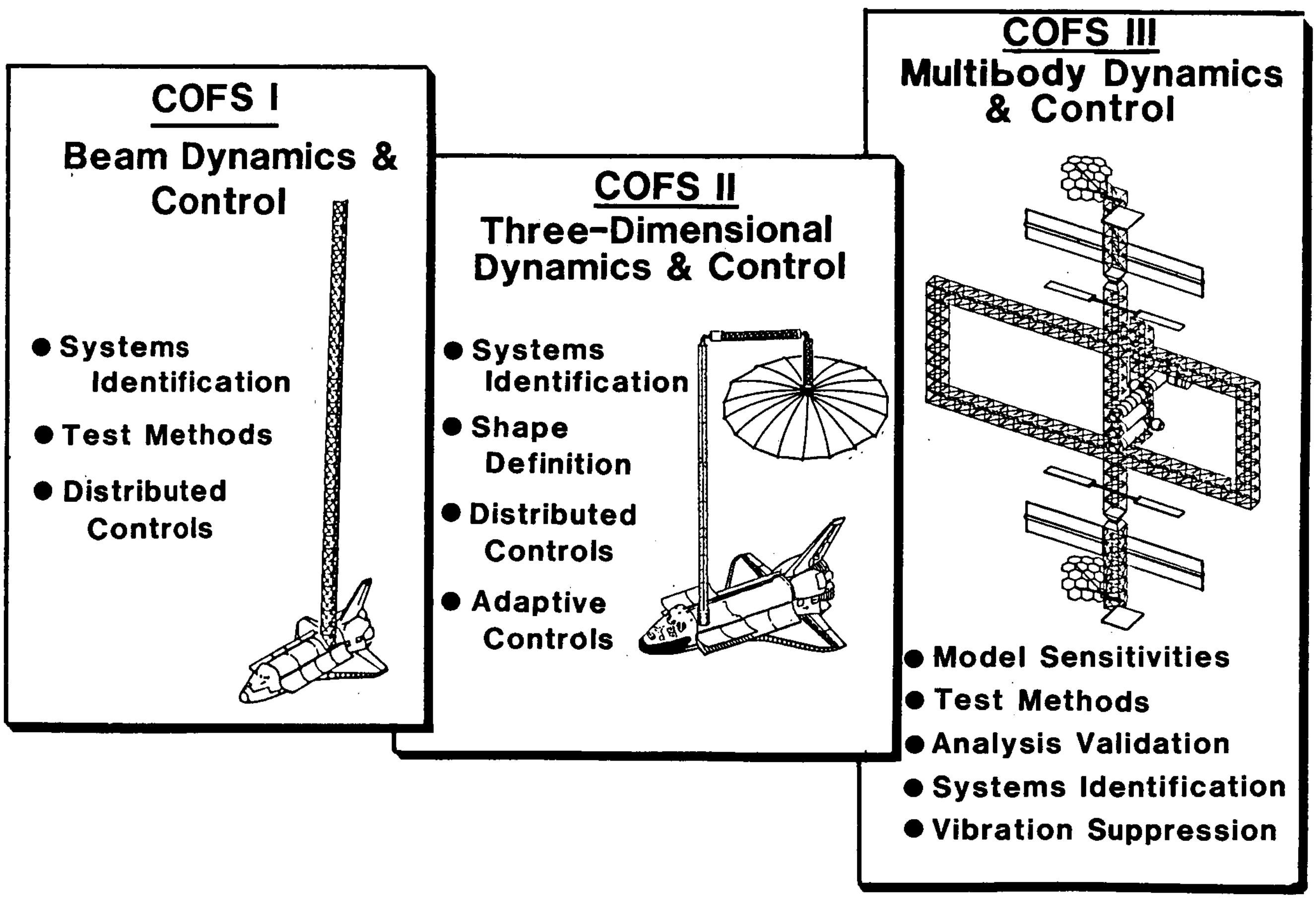
COFS III
MULTIBODY DYNAMICS & CONTROL TECHNOLOGY

Robert Letchworth
Paul E. McGowan
NASA Langley Research Center
Hampton, Virginia

First NASA/DOD CSI Technology Conference
Norfolk, Virignia
November 18-21, 1986

INTRODUCTION

COFS III is the third project within the COFS program. It deals with developing multibody dynamics and control technology for large space structures. It differs from COFS I & II in two respects. First, it addresses a more complex class of structure, and second it is basically a scale model ground test and analysis program while COFS I & II feature shuttle flight experiments. The specific technology thrusts within COFS III are model sensitivities, test methods, analysis validation, systems identification, and vibration suppression.



OBJECTIVE AND TECHNICAL APPROACH

The objective of COFS III is to develop a verified capability for predicting the structural dynamics behavior of multibodied, joint dominated articualted, flexible space structures, which are too large and heavy to be dynamically tested, when fully mated, in earth's one-g environment.

The technical approach for achieving this capability is to demonstrate that a combination of dynamically scaled model tests and theoretical analyses can provide a credible method for predicting the dynamics behavior of the full-scale structure and also provide a means for evaluating vibration control techniques.

OBJECTIVE:

- **VERIFIED CAPABILITY FOR STRUCTURAL DYNAMICS PREDICTION AND CONTROL OF**

LARGE MULTIBODIED, JOINT DOMINATED ARTICULATED, FLEXIBLE SPACE STRUCTURES

TECHNICAL APPROACH:

- **DYNAMICALLY SCALED MODEL TESTS**

PLUS

- **THEORETICAL DYNAMICS ANALYSIS**

→

PREDICTION OF FULL-SCALE DYNAMICS & VIBRATION CONTROL

PROJECT FOCUS

COFS III is a multibody dynamics and control technology project which focuses on the Space Station structure. The Space Station was selected for several reasons. First, it is the first very large operational structure planned to be built in space. Second, it is typical of the structures of interest. Third, the Space Station will provide the first opportunity to obtain direct full-scale measurements for correlation with model tests and analysis, thereby providing for the validation of the COFS III objectives. Fourth, studying the dynamics of the Space Station is the first step in understanding and developing the technology for the growth Space Station, which is one of Langley's roles in the overall Space Station effort.

