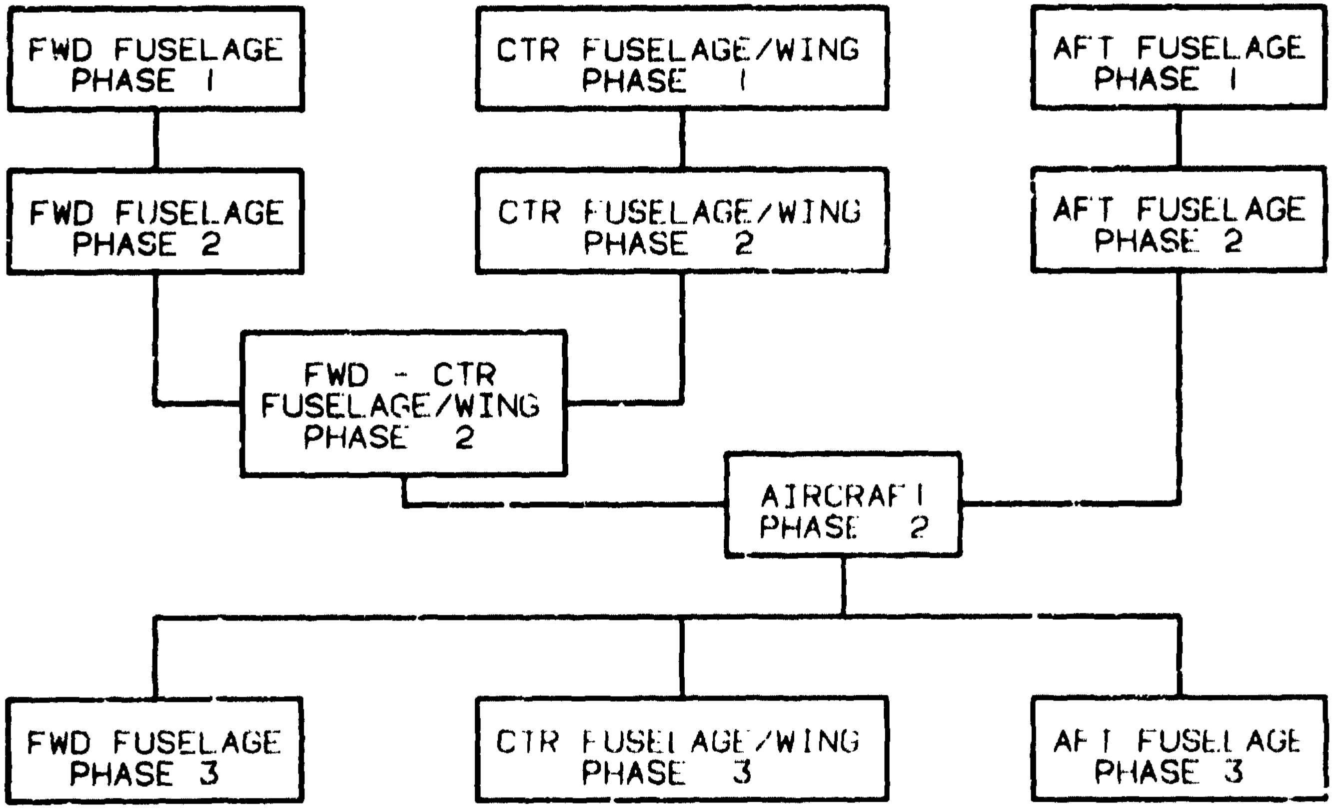

FIGURE 6: ANALYSIS FLOW FOR SUBSTRUCTURED C-5A MODEL