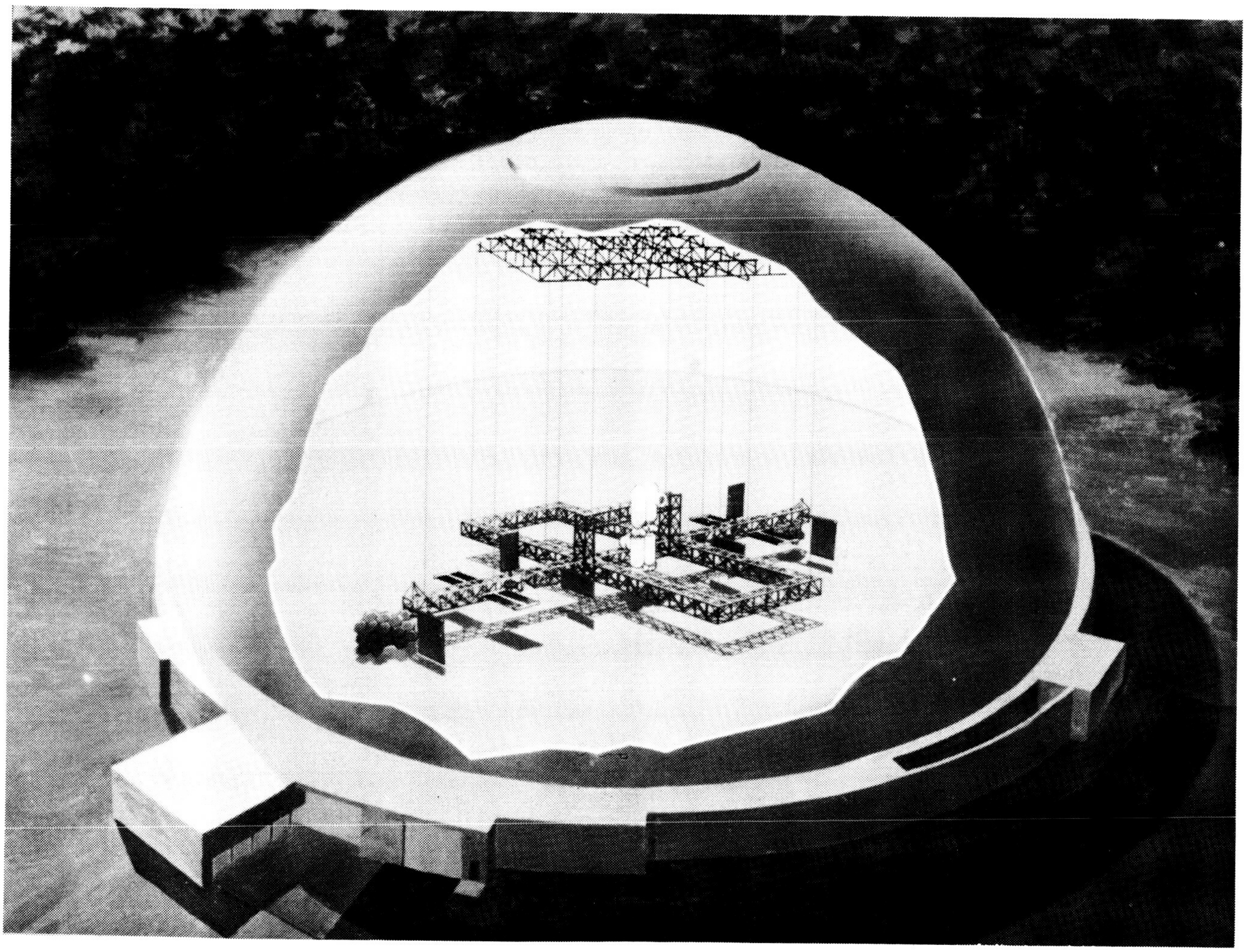
SPACE STATION

- **REAL STRUCTURE**
- **TYPICAL OF STRUCTURES OF INTEREST**
- **FIRST OPPORTUNITY TO OBTAIN FULL-SCALE DATA FOR CORRELATION**
  - **GROUND TEST OF KEY SUBASSEMBLIES**
  - **ON-ORBIT FLIGHT DATA**
- **MEANS FOR DEVELOPING TECHNOLOGY FOR GROWTH STATION**

ORIGINAL PAGE IS OF POOR QUALITY

PROPOSED LARGE SPACECRAFT LABORATORY (LSL)

This picture is an artist's conception of the COFS III model suspended in the proposed Large Spacecraft Laboratory (LSL) which will be constructed at Langley in 1988. It has been designed to provide the volume, dimensions, and suspension capabilities necessary to permit controlled ground tests of a variety of large space structures and models including the COFS III model. The dimensions of LSL are 310 ft in diameter at the base and 150 ft high.



PROJECT ELEMENTS

The COFS III project elements include both contractual and in-house activities. The first contractual effort is the just-completed model definition study by Lockheed Missile and Space Company, the results of which will be added to this presentation when they are available. These results will also be used by the project office to help define the requirements for the development, fabrication, and assembly of a modular model of the Space Station. The term modular means that the model will be designed with interchangeable parts so that it can be assembled and tested in configurations identical to any of the potential Space Station assembly sequences. The contract will also require a system for suspending and testing the model within the LSL; a set of modular analytical models that will be capable of being combined to depict the structure at each stage of the Space Station assembly sequence; limited test support for model tests which will be conducted at Langley; and an option for designing and building the components required to convert the basic model into a growth configuration of Space Station. The request for proposal (RFP) for this competitive procurement is planned to be released in December with a contract award in August, 1987.

The remaining two contractual efforts, one for an active vibration suppression system and one for an advanced suspension system, will be pursued in parallel but a year or two behind the main contract.

The in-house activities include joint and member scaling and characterization studies and experiments, the actual testing and analysis of the model, and the data correlation among the test results, analysis, and full-scale on-orbit data.

CONTRACTURAL

- **MODEL DEFINITION STUDY (MAY 86)**
- **MODULAR MODEL OF SPACE STATION: DESIGN, BUILD, ASSEMBLY**
  - **BASIC SUSPENSION SYSTEM**
  - **MODULAR ANALYTICAL MODELS**
  - **LIMITED TEST SUPPORT**
  - **OPTION FOR DESIGN & BUILD OF EVOLUTIONARY SPACE STATION**

  } **RFP: DEC 86 CONTRACT: AUG 87**
- **VIBRATION SUPPRESSION**
- **ADVANCED SUSPENSION**

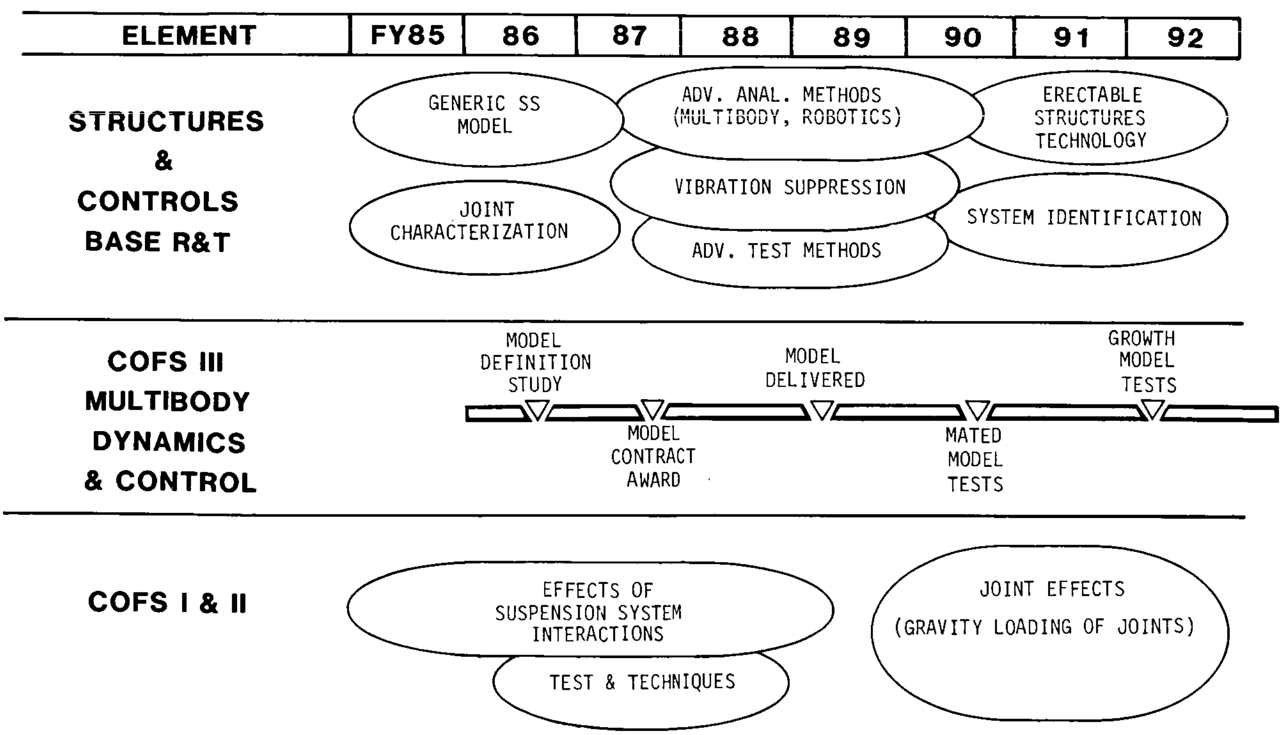
IN-HOUSE

- **JOINT & MEMBER SCALING/CHARACTERIZATION**
- **MODEL TESTING & ANALYSIS**
- **DATA CORRELATION**

RELATIONSHIP TO OTHER OAST ACTIVITIES

The schedule for the COFS III project shows the contract award in August 1987, the model delivery in January 1989, and the fully mated model tests beginning in May 1990 when LSL becomes operational. Component and subassembly testing will precede the fully mated model tests.

Superimposed above the schedule are those Research and Technology base activities that support COFS III, while the relevant COFS I & II activities are listed at the bottom.



KEY TASKS

The key technical tasks required to complete the COFS III project are listed on this chart. First we must understand the sensitivities of the various model parameters in order to identify the best approaches for scaling the full-scale structure. Then, hopefully, we will be able to design and construct dynamically scaled models of both the IOC and growth configurations of the Space Station. The next step will be to conduct a comprehensive ground test and analysis program using the scaled model, the companion analytical models, and any active vibration suppression techniques developed for the model.

The final step is to validate the predictions, which were made via the analyses and model ground tests, with any full-scale subassembly ground tests that are conducted during Space Station development and with Space Station flight data when it is available.

Note that the instrumentation of the Space Station and the reduction of flight data will be provided by another activity. As a minimum, the instrumentation for the required on-orbit structural verfication of the Space Station should provide sufficient data to validate the primary COFS III objective.

- **EVALUATE MODELING SENSITIVITIES AND APPROACHES**
- **DESIGN AND CONSTRUCT A MODULAR SCALE MODEL OF SPACE STATION**
  - **ISS**
  - **GROWTH STATION**
- **CONDUCT A COMPREHENSIVE GROUND TEST AND ANALYSIS PROGRAM**
  - **ANALYSIS TOOLS**
  - **GROUND TEST METHODS**
  - **CONTROL METHODS**
- *__VALIDATE ANALYSIS VIA CORRELATIONS WITH GROUND TEST DATA AND SPACE STATION FLIGHT DATA__

  *** SPACE STATION FLIGHT INSTRUMENTATION AND FLIGHT DATA REDUCTION TO BE PERFORMED UNDER A SEPARATE ACTIVITY**

TECHNICAL APPROACHES AND CHALLENGES

The two major challenges of this project are to (1) build as near a dynamics replica model of the full-scale structure as possible and (2) properly test the model. This chart lists four items that have a significant impact on these challenges. Each will be discussed in more detail.

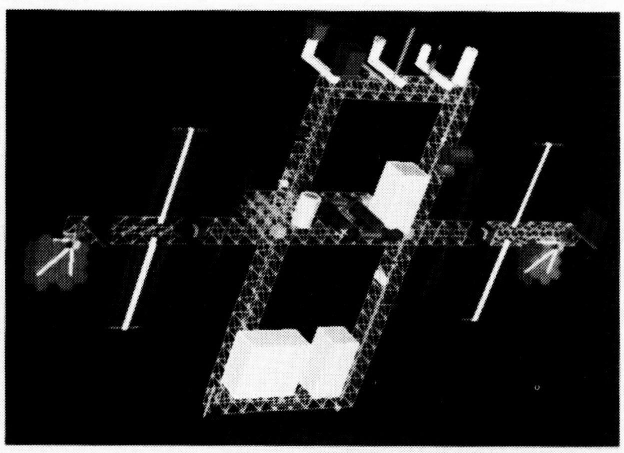
- **MODEL DESCRIPTION**
- **SCALING CONSIDERATIONS**
- **ANALYSIS**
- **HARDWARE/GROUND TESTS**

ORIGINAL PAGE IS
OF POOR QUALITY

DESIRED SCALE MODEL DESIGN FEATURES

This chart shows representative schematics of both the IOC and growth Space Station configurations and provides a summary description of the model using the IOC configuration shown as a baseline. The actual initial Space Station configuration is subject to change, however. In fact, as of this writing it is undergoing an extensive review. The exact configuration to be used for the COFS III model will be the one that will be identified at the Space Station System Design Requirements Review which is currently scheduled for December 1986. That configuration should be the baseline for the current configuration review.

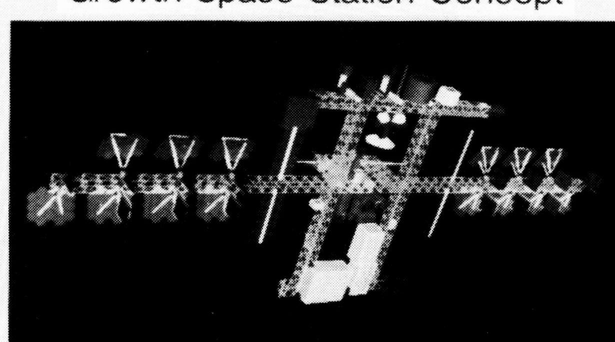
IOC Space Station Concept



- Dynamically scaled model of 5m erectable dual-keel hybrid space station
- Modular construction for buildup stages
- Interchangeable elements
- Aluminum joints
- GR/EP structural members
- Articulating joints (manual)
- Payloads attach kinematically same as full scale

GROWTH

Growth Space Station Concept



RATIONALE FOR USING DYNAMICALLY SCALED MODELS

The rationale for using dynamically scaled models to help predict the behavior of very large space structures is shown here. First, many of these structures are too large and heavy to be tested full scale. Second, the use of a model provides for a significant improvement in the analytical capability for the reasons shown. Third, in many instances the modeling of local flexibilities is overlooked when substructure synthesis methods are applied. This leads to errors or the failure to identify significant structural modes. Fourth, the model can uncover potential problems that can influence the design. Finally, the investigation of anticipated flight maneuvers and flight anomolies such as the degradation in performance from damaged, loose, or missing truss members can be accomplished.

- **MATED FULL-SCALE GROUND TESTS LIMITED BY GRAVITY & SIZE**
- **SIGNIFICANT IMPROVEMENTS IN ANALYSIS CAPABILITY POSSIBLE THROUGH:**
  - **HANDS-ON EXPERIENCE WITH REALISTIC HARDWARE**
  - **ACQUISITION OF MATED VEHICLE DATA PRIOR TO FLIGHT**
- **MODELING OF LOCAL FLEXIBILITIES OVERLOOKED IN SUBSTRUCTURES**
- **UNCOVER POTENTIAL PROBLEMS WHICH INFLUENCE DESIGN**
- **INVESTIGATION OF ANTICIPATED FLIGHT MANEUVERS AND FLIGHT ANOMALIES**

SCALE MODEL DEFINITION STUDY

A scale model definition study was initiated in May 1986 with Lockheed Missile and Space Company to help identify the scaling requirements for the COFS III model. The study was just completed in November 1986. Six key topics were addressed. First, an appropriate dual-keel hybrid Space Station configuration was selected as the baseline for the study. Second, the issue of replication versus simulation was investigated for each assembly phase, the IOC Space Station, the proposed SAVE flight experiment, and the growth Space Station. Third, the manufacturability of scaled joints and tubes was analyzed at a variety of scale factors. Fourth, the effects of a candidate model suspension system were investigated. Fifth, the impact of facility constraints was evaluated. And finally, the implications of expanding the model into a growth configuration were investigated. The results of these activities will be provided as soon as they are available.

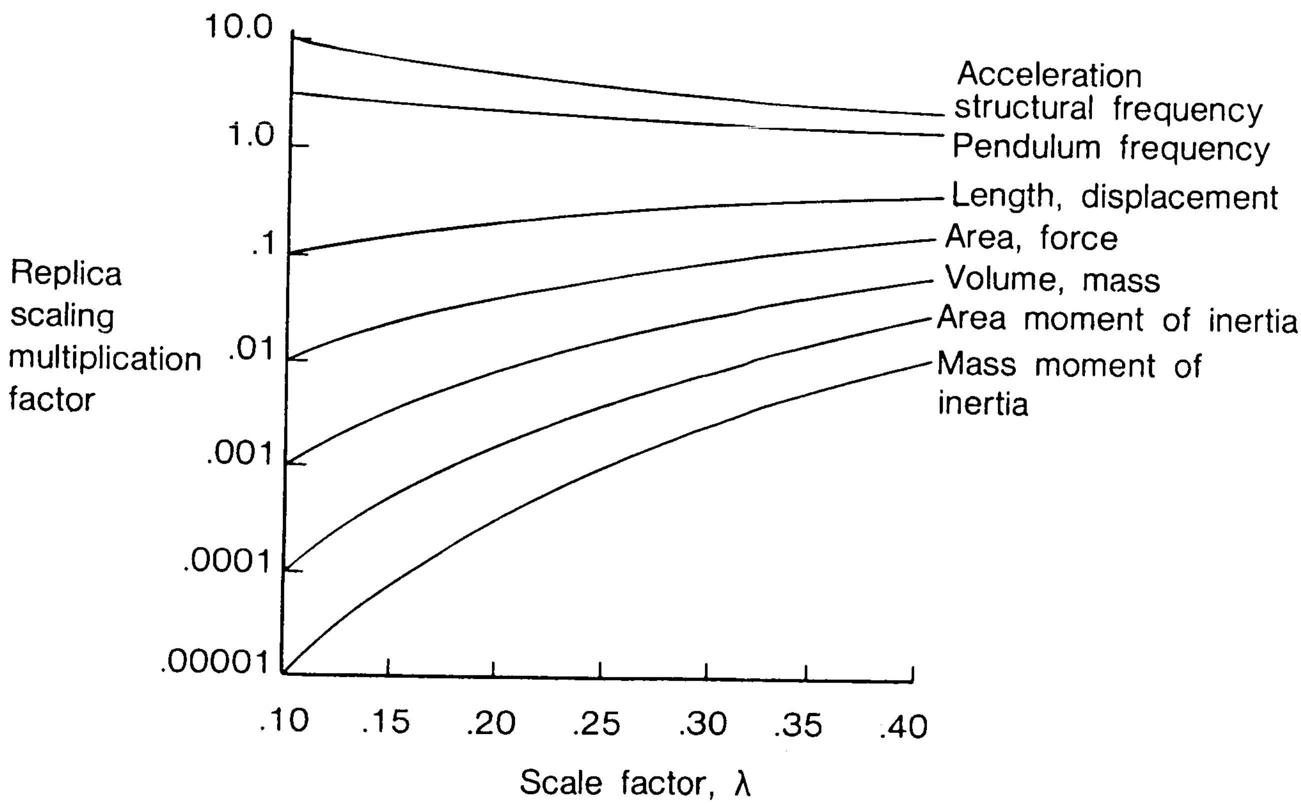
- **STUDY TASK INITIATED MAY 86 WITH LOCKHEED MSC**

  TASK: ESTABLISH OPTIMUM MODEL SCALE FACTOR CONSIDERING THE FOLLOWING:

  - **DUAL-KEEL HYBRID SPACE STATION CONFIGURATION**
  - **REPLICATION VERSUS SIMULATION FOR:**
    ASSEMBLY PHASE
    IOC
    SAVE FLIGHT EXPERIMENT
    GROWTH
  - **COMPONENT MANUFACTURABILITY**
    - **JOINTS**
    - **TUBES**
  - **MODEL SUSPENSION EFFECTS**
  - **FACILITY**
    - **LIMITATIONS**
    - **AVAILABILITY**
  - **EVOLUTIONARY CONFIGURATION**

VARIATION OF REPLICA SCALING

The selection of the model scale factor is a trade-off since all properties scale differently. This chart shows some of these differences. The curves represent well known theoretically derived replica scaling laws. It is our initial belief that for the basic truss structure, replica scaling should be pursued to the maximum extent in order to eliminate as much uncertainty as possible. For replica scaling, accelerations and structural frequencies vary with the inverse of the scale factor, thus they increase with decreasing scale factor. On the other hand, displacements scale directly with the scale factor. Some quantities even vary over several orders of magnitude, thus small changes in scale factor can significantly alter these quantities.



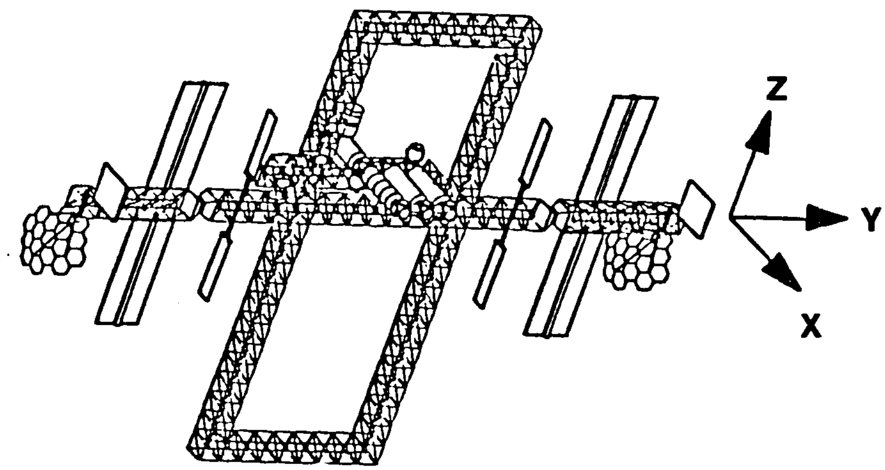
APPROXIMATE SCALE MODEL

Since the Space Station will be a large structure, sub-scale models of it will be large also. This chart shows the dimensions and weights of the dual-keel IOC configuration for scale factors from 1 to 1/4. Even a 1/4-scale model will be 155 ft x 90 ft x 29 ft which is about the size of a 727 aircraft.

APPROXIMATE SCALE MODEL SIZE & WEIGHT VS. SCALE FACTOR

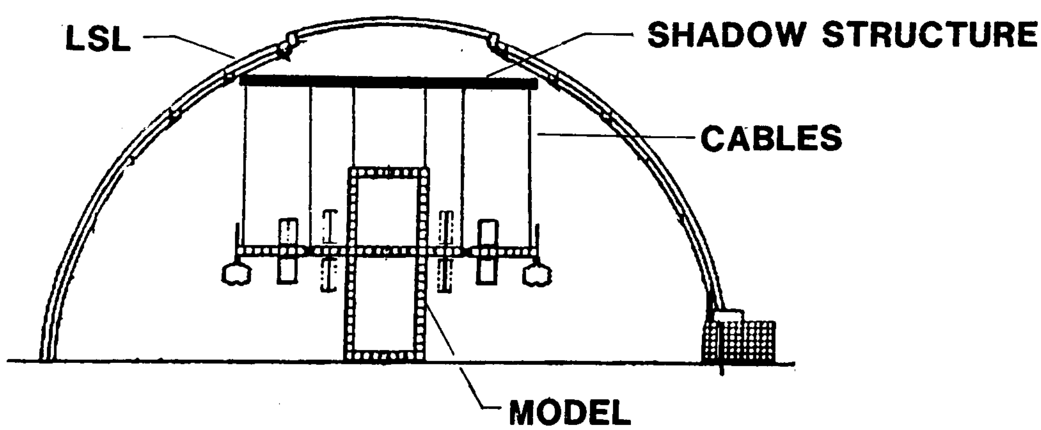
Dimensions (ft.)

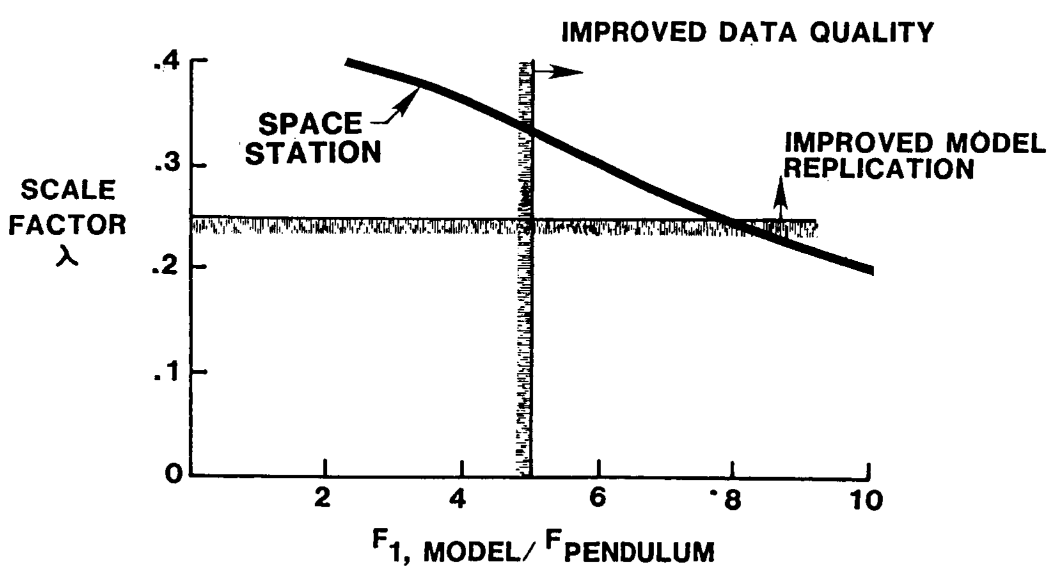
SCALE FACTOR	X	Y	Z	WEIGHT (KIPS)
1	115	621	361	547
1/2	57.5	310.5	180.5	68.4
1/3	38.3	207	120.3	20.3
1/4	28.8	155.3	90.3	8.5



EFFECT OF SCALE FACTOR ON MODEL FREQUENCY

The size of the model test facility can also place constraints on the selection of the model scale factor. For example the LSL, which will be 310 ft in diameter at the base and 150 ft high at the center, must provide sufficient test volume and dimensions for not just the scale model but for the model and suspension system combination. In addition the suspension system should have cable lengths such that the ratio of the first model structural frequency over the suspension system pendulum frequency is a factor of 5 or greater. This minimum frequency ratio of 5 should insure adequate data quality thereby allowing the suspension system interactions to be more easily identified and removed from the test results. This boundary is shown by the vertical line on the lower figure. A scale factor of .25 is believed to be the minimum for replica scaling such that the components can be manufactured within the tolerances required while providing for their interchangeability. This boundary is also shown on the figure. Thus the upper right quadrant represents the solution space for the model, not considering test facility constraints. The diagonal line represents the constraints imposed by the LSL facility. Thus a 1/3-scale model is the largest COFS III scale model that could be tested in LSL and not violate the above constraints.





ANALYTICAL CHALLENGES

In the area of analysis, there are many challenges. Some are listed on this chart.

As was previously mentioned, the model contractor will provide modular analytical models which can be configured to represent both the model and full-scale station assembilies at each stage of the selected build-up process in space. The degree of model fidelity required for each stage will be different, with more emphasis on local effects being required in the early build-up stages while such detail may not be required for those stages approaching the fully mated configuration. How the joints will be characterized analytically is another challenge, as is the means for analytically accounting for nonlinear effects. Boundary conditions, earth conditions such as gravity effects and aerodynamic forces, and suspension system interactions created by a multiplicity of suspension cables pose unique analytical challenges. One of the main challenges will be the extrapolation of sub-scale results to credible full-scale predictions.

Some preliminary analyses and a few tests have been conducted to give some insight into these issues. These are presented next.

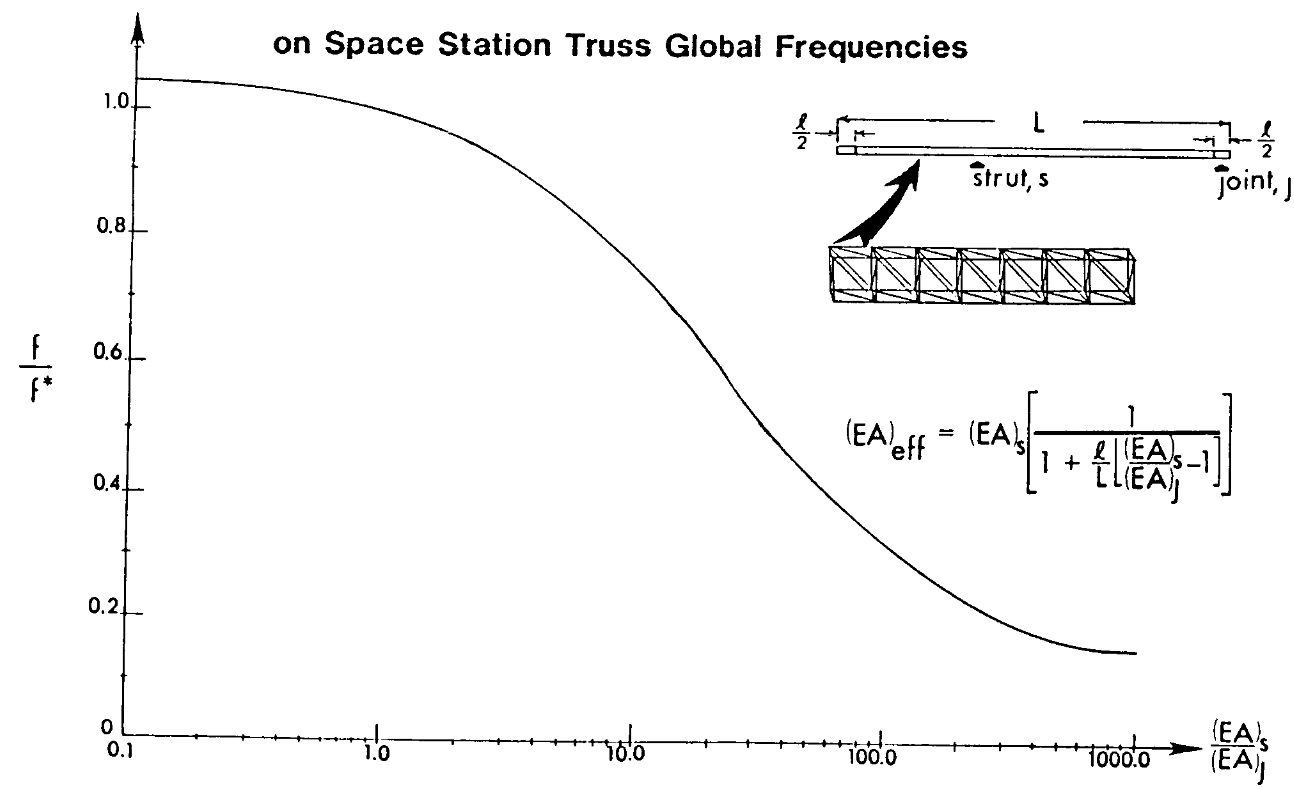
- **VARYING LEVELS OF ANALYTICAL MODEL FIDELITY REQUIRED FOR BUILD-UP STAGES**
- **JOINT CHARACTERIZATION**
- **NONLINEAR EFFECTS**
- **MODELING OF BOUNDARY CONDITIONS AND "EARTH CONDITIONS"**
- **SUSPENSION SYSTEM INTERACTIONS**
- **EXTRAPOLATION OF SUB-SCALE RESULTS TO FULL SCALE**

EFFECT OF JOINT AXIAL STIFFNESS

This chart shows analytically the effect of joint axial stiffness on the Space Station truss global frequencies. Specifically the variation in the truss frequency with the stiffness ratio is depicted. This stiffness ratio is the ratio of the axial stiffness of the strut to the axial stiffness of the joint. Note that for either small or large values of the stiffness ratio, the truss frequency is somewhat insensitive to small changes in this ratio; however, for intermediate values, small changes in the stiffness ratio can lead to large changes in the truss frequency. This implies the importance of accurately characterizing the joint stiffness. Typically for truss structures, the goal is to design the joint to have a stiffness ratio of approximately 2 or less so that the effective strut stiffness, including the joint, is as high as possible.

Effect of Joint Axial Stiffness

on Space Station Truss Global Frequencies

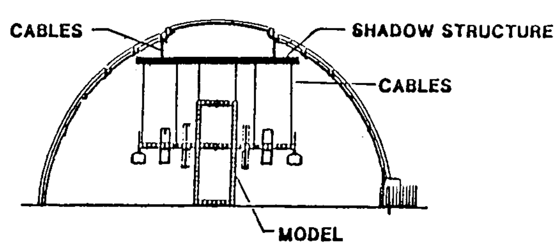


$f^* \equiv f$ obtained with $(EA)_s = (EA)_J$

SUSPENSION SYSTEM CONSIDERATIONS

The suspension system will add an additional measure of complexity to the process of designing, testing, and analyzing the COFS III model. Some considerations for the suspension system are shown here. Since we plan to replicate the basic Space Station structure, the model will not be designed to sustain the unsupported 1-G loads of the payloads and modules. An implied requirement for the suspension system is that it should allow the model to be tested without masking the model dynamics characteristics, e.g., minimizing constraints such that coupled mode shapes can be detected over a limited operating range. Because of the large number of concentrated masses and joints, a large number of suspension cables will probably be required to support the model. Also, as previously discussed, the facility size and model scale factor determine the closeness of pendulum and model structural frequencies. Finally, a concept such as the shadow structure, depicted at the bottom of the figure, provides testing versatility, isolation from the structure of the facility, and a simple method for attaching and detaching cables.

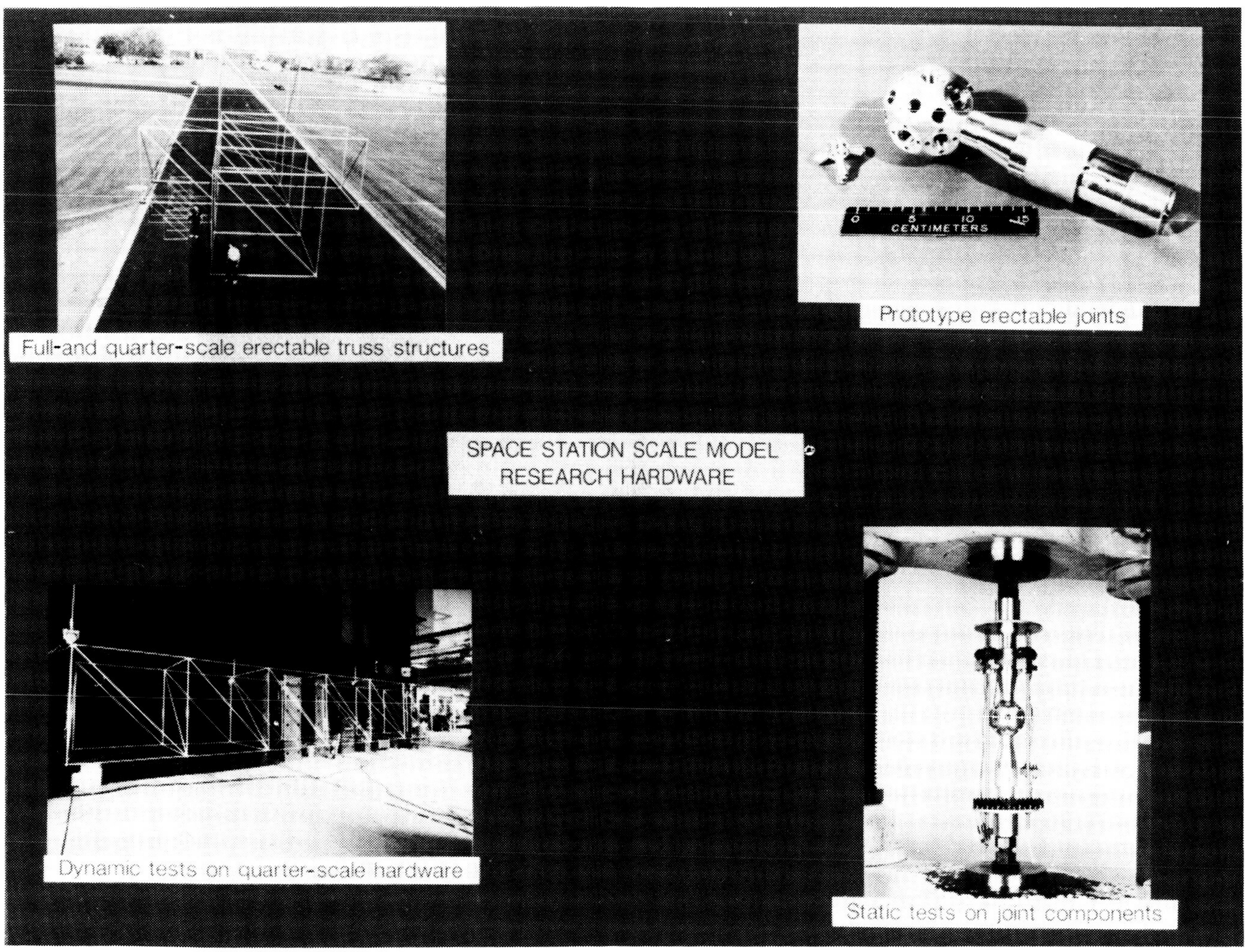
- **SPACE STATION REPLICATION IMPLIES MODEL NOT DESIGNED TO SUSTAIN UNSUPPORTED 1-G LOADS**
- **CABLE SUSPENSION SYSTEM DESIGN SHOULD NOT SIGNIFICANTLY ALTER MODEL DYNAMICS**
- **LARGE CONCENTRATED MASSES & NUMBER OF JOINTS SUGGESTS NUMEROUS CABLES REQUIRED**
- **FACILITY SIZE & MODEL SCALE FACTOR DETERMINE CLOSENESS OF PENDULUM AND STRUCTURAL FREQUENCIES**
- **"SHADOW" STRUCTURE CONCEPT PROVIDES:**
  - **MAXIMUM VERSATILITY IN CABLE ATTACHMENT LOCATIONS**
  - **EASE IN ATTACHING/DETACHING CABLES**
  - **PROVIDES ISOLATION FROM FACILITY**



EXPLORATORY HARDWARE

Some of the exploratory hardware developed and tested at Langley which is related to the Space Station and scaled models and also to COFS III is shown on this chart. Seven bays of a full-scale 15-ft erectable structure, plus seven bays of a 1/4-scale display model of the same structure, are shown in the upper left corner. A picture of the dynamics test setup for the 1/4-scale model configured as a seven-bay truss beam is shown at the lower left. At the upper right is pictured a full-scale prototype erectable joint along with a 1/4-scale model of that joint. The picture at the lower right shows the full-scale joint undergoing static characterization tests.

The results of the tests of the seven-bay 1/4-scale model truss structure and the tests of the full-scale joints are rather interesting. They will be discussed next.

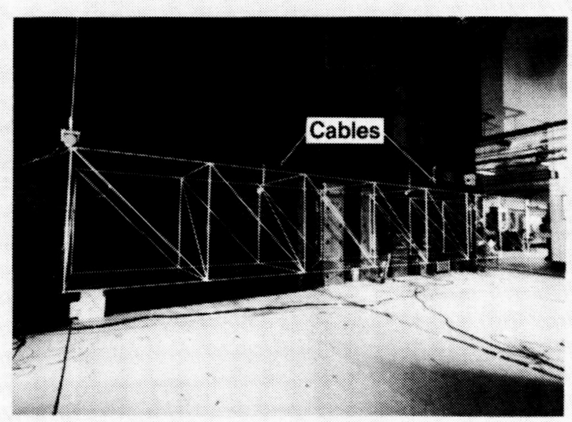


TEST AND ANALYSIS CORRELATION FOR 1/4-SCALE TRUSS

The correlation of the tests and analysis of the 1/4-scale truss revealed the importance of accounting for the local effects of the individual struts in these structures when they are lightly mass loaded. The local effects drive the global frequencies higher than a simple NASTRAN analysis predicts. A simple BUNVIS model, which is based on exact finite element technology and is equivalent to discretizing the simple NASTRAN model into smaller elements, is an improvement over the NASTRAN analysis but results in a slight overprediction. When the joint flexibilities are taken into account using estimates of the joint axial stiffness, there is an even better correlation.

As mass in the form of payloads and modules is added to this type of structure, the local effects will become less significant until at some point they will not appreciably effect the global frequencies. Exactly where that occurs has not been investigated and will probably depend on the number, masses, and placement of the payloads and modules.

Although the 1/4-scale model test results just described are encouraging, the model was not a replica of the full-scale structure. The model was built for demonstration and display purposes, not as a test article. Little attention was paid to replica scaling. Thus its dynamics properties probably do not represent the full-scale structure. But, since the model was available it provided an opportunity to obtain experience and to develop test and analysis techniques for this type structure. For these same reasons the full-scale seven-bay structure is also being tested at Langley. By testing this type of structure we will learn to account for joint effects, suspension systems interactions, and gravity effects.



Global Mode Number	Test (Frequency, Hz)	Analysis* (Frequency, Hz) Simple model Nastran	Simple model Bunvis	Refined model** Bunvis
1	77.12	49.22	82.35	77.74
2	78.62	56.62	89.41	79.15
3	83.01	64.32	95.13	83.03

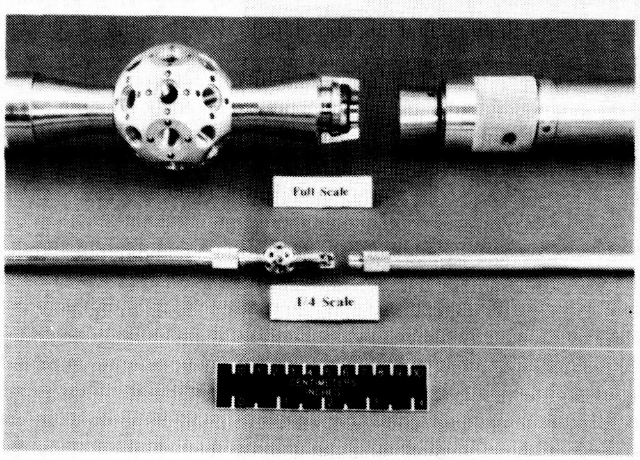
* 1 Element per member
** Joint flexibilities taken into account

JOINT AND TRUSS MEMBER SCALING EXAMPLES

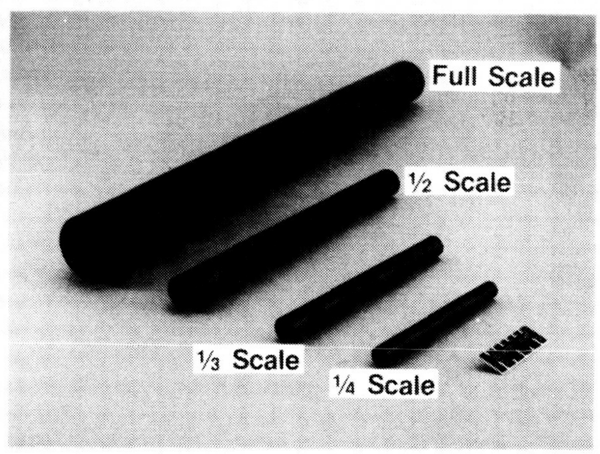
As previously mentioned, one of the major considerations for the COFS III model is replica scaling. This chart shows examples of some of Langley's initial exploratory development hardware being tested to give insight into the replica scaling issue. The picture on the left shows a full-scale prototype of one concept of a space station joint. It is identical to the one previously described. Below it is the best replica joint that could be manufactured at 1/4-scale by the same firm that built the full-scale hardware. Not shown is a 1/3-scale replica joint. Both the 1/4- and 1/3-scaled joints are undergoing characterization tests at Langley to determine how well they replicate the stiffness and damping properties of the full-scale hardware.

A similar investigation of the replica scaling of graphite/epoxy struts, is also under way. Since there were many possible variations as to ply orientation for the Space Station truss members, a simple approach was taken with these initial test specimens by having a unidirectional fiber orientation in the axial direction. This provided the opportunity to scale the thickness of the wall merely by reducing the number of plies.

Joints

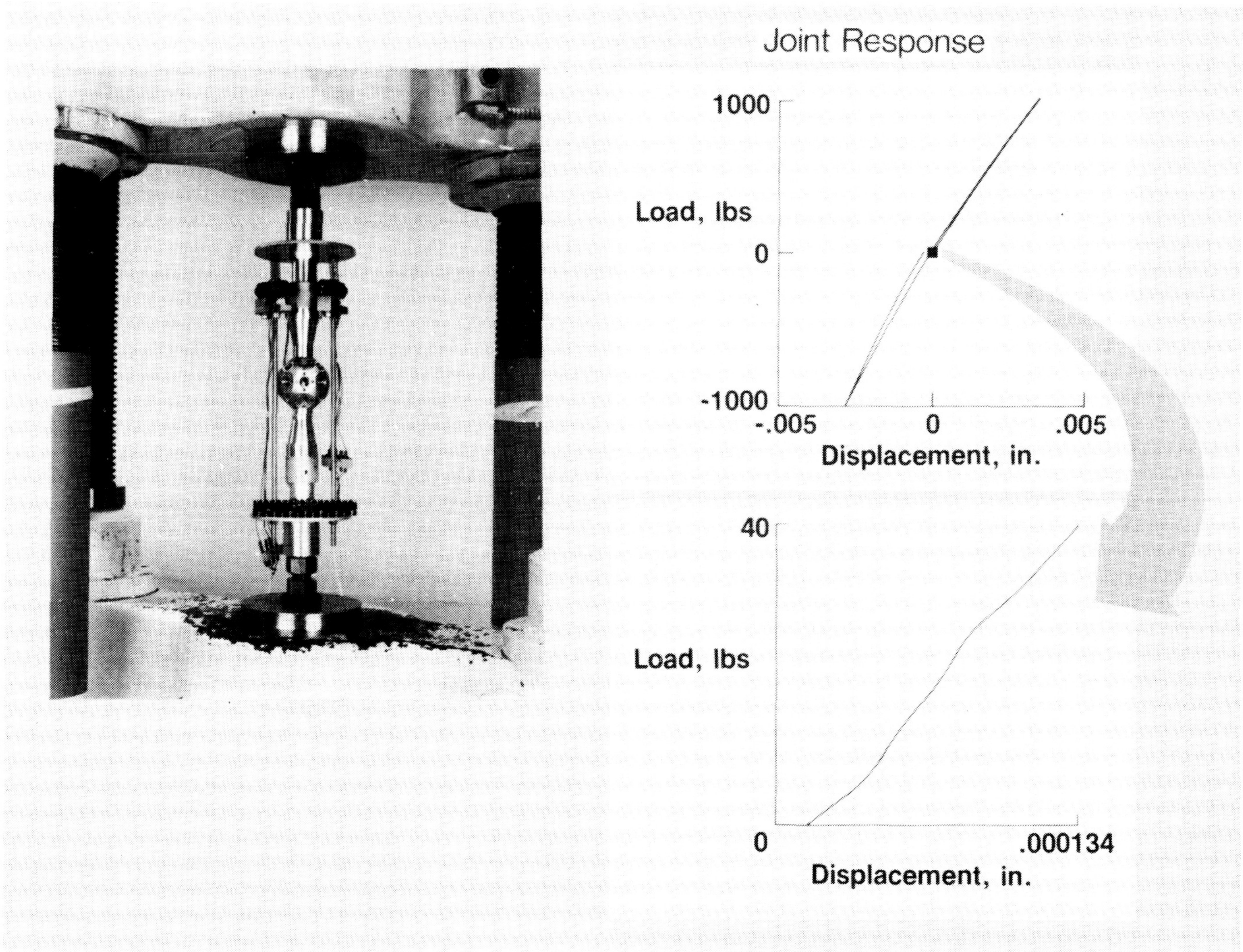


Graphite/Epoxy Tubes



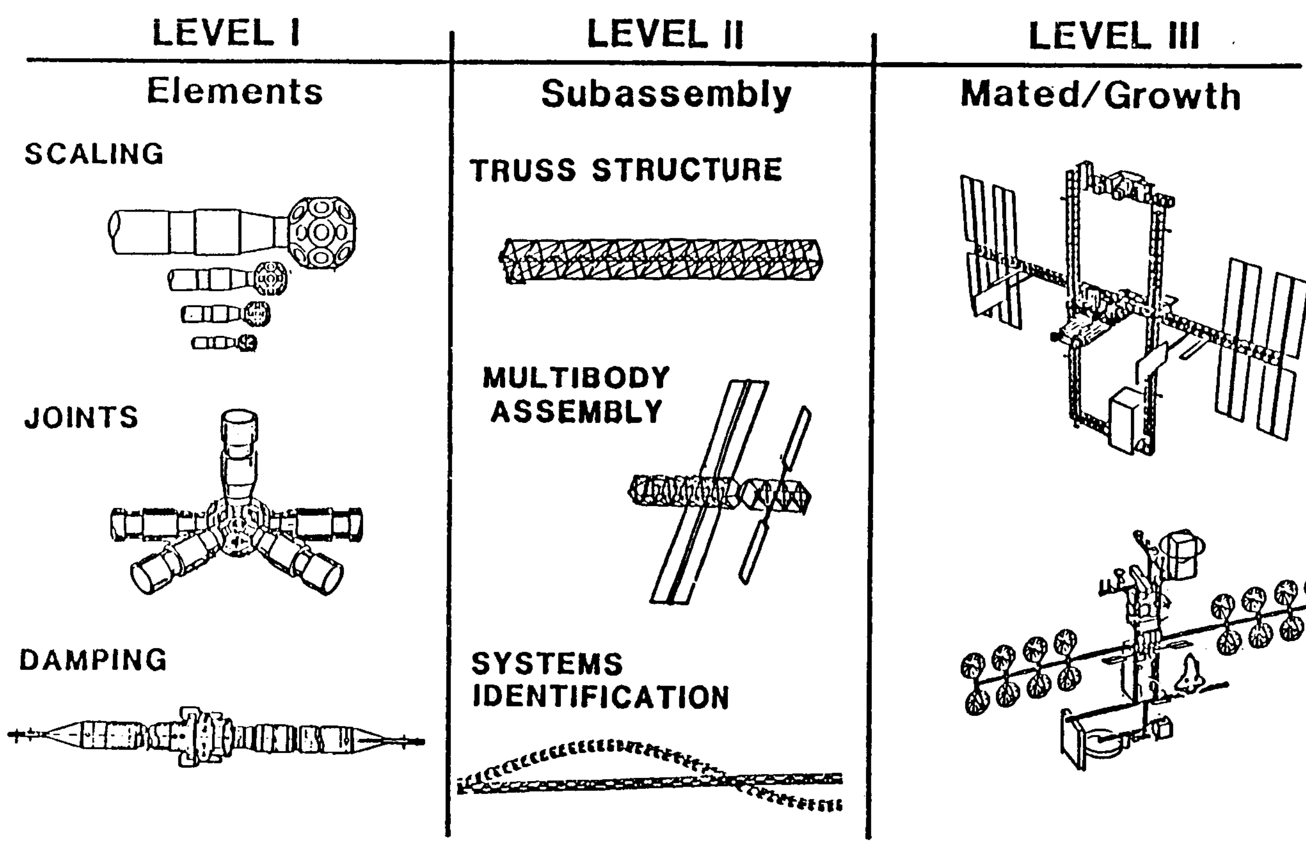
TYPICAL FULL-SCALE SS JOINT STATIC TEST DATA

Another interesting result of Langley's exploratory development involves the testing of a typical full-scale Space Station joint. The picture at the left shows the joint/end connector assembly in the static test rig. The upper graph shows a typical joint response curve which usually describes the displacement for loads of +1000 pounds. The first conclusion would be that the response is essentially linear; however, a look at a lower operating load range of 0-40 pounds, shown in the lower graph, reveals definite nonlinearities. It will be important to characterize the joint behavior at both load levels, low levels to simulate normal Space Station operations and high levels to simulate docking and reboosts.



GROUND TEST SCENARIO

This chart portrays the anticipated COFS III test scenarios. We have been discussing some of the exploratory work related to the level I tests and some initial incursions into the level II test area. When the COFS III model hardware is delivered, we will be able to test a variety of subassemblies including the proposed Structures and Assembly Verification Experiment (SAVE), which is a shuttle based experiment involving a large section of the Space Station structure. In addition we will investigate various multibody configurations including the buildup stages until we finally reach the fully mated configuration. The mated configuration will be tested extensively. Subsequent tests will include alternative growth Space Station configurations and the evaluation of the dynamics interactions of various Space Station experiments.



SUMMARY

In summary, the COFS III project is a technology project which will develop the methods for using dynamically scaled models and analysis to predict the structural dynamics of large space structures. The project uses the Space Station as a focus because it is typical of the structures of interest and provides the first opportunity to obtain full-scale on-orbit dynamics data. Finally it provides the means for developing the technology for growth Space Station and Space Station experiments.

- **TECHNOLOGY PROJECT**

  SCALE MODEL TESTS PLUS ANALYSIS → PREDICTION OF FULL-SCALE STRUCTURAL DYNAMICS

- **SPACE STATION FOCUS**

  TYPICAL STRUCTURE
  SOURCE FOR FULL-SCALE DATA

- **DEVELOPS TECHNOLOGY FOR**

  GROWTH SPACE STATION
  SPACE STATION EXPERIMENTS